NOV 3 ~ 1981

DATE ISSUED

ORNL-5787

ornl

OAK RIDGE NATIONAL LABORATORY

UNION CARBIDE

Physics Division Progress Report for Period Ending June 30, 1981

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL-5787
Distribution Category
UC-34

Contract No. W-7405-eng-26

PHYSICS DIVISION
PROGRESS REPORT
for Period Ending June 30, 1981

P. H. Stelson, Director

Date Published: November 1981

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

Reports previously issued in this series are as follows:

ORNL-2718	Period Ending March 10, 1959
ORNL-2910	Period Ending February 10, 1960
ORNL-3085	Period Ending February 10, 1961
ORNL-3268	Period Ending January 31, 1962
ORNL-3425	Period Ending May 21, 1963
ORNL-3582	Period Ending January 31, 1964
ORNL-3778	Period Ending December 13, 1964
ORNL-3924	Period Ending December 31, 1965
ORNL-4082	Period Ending December 31, 1966
ORNL-4230	Period Ending December 31, 1967
ORNL-4395	Period Ending December 31, 1968
ORNL-4513	Period Ending December 31, 1969
ORNL-4659	Period Ending December 31, 1970
ORNL-4743	Period Ending December 31, 1971
ORNL-4844	Period Ending December 31, 1972
ORNL-4937	Period Ending December 31, 1973
ORNL-5025	Period Ending December 31, 1974
ORNL-5137	Period Ending December 31, 1975
ORNL-5306	Period Ending June 30, 1977
ORNL-5498	Period Ending December 31, 1978

CONTENTS

1. HOLIFIED HEAVY-ION RESEARCH FACILITY 1

Facility Status 1

25-MV Tandem Accelerator—G. D. Alton, J. A. Benjamin, J. A. Biggerstaff, D. M. Galbraith, C. M. Jones, R. C. Juras, J. E. Mann, E. G. Richardson, N. F. Ziegler 1

SF_6 Handling System 2

Column Voltage Tests 2

Initial Operation with Beam 3

Coupled Operation 4

Current Status 4

Coupled Operation of the ORIC and the 25-MV Tandem—J. B. Ball, R. M. Beckers, T. P. Cleary, E. D. Hudson, R. S. Lord, C. A. Ludemann, J. A. Martin, N. F. Ziegler 5

Injection System 5

Beam Monitoring Diagnostic System 5

Foil Positioner 6

Beam Dynamics Computations 6

Operating Experience 8

ORIC Operations—S. W. Mosko, C. L. Viar, C. A. Ludemann, R. S. Lord, E. D. Hudson, J. W. Johnson, T. P. Cleary, H. L. Dickerson, D. M. Ezell, H. D. Hackler, C. L. Haley, N. L. Jones, R. F. Joy, S. N. Lane, C. T. LeCroy, S. N. Murray, G. A. Palmer, A. D. Higgins, E. W. Sparks, B. J. Casstevens 10

Data Acquisition System—W. H. Atkins, J. A. Biggerstaff, D. C. Hensley, W. T. Milner, R. O. Sayer, C. N. Thomas 11

Negative-Ion Source Development—G. D. Alton 12

Combination Prototype Refocus Sputter and Charge Exchange Source 12

Theoretical Analysis of Negative-Ion Source Performance 13

Experimental Facilities—R. L. Robinson, C. B. Fulmer, E. E. Gross, M. L. Halbert, D. C. Hensley, J. W. Johnson, N. R. Johnson, R. S. Lord, W. T. Milner, R. L. Mlekodaj, C. D. Moak, F. E. Obenshain, E. W. Spejewski 14

HHIRF Users' Support—R. L. Robinson, R. P. Cumby, J. W. Johnson, R. W. Miles, W. T. Milner, C. N. Reed, J. K. Thacker, C. N. Thomas 15

Users' Activities--R. L. Robinson 20

ORIC Superconducting Conversion Studies--J. B. Ball, J. K. Ballou, R. L. Brown, T. P. Cleary, W. H. Gray, E. D. Hudson, P. S. Litherland, R. S. Lord, C. A. Ludemann, C. H. Malarkey, J. A. Martin, G. S. McNeilly, S. W. Mosko, S. W. Schwenterly, T. A. Welton 22

Introduction 22

Beam Energies--Present and Future 22

Technical Details of the Conversion 23

Magnetic Field Design and Analysis 23

Superconducting coil and cryostat 24

Beam extraction system 25

Beam Transport and Shielding Modification 29

2. NUCLEAR PHYSICS 30

Introduction 30

Light-Heavy-Ion Scattering--C. B. Fulmer, R. L. Auble, J. B. Ball, F. E. Bertrand, N. M. Clarke, C. D. Goodman, E. E. Gross, D. C. Hensley, S. Mukhopadhyay, G. R. Satchler, M. Steeden, J. R. Wu 30

^{6}Li Scattering 31

^{10}B and ^{11}B Scattering 32

Fusion Cross Sections for Light Systems--J. Gomez del Campo, D. Shapira, Y.-D. Chan, M. E. Ortiz, D. DiGregorio, J. L. C. Ford, Jr., J. A. Biggerstaff, P. H. Stelson, R. A. Dayras, R. G. Stokstad, J. P. F. Sellschop, R. Parks, D. Weisser 34

The ^{26}Al System 34

The ^{24}Mg System 35

The ^{27}Al System 37

The ^{40}Ca System 37

Summary 38

Reaction Products at Backward Angles from ^{28}Si + ^{12}C--D. Shapira, R. Novotny, J. L. C. Ford, Jr., K. A. Erb, Y. D. Chan, J. C. Peng, J. D. Moses 39

Study of Deep-Inelastic Processes in Light-Heavy-Ion Collisons--D. Shapira, R. Novotny, J. L. C. Ford, Jr., K. A. Erb, Y. D. Chan 41

Correlated Mass and Charge Distributions from Ne + Al Reactions--F. E. Obenshain, R. L. Ferguson, F. Plasil, R. L. Robinson, D. Shapira, A. H. Snell, G. R. Young 43

Correlated Charge and Mass Distributions from Reactions of ^{56}Fe with ^{58}Ni and ^{64}Ni--H. C. Britt, M. Blann, P. R. Christensen, B. H. Erkkila, R. L. Ferguson, A. Gavron, O. Hansen, Y. Patin, F. Plasil, S. Pontoppidan, J. Randrup, R. H. Stokes, F. Videback, M. P. Webb, G. R. Young 46

Fission Barrier of ^{153}Tb--F. Plasil, R. L. Ferguson, R. L. Hahn, F. E. Obenshain, F. Pleasonton, G. R. Young 47

Mass and Charge Distributions from Reactions Between ^{86}Kr and ^{124}Sn--M. Blann, H. C. Britt, B. H. Erkkila, R. L. Ferguson, P. D. Goldstone, H. H. Gutbrod, F. Plasil, R. H. Stokes 49

Reactions of 142-MeV ^{16}O with ^{146}Nd—R. Novotny, J. R. Beene, M. L. Halbert, D. C. Hensley, J. H. Barker, D. G. Sarantites, M. Jääskeläinen, R. Woodward 49

Energetic $Z = 1,2$ Particles from Heavy-Ion-Induced Reactions—R. L. Robinson, R. L. Auble, C. B. Fulmer, J. B. Ball, F. E. Bertrand, R. L. Ferguson, J. Gomez del Campo, I. Y. Lee, M. J. Martin, G. R. Young, J. R. Wu, J. C. Wells, H. Yamada 53

Neutron Emission in Reactions Induced with Carbon, Oxygen, and Neon Ions—J. R. Beene, B. Cheynis, R. L. Ferguson, A. Gavron, K. Geoffroy Young, M. Jääskeläinen, C. F. Maguire, F. E. Obenshain, G. A. Petitt, F. Plasil, D. G. Sarantites, G. R. Young 55

Neutrons Associated with Evaporation Residues 56

Neutrons Associated with Projectile-Like Products in Reactions Between C and Gd 57

Neutron Emission in Deeply Inelastic Collisions of ^{16}O with ^{93}Nb at 204 MeV 58

Neutrons Associated with Fission Fragments 58

Alpha-Particle Emission in Deeply Inelastic Reactions of 204-MeV ^{16}O with ^{93}Nb—G. R. Young, R. L. Ferguson, A. Gavron, D. C. Hensley, C. F. Maguire, F. E. Obenshain, G. A. Petitt, F. Plasil, A. H. Snell, M. P. Webb 59

Analysis of Alpha Emission Associated with Deeply Inelastic Reactions—G. R. Young 61

Ambiguities in the Inference of Precompound Emission from Excitation-Function Analysis—M. Blann, R. L. Ferguson 62

Incomplete Fusion Reactions—J. R. Beene, M. L. Halbert, D. C. Hensley, J. H. Barker, D. G. Sarantites, K. Geoffroy Young, M. E. Jääskëlainen, R. Woodward 63

Localized ℓ Window from Partial Fusion Reactions Accompanied by Proton, Deuteron, and Triton Emission—H. Yamada, C. F. Maguire, J. H. Hamilton, A. V. Ramayya, D. C. Hensley, M. L. Halbert, R. L. Robinson, F. E. Bertrand, R. Woodward 64

Studies of the Fission Isomer ^{240M}Am Using Laser Techniques 66

Optical-Isomer Shift for $^{240M}Am(SF)$ 66

Hyperfine Optical Pumping of $^{240M}Am(SF)$ 66

Laser-Induced Nuclear Polarization of Isomeric States of Fr Isotopes—J. R. Beene, C. E. Bemis, Jr., J. P. Young 67

Spontaneous-Fission Branching in the Decay of $^{259}104$—C. E. Bemis, Jr., P. F. Dittner, R. L. Ferguson, D. C. Hensley, F. Plasil, F. Pleasonton 68

Production of Heavy Actinides and Attempted Production of Superheavy Elements in the $^{238}U + ^{248}Cm$ Reaction—R. L. Ferguson, R. L. Hahn, E. K. Hulet, R. W. Lougheed, J. M. Nitschke, W. Brüchle, H. Gäggeler, J. V. Kratz, M. Schädel, K. Sümmerer, G. Wirth, G. Herrmann, P. Peuser, R. Stakemann, G. Tittel, N. Trautman 68

High-Spin States in $Z = 32$ to 36 Nuclei—R. L. Robinson, J. H. Hamilton, A. V. Ramayya, A. Y. Ahmed, A. J. Caffrey, A. P. de Lima, E. de Lima, H. Kawakami, H. J. Kim, C. F. Maguire, W. T. Milner, R. B. Piercey,

S. Ramavataram, A. C. Rester, R. M. Ronningen, D. L. Sastry, R. O. Sayer, R. Soundranayagam, Z. J. Sun, B. Van Nooijen, J. C. Wells, Jr., H. Yamada, Z. Z. Zhao 70

Even-Even Nuclei 72

Odd-A-Nuclei 73

Odd-Odd Nuclei 73

Isomeric and High-Spin States of ^{94}Tc and the Search for Yrast Isomers Near $N = 50$—I. Y. Lee, N. R. Johnson, F. K. McGowan, G. R. Young, M. W. Guidry, S. W. Yates 74

High-Spin Isomers in the $N = 85$ Region—G. R. Young, C. Baktash, P. A. Butler, D. Cline, D. Elmore, R. Fridieu, D. Horn, R. Ledoux, C. L. Lister, J. Srebrny 75

A High-Spin Isomer in ^{148}Tb—J. R. Beene, M. L. Halbert, D. C. Hensley, J. H. Barker, D. G. Sarantites, L. Westerbrg, K. Geoffroy Young, J. Jastrzebski 77

Energy-Energy Correlation Measurements in the Gamma-Ray Continuum—I. Y. Lee, S. A. Hjorth, Th. Lindblad, L. L. Riedinger, R. O. Sayer, D. R. Haenni, N. R. Johnson, W. T. Milner, R. L. Robinson, G. R. Young, S. W. Yates 80

Backbending of the Moment of Inertia Above the Known Spin Limit in ^{158}Er—H. Yamada, A. Ahmed, J. D. Cole, M. L. Halbert, J. H. Hamilton, D. C. Hensley, M. Herath-Banada, S. Hjorth, C. F. Maguire, R. B. Piercey, A. V. Ramayya, R. L. Robinson 81

Lifetimes of Rotational States in ^{154}Sm—N. R. Johnson, R. J. Sturm, R. O. Sayer, M. W. Guidry, E. Eichler, D. C. Hensley, N. C. Singhal 83

Measurements of the Reduced Transition Probabilities in ^{152,154,156,158,160}Gd with ^{136}Xe Projectiles—I. Y. Lee, T. T. Sugihara, E. L. Robinson, N. R. Johnson, M. W. Guidry, R. M. Diamond, F. S. Stephens 84

High-Spin States in ^{160}Yb—L. L. Riedinger, S. A. Hjorth, I. Y. Lee, D. R. Haenni, N. R. Johnson, W. K. Luk, R. L. Robinson 86

New Yrast Bands in ^{162,164}Hf—L. L. Riedinger, M. P. Fewell, J. S. Hattula, I. Y. Lee, H. Ower, D. R. Haenni, S. A. Hjorth, N. R. Johnson 87

Moments of Inertia of Quasi-Particle Bands—S. Frauendorf, L. L. Riedinger 88

Lifetime Measurements in ^{162}Dy—M. W. Guidry, N. R. Johnson, I. Y. Lee, R. M. Diamond, F. S. Stephens 90

High-Spin Properties of ^{164}Er—N. R. Johnson, I. Y. Lee, L. L. Riedinger, A. C. Kahler, R. S. Simon, P. Colombani, R. M. Diamond, R. D. Hichwa, S. W. Yates, E. Eichler, M. W. Guidry, D. Cline, P. A. Butler, F. S. Stephens, R. M. Ronningen, J. H. Hamilton, E. L. Robinson 91

Reduced $M1$, $E1$, $E2$, and $E3$ Transition Probabilities for Transitions in $^{156-160}$Gd and $^{160-164}$Dy—F. K. McGowan, W. T. Milner 93

Interacting Boson Approximation Model Analysis of $E2$ Transition Probabilities for Transitions in $^{166-170}$Er—F. K. McGowan 93

Coulomb Excitation Study of $^{182,184,186}W$ Isotopes—Ph. Hubert, H. Sergolle, J. M. La Grange, C. Roulet, P. Colombani, J. Vanhorenbeeck, N. R. Johnson 95

Interpretation of the 21-ns Isomer in ^{190}Hg As$(\nu i_{13/2})^2$ from a G-Factor Measurement—S. A. Hjorth, J. R. Beene, D. R. Haenni, Felix E. Obenshain, I. Y. Lee, C. Roulet, Noah R. Johnson, G. R. Young 96

Coulomb Excitation of States in $^{191,193}Ir$ and a Test of the Particle-Asymmetric-Rigid-Rotor-Model Description of These States—F. K. McGowan, I. Y. Lee, M. W. Guidry, R. M. Diamond, J. X. Saladin, N. R. Johnson, W. T. Milner, C. Roulet, F. S. Stephens, A. A. Hussein 98

Columb Excitation of Rotational States in ^{243}Am and Ground-State Quadrupole Moment—C. E. Bemis, Jr., F. K. McGowan, J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, P. H. Stelson 100

Precision Mass Measurements Utilizing Beta End Points—D. M. Moltz, F. T. Avignone III, B. G. Ritchie, K. S. Toth, H. Noma, B. D. Kern 102

Identification of ^{144}Tb and ^{145}Tb; Levels in the $N = 81$ Nucleus ^{145}Gd—K. S. Toth, C. R. Bingham, D. C. Sousa, A. C. Kahler, D. R. Zolnowski 104

Contradiction of the Reported Anomaly in Alpha-Decay Rates of Lead Isotopes—K. S. Toth, Y. A. Ellis-Akovali, D. M. Moltz, C. R. Bingham, H. K. Carter, R. L. Mlekodaj, E. H. Spejewski, M. A. Ijaz, J. Lin, D. C. Sousa 107

Studies Near $N = 82$; Evidence for a Shell Closure at $Z = 64$—K. S. Toth, C. R. Bingham, H. K. Carter, D. C. Sousa 110

Energy Loss and Straggling of 7.3-MeV-Per-Nucleon ^{84}Kr Ions—R. L. Hahn, K. S. Toth, R. L. Ferguson, F. Plasil 112

Stopping Powers 112

Straggling 113

The $^{12}C(p,n)$ ^{12}N Reaction at 120, 160, and 200 MeV—J. Rapaport, T. Taddeucci, C. Gaarde, C. D. Goodman, C. C. Foster, C. A. Goulding, D. Horen, E. Sugarbaker, T. G. Masterson, D. Lind 114

Search for Isobaric Analogs of $M1$ States and Giant Spin-Flip Resonances in the $^{208}Pb(p,n)$ Reaction—D. J. Horen, C. D. Goodman, C. C. Foster, C. A. Goulding, T. G. Masterson, M. B. Greenfield, J. Rapaport, D. E. Bainum, E. Sugarbaker, F. Petrovich, W. G. Love 115

Observation of Giant Particle-Hole Resonances in $^{90}Zr(P,n)$ ^{90}NB—D. E. Bainum, J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, C. A. Goudling 116

Energy Systematics of the Giant Gamow-Teller Resonance and a Charge-Exchange Dipole Spin-Flip Resonance—D. J. Horen, C. D. Goddman, D. E. Bainum, C. C. Foster, C. Gaarde, C. A. Goudling, M. B. Greenfield, J. Rapaport, T. Taddeucci, E. Sugarbaker, T. Masterson, S. M. Austin, A. Galonsky, W. Sterrenburg 117

Excitation of Giant Resonances by Inelastic Scattering of 200-Mev Portons—F. E. Bertrand, E. E. Gross, D. J. Horen, J. R. Wu, J. Tinsley, D. K. McDaniels, L. W. Swenson, R. Liljestrand 118

Giant Multipole Resonances from Inelastic Scattering of 152-MeV Alpha Particles—F. E. Bertrand, G. R. Satchler, D. J. Horen, J. R. Wu, A. D. Bacher, G. T. Emery, W. P. Jones, D. W. Miller, A. ven der Woude 121

The Fission Probability of ^{239}U at High Excitation Measured with the ^{238}U(α, ^{3}Hef) Reaction—J. R. Wu, J. R. Beene, C. E. Bemis, Jr., F. E. Bertrand, E. E. Gross, D. J. Horen, W. P. Jones 121

Fission Decay of the Giant Quadrupole Resonance in ^{238}U—E. E. Gross, J. R. Benne, C. E. Bemis, Jr., F. E. Bertrand, D. J. Horen, J. R. Wu, W. P. Jones 121

The Reaction $\pi^+ + d \rightarrow p + p$ at 20 to 65 MeV—B. G. Ritchie, R. D. Edge, D. J. Malbrough, B. M. Preedom, F. E. Bertrand, E. E. Gross, F. E. Obenshain, J. R. Wu, M. Blecher, K. Gotow, R. L. Burman, R. Carlini, M. E. Hamm, M. J. Leitch, M. A. Moinester 122

Positive-Pion–Nucleus Elastic Scattering at 20 MeV—F. E. Obenshain, F. E. Bertrand, M. Blecher, R. L. Burman, R. D. Edge, K. Gotow, E. E. Gross, M. Hamm, N. W. Hill, M. J. Leitch, M. A. Moinester, B. M. Preedom, R. P. Redwine, J. R. Wu 123

Elastic Scattering of π^+ and π^- from ^{40}Ca at 64.8 MeV—F. E. Bertrand, E. E. Gross, S. H. Dam, R. D. Edge, B. M. Preedom, M. Hamm, R. L. Burman, R. Carlini, R. P. Redwine, M. A. Yates, M. Blecher, K. Gotow, M. A. Moinester 125

Elastic Scattering of $\pi^{\pm}$ at 80 MeV—F. E. Obenshain, F. E. Bertrand, M. Blecher, R. L. Burman, R. D. Edge, K. Gotow, E. E. Gross, M. Hamm, N. W. Hill, M. J. Leitch, M. A. Moinester, B. M. Preedom, R. P. Redwine, J. R. Wu 128

A Windowless Supersonic Gas-Jet Target—J. L. C. Ford, Jr., D. Shapira, R. Novotny, R. L. Parks, S. T. Thornton 128

Development of Polarized Targets for Heavy-Ion Reaction Studies—J. R. Beene, C. E. Bemis, Jr., J. L. C. Ford, Jr., K. A. Erb, D. Shapira 132

The Spin Spectrometer—D. G. Sarantites, M. Jääskeläinen, R. Woodward, J. T. Hood, F. A. Dilmanian, M. L. Halbert, D. C. Hensley, J. H. Barker, R. Novotny, D. Pelte 133

Detector Elements 134

Electronics and Data Acquisition 135

Beam Transport 135

Background Radiation 136

Neutron Response 136

Computer Processing 137

First Experiments 137

Hybrid Ionization Counters—D. Shapira, J. L. C. Ford, Jr., J. L. Blankenship, R. Novotny, T. P. Sijoreen 139

Large—Area Ionization Chamber—R. Novotny 140

A Vertical-Drift Focal-Plane Detector—J. L. C. Ford, Jr., J. L. Blankenship, T. P. Sjoreen, F. E. Bertrand, D. C. Hensley, M. V. Hynes 142

A Constant-Fraction Timing Discriminator for the Vertical-Drift Chamber—J. L. Blankenship 144

Large Gas Telescope—J. L. Blankenship, B. Cheynis, C. A. Reed, A. H. Snell 145

Avalanche Detector Development—I. Y. Lee, G. R. Young, N. R. Johnson, F. E. Obenshain, R. Novotny 145

Wire Stretcher Apparatus—I. Y. Lee, G. R. Young, J. W. Johnson 147

A Doppler-Shift Recoil-Distance Device for Use with an NaI Sum Spectrometer—N. R. Johnson, J. W. Johnson, I. Y. Lee, J. E. Weidley, D. R. Haenni, J. R. Tarrant 147

The Helium-Jet-Coupled Mass Separator: Advances and Directions—D. M. Moltz, K. S. Toth 149

Heavy-Ion Applications—S. Raman, C. R. Vane, R. L. Auble, L. D. Hulett, Jr., S. Kahane, H. J. Kim, G. Lapicki, F. D. McDaniel, W. T. Milner, G. D. O'Kelley, T. Rosseel, O. Shahal, G. G. Slaughter, S. L. Varghese, J. P. Young 151

3. THE UNISOR PROGRAM 153

Recent Improvements in the Unisor Facility—R. L. Mlekodaj, E. H. Spejewski, E. F. Zganjar, B. G. Ritchie, H. K. Carter, J. D. Cole, F. T. Avigonone III, H. Noma 153

Ion Sources 153

Targets 153

Separator 154

Isotope Collection Systems 154

Detection Systems 155

Data Acquisition 155

Development of a Laser Spectroscopy Facility—H. K. Carter, C. R. Bingham, D. J. Pegg, M. L. Gaillard, P. M. Griffin, R. L. Mlekodaj, E. J. Spejewski, J. D. Cole, E. F. Zganjar 155

Atomic Lifetimes by Rapid Doppler Tuning—M. L. Gaillard, D. J. Pegg, C. R. Bingham, H. K. Carter 157

Dynamical Supersymmetries and the Positive Parity States in ^{193}Au—J. L. Wood 158

Radioactive Decay of ^{192}Tl and ^{192}Pb—D. C. Sousa, L. L. Riedinger, C. R. Bingham, F. E. Turner, K. S. Toth, H. K. Carter, R. L. Mlekodaj, E. H. Spejewski 159

Studies of ^{193,195,197}Pb, Decay—L. L. Collin L. L. Riedinger, G. D. O'Kelley, A. C. Kahler, C. R. Bingham, J. L. Wood, R. W. Fink, E. H. Spejewski, H. K. Carter, R. L. Mlekodaj, E. F. Zganjar, J. H. Hamilton 161

Excited States in ^{186,188}Pt—J. D. Cole, E. F. Zganjar, J. L. Wood, J. H. Hamilton 163

A Unique Ground-State Structure: The Neutron-Deficient Even-Pt Isotopes and Particle-Core Coupling in ^{187}Au—M. A. Grimm, J. L. Wood, J. D. Cole, E. F. Zganjar 163

Strongly Deformed States Near Closed Shells: Excited States in ^{187,189}Hg—J. G. Cole, E. F. Zganjar, J. W. Wood 165

A Shape Transition in the Neutron-Deficient ODD-Pt Isotopes—B. E. Gnade, R. A. Braga, J. L. Wood 166

Excited States in ^{189}Tl—E. F. Zganjar, J. D. Cole, J. L. Wood, L. L. Riedinger, G. M. Gowdy 166

Decay of ^{199m,g}Po: Isomeric Transitions in ^{199}Po and ^{199}Bi—C. R. Bingham, R. E. Stone, L. L. Riedinger, R. W. Lide, H. K. Carter, R. L. Mlekodaj, E. H. Spejewski 167

Level Schemes of ^{202,204}Po—R. G. Helmer, C. W. Reich, A. J. Caffrey, M. P. M. Ramos, C. R. Bingham, L. L. Riedinger, R. W. Lide, B. G. Ritchie 168

Barium Isotope Production Cross Sections in ^{12}C-Induced Reactions—E. F. Zganjar, J. D. Cole, R. G. Helmer, H. K. Carter, R. L. Mlekodaj, E. H. Spejewski 169

4. NEUTRON PHYSICS 170

Introduction 170

Model-Independent Optical Phase Shifts from High-Resolution Neutron Cross Sections—C. H. Johnson, R. R. Winters, W. M. MacDonald 170

High-Resolution Study of the ^{204}Pb + n Reaction—D. J. Horen, J. A. Harvey, N. W. Hill 172

^{206}Pb + n Resonances for E = 600 to 900 keV—D. J. Horen, J. A. Harvey, N. W. Hill 172

Neutron Total Cross Sections for Neutron Filter Applications—J. A. Harvey, N. W. Hill, J. R. Harvey 173

Measurement of Neutron Total Cross Sections at Orela to 80 MeV—D. C. Larson, J. A. Harvey, N. W. Hill 174

Neutron Resonance Study of ^{86}Kr—B. Fogelberg, R. L. Macklin, J. A. Harvey, S. Raman, P. H. Stelson 174

Statistical Properties of Complex States of the Isotopes of Zn—J. B. Garg, V. K. Tikku, J. A. Harvey, R. L. Macklin, J. Halperin 175

Neutron Capture Cross Sections Extended to 2 MeV—R. L. Macklin, R. R. Winters 175

Fission Product Neutron Capture Cross Section—R. L. Macklin, R. R. Winters 176

^{238}U Inelastic Neutron Scattering—R. R. Winters, N. W. Hill, R. L. Macklin, J. A. Harvey, D. K. Olsen, G. L. Morgan 176

Sammy: A Computer Model for Multilevel R-Matrix Fits to Neutron Data Using Bayes's Equations—Nancy M. Larson, Francis G. Perey 177

Majority-Logic NE-110 Detector for keV Neutrons—N. W. Hill, J. A. Harvey, D. J. Horen, G. L. Morgan, R. R. Winters 177

Thermal and Resonance Neutron Capture Gamma-Ray Measurements—S. Raman, G. G. Slaughter, R. F. Carlton, J. A. Harvey, A. Z. Hussein, E. T. Jurney, S. Kahane, M. J. Kenny, D. A. McClure, W. Ratynski, O. Shahal, R. R. Spencer, J. S. Tang, J. C. Wells, Jr. 178

Thermal-Neutron Absorption Cross Section of Sulfur and the ^{252}Cf $\bar{\nu}$ Problem—E. T. Jurney, S. Raman, R. R. Spencer 178

Direct Capture in the ^{34}S$(n,\gamma)^{35}$S Reaction with Thermal Neutrons—R. F. Carlton, S. Raman, E. T. Jurney 179

The $^{36}S(n,\gamma)^{37}S$ Reaction with Thermal Neutrons—S. Raman W. Ratynski, E. T. Jurney 180

Parity of the 398-eV Resonance in ^{35}Cl—A. Z. Hussein, S. Raman, J. A. Harvey 181

Test of Axel-Brink Predictions in ^{174}Yb and ^{168}Er—S. Raman, O. Shahal, S. Kahane, G. G. Slaughter 181

The Use of Oxide Targets in 2-keV Average Neutron Capture Measurements—J. S. Tang, S. Raman 183

Anomalous Transitions in ^{144}Nd and ^{146}Nd in "2-kev" (n,γ) Measurements—S. Raman, O. Shahal, D. A. McClure, M. J. Kenny 184

Measurement of the Fission Cross Section of ^{241}Am—J. W. T. Dabbs, C. H. Johnson, C. E. Bemis, Jr., K. Rush 185

Measurement of the Neutron-Induced Fission Cross Section of ^{242m}Am—J. W. T. Dabbs, C. E. Bemis, Jr., R. J. Dougan, R. W. Hoff, S. Raman 186

Measurement of the Fission Cross Section of ^{249}Cf at ORELA—J. W. T. Dabbs, C. E. Bemis, Jr. 187

Fission and Total Cross Sections of ^{231}Pa—S. Plattard, G. F. Auchampaugh, N. W. Hill, G. deSaussure, J. A. Harvye, R. B. Perez 188

Neutron Capture Cross Section Measurements on Actinide Nuclei—L. W. Weston, J. H. Todd 189

Parameters of Neutron Resonances of ^{249}Cf—R. F. Carlton, J. A. Harvey, N. W. Hill, M. S. Pandey, R. W. Benjamin 189

Prompt $\bar{\nu}p$ of ^{242}Cm—J. Halperin, C. E. Bemis, Jr., J. W. T. Dabbs, B. J. Ketelle, R. W. Stoughton, R. W. Hoff, R. J. Dougan 190

Measurement of Fission Cross Section of Spontaneously Fissioning Actinides—H. T. Maguire, C. Stopa, D. R. Harris, R. C. Block, R. E. Slovacek, R. W. Hoff, R. Lougheed, J. W. T. Dabbs 190

Actinide Calculations; Impact of Actinide Cross-Section Measurements—C. R. Weisbin, D. Gilai, M. L. Williams 190

Actinide Newsletter—S. Raman 191

Oak Ridge Electron Linear Accelerator—H. A. Todd, T. A. Lewis, J. A. Harvey, R. W. Peelle 191

Experimental and Calculational Analyses of Actinide Samples Irradiated in EBR-II—S. Raman, P. H. Stelson, J. H. Cooper, D. Gilai, W. R. Laing, R. L. Walker, M. L. Williams 191

U.S./U.K. Higher Actinide Irradiations in the Dounreay PFR—S. Raman, H. L. Adair, J. L. Botts, J. H. Cooper, E. H. Kobisk, R. Pope, T. C. Quinby, R. L. Walker 192

5. THEORETICAL PHYSICS 194

Introduction—J. B. McGrory 194

Nuclear Structure Theory—G. Leander, J. B. McGrory 194

Shell-Model Calculations of $B(M1)$ Strengths in the Calcium Isotopes and the Quenching of the Spin Operator—J. B. McGrory, B. H. Wildenthal 194

Isotope Shifts in the Pb Isotopes—J. B. McGrory 195

Nuclear Direct Reactions—G. R. Satchler 195
Folded Potentials—G. R. Satchler, W. G. Love 195
Heavy-Ion Scattering—S. Mukhopadhyay, G. R. Satchler, M. J. Rhoades-Brown 196
Dynamic Polarization Potential for $^{12}C + ^{12}C$ — R. Wolf, O. Tanimura, U. Mosel, G. R. Satchler 197
Giant Resonances—G. R. Stachler 197
Heavy-Ion Direct Reactions—M. J. Rhoades-Brown 197
Quantum-Mechanical and Classical-Limit Coupled-Channels Calculations for Very Heavy Systems—M. J. Rhoades-Brown, R. J. Donangelo, M. W. Guidry, R. E. Neese 197
Angular Localization and Approximations to the Deformed Nuclear Potential in Heavy-Ion Reactions—R. J. Donangelo, M. W. Guidry, R. E. Neese, M. J. Rhoades-Brown 198
Classical Limits for Complex Optical Potentials—M. J. Rhoades-Brown, R. Y. Cusson, P. G. Reinhardt 199
Multichannel Analysis Including Mutual Excitation—M. J. Rhoades-Brown 200
Studies of Heavy-Ion Collisons in the Time-Dependent Hartree-Fock Approximation—K. T. R. Davies 200
TDHF Studies of Kr-Induced Reactions—K. T. R. Davies, K. R. Sandhya Devi, S. E. Koonin, M. R. Strayer 200
TDHF Calculations of $^{136}Xe + ^{209}Bi$—A. K. Dhar, B. S. Nilsson, K. T. R. Davies, S. E. Koonin 203
Results of TDHF Calculations of $^{16}O + ^{93}Nb$ at $E_{lab} = 204$ MeV, Including Preequilibrium Emission of Nucleons—K. R. Sandhya Devi, M. R. Strayer, K. T. R. Davies, S. E. Koonin, A. K. Dhar, J. M. Irvine 204
Transformations between Harmonic Oscillator Wave Functions in Different Coordinate Bases—K. T. R. Davies, S. J. Krieger 205
Effect of Dissipation on the Eigensolution near the Fission Saddle Point—K. T. R. Davies, J. R. Nix, A. J. Sierk 206
Nuclear Dynamics from a Microscopic and a Macroscopic Viewpoint—C. Y. Wong 206
Elastic Nuclear Vibrations—C. Y. Wong, N. Azziz 206
Extended TDHF Calculations—C. Y. Wong, K. T. R. Davies 207
Mean Field Effects in Intermediate-Energy (about 200 MeV/A) $^{16}O + ^{40}Ca$ Collisions—C. Y. Wong, K. T. R. Davies 207
Studies of Transverse Momentum Widths in Intermediate-Energy Heavy-Ion Collisions—K. van Bibber, C. Y. Wong 207
Fragmentation and Hard-Scattering Processes in Relativistic Heavy-Ion Collisions—C. Y. Wong, R. Blankenbeeler 207
A Basic Distribution Model for Intermediate-Energy Heavy-Ion Collisions—C. Y. Wong 207
The Unisor Nuclear Structure Theory Program—G. A. Leander 208
Transitional Nuclei 208
Deformed Nuclei 208

Nuclei at Very High Spins 208
Theoretical Atomic Physics—R. L. Becker, C. Bottcher 208
Contributions of Multielectron Processes to Innershell Charge Transfer and Vacancy Production—R. L. Becker, A. L. Ford, J. F. Reading 208
A New Version of Atomic-Orbital Coupled-Channels Theory, the "One-and-a-Half-Center Expansion"—J. F. Reading, A. L. Ford, and R. L. Becker 209
Nonstatistical Theory of Multiple Vacancy Production in Atomic Collisions—R. L. Becker, J. F. Reading, A. L. Ford 209
Initial-*l* Dependence of Ion-Rydberg-Atom Cross Sections—R. L. Becker and A. D. MacKellar 210
Numerical Solution of the Schrödinger Equation—C. Bottcher 210
Autionizing Contributions to Electron Impact Ionization of Positive Ions—C. Bottcher, D. C. Griffin, M. S. Pindzola 211
Charge Transfer to Highly Stripped Ions at Low Energies—C. Bottcher, T. G. Heil 212
Response of Molecules to Coherent Radiation—C. Bottcher, C. Feuillade 212

6. NUCLEAR DATA PROJECT—S. J. Ball, Y. A. Ellis-Akovali, W. B. Ewbank, B. Harmatz, F. W. Hurley, M. J. Martin, M. R. McGinnis, J. T. Miller, S. Ramavataram, M. R. Schmorak 214
Activities 214
Nuclear Structure References (Responsibility Now of BNL/NNDC) 214
Data Evaluation 214
Publication Activities 214
Special Activities 214

7. ATOMIC AND PLASMA PHYSICS GROUP 216
Overview 216
Controlled Fusion Atomic Data Center—D. H. Crandall, B. J. Farmer, P. M. Hafford, C. F. Barnett, D. C. Gregory, F. W. Meyer, R. A. Phaneuf 216
Dissociation of Triatomic Hydrogen Molecular Ions in H_2—C. F. Barnett 217
Beam Specie Analyzer for Intense Neutral Beams—C. F. Barnett, J. A. Ray, R. R. Feezell 218
Electron Loss from Atomic Hydrogen in Collisions with Multicharged Ions—F. W. Meyer, H. J. Kim 218
Electron-Ion Crossed-Beams Experiment—D. H. Crandall, R. A. Phaneuf, R. A. Falk, D. C. Gregory, J. W. Hale, G. H. Dunn 220
Low-Energy Electron Capture Measurements—R. A. Phaneuf, R. H. Hughes 222
Measurements of Tokamak Poloidal Fields by Faraday Rotation—D. P. Hutchinson, P. A. Staats, K. L. Vander Sluis, C. H. Ma 223
Plasma Ion Temperature Measurement by Thomson Scattering—D. P. Hutchinson, P. H. Staats, C. H. Ma, K. L. Vander Sluis 226

8. ACCELERATOR-BASED ATOMIC PHYSICS 228
Introduction—P. D. Miller 228

Merge Electron-Heavy-Ion Beams—P. F. Dittner, W. B. Dress, P. D. Miller, C. D. Moak, P. H. Stelson, S. Datz 229

Charge-State Dependence of Channeled-Ion Energy Loss—J. A. Golovchenko, A. N. Goland, J. S. Rosner, C. E. Thorn, H. E. Wegner, H. Knudsen, C. D. Moak 230

Single and Multiple Electron-Loss Cross-Section Measurements—G. D. Alton, L. B. Bridwell, M. Lucas, C. D. Moak, P. D. Miller, C. M. Jones, Q. C. Kessel, A. A. Antar, M. D. Brown 232

Forward Ejected Electron Spectroscopy—I. A. Sellin, M. Breinig, S. B. Elston, L. Liljeby, R. S. Thoe, C. R. Vane, H. Gould, R. Marrus, R. Laubert, M. M. Schauer, M. Suter, S. Huldt, S. Datz, S. Overbury 234

Stored Highly Ionized Particle Spectroscopy (Ships)—S. L. A. Huldt, S. D. Berry, M. Breinig, W. S. Burns, D. A. Church, S. B. Elston, G. A. Glass, R. M. Holmes, R. A. Kennefick, I. A. Sellin 235

Resonant Coherent Excitation of Channeled Ions—C. D. Moak, J. A. Biggerstaff, O. H. Crawford, P. F. Dittner, S. Datz, J. Gomez del Campo, P. Hvelplund, H. Knudsen, H. F. Krause, P. D. Miller, S. H. Overbury 235

Interplanar Potentials Derived from Transverse Oscillations of 3.5-MeV/amu Helium and Lithium Nuclei in Planar Channels of Silicon—C. D. Moak, J. Gomez del Campo, J. A. Biggerstaff, S. Datz, P. F. Dittner, H. F. Krause, P. D. Miller 238

L- and *M*-Shell Vacancy Production by Direct Ionization and Electron Capture to the Projectile *K* Shell—F. D. McDaniel, R. G. Albridge, M. C. Andrews, F. Breyer, J. L. Duggan, A. Hamdi, R. Mehta, P. D. Miller, R. S. Peterson, A. Ramyya, P. V. Rao, L. Rayburn, Y. P. Sangsingkeow, A. Zander 240

Studies of the Lifetime, Photodetachment, and Collisional Detachment of He^-—G. D. Alton, R. N. Cmpton, D. J. Pegg 241

EN Tandem Operations (Covering Period—January 1979 to April 1981)—G. F. Wells, P. D. Miller 243

9. HIGH-ENERGY PHYSICS—H. O. Cohn, W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, H. R. Brashear 245

Some *g* (1700) Decay Modes—W. M. Bugg, G. T. Condo, H. O. Cohn, E. L. Hart, T. Handler 246

A Proposed Neutron-Antineutron Transition Experiment—W. M. Bugg, H. O. Cohn, G. T. Condo, T. A. Gabriel, M. S. Goodman, T. Handler, E. L. Hart, R. A. Lillie, P. D. Miller, F. E. Obenshain, R. Wilson, G. R. Young 250

10. PUBLICATIONS 255

11. PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS JANUARY 1979 THROUGH APRIL 1981 293

12. GENERAL INFORMATION 318

1. Holifield Heavy-Ion Research Facility

FACILITY STATUS

In the period since the last progress report the construction phase of the project has been completed and the facility prepared for initiation of the experimental program.

Acceptance tests of the 25-MV tandem electrostatic accelerator were performed successfully at 7.5 and 17.5 MV terminal potential. The final tests at 25 MV on terminal remain to be demonstrated. Successful operation of the coupled accelerators, with the ORIC serving as a booster accelerator for beam injected from the tandem, was also demonstrated.

During most of this period the ORIC continued to operate in support of the ongoing research program. Work also continued on development of new experimental devices, implementation of the new data acquisition system, and planning for future modifications to the accelerators that will provide improved facility capabilities. More details of the various facets of this program are provided in the sections which follow.

On December 8, 1980, the facility (Fig. 1.1) was formally dedicated in honor of retired U.S. Congressman Chet Holifield.

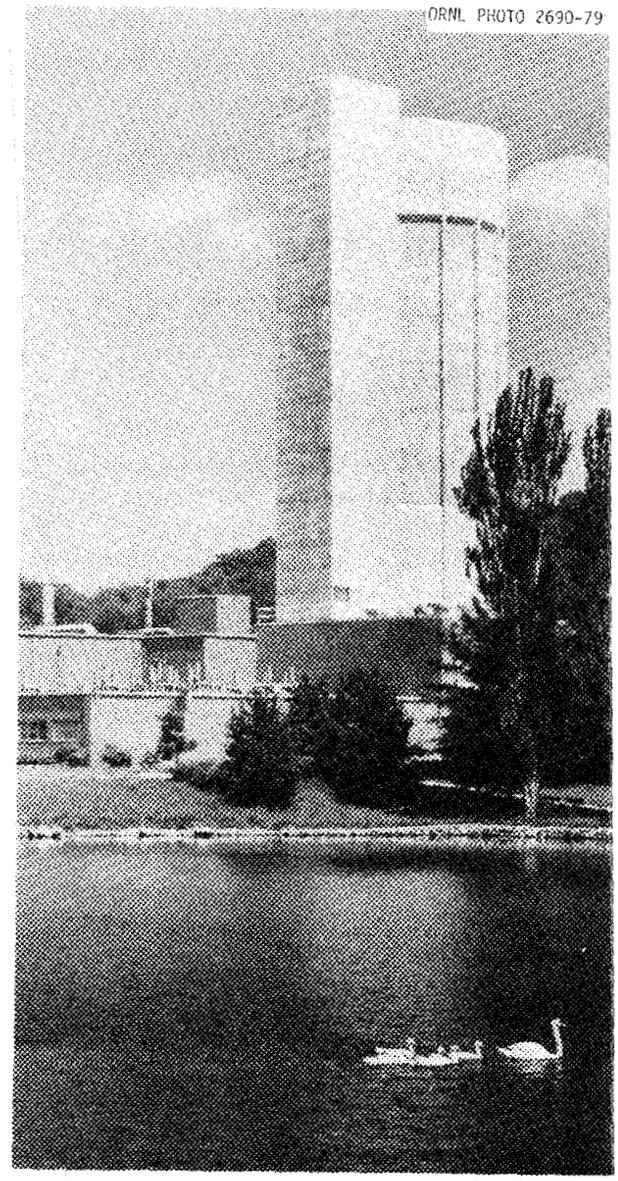


Fig. 1.1. View of the Holifield Heavy-Ion Research Facility.

25-MV TANDEM ACCELERATOR

G. D. Alton
J. A. Benjamin
J. A. Biggerstaff
D. M. Galbraith
C. M. Jones
R. C. Juras[1]
J. E. Mann
E. G. Richardson
N. F. Ziegler

During the period covered by this report, installation of the tandem accelerator was completed, and commissioning activities were begun. Major milestones during this period are shown in Table 1.1.

Table 1.1. 25 MV-tandem accelerator milestones

April 1979:	
	Column installation completed (with charging chains and rotating power shafts)
	SF_6 transfer system commissioned
May 1979:	
	Column voltage tests (without acceleration tubes)
May 1980:	
	First successful transmission of beam through entire system ($^{16}O^{6+}$ at 15.5 MV)
July–August 1980:	
	All acceptance tests at 7.5 and 17.5 MV performed successfully
January 1981:	
	First successful coupled operation of tandem accelerator and ORIC (extracted beam of 401 MeV $^{16}O^{8+}$)
May 1981:	
	Commencement of interim operation for the experimental program

SF_6 Handling System

The SF_6 transfer system was commissioned in April 1979 and used for the first time to fill the accelerator vessel to full pressure in May 1979. Since that time, 26 complete transfers (storage to accelerator to storage) have been accomplished without major incident or significant SF_6 loss. The present transfer times under optimum conditions are storage to accelerator [0.55 MPa (guage)], 13¼ h; and accelerator [0.55 MPa (guage)] to storage, 11¼ h. Since April 1979, the estimated loss in SF_6 inventory has been $1.7^{+1.0}_{-0.5}\%$, while the estimated air concentration has increased from 0.03% to 0.35% (mole fraction).

Column Voltage Tests

Tests of the voltage holding capability of the column structure, before installation of acceleration tubes, were performed by National Electrostatics Corp. (NEC) in May 1979. In these tests, which have been described in detail in ref. 2, the accelerator was filled with SF_6 to a set of pressures ranging between 0.034 MPa (guage) (5 psig) and 0.62 MPa (guage) (90 psig). At each pressure, a set of measurements was made in which the terminal potential was slowly increased until a spark occurred, thus giving a distribution in breakdown voltage at each pressure. The absolute calibration for the voltage scale of these measurements was established from previous calibrations (in other NEC accelerators) of current vs gradient in the corona voltage grading system and is estimated to be accurate to ±5%.

A plot of breakdown voltage in the order of occurrence is shown in Fig. 1.2. Examination of this figure reveals two important points. The first is that the number of data points is small—a reflection of the fact that the tests were performed over a short interval, namely, about four working days. The second is that whereas there is no suggestion of conditioning at the lower pressures, there is good evidence for a conditioning phenomenon at the higher pressures in the sense that breakdown voltage tends to increase with breakdown number. At the highest pressure, for which we have 13 data points, this increase averages about 1.3% per breakdown and does not appear to change over the 13 breakdowns; that is, the breakdown voltage does not appear to level off with breakdown number for the number of breakdowns observed. For this reason we believe that the breakdown voltages observed at 0.62 MPa

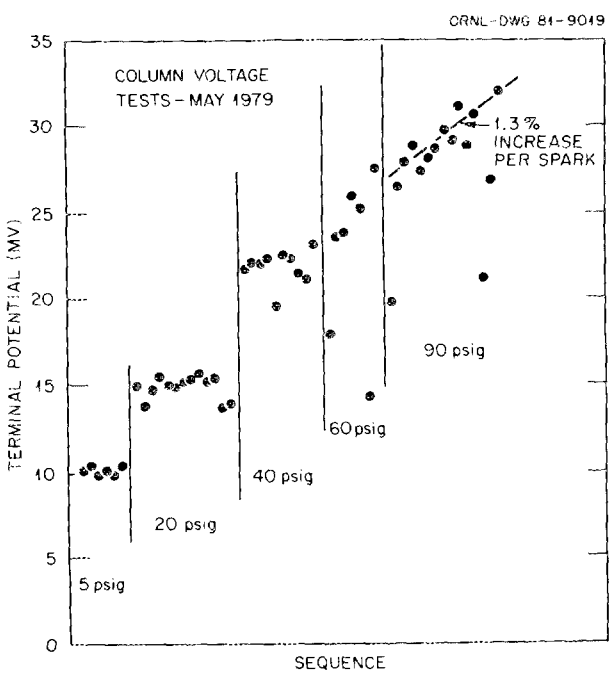


Fig. 1.2. Values of terminal voltage at breakdown plotted as a function of sequence for the May 1979 column voltage tests of the Oak Ridge 25-MV tandem accelerator. The absolute voltage scale has an estimated uncertainty of ±5%.

represent a conservative measure of the ultimate voltage holding capability of the column structure.

A plot of these same data as a function of pressure is shown in Fig. 1.3. Because of the limited number of data points and the conditioning effect, noted above, the dependence of breakdown voltage on pressure is not completely determined. If one assumes that the higher values of breakdown voltage are representative at 60 and 90 psig, the observed functional dependence is reasonably consistent with the $\rho^{0.66}$ dependence reported for type MP accelerators.[1]

Examination of the column structure after these tests revealed 42 spark hits. The largest of these were characterized by a discoloration of 1 to 2 cm in diameter, with some melting in the center and roughness of the order of 0.25 mm. There was no evidence of any other physical damage to the column structure and no evidence that sparks tended to occur at a previous spark site. Specifically, we see no reason to suppose that the surface roughness associated with a spark hit will pose a functional problem. The distribution of spark hits was approximately uniform over the surface of the high-voltage terminal and upper column, although there was some preference for upper terminal surfaces with compound curvature.

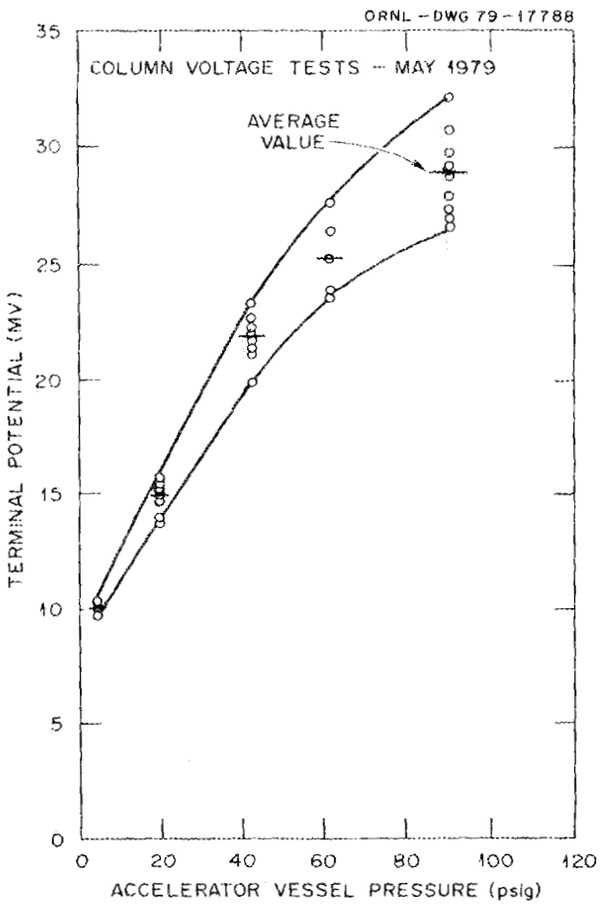


Fig. 1.3. Values of terminal voltage at breakdown plotted as a function of accelerator vessel guage pressure for the May 1979 column voltage tests of the Oak Ridge 25-MV tandem accelerator. The absolute voltage scale has an estimated uncertainty of ±5%.

Initial Operation with Beam

In the interval June–December 1979, NEC installed the acceleration tubes, terminal magnet, and other column components such as pumps, lenses, etc.; and in January 1980, NEC began the process of commissioning the column in preparation for beam and voltage tests. The interval between January and May 1980 was characterized by several nonfundamental but time-consuming problems which delayed the successful transmission of beam completely through the accelerator until May 12. In this first test, an analyzed beam of 60 pnA of $^{16}O^{6+}$ was accelerated at a terminal potential of 15.5 MV. Subsequent milestones for operation with beam are summarized in Table 1.2.

The first task to be performed after initial operation of the accelerator with beam was a preliminary calibration of the analyzing magnet over the mass-energy product range 29 to 110, using ^{16}O beams of various charge states at a terminal potential of 9.2 MV. An absolute calibration was obtained as part of this series with a 27.4-MeV $^{16}O^{2+}$ beam, using the nuclear reaction $^{12}C(^{16}O,\alpha_1)^{24}Mg^*$.

The initial magnet calibration was then followed by performance of the acceptance tests, summarized in Table 1.2. In this table, "transmission factor" is defined as the ratio of injected beam, as measured at the injector magnet image slits, to the accelerated beam, as measured at the analyzing magnet image slits. These acceptance tests constitute the complete set of system acceptance tests required for terminal potentials of 7.5 and 17 MV. During the 7.5-MV gas stripper tests, various charge state ^{127}I beams were also used to perform a preliminary calibration of the analyzing magnet over the mass-energy product range 106 to 302.

We have been pleased to note that initial operation of the accelerator with beam and, more specifically, adjustment of the terminal and analyzing

Table 1.2. Milestones for operation with beam

May 1980:
First complete transmission of beam through accelerator system—$^{16}O^{6+}$ at 15.5 MV

June 1980:
Absolute calibration of analyzing magnet with the reaction $^{12}C(^{16}O,\alpha_1)^{24}Mg^*$

July 1980:
First system acceptance test
$^{127}I^{10+}$, 7.5 MV, foil stripper, 10 pnA for 10 min

August 1980:
System acceptance tests
$^{127}I^{4+}$, 7.5 MV, gas stripper, 1 pμA for 60 min, 9.1 transmission factor

$^{127}I^{6+}$, 17.5 MV, gas stripper, 1 pμA for 60 min, 8.9 transmission factor

$^{127}I^{13+}$, 17.5 MV, foil stripper, 10 pμA for 10 min

January 1981:
First successful coupled operation of tandem accelerator and ORIC (see ref. 7)

Injected beam: 38 MeV $^{16}O^{2+}$
Extracted beam: 401 MeV $^{16}O^{8+}$

April 1981:
Demonstration of stable operation with an ^{16}O beam at 20.0 MV

magnets in conjunction with the terminal potential have been straightforward. In cases where the terminal gas stripper has been employed, the overall transmission from injector magnet image slits to analyzing magnet image slits, when corrected for the charge state fraction characteristic of the terminal stripping process, typically exceeds 50%. The most significant loss in transmission appears to occur in the low-energy acceleration tube—for reasons which are not yet clear.

Coupled Operation

In the interval September–October 1980 the accelerator vessel was open for a major maintenance period in which a number of tasks were performed. These included careful baking of the acceleration tubes and replacement of the closed corona voltage grading system with a new open system similar to that used in the Canberra 14UD accelerator.[4]

The interval from mid-October to early December 1980 was devoted to initial conditioning of the acceleration tubes in groups of four and five 61-cm sections. (Only minimal conditioning was required for the earlier acceptance tests with beam.) In early December 1980 it was discovered that eight 20.3-cm acceleration tube modules had been damaged by deposition of electrode material onto the inner insulator surfaces. This damage, which is primarily concentrated at end gaps, is thought by NEC to be due to excessive spacing between the acceleration tube spark gaps and to conditioning at too high a tank gas pressure. The remainder of December and the first part of January 1981 were devoted to replacement of the damaged tube modules and to adjustment of spark gaps at each end of each tube module.

In the latter part of January 1981, the first demonstration of coupled operation of the tandem accelerator and the ORIC was successfully completed. For these tests, which are described in detail below, the tandem accelerator provided bunched beams of typically 0.2 pμA of $^{16}O^{2+}$ at energies in the range 36 to 40 MeV. Typical bunch widths for these initial tests are estimated to be 1 to 1.5 ns. The buncher and associated control system used for these tests[5,6] were developed on the Beam-Bunching and Pulse-Detection Test Facility described in the previous progress report.[7]

Current status

In the interval February–April 1981 the accelerator was conditioned, mostly in groups of sections, in preparation for operation with beam at high terminal potentials. Individual 61-cm sections were conditioned to gradients above 1 MV/section, and the entire column was conditioned to potentials as high as 22.5 MV. In the latter part of April 1981, stable operation of the accelerator at a terminal potential of 20.0 MV was demonstrated with an accelerated beam of ^{16}O. No further significant acceleration tube damage has been observed.

Although operation with beam at potentials of the order of 20 to 22 MV now appears to be feasible, NEC has concluded that further development work will be required before operation at 25 MV will be possible. Accordingly, a contract modification has been negotiated which will allow use of the accelerator for the HHIRF research program at potentials not exceeding 22 MV for a period beginning May 6 and not exceeding six months. During this period, NEC will engage in further development work, with special emphasis on spark gaps, on the 2OURC accelerator at the JAERI

Research Establishment at Toaki. Since this accelerator is similar in configuration to the ORNL accelerator, it is expected that the results obtained will be directly applicable to the ORNL accelerator. At the end of the six-month period, NEC plans to return for a period of about three months to make appropriate modifications and to attempt the 25-MV acceptance tests.

1. Instrumentation and Controls Division.
2. C. M. Jones, "The 25-MV Tandem Accelerator at Oak Ridge," Proceedings of the Fifth Tandem Conference, Catania, Italy, June 9–12, 1980, to be published in *Nucl. Instrum. Methods*.
3. S. J. Skorka, *Rev. Phys. Appl.* **12,** 1279 (1977).
4. D. C. Weisser, *Rev. Phys. Appl.* **12,** 1303 (1977).
5. W. T. Milner, *IEEE Trans. Nucl. Sci.* **NS-26**(1), 1445 (1979).
6. N. F. Ziegler, *IEEE Trans. Nucl. Sci.* **NS-26**(3), 3304 (1979).
7. ORNL-5306 (1977), unpublished.

COUPLED OPERATION OF THE ORIC AND THE 25-MV TANDEM

J. B. Ball
R. M. Beckers[1]
T. P. Cleary[2]
E. D. Hudson
R. S. Lord
C. A. Ludemann
J. A. Martin
N. F. Ziegler

Coupled operation of the 25-MV tandem and the ORIC was achieved on January 27, 1981. A beam of 38-MeV $^{16}O^{2+}$ was injected into the ORIC, stripped to 8^+, and accelerated to 324 MeV. Shortly afterward, the energy was increased to the maximum design value of 25 MeV/amu (400 MeV). A spectrum taken of the scattering of this beam from a thin ^{208}Pb target in the broad-range spectrograph exhibited a resolution of 115 keV (FWHM). Performance of the system was in close agreement with that predicted from calculations.

Injection System

The concept and some of the major design features of the injection system have been described briefly in previous reports.[3–5]

The tandem and the cyclotron are separated by a distance of about 36 m. The injection system includes the pair of magnets that turn the beam path from vertical to horizontal, two quadrupoles, an inflection magnet to aim the beam at the right spot in the cyclotron, a stripping foil inside the cyclotron, and the control and diagnostic systems. Since the acceptance of the cyclotron for an energy spread of 1 in 1000 is $\pm 3°$ of the rf period (or 1 to 2 ns for the required frequency range), the beam is bunched before acceleration in the tandem. The double-drift klystron buncher, in a test on the EN tandem, was able to put over 50% of the beam into the desired period. To preserve the time structure of the beam, transmission to the cyclotron must take essentially the same time for all portions of the beam bunch. This was accomplished by designing the optics magnets and beam waist locations to minimize the time dispersion (100 to 150 ps). The optics system must also transform the circular beam spot that comes out of the tandem to a rectangular spot about 1×5 mm at the stripping foil in the cyclotron.

The injected beam must be sufficiently rigid as it enters the cyclotron so that it can cross the cyclotron field and arrive at the stripping foil (Fig. 1.4). This, when the radial limits on the travel of the foil are considered, implies also that a stripping ratio of 2:1 or greater is required to capture the beam in an orbit suitable for acceleration. For lighter ions it is necessary to limit the charge change that occurs in the tandem terminal to assure that a 2:1 charge change at the stripping foil in the cyclotron is achievable. For carbon, nitrogen, and oxygen, which would normally be almost fully stripped in the terminal with ordinary pressures in the stripping channel, this is accomplished with no significant loss of intensity by operating the stripping channel at lower than normal pressure, thus intensifying the desired charge state.[6] For the heavier particles, higher charge states in the terminal are usable and desirable to achieve maximum final energy.

Beam Monitoring Diagnostic System

Six quartz-plate viewers with closed-circuit television cameras have been provided for setting up a beam through the injection system. With these viewers the position of the beam can be adjusted to coincide with the axis of the injection line, the shape can be monitored approximately, and it can be determined whether the beam is passing through the quadrupoles on-axis. One of the quartz viewers is located inside the cyclotron and can be substituted in place of the foil for aiming and focusing the beam. The beam also causes the

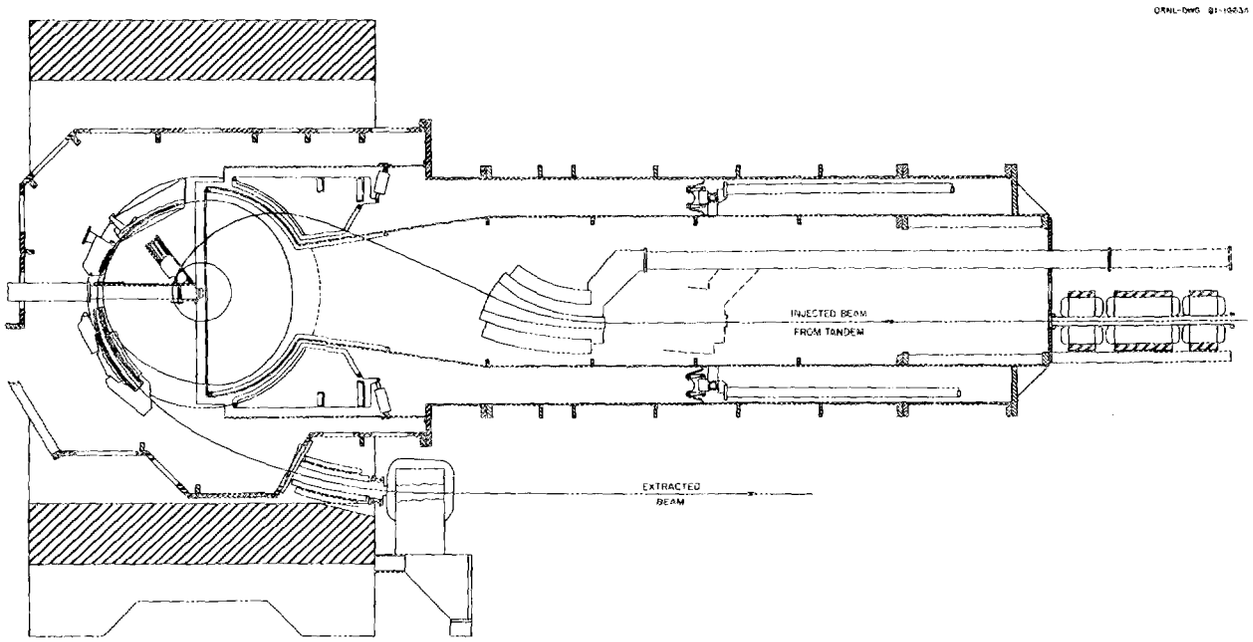


Fig. 1.4. Injected beam enters the cyclotron through the rf resonator and is directed by the inflection magnet to the stripping foil, which is placed on an orbit suitable for acceleration. The incoming beam must have a sufficiently large rigidity ($B\rho$) to cross the field to the foil. The inflection magnet has an angular range of 17 to 37° to accommodate beams of different rigidity requiring different trajectories.

foil to glow visibly during operation. A 3-m fiber-optic viewing system was required so that this TV camera could be mounted where the cyclotron stray field was sufficiently low. In addition to the TV monitoring systems, two Faraday cups are used, one at each of the beam waists. The first is located after the regulating slits between the 25 and 65° magnets that turn the beam path from vertical to horizontal. Tuning for maximum beam passing through the slits at this point produces a waist that is required for minimum time dispersion. The second cup, about halfway along the line, is capable of measuring the time structure of the beam from initial adjustment of the buncher. Final adjustment of the buncher is, of course, done by observing the intensity of the beam extracted from the cyclotron while varying buncher phase and amplitude. A foil can be inserted into the beam ahead of the 65° magnet so that the charge-state distribution of the stripped beam in the cyclotron can be determined prior to injection.

Foil Positioner

The foil positioner in the cyclotron is designed to be inserted in place of the internal ion source when running in the coupled mode (Figs. 1.5, 1.6). It can position a foil over an azimuthal range of ~85° and a radial range of 24 to 51 cm to accommodate injected beams of varying energies. A foil carrier (Fig. 1.7) mounted on the pivoted arm holds up to 20 foils, which can be indexed into position remotely in a few seconds. A different carrier containing a new set of foils can be installed in about 30 min by withdrawing the foil positioner through a vacuum lock. The pivot point of the foil positioner arm is not at the center of the cyclotron, so the cyclotron control computer calculates the radius and azimuth of the foil with the appropriate coordinate transformation. These parameters are displayed in both coordinate systems. The potential mechanical interference between the foil carrier and the internal beam probe mounted on the foil positioner is avoided by a software interlock system that keeps track of the probe and carrier positions. There is also a microprocessor backup for this software interlock.

Beam Dynamics Computations

In 1977 the magnetic field of the cyclotron was remeasured[7] to obtain data for the fringe field and

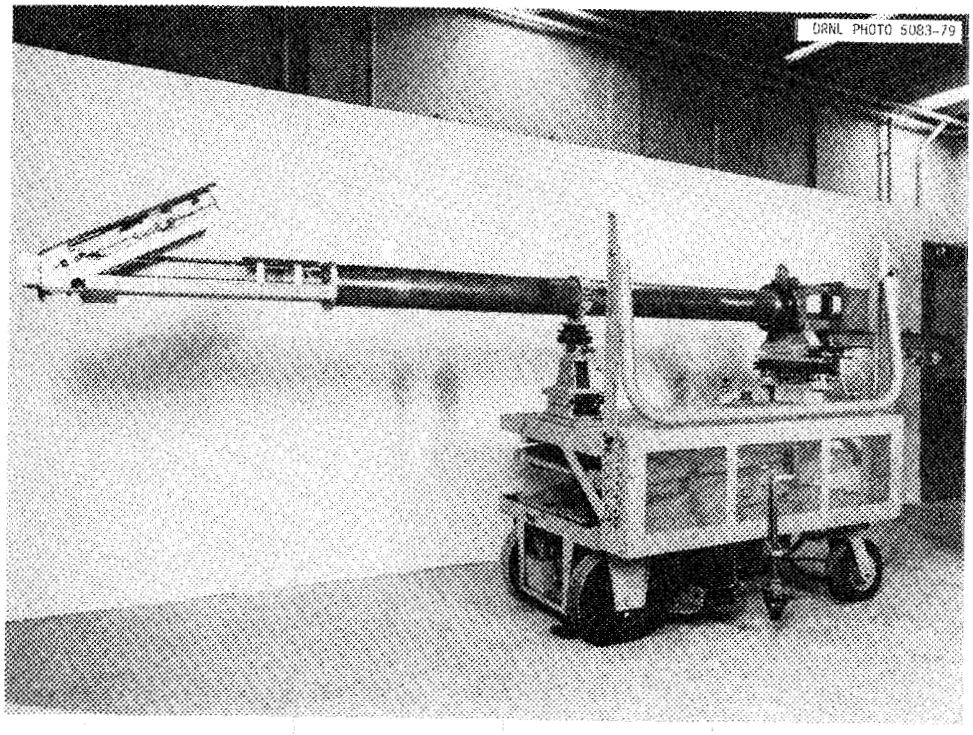


Fig. 1.5. Foil positioner on its handling dolly. The foil arm is raised to a typical operating position.

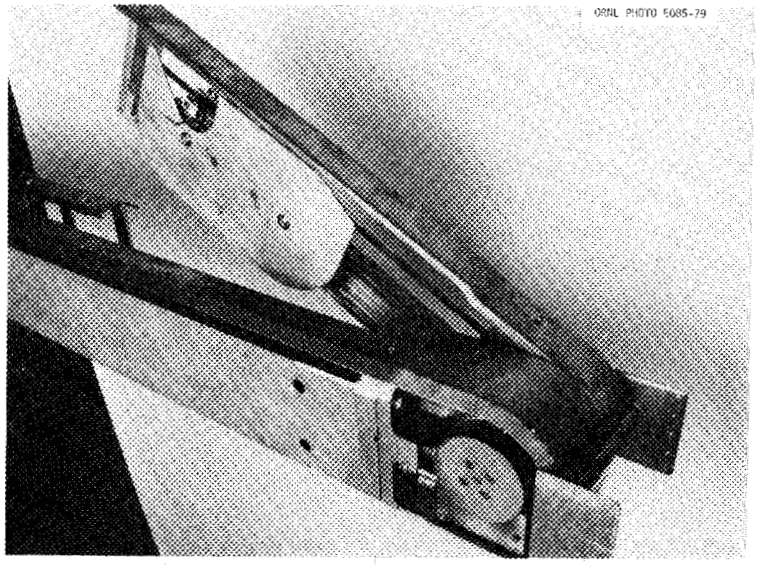


Fig. 1.6. Foil arm with the foil carrier installed. One of the foil holders is flipped out into the operating position.

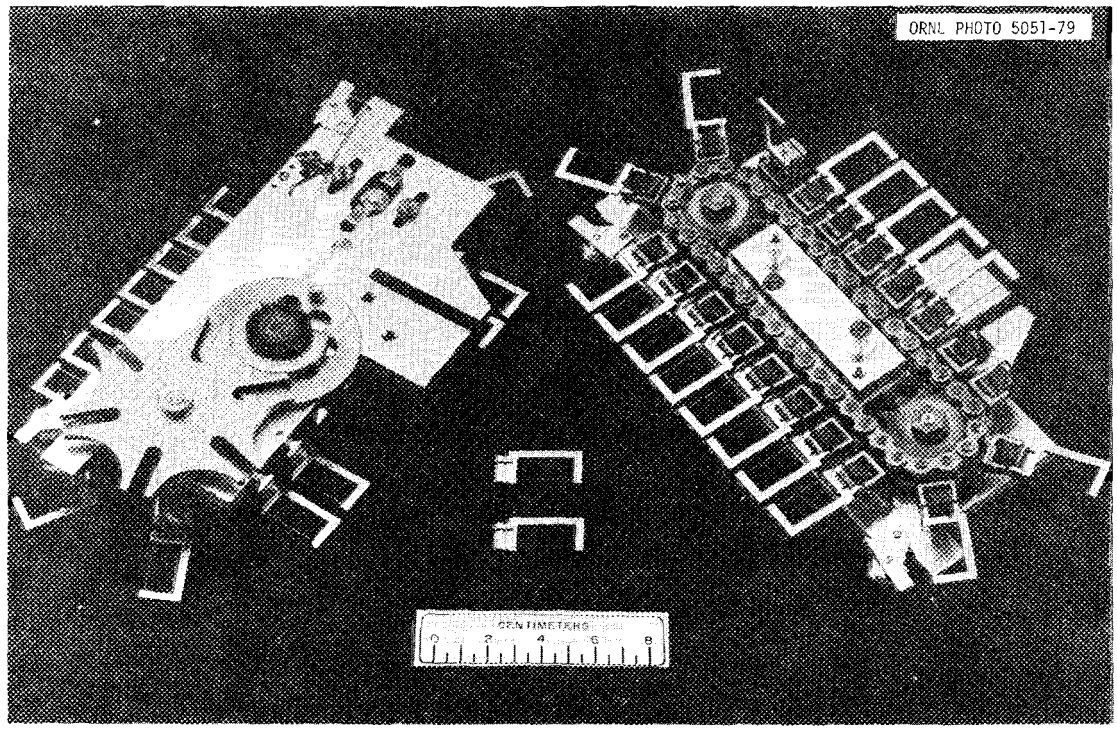


Fig. 1.7. Front and back view of a foil carrier. Twenty positions for foils are provided.

for the high fields now used. The field data were parameterized,[8] and programs have been developed for computing trim and harmonic coil settings, injection trajectories, foil azimuth and radius, inflection magnet strength and position, and extraction system mechanical and magnetic settings. The extraction system program is operator interactive so that the system parameters may be iteratively adjusted while observing a graphic display of the calculated extracted beam trajectory (Fig. 1.8).

The programs for acceleration and extraction of the beam have been in routine use with the internal source since June 1980 and almost always are successful in producing extracted beam with only minor tuning by the operator. The injection program proved invaluable in predicting the foil position and inflection magnet setting for the first injected beam. The operating position of the foil, determined by optimizing the extracted beam, was only a few millimeters from the predicted position.

Operating Experience

In January 1981 the tandem, although still undergoing acceptance tests, was made available for two brief tests of coupled operation. During the first 24-h test the transport and diagnostic systems were checked out with beam, which was then stripped and accelerated to full radius. Because of a leak in one of the extraction channels when it was energized, we were unable to extract the beam. Two weeks later a period of three days was allotted to testing coupled operation. The first extracted beam was obtained on January 27, within a few hours of starting the test. The parameters are given in Table 1.3. This beam was used briefly by the experimenters to obtain a spectrum; then the energy was increased in steps by raising the cyclotron frequency and magnetic field to the full design energy of 25 MeV/amu. At this point further measurements were made using a ^{208}Pb foil target and a broad-range spectrograph (Fig. 1.9). The energy

ORNL PHOTO 1383-81

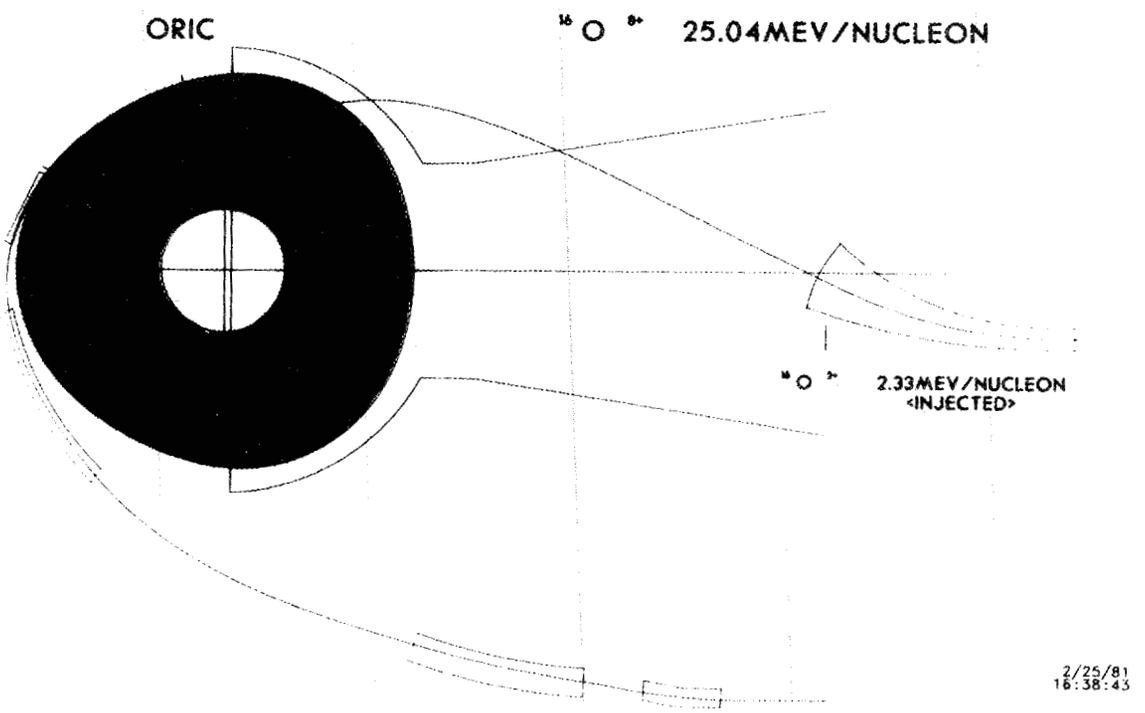


Fig. 1.8. Calculated injection, acceleration, and extraction trajectories for the 400-MeV $^{16}O^{8+}$ beam. The program finds the optimum positions for the foil and the inflection magnet. The operator iteratively adjusts the positions and strengths of the five extraction elements to achieve the desired calculated result, in a manner similar to actual operation.

Table 1.3. Parameters for first coupled operation

Tandem:	
Terminal voltage	12.2 MV
Injector voltage	300 kV
Low-energy ion	OH^-
Accelerated ion	$^{16}O^{2+}$
Analyzed current	400 nA
Output energy	38 MeV
Cyclotron:	
Accelerated ion	$^{16}O^{8+}$
Circulating beam	180 nA
Extracted beam	125 nA
Energy	324 MeV
Analyzed beam on target	60 nA

resolution during this experiment was 115 keV (FWHM), or about 1 in 3500.

During these experiments we did not experience a foil failure. This was consistent with the predicted life of 150 pμA-h of the 38-MeV ^{16}O beam for the 5- to 10-g/cm^2 carbon foils made by deposition of carbon from an ethylene gas glow discharge.

1. UCC-ND Engineering Division.
2. World Information Technology Systems Corp.
3. *Phys. Div. Annu. Prog. Rep. May 1974,* ORNL-4937, pp. 95–101.
4. *Phys. Div. Annu. Prog. Rep. May 1975,* ORNL-5025, pp. 156–59.
5. *Phys. Div. Annu. Prog. Rep. Sept. 1977,* ORNL-5306, pp. 4–5.
6. Ibid., pp. 15–17.
7. Ibid., pp. 22–23.
8. *Phys. Div. Annu. Prog. Rep. June 1979,* ORNL-5498, p. 11.

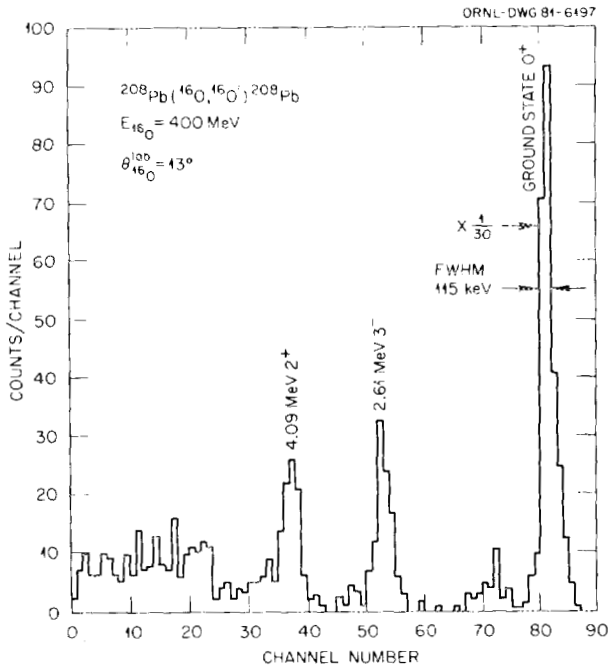


Fig. 1.9. Spectrum of ^{16}O ions scattered from a ^{208}Pb target. Scattered particles were detected using a silicon position-sensitive detector placed in the focal plane of a magnetic spectrograph. Clearly visible are peaks from elastic scattering (ground state) and excitation of 2.61- and 4.09-MeV levels of the ^{208}Pb nucleus. The measured energy resolution was 115 keV (FWHM), which includes contributions from such sources as the beam energy spread, beam angular divergence, inherent detector resolution, electronic noise spread, and energy straggling in the target.

Table 1.4. Time analysis of ORIC operation for CY 1979–80

(An additional factor in breakdown time, but not separated, is time lost while maintenance manpower is not available. This factor was estimated at 260 h or 6.4% of the scheduled operation time during 1980.)

	Hours	Percent
Beam on target	3958	49
Beam adjustment	435	5
Target setup	188	2
Start-up and shutdown	726	9
Machine research	534	7
Source changes	641	8
Total machine operable (reliability factor)	6482	81
Vacuum outage	150	2
Rf outage	89	1
Power supply outage	313	4
Electrical component outage	209	3
Mechanical component outage	198	2
Water leak outage	581	7
Radiation outage	3	
Computer outage	6	
Total breakdown outage	1549	19
Total scheduled operation	8031	100
Scheduled maintenance	742	
Scheduled engineering	1458	
Electrical power restriction	3	
Total program schedule	10234	

ORIC OPERATIONS

S. W. Mosko
C. L. Viar
C. A. Ludemann
R. S. Lord
E. D. Hudson
J. W. Johnson
T. P. Cleary[1]
H. L. Dickerson[1]
D. M. Ezell[1]
H. D. Hackler
C. L. Haley
N. L. Jones
R. F. Joy[1]
S. N. Lane
C. T. LeCroy
S. N. Murray
G. A. Palmer[1]
A. D. Higgins[2]
E. W. Sparks[3]
B. J. Casstevens[4]

The ORIC continued operating on a 15-shift-per-week basis through 1979 and 1980, except during extended shutdown periods dedicated to installation of injection beam line components and other beam injection equipment. An analysis of scheduled operation time is presented in Table 1.4; beam time distribution by accelerated particle is presented in Table 1.5. As in recent years, the heaviest ions available tend to be the most popular. A list of nonresident research scientists utilizing the facility during this period is given in Chapter 12.

Computer control capability has continued its expansion. The computer control panels were moved from a temporary "pendant cabinet" to the main cyclotron control console. Most magnetic components, including circular and harmonic trimming coils (previously reported) and beam-line optics, are now under computer control. Other equipment with computer interfacing includes the injection system stripper foil positioner and the rf system frequency synthesizer. New equipment for automatic recording of operation data is now being assembled and prepared for installation. Also to be added is a serial highway system and remote CAMAC crates for interfacing additional equipment.

Table 1.5. ORIC beam time distribution by particle for CY 1979–80

Particle	Mass	Maximum energy used (MeV)	Total hours	Percent
Deuterons	2	24	111	2
Alphas	4	94	249	4
Lithium	7	88	537	9
Boron	10	88	104	1
Boron	11	80	17	1
Carbon	12	192	1012	16
Nitrogen	14	188	766	12
Oxygen	16	209	1181	19
Neon	20	180	1417	23
Neon	22	160	70	1
Argon	40	161	705	12
			6169	100

New power supplies were acquired for the harmonic trimming coils; three units are in operation. Six others are installed, but waiting for completion of control wiring. Three of the original harmonic supplies have been reconnected to the valley coils to permit operation of these coils as harmonic as well as flutter coils. The resulting improvement in harmonic compensation allows ion acceleration to larger radii than that previously possible and provides some increase in ion beam extraction efficiency.

Preoperation computation of all cyclotron setup parameters, including extraction system positions, is now performed routinely, using the 1977 field measurement data in an orbit isochronization program. The use of computed parameters has been highly successful with fundamental mode ions, but substantial retuning is required on third harmonic mode ions due to incomplete central region data. The use of precomputed setup parameters was especially successful in the first opportunities to accelerate injected ion beams produced in the tandem accelerator.

Energy conservation now plays an important role in cyclotron operation due to the impact of electric power costs on the cyclotron operations budget. Improvements noted in computer control and computation of setup parameters help improve the utilization of cyclotron operation time. Some improvement in actual operation cost has also been realized through changes in the water coolant circulation system. The main heat exchanger was converted from an eight- to a four-pass configuration to reduce return-line back pressure. Consequently, it was possible to take one of three large circulation pumps out of service.

1. Resigned, retired, or deceased.
2. Plant and Equipment Division.
3. Instrumentation and Controls Division.
4. Computer Sciences Division.

DATA ACQUISITION SYSTEM

W. H. Atkins[1] W. T. Milner
J. A. Biggerstaff R. O. Sayer[1]
D. C. Hensley C. N. Thomas[2]

The data acquisition system described in the previous report in this series (ORNL-5498, p. 5) is nearing completion and is in use for data acquisition and processing and for software development. The system now comprises three Perkin-Elmer model 3220 CPUs with 1 megabyte of memory each, three 300-megabyte disk drives, two 800/1600 bpi tape drives, a fully implemented CAMAC branch highway to the cyclotron counting room, and a partially implemented (only one driver) highway to the tandem counting room, a Trilog color printer–plotter, various graphic and alphanumeric video terminals, and miscellaneous standard computer peripherals. By the time this report appears in print, four 1600/6250 bpi tape drives, an additional disk drive and controller, and the remaining CAMAC driver hardware should be installed.

Software is available for event-by-event acquisition to tape with real-time monitoring of singles histograms of up to 255 parameters and has been used for spin-spectrometer and gamma-gamma correlation experiments. Another software package has been used to control, monitor, and acquire data from an x-ray spectrometer system. A major software package is available for real-time or off-line (tape playback) sorting of data into multimegachannel arrays of one- and two-parameter histograms. Powerful and flexible gating algorithms are provided, and there are "hooks" in the system to incorporate user-supplied software to preanalyze each event and generate virtual parameters when necessary. Software to display one- and two-parameter histograms on color video terminals and to obtain hard copies of these displays is available.

Software for interactive processing of such data is in an advanced stage of development.

1. UCC-ND Computer Sciences Division.
2. Oak Ridge Associated Universities.

NEGATIVE-ION SOURCE DEVELOPMENT

G. D. Alton

Two refocus-type commercial sources have been procured and modified to accept ORNL surface ionization sources. Both sources have been evaluated in terms of negative-ion yields for certain species; and operational characteristics such as negative-ion current vs ion energy and cesium oven temperature, and cesium oven temperature vs power input, have been established. A number of experiments designed to accumulate information for better understanding of the processes involved in negative-ion sources have been performed, and many are planned for the future.

Combination Prototype Refocus Sputter and Charge Exchange Source

A prototype source has been built which incorporates the basic design features of the Middleton-Adams source in conjunction with provisions for supplying additional cesium to the sample surface during the sputtering process. Preliminary results indicate that factors in yield >30 can be realized over those normally observed for Cu^-.

The source, shown in Fig. 1.10, is comprised of an ORNL designed and developed Cs^+ surface ionization source and a combination steering-lens assembly for positioning and focusing the Cs^+ ion beam onto the target surface. The source is also equipped with an additional cesium oven for vaporizing supplemental cesium onto the sample surface. A balance between cesium arriving at the surface and leaving through evaporation and sputtering processes is necessary in order to maintain a steady-state-effective monolayer of surface cesium. The degree to which this control can be imple-

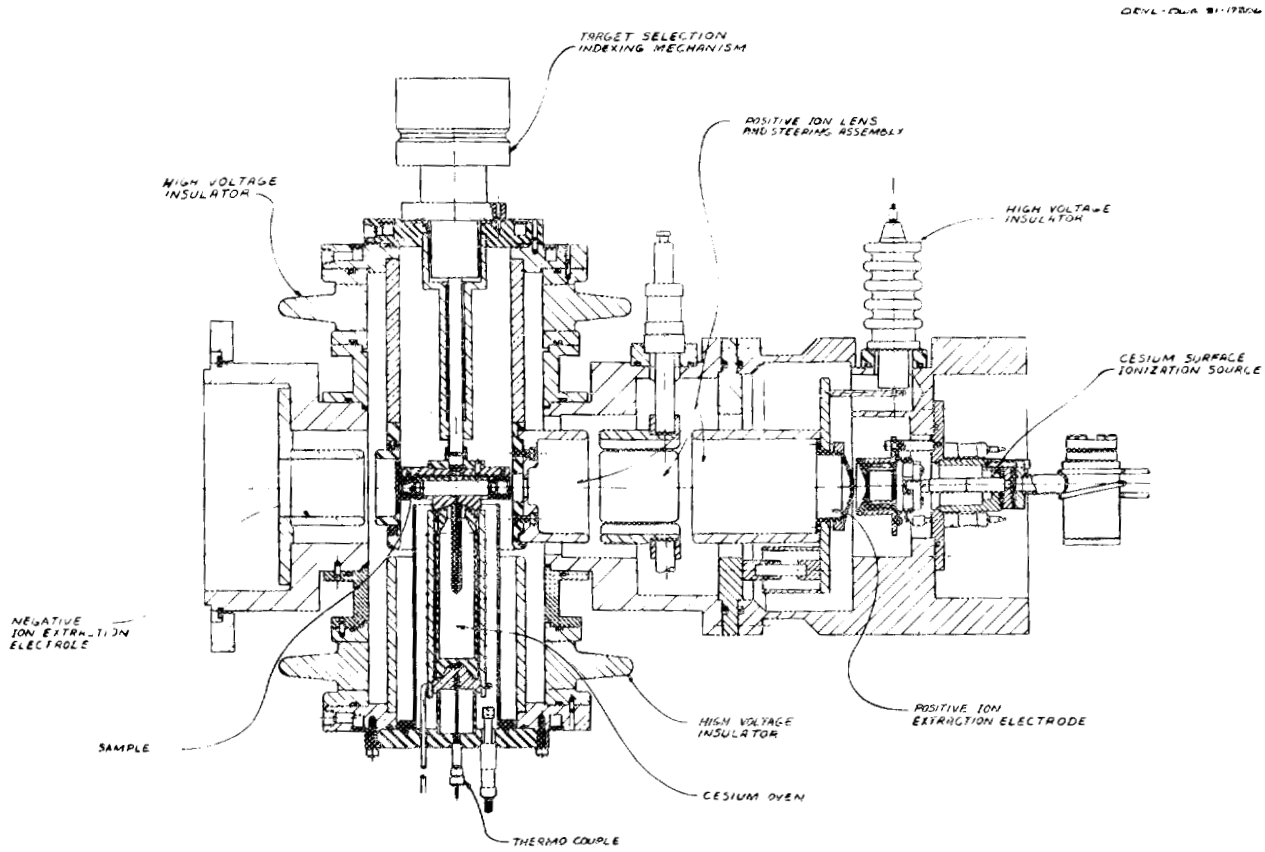


Fig. 1.10. Combination refocus-sputter and charge exchange prototype source.

mented will determine, to a great extent, the success of the source concept. Sufficient experience in operating the source has not been gained to date to establish whether control can be maintained sufficiently to eliminate fluctuations in yield. Such fluctuations can result from either too little or too high cesium feed rates. However, one should be able to compensate for the latter situation by increasing the rate of sample sputtering.

The oven and vapor dispensing chamber were also designed for use as a charge exchange canal so that the source can be used for production of metastable or stable atomic ion beams through charge exchange processes from materials difficult or impossible to produce by more conventional sputter mechanisms (e.g., He^-, Li^-, Na^-, Ca^-, etc.). In order to convert the source from the sputter mode of operation for production of a particular species, the surface ionization source will be replaced with a source appropriate for producing positive-ion beams of the desired species. The source has not been operated as a charge exchange source to date. Several problems associated with the sputter mode of operation require resolution prior to charge exchange source evaluation.

Theoretical Analysis of Negative-Ion Source Performance

Theoretical formulation of the negative-ion generation mechanism, based on sputtering and surface ionization theories, has been used to calculate probabilities for surface ionization and negative-ion yields under ideal conditions.[1,2] Comparisons of measured and calculated probabilities are shown in Table 1.6. The measured probabilities (Table 1.6) were obtained from the ORNL-modified University of Aarhus source data, using measured currents, probe voltages, and calculated sputtering ratios. Many of the measured and calculated values agree quite closely, while a few elements such as Ta and W overproduce relative to theory. Explanations for these and other deviations are not available at this time, although a recent publication by Los et al. describes an affinity level shifting mechanism which may explain such disagreements.[3]

As indicated, the measured values for the probability of surface ionization P_I shown in Table 1.6 were determined from ORNL–University of Aarhus geometry negative-ion source data. Such cesium-rich plasma discharge sources provide close to ideal conditions for maximum negative-ion currents. On the other hand, conventional Middleton-Adams sources[4] rarely provide adequate surface cesium necessary for optimum yields. The probability of extraction as well may be considerably less than unity.

Figures 1.11 and 1.12 compare theoretical and experimental values for C^- and Cu^- computed for a Middleton-Adams refocus-type source operated under ideal conditions. There is close agreement

Table 1.6. Observed[a] and calculated probabilities for surface ionization

Ion species	ϕ_0 (eV)	E_A (eV)	P (meas)	P (calc)	E_A (eV)[b]	P^b (calc)
C^-	4.39	1.268	2.67×10^{-3}	2.5×10^{-3}		
V^-	4.11	0.5	4×10^{-5}	3.8×10^{-10}	(1.15)	(5.39×10^{-5})
Co^-	4.18	0.7	1.35×10^{-4}	1.5×10^{-8}	(1.26)	(2.34×10^{-4})
Ni^-	4.84	1.15	1.77×10^{-3}	2.13×10^{-3}		
Cu^-	4.47	1.226	1.32×10^{-3}	1.3×10^{-3}		
Nb^-	3.99	1.0	6.67×10^{-5}	1.21×10^{-6}	(1.15)	(6.43×10^{-5})
Mo^-	4.27	1.0	2×10^{-5}	1.6×10^{-5}		
Ag^-	1.303	4.28	5.7×10^{-4}	7.4×10^{-4}		
Sn^-	1.25	4.11	5.3×10^{-4}	5.8×10^{-4}		
Sb^-	1.05	4.08	4.5×10^{-5}	4.14×10^{-6}		
Ta^-	0.6	4.12	4×10^{-6}	2×10^{-8}	(1.02)	(2.1×10^{-6})
W^-	0.6	4.52	4.7×10^{-5}	4×10^{-8}	(1.02)	(6×10^{-5})
Pb^-	1.1	4.02	2×10^{-5}	3×10^{-5}		

[a]Observed data measured with versions of Aarhus negative-ion source.
[b]Electron affinity necessary for theoretical ionization probability.

ORNL-DWG 81-8956R

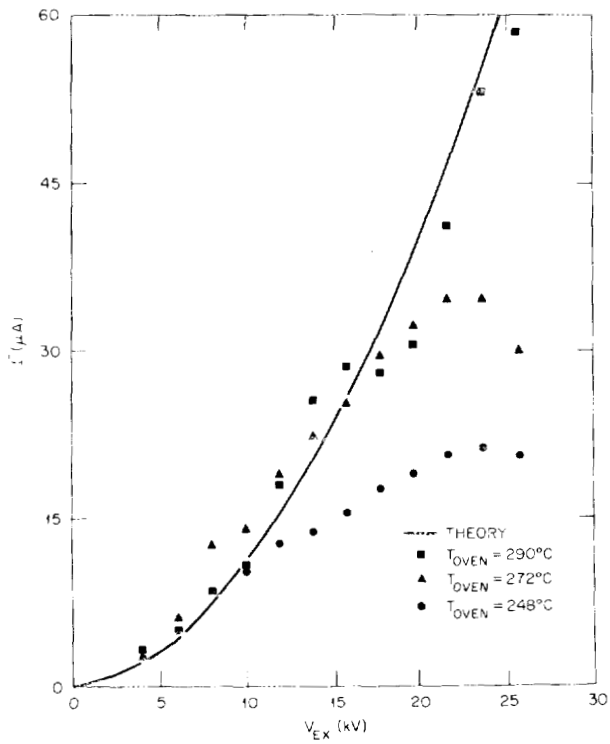


Fig. 1.11. Comparison of negative-ion currents for C^- extracted from a refocus Middleton-Adams type of source with theoretically predicted values as a function of extraction voltage V_{ex}. Theoretical values were computed by assuming space-charge-limited positive-ion currents, positive-ion impact angles with respect to the surface of $\theta = 0°$, and that the probability of extraction once formed is $P_{ex} = 1$.

ORNL-DWG 81-8955R

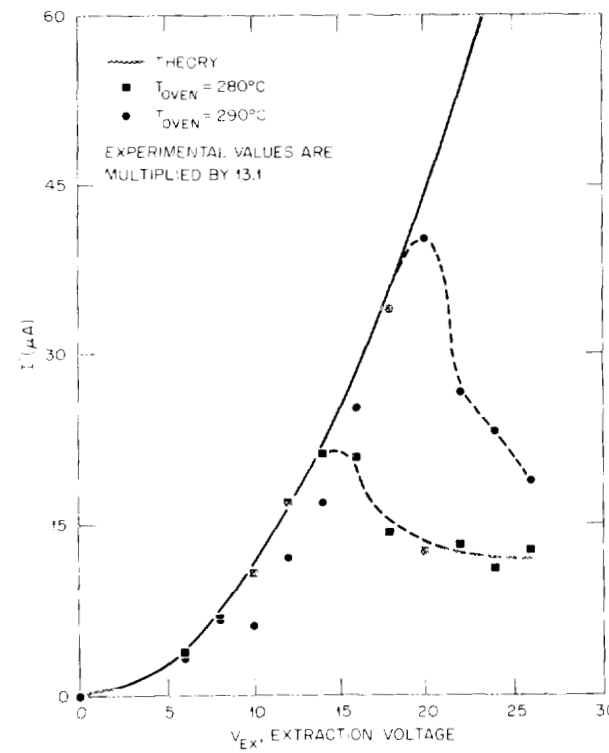


Fig. 1.12. Comparison of negative-ion currents for Cu^- extracted from a refocus Middleton-Adams type of source with theoretically predicted values as a function of the extraction voltage V_{ex}. Theoretical values were computed by assuming space-charge-limited positive-ion currents, positive-ion impact angles with respect to the surface normal of $\theta = 70°$, and that the probability of extraction once formed is $P_{ex} = 1$.

for the case of C^-, while the yields of Cu^- have to be multiplied by large factors in order to bring them into agreement with theory. The differences can be explained by the fact that the cesium surface content is inversely proportional to the sputtering ratio. Carbon has a low sputtering coefficient ratio, and thus high cesium surface content, while copper has a very high coefficient and low cesium surface content.

1. G. D. Alton and G. C. Blazey, *Nucl. Instrum. Methods* **166**, 105 (1979).

2. G. D. Alton (to be published in the Proceedings of the Third International Conference on Electrostatic Accelerator Technology, Oak Ridge, Tenn., 1981).

3. J. Los, E. A. Overbosch, and J. van Wunnik, to be published.

4. R. Middleton and C. T. Adams, *Nucl. Instrum. Methods* **118**, 329 (1974).

EXPERIMENTAL FACILITIES

R. L. Robinson	N. R. Johnson
C. B. Fulmer	R. S. Lord
E. E. Gross	W. T. Milner
M. L. Halbert	R. L. Mlekodaj[1]
D. C. Hensley	C. D. Moak
J. W. Johnson	F. E. Obenshain
E. H. Spejewski[1]	

In 1976 an ORNL group composed of C. E. Bemis, E. D. Hudson, J. E. Mann, M. B. Marshall,

R. L. Mlekodaj, F. E. Obenshain, R. L. Robinson, and K. S. Toth developed a proposed experimental layout for the HHIRF. This plan incorporated the recommendations of eight working groups appointed by the Executive Committee of the Users' Group to review specific experimental apparatus. Except for two beam lines, the experimental layout essentially as proposed has been completed; the layout is shown in Fig. 1.13. Major equipment completed since the last progress report is: beam lines labeled 23, 31, 33, and 35, which were funded as part of the phase I HHIRF project; the extension of beam line 31, which links the tandem accelerator to the UNISOR; the 1.6-m-diam scattering chamber; the spin spectrometer; and a gamma-ray spectrometer system on beam line 23.

The 1.6-m-diam scattering chamber (Fig. 1.14), first used in an experiment in October 1980, has very few internal parts; the major ones are the central target hub, two rotating rings which can be linked to the central hub via spokes, and an out-of-plane ring. This unencumbered design is to allow more flexibility in adapting to a variety of detector types and configurations. A configuration involving 45 detectors is illustrated in Fig. 1.15.

The spin spectrometer (Fig. 1.16), which was designed by Demetrios Sarantites of Washington University, is composed of 70 tightly packed NaI crystals in a spherical array surrounding a 36-cm-diam scattering chamber. This device permits the measurement of the gamma-ray multiplicity and the total gamma energy on an event-by-event basis.

The heart of the new gamma-ray spectrometer system (Fig. 1.17) is a precisely aligned column, which serves as the hub for detector arms. The top of the column has pump-out ports and can serve as the base of the scattering chamber. There is an overhead movable cradle which could, for example, support a large NaI crystal.

The split-pole magnetic spectrometer (Fig. 1.18), which was located on the EN tandem accelerator for the past decade, has been relocated on a beam line from the 25-MV tandem accelerator. The vacuum system of the spectrometer has been substantially improved by replacing the original diffusion pumps with three 1000-liter/s cryogenic pumps.

Funds were approved in September 1980 for a velocity filter-beam trap to be designed and fabricated under the direction of Harald Enge at MIT. This device will be brought to the HHIRF early in 1982. The virtue of this system is that it can remove the primary beam and permit study of reaction products near and at the important angle of 0°.

A laser has been installed at the UNISOR and has been used successfully in an off-line experiment. This device will shortly be used to excite the atomic hyperfine structure of radioactive nuclei far from the valley of beta stability. Ground-state properties of very neutron-deficient nuclei will be determined through these measurements.

Funds have been allocated for a 316-m^2 (3400-ft^2) building addition to the HHIRF, and design of the structure is in progress. Figure 1.19*a* illustrates the plan view of the building addition scheduled for completion in late 1982. The primary justification is to free space for additional experimental target rooms. The present plan is to relocate UNISOR in the new annex and to reconfigure the existing high-bay area as illustrated in Fig. 1.19*b*. This could be completed by mid-1984 and would increase the number of target stations from three to six that receive a beam from either the tandem accelerator or the ORIC along the same beam transport line.

1. Oak Ridge Associated Universities.

HHIRF USERS' SUPPORT

R. L. Robinson	W. T. Milner
R. P. Cumby	C. N. Reed[1]
J. W. Johnson	J. K. Thacker
R. W. Miles	C. N. Thomas[1]

As a national facility, the HHIRF is available to any research group with an approved experiment. Assignment of accelerator time is based on the recommendations of the Program Advisory Committee (PAC).

An Experimental Support Group has been formed with a mission of supporting these researchers while they are performing their experimental programs at the HHIRF. This task includes maintaining the experimental apparatus available to all researchers. There are two arms of the Experimental Support Group: the mentors and the technical personnel. The mentors are resident scientists at the HHIRF who provide up to 20% of their time in taking responsibility for one major device at the HHIRF. Currently there are 11 mentors.

ORNL-DWG 77-3312CR3

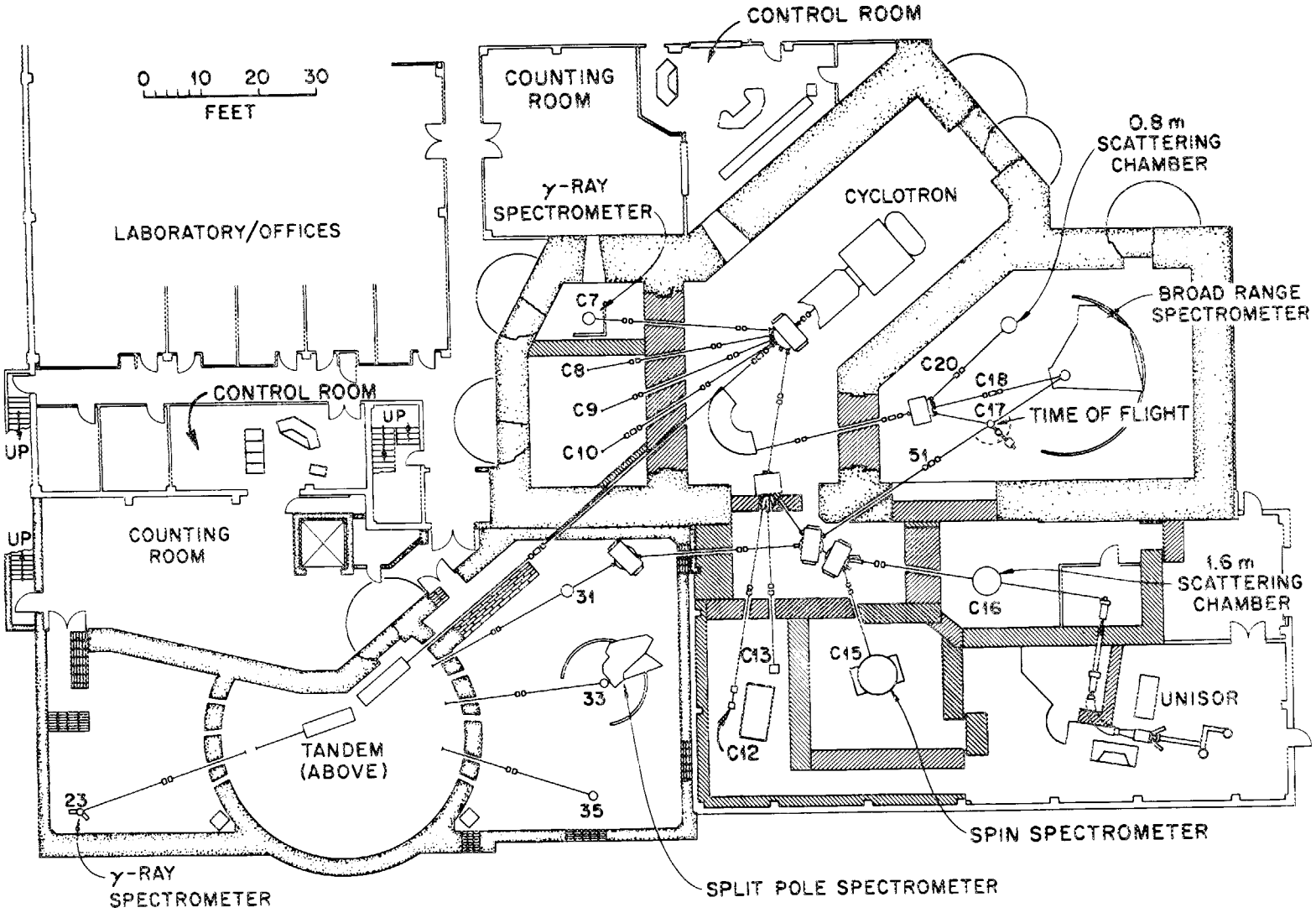


Fig. 1.13. Experimental layout of the HHIRF.

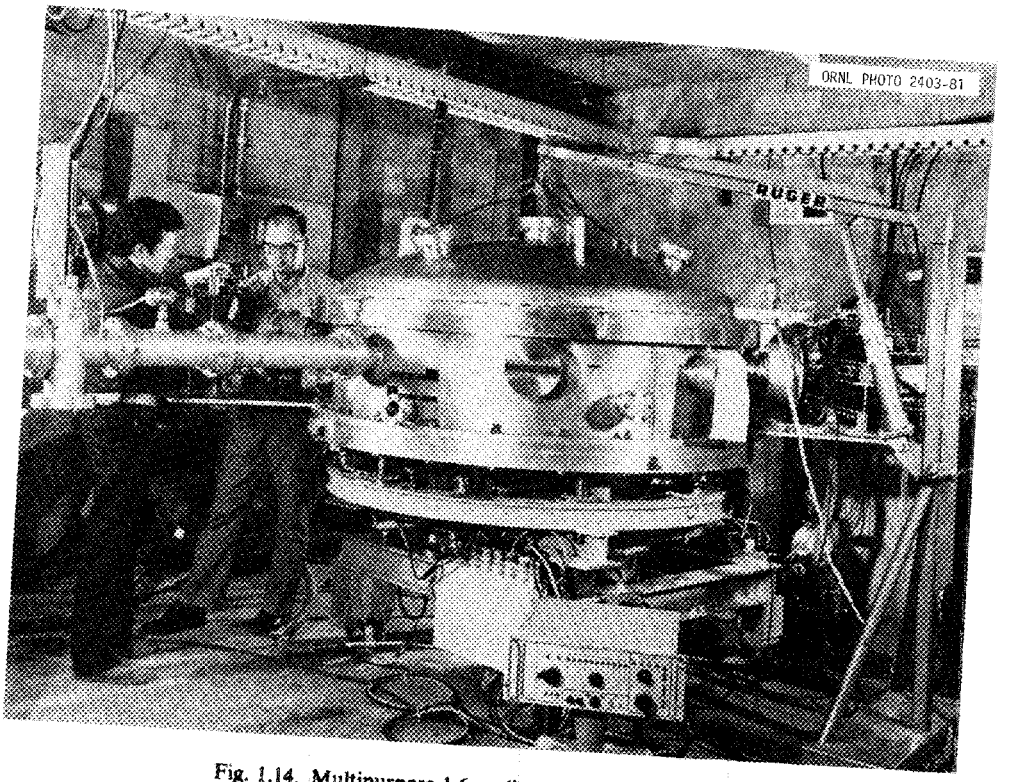


Fig. 1.14. Multipurpose 1.6-m-diam scattering chamber.

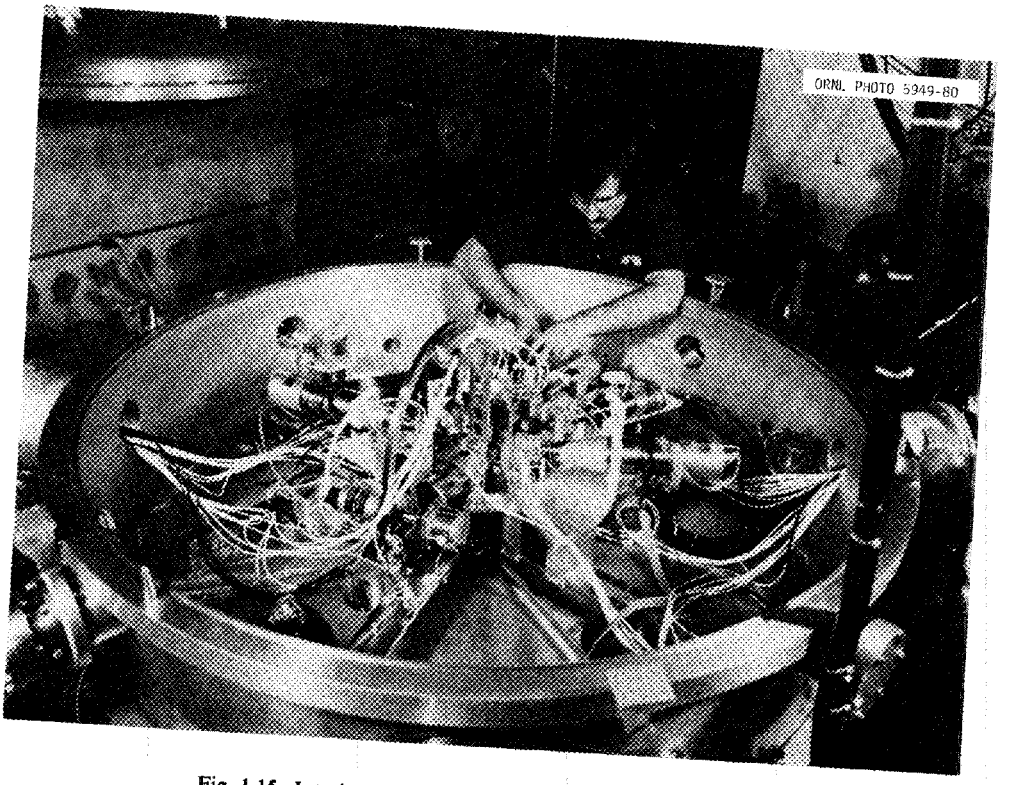


Fig. 1.15. Interior view of the 1.6-m-diam scattering chamber.

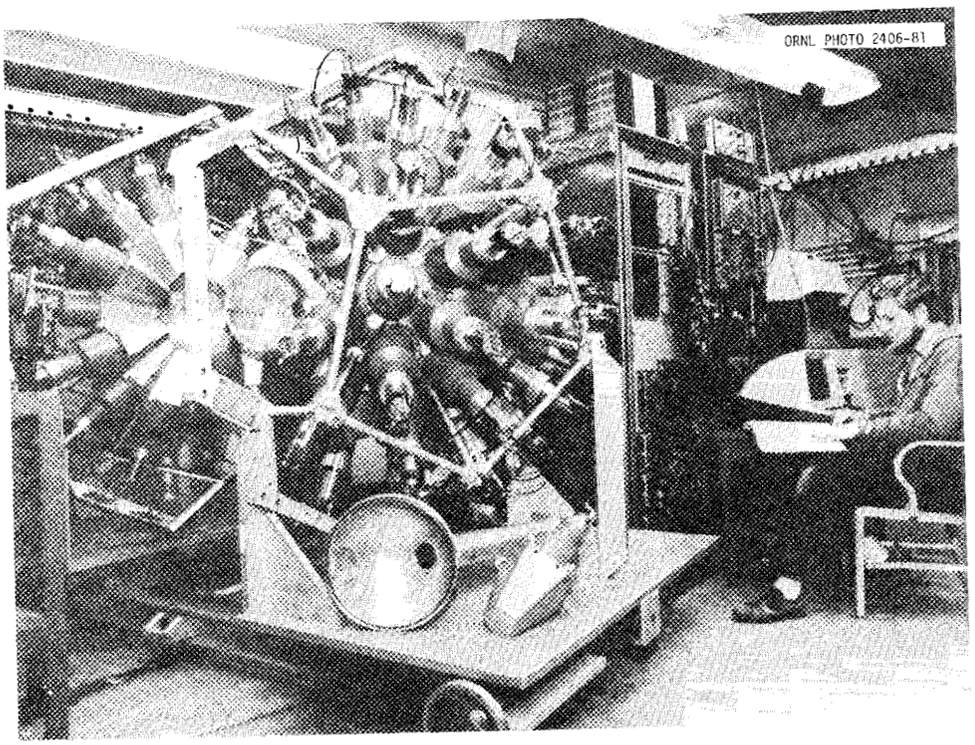


Fig. 1.16. Spin spectrometer.

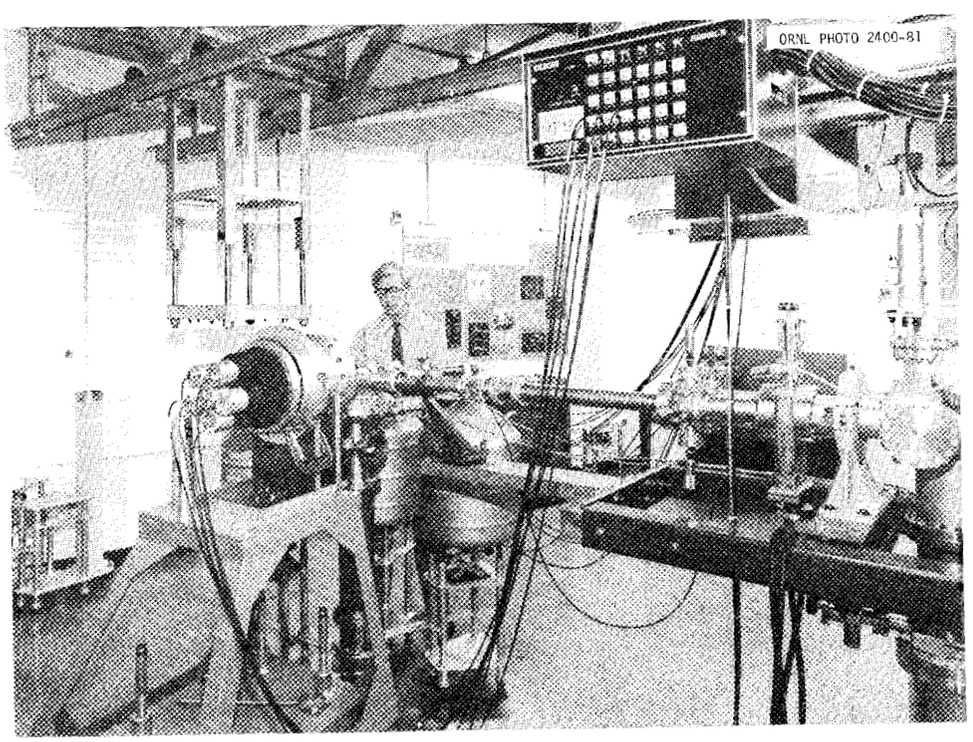


Fig. 1.17. Gamma-ray spectrometer system.

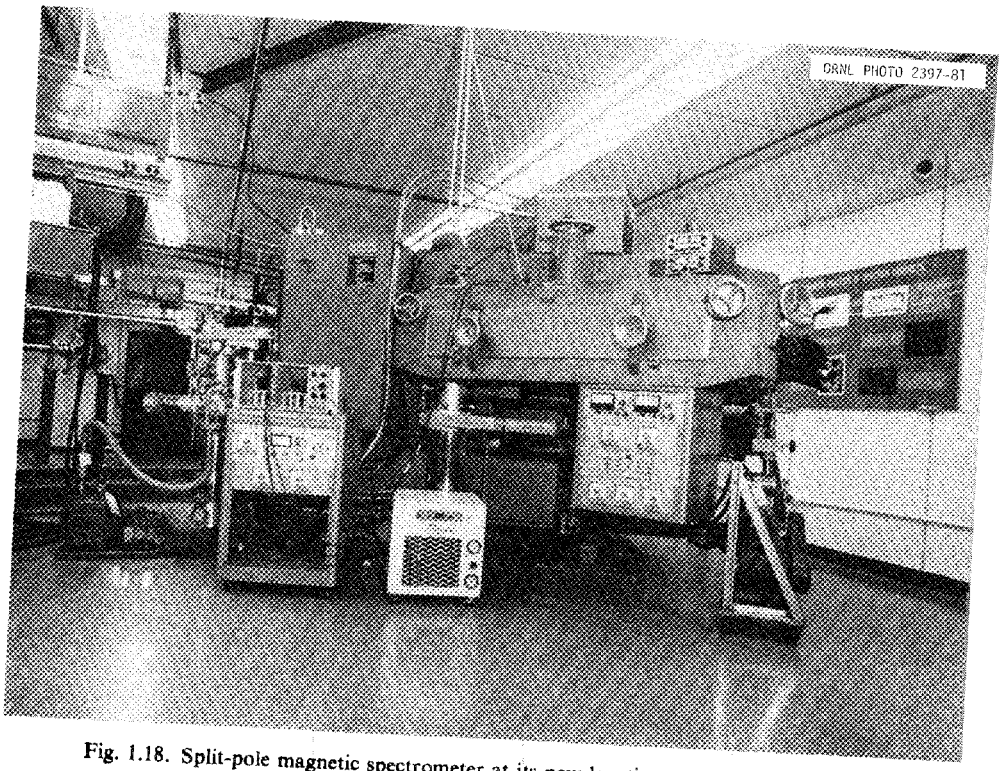


Fig. 1.18. Split-pole magnetic spectrometer at its new location on a tandem beam line.

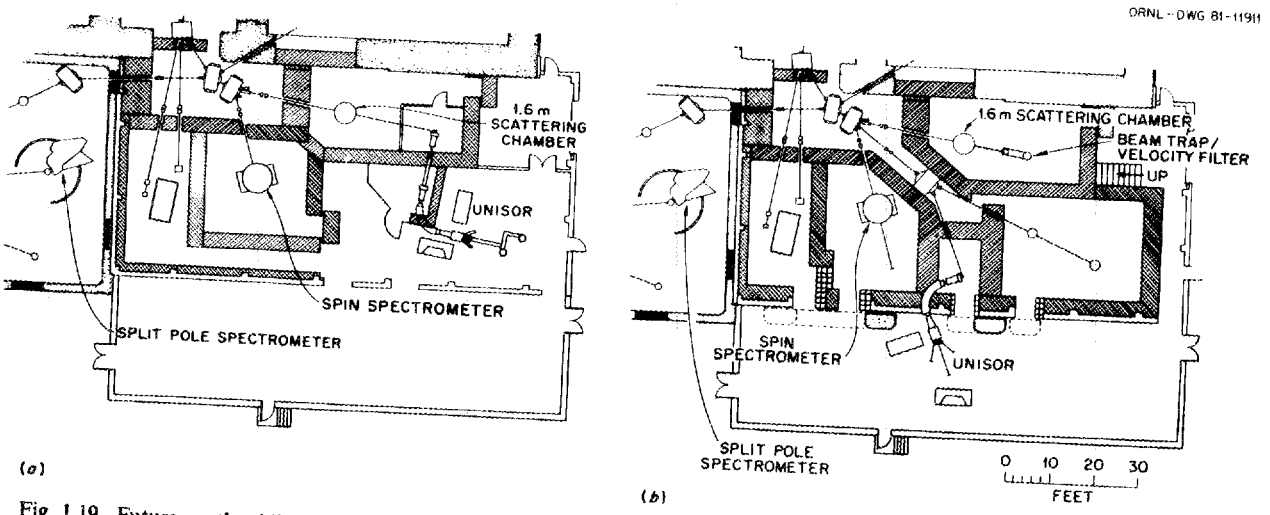


Fig. 1.19. Future south addition to the HHIRF building. (*a*) The part that has been funded; (*b*) the proposed reconfiguration.

The number of persons, and their area of expertise, that make up the technical arm of the Experimental Support Group are:

1	liaison secretary
¼	mechanical engineer
¼	computer programmer
2	laboratory technicians
1	electronics technician
1	computer technician

Members of this group support the mentors in the maintenance and improvement of experimental apparatus. The four technicians provide the first line of support to users. Questions and problems beyond their scope of expertise are referred to the mentors.

A users' handbook was prepared and was sent to users in April 1980. An impression of the material in this handbook is given by its Table of Contents, shown in Table 1.7.

The ground-breaking ceremonies for the first building of the Joint Institute for Heavy-Ion Research were held on July 10, 1979; on May 5 the building was opened for occupancy. This 375-m^2 (4000-ft^2) structure (Fig. 1.20) contains offices with accommodations for 16 persons, office-living space for four persons, sleeping alcoves, a full kitchen, and a commons area (Fig. 1.21), all of which are available to outside users while at the HHIRF acquiring data or reducing data. The construction of this building was made possible by combined funding from Vanderbilt University, the State of Tennessee (through the University of Tennessee), and the Department of Energy (through ORNL).

Funds have been appropriated by the State of Tennessee for a second building for the Joint Institute that is comparable in size to the first. As part of this building, there will be a small auditorium where miniconferences, of the order of 100 persons, can be held. The long-range objective of the Institute is to support and improve the quality of research at the HHIRF by bringing together scientists in a suitable environment.

1. Oak Ridge Associated Universities.

Table 1.7. Table of Contents of Users Handbook

Chapter	Title
	Foreword
I	General Comments on the HHIRF
II	Requests for Accelerator Time
III	Responsibilities of Users
IV	Accelerator Systems
	A. Tandem Accelerator
	B. ORIC
	C. Coupled Mode
V	Experimental Apparatus
	A. Nuclear Physics Apparatus
	1. 76-cm-diam Scattering Chamber
	2. 1.6-m-diam Scattering Chamber
	3. Magnetic Spectrometers
	4. Time-of-Flight Spectrometer
	5. UNISOR Facility
	6. γ-ray Spectrometer Systems
	7. Spin Spectrometer
	B. Atomic Physics Apparatus
	C. Electronics
	D. Equipment Not Provided by HHIRF
	E. Apparatus Provided by User
	F. Signal Transport
VI	Computer Facility
VII	Support to Users
VIII	Site and Travel
IX	Organization
Appendix A	ORIC Extracted Heavy-Ion Beams
Appendix B	Pool of Electronic Modules
Appendix C	ORIC Users Safety Guide
Appendix D	HHIRF Users Group Charter

USERS' ACTIVITIES

R. L. Robinson

There are 390 members of the HHIRF Users Group. Annual meetings of the group were held in October 1979 at Knoxville, Tennessee, and in April 1980 at Washington, D.C.

Those who have served on the Executive Committee of the HHIRF Users Group since 1979 are:

1978–79 H. C. Britt (Los Alamos National Laboratory)
D. Cline, Chairman 1979 (University of Rochester)
C. D. Moak (Oak Ridge National Laboratory)

Fig. 1.20. Joint Institute for Heavy-Ion Research.

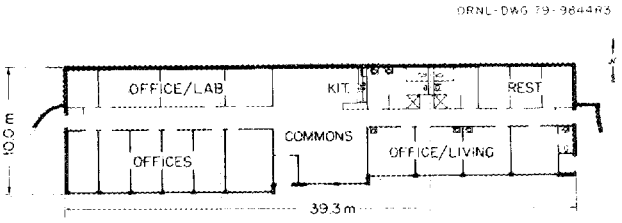


Fig. 1.21. Floor plan of the Joint Institute for Heavy-Ion Research.

D. G. Sarantites (Washington University) (completed term of Britt)

1979–80 K. W. Kemper (Florida State University)
F. Plasil (Oak Ridge National Laboratory)
V. E. Viola, Chairman 1980 (University of Maryland)

1980–81 J. V. Maher (University of Pittsburgh)
L. L. Riedinger, Chairman 1981 (University of Tennessee)
D. Ward (Chalk River National Laboratory)

1981–82 P. D. Bond (Brookhaven National Laboratory)
P. Braun-Munzinger (SUNY at Stony Brook)
M. L. Halbert (Oak Ridge National Laboratory)

The Executive Committee has continued to provide important guidance in operation of the facility and in the planning of future apparatus. It also recommended persons to serve on the first PAC and participated in developing guidelines for the PAC; these are summarized in Table 1.8.

Table 1.8. Recommendations for HHIRF Program Advisory Committee

Membership: Six to eight persons
Term: Two years, staggered
Restrictions: No more than two members from the same institution
Appointment: By ORNL, taking into consideration recommendations of the Executive Committee of the Users Group and recommendations of the HHIRF Policy Review Committee
Meetings: Three per year

The committee recommended that the proposals be in written form with no oral presentation unless specifically requested by the PAC. Proposals may be for either a single run or for a single experiment which may involve more than one run. In the latter case, the time approved must be used within a year of approval.

Members of the first PAC are:

E. E. Gross (Oak Ridge National Laboratory)
F. Iachello (Yale University)
P. Richard (Kansas State University)
P. H. Stelson (Oak Ridge National Laboratory)
F. S. Stephens (Lawrence Berkeley Laboratory)
K. L. Wolf (Argonne National Laboratory)

This PAC met (with Joe McGrory substituting for Iachello) on November 10–11, 1980, to review proposals requesting 605 8-h shifts in the first cycle and 893 shifts in total. The committee recommended that experiments requiring 265 shifts be approved for the first cycle. The number of participants in the approved proposals by institution is given in Table 1.9.

Table 1.9. Number of participants by institution that were approved accelerator time in first cycle at the HHIRF

Vanderbilt University	5
Tennessee Technological University	2
University of Koln (W. Germany)	2
University of Virginia	2
Louisiana State University	2
University of Witwatersrand (South Africa)	5
University of Lund (Sweden)	1
Research Institute for Atomic Physics	1
Lawrence Berkeley Laboratory and University of California, Berkeley	3
Georgia State University	1
Brookhaven National Laboratory	2
St. Louis University	1
University of Tennessee	11
Oak Ridge National Laboratory	36
University of Kentucky	3
Georgia Institute of Technology	2
Indiana University	1
Los Alamos National Laboratory	4
University of Eastern Kentucky	1
Virginia Polytechnic Institute	1
Washington University	5
East Carolina University	1
Texas A&M University	5
University of Frankfurt (W. Germany)	1
Kansas State University	3
Niels Bohr Institute (Denmark)	5

ORIC SUPERCONDUCTING CONVERSION STUDIES

J. B. Ball
J. K. Ballou[1]
R. L. Brown[1]
T. P. Cleary[2]
W. H. Gray[1]
E. D. Hudson
P. S. Litherland[3]
R. S. Lord
C. A. Ludemann
C. H. Malarkey[4]
J. A. Martin
G. S. McNeilly[4]
S. W. Mosko
S. W. Schwenterly[1]
T. A. Welton

Introduction

In the last progress report we discussed the continuing evolution of plans for phase II of the Holifield facility to replace the ORIC with a more powerful booster accelerator. At that time, our proposal was for a K-1200 superconducting cyclotron similar to the MSU phase II accelerator. That proposal was not recommended by the Nuclear Science Advisory Committee (NUSAC) for funding; we were admonished to develop plans for a facility to provide significantly higher energies. Several studies of single- and multistage booster designs followed; rough scoping of accelerator systems for energies in the 600-MeV/A range gave cost estimates in the 50 to 70 million-dollar range. As a result of the high projected cost and heeding the 1979 NUSAC long-range plan (which does not recommend any new major heavy-ion facilities in the period 1980–89), we are now proposing a more modest upgrade that will increase the energy capabilities of the ORIC by increasing the magnetic field strength through the use of superconducting coils. This upgrade, at a final cost of about 10 million dollars, will open the exciting possibility of extending our research to the full range of ion masses at energies two to seven times the Coulomb barrier. With the conversion, the facility will not only be able to fully exploit the large variety of negative ions made possible by present negative-ion source technology, but also to immediately utilize the experimental devices and data acquisition computers that are a part of the Holifield facility.

Beam Energies—Present and Future

The ORIC now provides maximum beam energies of 100 q^2/A^2 MeV/A. With the ion charge states available from the internal Penning-type ion source, the cyclotron provides beams up to $A = 40$ with energy high enough for nuclear physics

research. With the completion of the new 25-MV tandem and the beam injection system for the use of the cyclotron as an energy booster, much higher beam energies will be available. In coupled operation of the tandem and cyclotron, ion energies above the Coulomb barrier will be available up to $A = 160$.

The superconducting conversion of the cyclotron will provide a large increase in energy capability (Fig. 1.22). For ions heavier than $A = 130$ the increase in energy is a factor of 3, from 100 q^2/A^2 MeV/A to 300 q^2/A^2 MeV/A. For lighter ions the increase is somewhat less. For $^{16}O^{8+}$, for example, the energy will be increased by a factor of 1.5, from 25 to 37.5 MeV/A.

Technical Details of the Conversion

The conversion includes a new superconducting coil system to replace the existing aluminum magnet coils, a new beam extraction system, and modifications to the beam transport system and radiation shielding to accommodate the higher-energy particles. The superconducting coil system will permit an increase in the magnetic field of the cyclotron from 1.9 to 3.3 T.

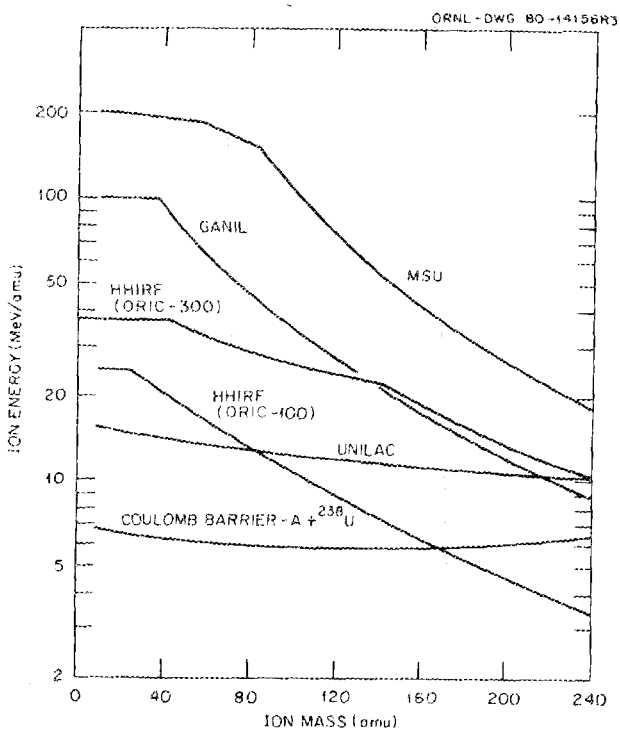


Fig. 1.22. Energy vs mass characteristics for the ORIC in present coupled operation with the 25-MV tandem (HHIRF phase I) and for the conversion HHIRF (ORIC-300) for beam intensities of 10^{11} particles/s.

Magnetic field design and analysis

Increasing the energy of the ORIC with superconducting main magnet coils was examined in a preliminary study in 1975.[5] Since that time a complete remapping of the magnetic field has been completed. The new measurements have been Fourier-analyzed, and the coefficients have been parameterized in terms of the currents in the main coil, average-field-trimming coils, harmonic correction coils, and valley coils, in a way which takes into account the variable saturation of the iron.[6] This description of the magnetic field is now used in a computer program which provides essentially exact current settings for the various coil systems. We have used this program to predict the magnet characteristics at the $K = 300$ field levels. A close fit to the isochronous magnetic field was obtained by increasing the radius of the main magnet coils and locating them nearer the median plane (Figs. 1.23 and 1.24). The magnetic fields of the new geometry were incorporated into the parameterization; orbit code analyses show that the new geometry provides magnetic fields which are a good fit to the isochronous requirements over the required range.

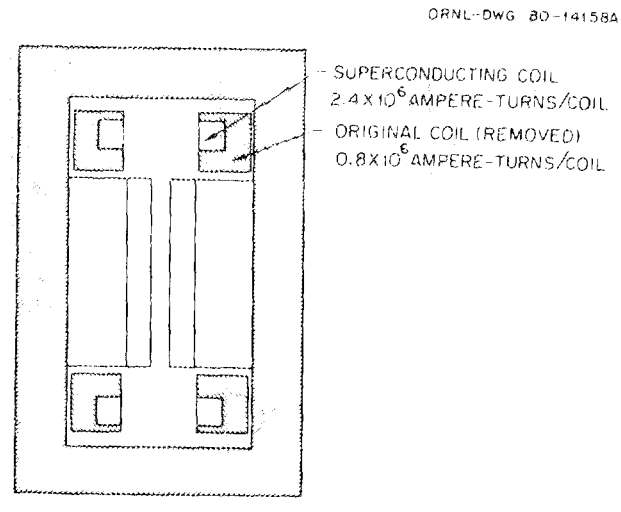


Fig. 1.23. Superconducting coils will have a smaller cross section than the present coils, are of larger radius, and are closer to the median plane.

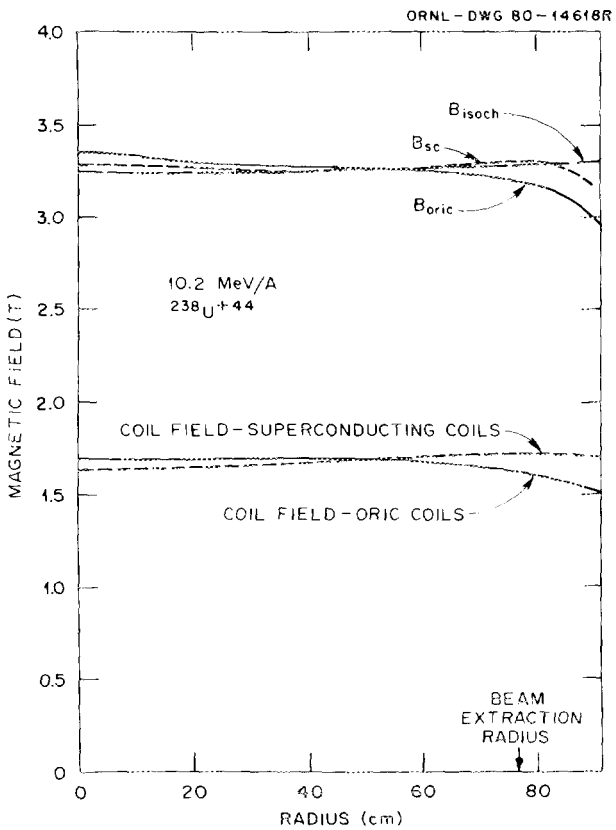


Fig 1.24. Radial profile of average magnetic field for the conversion, showing the improvement in shape obtained with optimized coil geometry.

The computer program GFUN-3D,[7] which calculates the magnetic field of complex three-dimensional systems of coils and iron, has been used to compute the ORIC magnetic fields. Comparison of GFUN-3D results with the measurements at 1.85 T, and with the analytical extrapolations at 3.3 T, shows good agreement. These results lend confidence to our predictions of the characteristics of the conversion.

The energy of an isochronous cyclotron may be limited by the bending power of the magnet, $E = K_B\ q^2/A^2$ MeV/A, or by focusing, $E = K_f\ q/A$ MeV/A. The focusing limit occurs at the onset of loss of axial focusing. We have determined through equilibrium orbit code studies, using extrapolated ORIC magnetic fields, that K_f for the conversion is approximately 75 MeV/A. The ion energy characteristics of the conversion, Fig. 1.22, take into account the focusing and bending limits of the magnetic field and the charge states obtained by injection of tandem beams. The maximum energy is limited by focusing below approximately $A = 130$.

Superconducting coil and cryostat

The new coil system (Fig. 1.25) is designed to replace the existing coil system exactly; the cryostats for the superconducting coils will bolt onto the cyclotron yoke, using the same mounting holes. A yoke stiffening system (not shown in the figure) will be provided to accommodate the increased magnet forces.

The two superconducting coils have inner and outer diameters of 2.5 and 3.1 m and are 0.25 m wide. Each winding contains 564 turns of NbTi conductor wound in six double pancakes. G-10 epoxy fiberglass insulation will be used: 0.12-cm-thick slotted material between turns and 0.16-cm perforated sheet between pancakes. The maximum operating current is approximately 4300 A. The conductors will be cooled by pool-boiling 4.5 K helium from a liquefier. The conductor is designed to be fully cryostable. With a copper stabilizer bar 2.0 cm wide and 0.5 cm thick, the quench heat flux is 0.26 W/cm^2. The overall current density is 3200 A/cm^2. The stored energy in the system is 55 MJ.

To ensure safe and reliable operation, all features of the coil design will incorporate substantial safety factors. The critical current of the conductor is 7000 A at 4 T. The peak dump voltage is only 150 V, and the maximum conductor temperature reached in a dump is estimated to be 104 K. The peak pressure in the cryostat during a quench is approximately 7 atm.

Mechanical stresses in the winding have been computed using the computer code STANSOL.[8] Stresses from winding preload, cooldown, and energization were considered. A winding preload of about 49 MPa (7000 psi) is sufficient to prevent the windings from lifting off the bobbin. The maximum tensile stress in the conductor at full field is 80.5 MPa (11,500 psi).

The mechanical suspension for the coils must support the attractive force of 3.9 MN (880,000 lb) between the coils with acceptably low heat leakage and deflection and maintain the coils concentric and coplanar with the median plane to within ±0.5 mm. The coil forces must be supported from the yoke through the cryostat. The

ORNL-DWG 81-6578

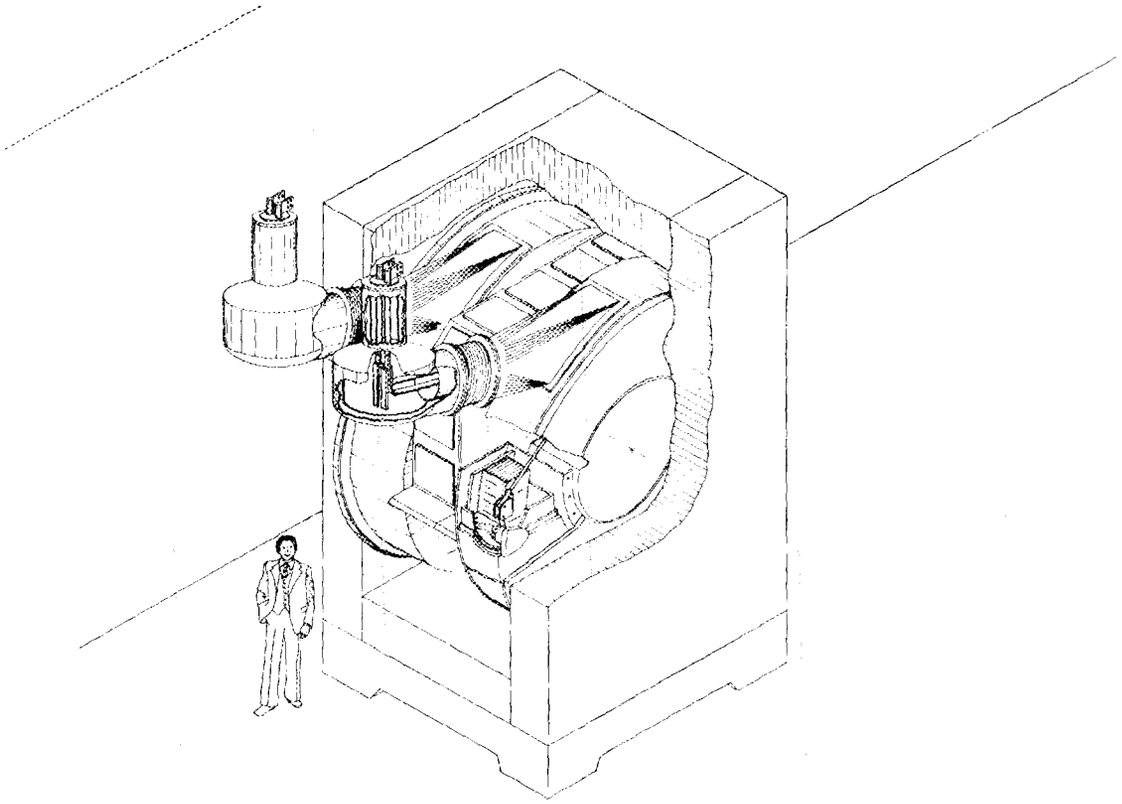


Fig. 1.25. Superconducting coils are in separate cryostats, which occupy the same space used by the present aluminum coils.

design adopted (Figs. 1.26 and 1.27) incorporates epoxy-fiberglass links between the 4 K coils and the 77 K liquid-nitrogen shield, which is mounted on short tubular stainless steel supports from the base plate at 300 K. Stainless steel transverse support rods, cantilevered from the tubes, support the 76-kN (17,000-lb) gravity load and the coil decentering forces, which are calculated to be a maximum of 46.6 kN/cm (26,600 lb/in.). The safety factors of this design are approximately 7 for the epoxy-fiberglass and 3 for the stainless steel components. The two coils will consume about 25 liters/h of liquid helium and an equal amount of liquid nitrogen.

Beam extraction system

The beam extraction system for the conversion (Fig. 1.28) will consist of an electrostatic deflector operating at a gradient of 120 kV/cm, followed by two −0.5-T room-temperature coaxial magnetic channels[9] and a −2.4-T superconducting coil channel.

Two concepts are being evaluated for the −2.4-T magnetic channel. One is based on the use of a cosine current distribution in an inner (main) winding and a similar outer (compensating) winding with current of opposite sign to cancel the external magnetic field. The alternate design

ORNL-DWG 81-6577

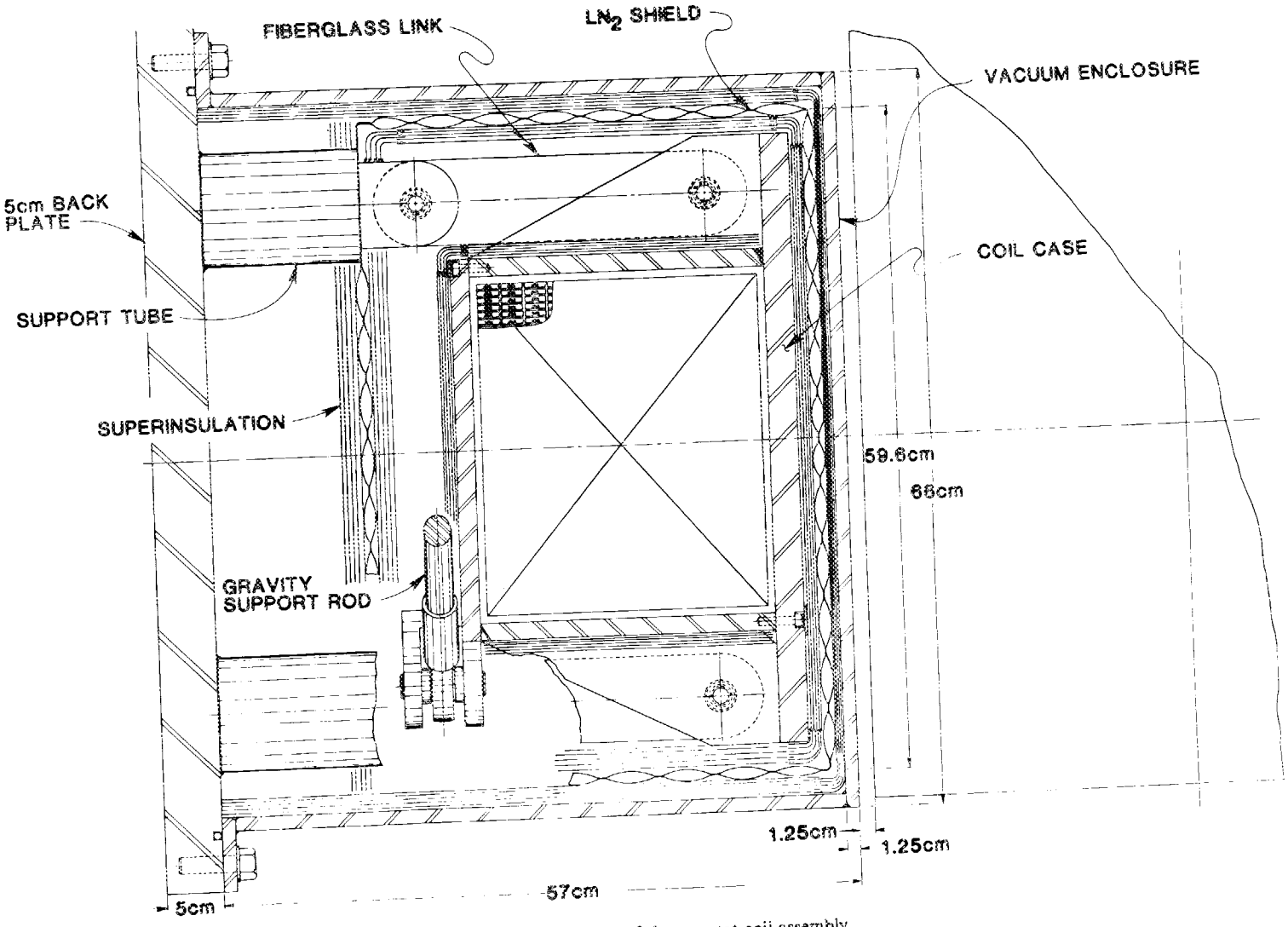


Fig. 1.26. Cross section of the cryostat-coil assembly.

ORNL-DWG 81-6576

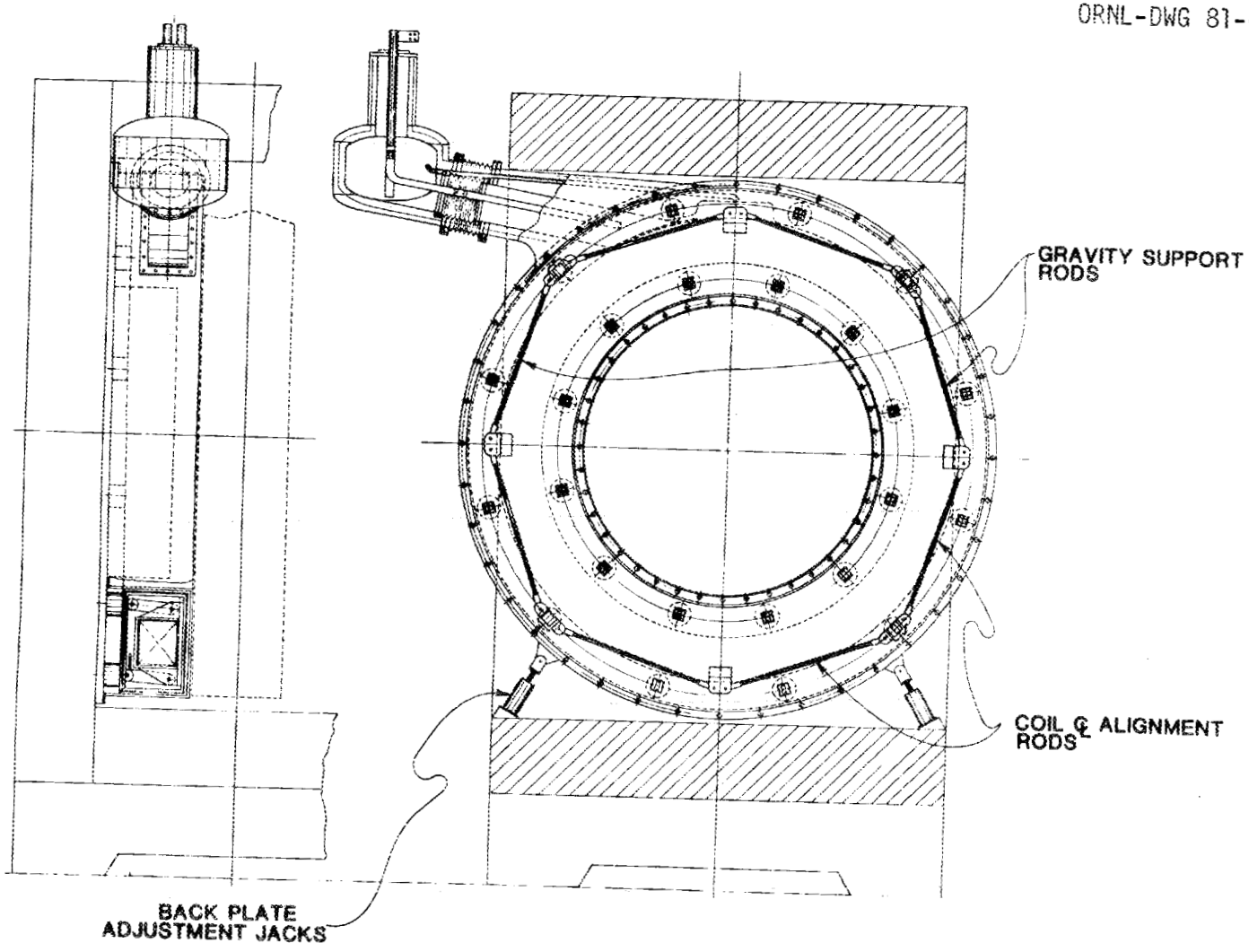


Fig. 1.27. Side view of the cryostat-coil assembly, showing the coil centering supports, alignment system, and coil leads.

ORNL-DWG 80-20638

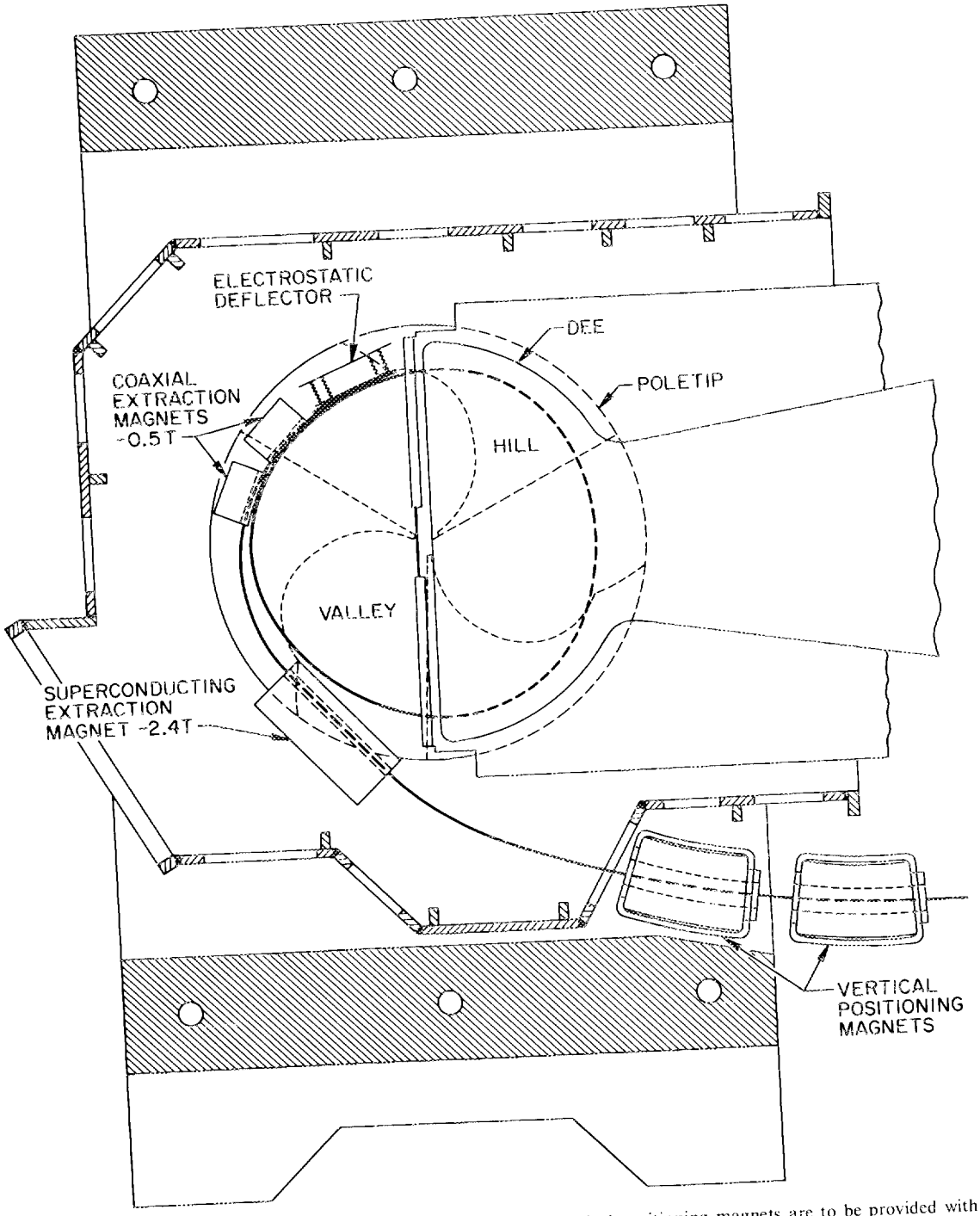


Fig. 1.28. Beam extraction system for the conversion. The two vertical positioning magnets are to be provided with coils to compensate for the effect of the stray field on the iron yokes.

includes a set of main conductors to produce the channel field and a distributed array of compensating conductors.

The channel location and strength were chosen to produce a nearly linear path so that a straight channel element may be used with consequent ease of construction.

Beam transport and shielding modifications

Only minor modifications of the beam transport system are required to serve all existing and planned experimental stations with the higher-energy ion beams of the conversion. A small amount of additional radiation shielding will be required.

---

1. Fusion Energy Division.
2. World Information and Technology Systems Corp., Willowdale, Ontario, Canada.
3. UCC-ND Engineering Division.
4. UCC-ND Computer Sciences Division.

5. G. S. McNeilly et al., *Proceedings of the Seventh International Conference on Cyclotrons and Their Applications,* Birkhauser, Basel, 1975, p. 626.

6. T. P. Cleary, *IEEE Trans. Nucl. Sci.* **NS-26,** 3097 (1979).

7. A. G. A. M. Armstrong et al., *New Developments in the Magnet Design Program GFUN,* RL-75-066 (Rutherford Laboratory, 1975).

8. N. R. Johnson, W. H. Gray, and R. A. Weed, Proceedings of the 6th Symposium on Engineering Problems of Fusion Research.

9. E. D. Hudson and R. S. Lord, Proceedings of International Conference on Magnet Technology, Stanford University, California, 1965.

2. Nuclear Physics

INTRODUCTION

The following accounts represent the efforts of approximately 30 ORNL staff and their collaborators. We are organized into three groups of roughly equal strength, focused on three different aspects of heavy-ion physics, which may be loosely characterized as heavy-ion microscopic physics, heavy-ion macroscopic physics, and gamma-ray spectroscopy. Fortunately, these subdivisions are not always clean, and the groups continually experience an overlapping of interests leading to a lively interaction and interchange of personnel as the research programs evolve. In addition to the heavy-ion program, we carry out small, but productive, programs in light-ion physics and meson physics which are reported herein. An important part of our research is the continuing development of equipment, and an account of this aspect of our effort is also included. What are not adequately covered here are our contributions to the HHIRF project as mentors for much of the large-scale equipment. Mentorship requires complete involvement from the initial design stage to the maintenance and upgrade of the final research facility.

This period has produced many solid scientific advances in all of our programs. Of particular note are contributions to the areas of giant resonances, preequilibrium particle emission, incomplete fusion, and gamma-ray systematics. This period is also noteworthy for the completion of the "spin spectrometer" and the gas-jet target—two devices which greatly enhance research possibilities at the HHIRF.

LIGHT-HEAVY-ION SCATTERING

C. B. Fulmer
R. L. Auble
J. B. Ball
F. E. Bertrand
N. M. Clarke[1]
C. D. Goodman[2]
E. E. Gross
D. C. Hensley
S. Mukhopadhyay[3]
G. R. Satchler
M. Steeden[1]
J. R. Wu[4]

The scattering of light heavy ions ($4 < A < 12$) is of interest because the elastic scattering is said to exhibit a transition[5] between that characteristic of light ions ($A \leqslant 4$) and that characteristic of heavy ions ($A \gtrsim 12$). For light ions at lower scattering energies the elastic scattering is characterized by incomplete absorption and can be well described by the optical model using a Woods-Saxon form factor for both real and imaginary parts of the potential, albeit with an ambiguity of discrete families of real-potential well depth. Heavy-ion elastic scattering is characterized by complete absorption. Optical-model fits with a Woods-Saxon potential and other shapes for the real well exhibit continuous ambiguities in the potential and little or no energy dependence. Heavy-ion elastic scattering is also well described by the double-folding optical model with a semirealistic interaction[6] to generate the real part of the nucleus-nucleus potential.

The energies of light heavy ions available at both the ORIC and the HHIRF tandem are sufficiently high that scattering angular distributions from a wide range of targets exhibit oscillations characteristic of Fraunhofer diffraction and are more sensitive to details of the potential than scattering at lower beam energies where the scattering angular distributions show typical Fresnel-like patterns. Also, the high beam intensities available from the HHIRF tandem make it feasible to measure scattering at very large angles.

Table 2.1 is a list of stable nuclei in the $4 < A < 12$ mass region which are available as projectiles for intermediate-mass ion scattering measurements. The first excited states are all sufficiently separated from the ground states that modest energy resolution is adequate for elastic scattering measurements from a wide choice of target nuclei. There is also a variety of projectile spins and nucleon and alpha binding energies, so the effects of these on the scattering can be studied.

Table 2.1. Stable light heavy ions available for scattering measurements

Projectile	J^π	1st excited state (MeV)	Binding energy (MeV) n	p	α
^{6}Li	1^+	2.18	5.7	4.7	1.5
^{7}Li	$3/2^-$	0.48	7.3	10.0	2.5
^{9}Be	$3/2^-$	1.67	1.7	16.9	2.5
^{10}B	3^+	0.72	6.8	19.6	7.4
^{11}B	$3/2^-$	2.14	8.4	6.6	4.5

We have performed measurements with 88-MeV ^{6}Li ions, with 87.5-MeV ^{10}B ions, and with 79.5-MeV ^{11}B ions. Measurements are planned for scattering of ^{9}Be ions accelerated by the HHIRF tandem.

^{6}Li Scattering

Preliminary results of 88-MeV ^{6}Li elastic scattering were reported in the last Physics Division Progress Report.[7] These data have been extended to include measurements at larger angles and for a wider range of targets. Elastic scattering was studied for 11 targets ranging in mass from ^{24}Mg to ^{208}Pb. Angular distributions were measured from about 10° c.m. in steps of 0.5° mostly out to 60° or 70°, where the elastic cross sections range from 10^{-3} to 10^{-5} of the Rutherford values. Significant odd-A even-A differences were observed in the elastic scattering from three pairs of neighboring mass targets. Inelastic scattering cross sections for exciting the lowest 2^+ states of ^{24,26}Mg and ^{60}Ni were also obtained.

The elastic data were analyzed using the optical model, with potentials of both Woods-Saxon and double-folding form factors. Good fits were obtained with both types of potentials. The heavy targets, whose elastic scattering exhibits Fresnel-like patterns, require only a four-parameter Woods-Saxon potential. The data from the lighter targets, which exhibit Fraunhofer-like structure, require six-parameter Woods-Saxon potentials. The folding-model analyses with the "realistic" M3Y interaction, used previously for a wide range of heavy-ion scattering data,[6] overestimate the real potential for ^{6}Li by about 60%, in agreement with analyses of other ^{6}Li data at energies ranging from 28 to 156 MeV. Examples of the data and optical-model fits are shown in Figs. 2.1 and 2.2.

The optical-model potentials for ^{6}Li deduced from analysis of the data show a number of systematic features. Both real and imaginary potentials have very diffuse surfaces (i.e., large values of a_V and a_W) compared with many other heavy ions, and the imaginary potentials have large radii. As a consequence the imaginary potential is generally

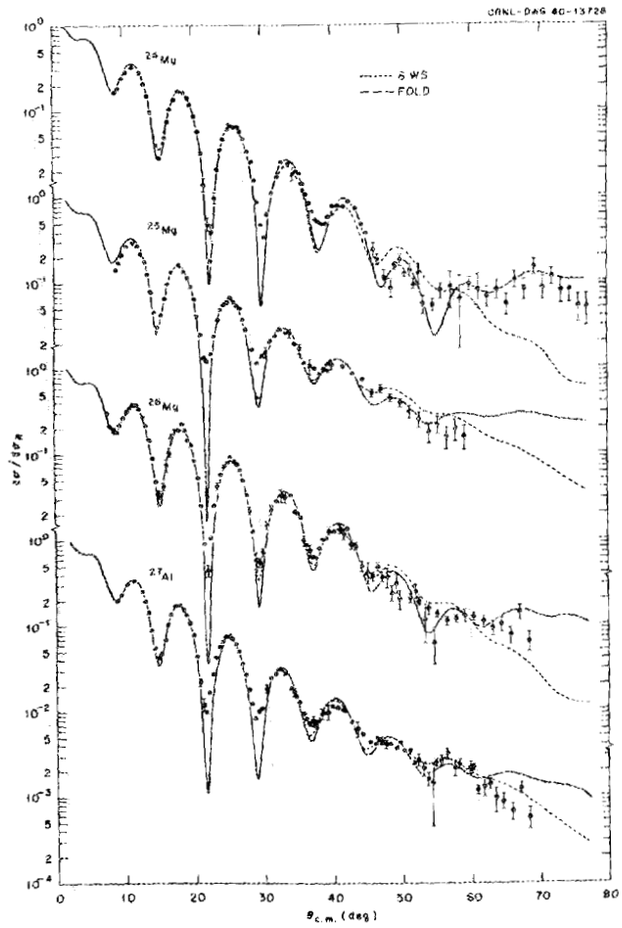


Fig. 2.1. Elastic scattering of 88-MeV ^{6}Li from ^{24,25,26}Mg and ^{27}Al. The theoretical curves are for six-parameter Woods-Saxon (6WS) and four-parameter folded (FOLD) optical-model potentials.

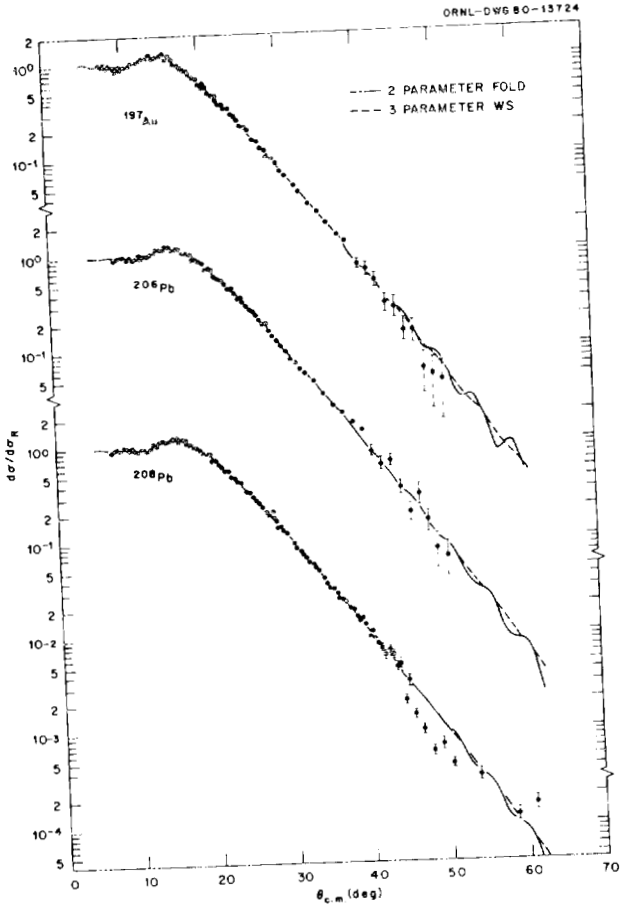


Fig. 2.2. Elastic scattering of 88-MeV ^{6}Li from ^{197}Au and ^{206,208}Pb compared with optical-model predictions for Woods-Saxon and folding-model potentials.

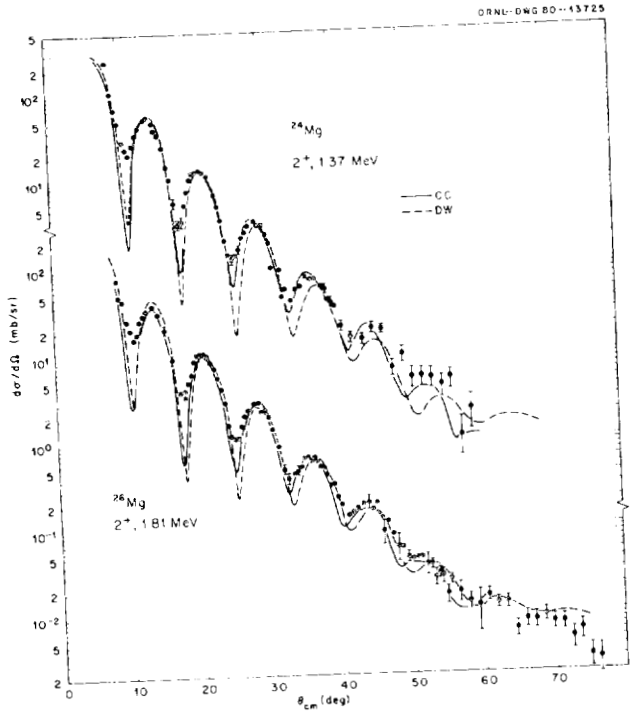


Fig. 2.3. Inelastic scattering of 88-MeV ^{6}Li exciting the lowest 2^+ states of ^{24}Mg and ^{26}Mg compared with coupled-channels and distorted-wave calculations.

stronger than the real one near the strong-absorption radius, whereas the opposite is true in the interior region.

The inelastic data were analyzed with both distorted-wave and coupled-channels calculations. Examples of the inelastic data and the calculations are shown in Fig. 2.3. The coupled-channels calculations showed that reorientation effects in the ground states of the odd-A nuclei, due to scattering from the ground-state quadrupole moment, can account for the differences in elastic scattering from neighboring odd-A and even-A target nuclei.

The ^{6}Li scattering data are reported in tabular and graphical form[8] and also with the results of the analyses[9].

^{10}B and ^{11}B Scattering

Measurements were performed for scattering of ^{11}B from targets of ^{24,25,26}Mg, ^{27}Al, ^{59}Co, ^{60}Ni, and ^{197}Au and of ^{10}B from ^{24,25}Mg and ^{60}Ni. All of these targets were also used in the ^{6}Li scattering measurements described above. For ^{11}B an incident beam energy of 79.6 MeV was used, which is near the highest available from the ORIC with ^{11}B in the $^{+3}$ charge state (for higher charge states the available intensity is orders of magnitude lower). Subsequently a ^{10}B beam was obtained quickly by adjusting the rf frequency only and leaving the magnetic fields unchanged. This resulted in 20% larger energy per nucleon for the ^{10}B beam.

The elastic angular distributions for Co, Ni, and Au show typical Fresnel-like patterns and no oscillatory structure, while those of the Mg and Al targets exhibit oscillations more typical of Fraunhofer diffraction.

It has been demonstrated that elastic scattering of composite particles may include quadrupole contributions from the target[10] (of spin ≥1) and/or the projectile (of spin ≥1).[11] The target quadrupole contribution is allowed for odd-A targets (e.g., ^{25}Mg) but not even-A targets (e.g., ^{24}Mg). The quadrupole moment[12] of ^{11}B is about half that of ^{10}B, so the projectile quadrupole contribution to elastic scattering is larger for ^{10}B. A qualitative

comparison of the two effects is shown in Fig. 2.4, where the experimental elastic angular distributions are represented by smooth curves. In Fig. 2.4*a* the pronounced differences in the two angular distributions are principally due to quadrupole contributions from the ^{25}Mg target; these are obscured by the larger projectile quadrupole contributions of ^{10}B to the angular distributions compared in Fig. 2.4*b*.

The ^{11}B data for ^{59}Co and ^{60}Ni (shown in Fig. 2.5) are very similar, with no apparent differences due to odd-*A* and even-*A* target effects. This is in contrast to the differences observed in ^{11}B scattering from the Mg and Al targets (shown in Fig. 2.6) and to the differences observed in 88-MeV ^{6}Li scattering from the Co and Ni targets,[8] where there was structure in the angular distributions. The elastic angular distributions for ^{11}B and ^{10}B scattering from ^{60}Ni show no significant differences such as are observed for ^{24}Mg. The quadrupole moment effects of either target or projectile are not apparent in elastic angular distributions characterized by Fresnel-like patterns.

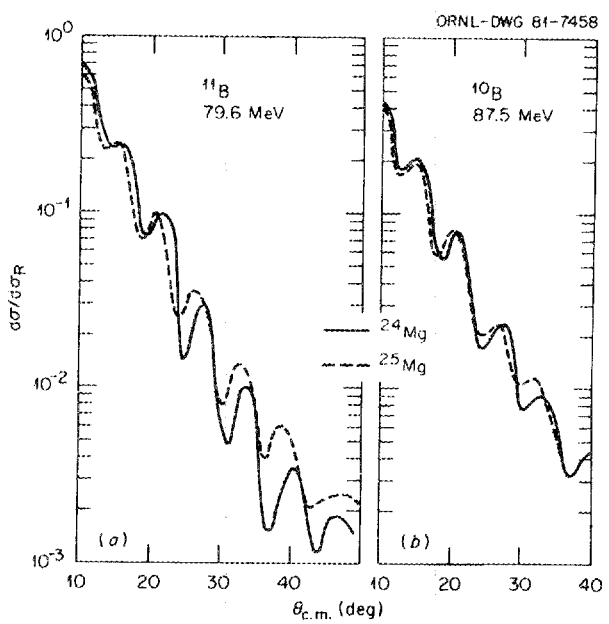


Fig. 2.4. Elastic scattering of ^{10,11}B from ^{24,25}Mg. The curves represent experimental data.

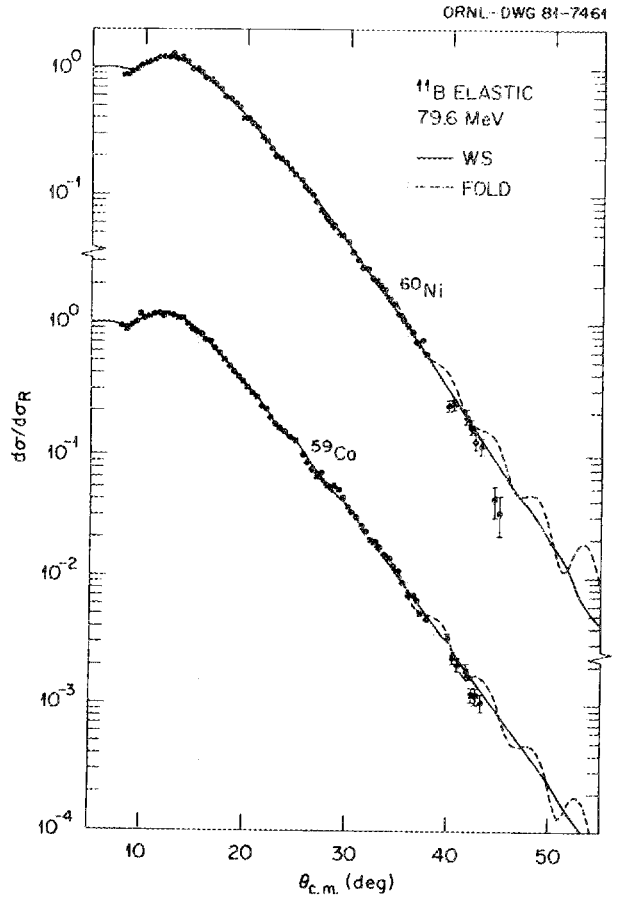


Fig. 2.5. Elastic scattering of ^{11}B from ^{59}Co and ^{60}Ni. The data are compared with optical-model fits for both Woods-Saxon and folding-model real-potential form factors.

Analyses of the data with both Woods-Saxon and folding-model potentials are discussed in the theory section of this report.

---

1. Wheatstone Laboratory, King's College, University of London, Strand, London WC2R 2LS, U.K.
2. Present address: Physics Department, University of Indiana, Bloomington.
3. 1980–81 visitor from Khalsa College, Matunga, Bombay, India.
4. Present address: Bell Laboratories, Naperville, Ill.
5. R. M. DeVries, D. A. Goldberg, J. W. Watson, M. S. Zisman, and J. G. Cramer, *Phys. Rev. Lett.* **39**, 450 (1977).
6. G. R. Satchler and W. G. Love, *Phys. Rep.* **55**, 183 (1979).

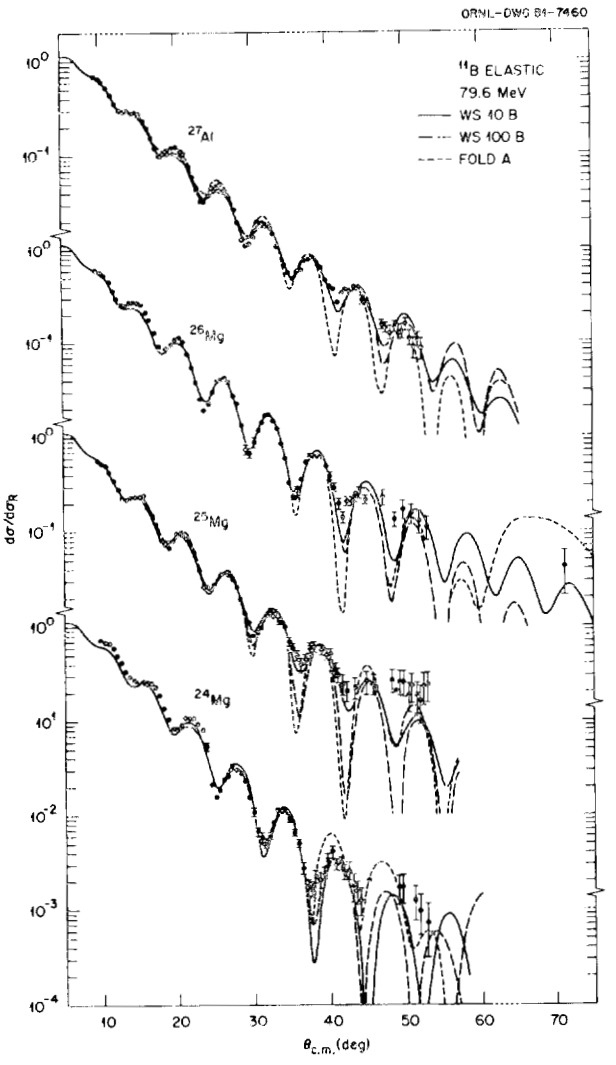


Fig. 2.6. Elastic scattering of ^{11}B from ^{24,25,26}Mg and ^{27}Al. The data are compared with optical-model fits for both Woods-Saxon and folding-model real-potential form factors.

7. N. M. Clarke, C. B. Fulmer, C. D. Goodman, E. E. Gross, and M. Steeden, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498, p. 29 (1979).

8. C. B. Fulmer, N. M. Clarke, E. E. Gross, F. E. Bertrand, C. D. Goodman, D. C. Hensley, G. R. Satchler, M. F. Steeden, and J. R. Wu, ORNL/TM-7510 (1980).

9. C. B. Fulmer, G. R. Satchler, E. E. Gross, F. E. Bertrand, C. D. Goodman, D. C. Hensley, J. R. Wu, N. M. Clarke, and M. F. Steeden, *Nucl. Phys.* **A356**, 235 (1981).

10. J. S. Blair, *Phys. Rev.* **115**, 928 (1959); J. S. Blair and J. M. Naquib, *Phys. Rev. C* **1**, 569 (1970); G. R. Satchler and C. B. Fulmer, *Phys. Lett.* **50B**, 309 (1974).

11. L. A. Parks, K. W. Kemper, A. H. Lumpkin, R. I. Cutler, L. H. Harwood, D. P. Stanley, P. Nagel, and F. Petrovich, *Phys. Lett.* **70B**, 27 (1977); L. A. Parks, D. P. Stanley, L. H. Courtney, and K. W. Kemper, *Phys. Rev. C* **21**, 217 (1980).

12. G. H. Fuller and V. W. Cohen, *Nucl. Data Tables* **A5**, 433 (1969).

FUSION CROSS SECTIONS FOR LIGHT SYSTEMS

J. Gomez del Campo — J. A. Biggerstaff
D. Shapira — P. H. Stelson
Y.-D. Chan — R. A. Dayras[3]
M. E. Ortiz[1] — R. G. Stokstad[4]
D. DiGregorio[2] — J. P. F. Sellschop[5]
J. L. C. Ford, Jr. — R. Parks[6]
D. Weisser[7]

A systematic study of heavy-ion fusion cross sections for light systems for which $A_T + A_P \leq 40$ and for bombarding energies up to about 18 MeV/A is in progress at ORNL. A detailed study of the fusion of ^{16}O + ^{10}B and ^{14}N + ^{12}C (refs. 8, 9) revealed that, even at energies up to 18 MeV/A, the evaporation- residue (ER) energy spectra, angular distributions, and total yields are consistent with the equilibrium decay of the compound nucleus. Also, for these two systems, the fusion cross sections appear to be dominated by entrance-channel effects of a microscopic nature. In addition, an absolute angular momentum limit has been found at $J_c = 27\hbar$. To achieve a better understanding of these effects, further measurements of the ^{14}N + ^{12}C system have been carried out, as well as comparisons with the ^{10}B + ^{16}O system. To extend the systematic study, other systems have been measured, and data are presented in this report for the ^{14}N + ^{10}B, ^{17}O + ^{10}B, ^{20}Ne + ^{20}Ne, and ^{20}Ne + ^{16}O systems covering a range of bombarding energies from 2 MeV/A to about 13 MeV/A.

The ^{26}Al System

To study the behavior of the fusion cross section at high energies it is necessary to address the problem of complete fusion and equilibrium decay. For this purpose the comparison of the ^{14}N + ^{12}C and ^{16}O + ^{10}B systems is particularly useful. Comparisons of the centroids of the velocity distributions of ER have been made for bombarding energies from 3 MeV/A to about 18 MeV/A. Shown in Fig. 2.7 are the results for the ratio $\bar{V}_R/V_{CN} \cos \theta_L$, where $\bar{V}_R$ is the centroid of the velocity distribution and $V_{CN} \cos \theta_L$ is the centroid expected[8] under the assumption of complete fusion and equilibrium decay. V_{CN} is the velocity of the

compound nucleus and θ_L the laboratory angle of the ER. The values of $\bar{V}_R/V_{CN} \cos \theta_L$ given in Fig. 2.7 for both systems have been averaged over a wide angular range ($\theta_L = 4°$ to $15°$), and, as shown in the figure, $\bar{V}_R/V_{CN} \cos \theta_L \cong 1.0$. No trend toward smaller values of this ratio as a function of V_{CN} is observed, confirming that the basic mechanism is that of complete fusion and equilibrium decay.

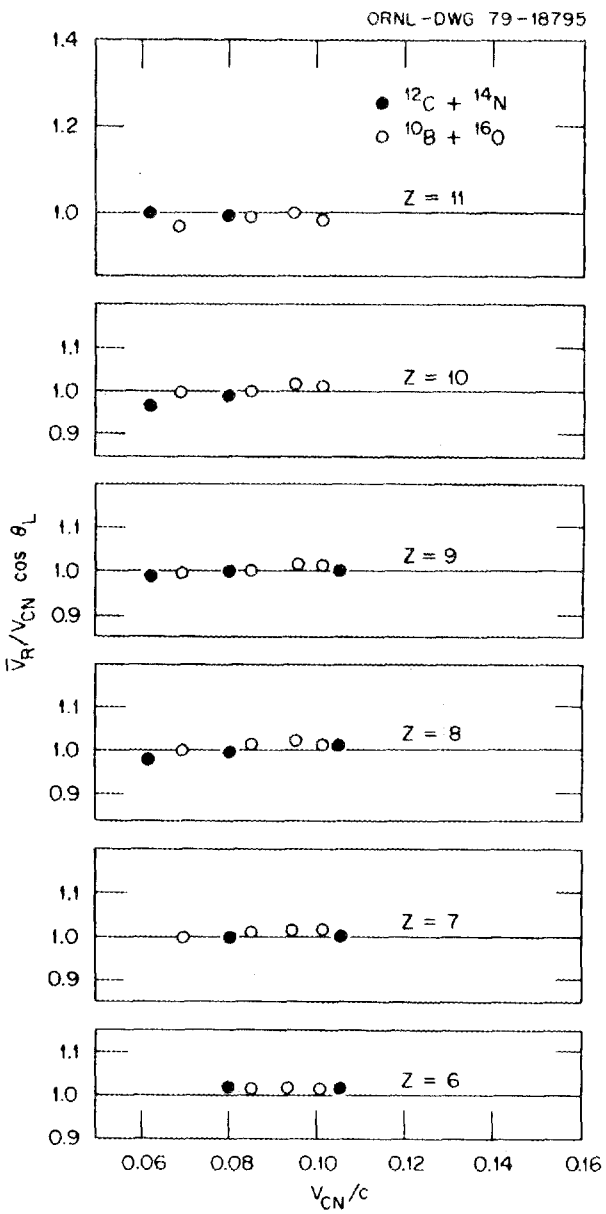


Fig. 2.7. Kinematical analysis for the evaporation residues of the $^{14}N + ^{12}C$ (solid points) and $^{10}B + ^{16}O$ (open points) systems. The vertical scale shows the centroids of the velocity distributions V_R (averaged over several laboratory angles) divided by $V_{CN} \cos \theta_L$. The horizontal scale gives the compound-nucleus velocity in units of the speed of light (c). The lowest-velocity data points correspond to $E^{14N} = 86$ MeV and the highest to $E_{14N} = 248$ MeV.

Another sensitive test for the reaction mechanism can be made through the study of mass and charge distributions of the ER. For the $^{14}N + ^{12}C$ system, time-of-flight (TOF) measurements were made at $E_{14N} = 182$ MeV using the ORNL TOF facility. Figure 2.8*a* shows the results of the angle-integrated yields of ER as a function of mass and charge, and Figs. 2.8*b* and *c* give the energy spectra for ^{12}C and ^{13}C ions. The histograms given in Fig 2.8 are the results of Monte Carlo Hauser-Feshbach calculations using the code LILITA.[10] The reasonable agreement between calculations and experiment for the yield of ER (Fig. 2.8*a*), as well as for the ER energy spectra (lower-energy groups in Figs. 2.8*b* and 2.8*c*), supports the complete fusion and equilibrium decay picture.

The data presented in Figs. 2.7 and 2.8, as well as the analysis given in refs. 8 and 9, lead one to the conclusion that there is a strong tendency to complete fusion and equilibrium decay in these systems, which contrast drastically with the preequilibrium and incomplete fusion processes observed for heavier systems at bombarding energies of about 10 MeV/A. Also, it should be noted that, for the energy range covered in these experiments, the ^{26}Al compound nucleus has been formed in equilibrium at quite a high temperature ($T \cong 5.8$ MeV for $^{14}N + ^{12}C$ at $E_{14N} = 248$ MeV).

The ^{24}Mg System

The fusion of $^{14}N + ^{10}B$ leading to ^{24}Mg has been studied in the energy range E_{14N} from 80 to 182 MeV, using ^{14}N beams from the ORIC. The evaporation residues and direct reaction products were detected with an array of ΔE-E solid-state telescopes for angles more forward than 10° and a ΔE (ionization chamber) and E (solid-state position-sensitive) telescope for angles greater than 10°. The separation of ER and direct reaction products is done using the procedure described in ref. 8, and comparisons of the energy spectra, angular distributions, and total yields of the ER to Monte Carlo calculations indicate an overall agreement with the complete-fusion mechanism. The results of the fusion cross-section measurements are shown in Fig. 2.9 (solid circles) in the usual excitation energy vs $J_c(J_c + 1)$ plot. At the highest excitation energies, $E_x \cong 90$ MeV, a saturation of the critical

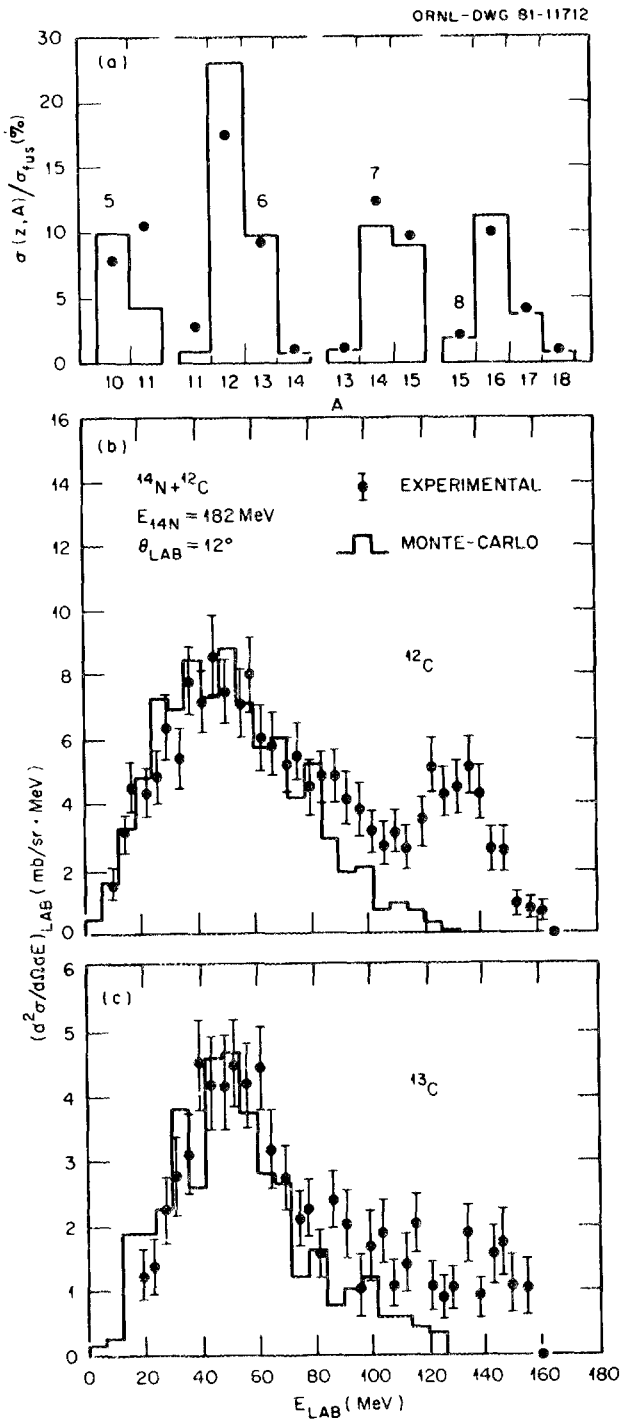


Fig. 2.8. Results of time-of-flight measurements on the system $^{14}N + ^{12}C$. (*a*) Distributions of evaporation residues by element and isotope. The experimental distributions are given by dots, and those calculated with code LILITA are given by histograms. Energy spectra of ^{12}C (*b*) and ^{13}C (*c*) ions were obtained in a measurement of ΔE-E and time of flight. Note how the Monte Carlo calculations (histograms) reproduce the respective shapes of the evaporation-residue portion of the yield.

angular momentum is observed for $J_c \cong 21\hbar$. Measurements of other groups are also shown in Fig. 2.9, where the absolute errors have been omitted to emphasize the relative ones, which are most important in determining the trend of E_x vs $J_c(J_c + 1)$. In Fig. 2.9 the open circles correspond to the $^{14}N + ^{10}B$ measurements given in ref. 11, and the crosses (ref. 11), dots (ref. 12), and open triangles (ref. 13) are reported values for the $^{12}C + ^{12}C$ system. The solid lines in Fig. 2.9 are the results of Glas-Mosel calculations[14] using the parameters $\hbar\omega = 2$ MeV, $r_B = 1.5$ fm, $V_B = 6.8$ MeV, $r_c = 1.2$ fm, and $V_c = -1$ MeV, obtained from a fit to the $^{14}N + ^{10}B$ system. Although the $^{12}C + ^{12}C$ data show large discrepancies between the various experimental measurements, still they indicate that the general trend is that of an entrance-channel limitation, since they follow the Glas-Mosel prediction using the same parameters as for the $^{14}N + ^{10}B$ calculation. The data for both systems appear to parallel each other, which indicates that the limitation is in the entrance channel, since interpretations based on limitations imposed by the compound nucleus, such as the statistical yrast line limitation (refs. 15, 16) would require the overlap of the two fusion bands.

For the highest energies there is a pronounced difference between $^{14}N + ^{10}B$ and $^{12}C + ^{12}C$, since the former system indicates a saturation of J_c and the latter does not. This behavior is also quite different from that seen in the $^{16}O + ^{10}B$ and $^{14}N + ^{12}C$ systems, where both show the same saturation

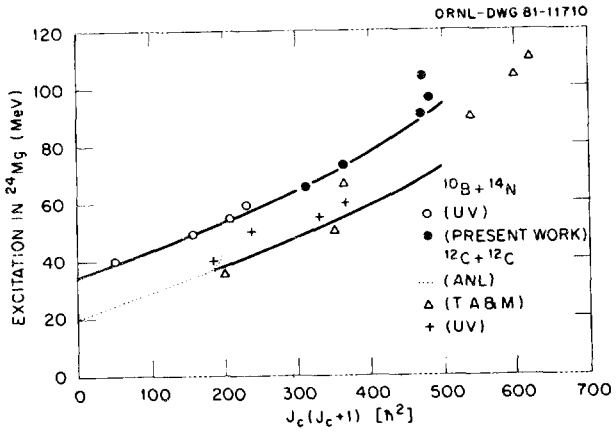


Fig. 2.9. Comparison of the critical angular momentum J_c vs excitation energy in ^{24}Mg for the $^{10}B + ^{14}N$ and $^{12}C + ^{12}C$ systems. The solid lines are the results of Glass-Mosel calculations using the same set of parameters for both systems.

of the angular momentum at $J_c \cong 26\hbar$ (ref. 8). Due to the large relative errors observed in the measurements of the $^{12}C + {}^{12}C$ system, we believe it is extremely important to improve the accuracy of these measurements to confirm the above observation.

The ^{27}Al System

The ^{27}Al nucleus is unique among the light systems in the sense that it can be populated by four different heavy-ion entrance channels which are accesible to experimental measurements. These channels are $^{15}N + {}^{12}C$ (Q_{CN} = 17.2 MeV), $^{16}O + {}^{11}B$ (Q_{CN} = 21.1 MeV), $^{14}N + {}^{13}C$ (Q_{CN} = 23.2 MeV), and $^{17}O + {}^{10}B$ (Q_{CN} = 28.4 MeV), and they provide a large data set to test the various theoretical models for fusion, particularly those related to the Q_{CN} value dependence and compound-nucleus limitations.[15,16] Fusion cross sections for $^{17}O + {}^{10}B$ were measured at four ^{17}O bombarding energies (54, 72, 104, 124 MeV) using the BNL tandem facility, and reaction products were measured with a ΔE (ionization chamber) E (solid-state position-sensitive) detection system. The evaporation residues were extracted in a similar manner, as described in ref. 8. Results for the four bombarding energies are shown in Fig. 2.10, where the excitation energy in ^{27}Al is plotted vs the critical angular momentum J_c extracted from the fusion data using the sharp-cutoff approximation. Also given in this figure are data points from the Argonne and Saclay laboratories. The continuous curves drawn through the different data points are fits to the fusion cross sections using the entrance-channel model of Glas and Mosel. The fusion barrier parameters r_B and V_B are 1.5 fm and 6.7 MeV for all systems except $^{11}B + {}^{16}O$, for which V_B = 7.7 MeV. Below E_x = 55 MeV the fusion bands for all four systems parallel each other and are displaced by amounts equal to their differences in the Q_{CN} values, indicating that in this energy regime the limitation is due to the entrance channel as expected. However, for the higher energies, $E_x >$ 55 MeV, there is clearly a convergence of the bands for the $^{10}B + {}^{17}O$, $^{14}N + {}^{13}C$, and $^{11}B + {}^{16}O$ systems, which may be indicative of a limitation imposed by the compound nucleus.[15, 16] In terms of the entrance-channel parametrization of Glas and Mosel, the convergence of the different fusion bands is due to different critical distances: r_c = 1.28 fm for $^{10}B + {}^{17}O$ and r_c = 1.2 for $^{14}N + {}^{13}C$ and $^{11}B + {}^{16}O$.

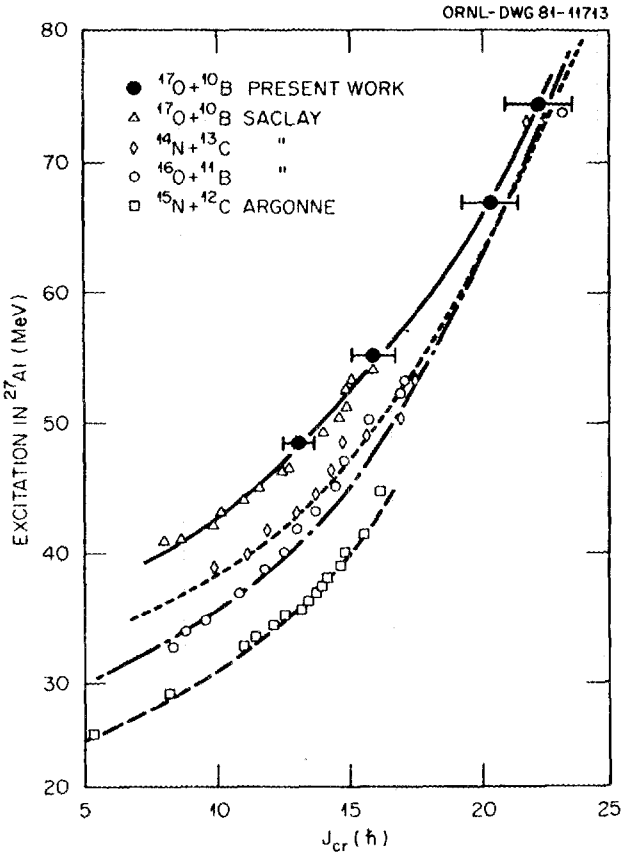


Fig. 2.10. Excitation energy in ^{27}Al vs the critical angular momentum J_c for the $^{10}B + {}^{17}O$ (present measurements), $^{14}N + {}^{13}C$, $^{11}B + {}^{16}O$, and $^{15}N + {}^{12}C$ systems.

The ^{40}Ca System

Data for the fusion of $^{20}Ne + {}^{20}Ne$ have been measured in the ^{20}Ne bombarding-energy range of 68–160 MeV using ^{20}Ne beams from the ORIC and a recently developed gas-cell target.[17] The development of this gas-cell target has been an important contribution which allows fusion cross-section measurements for a variety of systems. In addition, the accurate control of the target thickness, as well as the absolute normalization procedure (based on a small, about 0.2%, admixture of Xe with the gas target), allows fusion measurements of high precision (about 5%). The fusion of $^{20}Ne + {}^{20}Ne$ given in this report is an example of such measurements.

For slightly heavier systems, such as $^{20}Ne + {}^{20}Ne$, the extraction of the evaporation residue cross sections can be done without the deconvolution procedures employed for the lighter systems, since about 95% of the ER cross section occurs for ions

of nuclear charge greater than the projectile. Fusion cross sections for the ^{20}Ne + ^{20}Ne system were measured at five bombarding energies, and the results are given in Fig. 2.11. The solid line corresponds to the Glas-Mosel fits using the parameters $\hbar\omega$ = 5.0 MeV, r_B = 1.5 fm, V_B = 16 MeV, r_c = 1.0 fm, and V_c = −10 MeV. The critical-distance model of Bass[18] has been used successfully for heavy systems with a universal parameter set. For lighter systems, however, this model underpredicts the fusion cross section at high energy (e.g., ^{12}C + ^{14}N). Nevertheless, for the ^{20}Ne + ^{20}Ne system, the fusion cross section can be fitted with the same universal parameter set used for heavier systems (dashed line in Fig. 2.11). The entrance-channel model of Horn and Ferguson[19] also employs a universal set of parameters and reproduces the fusion cross section at high energies but overestimates the amount of fusion at the lower energy. The statistical yrast line model discussed by Vandenbosch and Lazzarini[17] predicts fusion cross sections too high by about 40% for the ^{20}Ne + ^{20}Ne system. The success of the Bass model in fitting the ^{20}Ne + ^{20}Ne system may be taken as evidence that for systems of $A \geqslant 40$ the fusion cross section is mostly limited by the entrance channel.

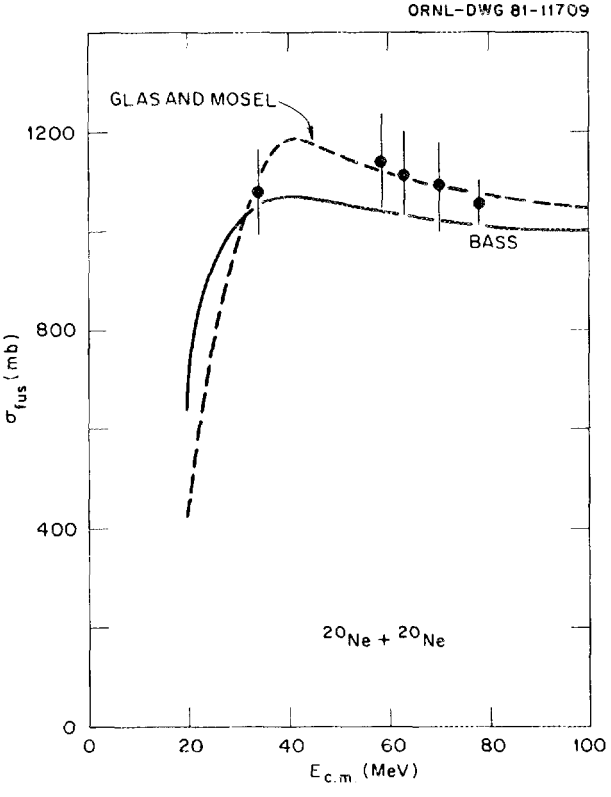


Fig. 2.11. Fusion cross sections σ_{fus} for the ^{20}Ne + ^{20}Ne system plotted vs the center-of-mass energy E_{cm}. Calculations are shown using the Bass model (solid line) and the Glas-Mosel fit (dashed line).

Summary

From a systematic study of fusion cross sections for light systems, the following obervations can be made:

1. For all systems studied the dominant mechanism leading to ER-like events is that of complete fusion and equilibrium decay, even at energies above 10 MeV/A. This is further illustrated in Fig. 2.12, which shows the total yield distributions for the ER as a function of Z for ^{20}Ne + ^{20}Ne, ^{20}Ne + ^{16}O, ^{17}O + ^{10}B, and ^{14}N + ^{10}B at the highest excitation energies studied. The histograms are the results of the Monte Carlo Hauser-Feshbach calculation using the code LILITA.[10]

2. For all cases presented in this report, the fusion cross sections appear to be dominated by the entrance channel, with the possible exception of ^{27}Al, for which the various fusion bands of different entrance channels show a tendency to converge at the highest energies (see Fig. 2.10). In this

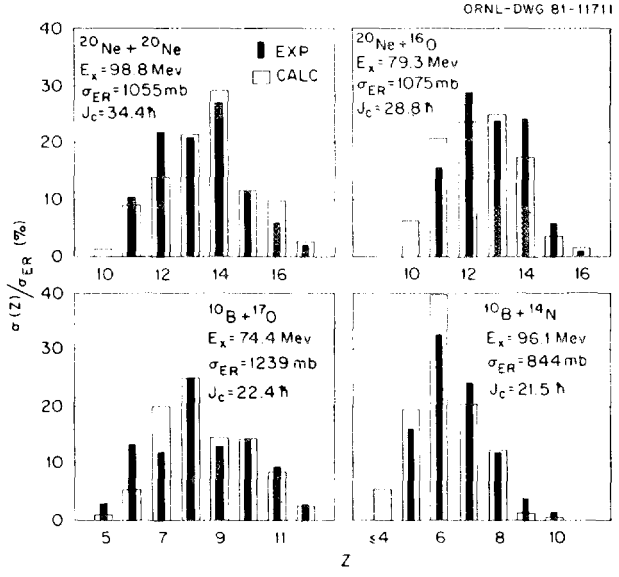


Fig. 2.12. Relative yields of evaporation residues, given as a percent of σ_{fus} for the ^{20}Ne + ^{20}Ne, ^{20}Ne + ^{16}O, ^{10}B + ^{17}O, and ^{10}B + ^{14}N systems. The solid bars are the experimental yields, and the histograms are the results of the Monte Carlo calculations using code LILITA.

respect, it is important to note that measurements of the $^{15}N + ^{12}C$ system at high energies are needed to confirm such tendencies.

3. The behavior of the fusion cross section at high energies shows drastic changes with respect to the addition or removal of nucleons from target or projectile and should be taken as evidence for strong influence of microscopic structure on the fusion process. None of the present entrance-channel or compound-nucleus models for fusion account for such changes. This is further illustrated in Table 2.2, where the critical radius r_c (which is given by the slope of σ_{fus} vs $1/E_{c.m.}$ at high energies) extracted from the Glas-Mosel fits is given.

Table 2.2. Critical distance r_c and potential at the critical radius V_c, derived from the Glas-Mosel formula

System	r_c (fm)	V_c (MeV)
$^{10}B + ^{14}N$	1.2	−1
$^{12}C + ^{12}C$	1.2	−1
$^{14}N + ^{12}C$	1.11	−1.9
$^{10}B + ^{16}O$	1.35	2.5
$^{14}N + ^{13}C$	1.2	1.0
$^{11}B + ^{16}O$	1.2	0.0
$^{10}B + ^{17}O$	1.28	0.0
$^{20}Ne + ^{20}Ne$	1.0	−10

4. The saturation of the critical angular momentum, which can be interpreted as a liquid-drop limit effect, has been seen at $J_{max} = 27\hbar$ for ^{26}Al and $J_{max} \cong 21\hbar$ for $^{14}N + ^{10}B$, although the $^{12}C + ^{12}C$ system does not show such saturation. Therefore, more data are need above 18 MeV/A to understand this maximum angular momentum limit.

1. Instituto de Fisica, National University of Mexico, Mexico City.
2. On leave from Comision Nacional de Energia Atomica, Buenos Aires, Argentina.
3. DPh — N/BE, CEN, Saclay, France.
4. Lawrence Berkeley Laboratory.
5. Nuclear Physics Research Unit, University of Witwatersrand, Johannesburg, S.A.
6. University of Virginia, Charlottesville.
7. Australian National University, Canberra.

8. J. Gomez del Campo et al., *Phys. Rev. C* **19**, 2170 (1979).
9. J. Gomez del Campo et al., *Phys. Rev. Lett.* **43**, 26 (1979).
10. *LILITA — a Monte Carlo Statistical Model Code*, J. Gomez del Campo and R. G. Stokstad, ORNL/TM-7295.
11. R. L. Parks et al., *Nucl. Phys.* **A348**, 350 (1980).
12. D. G. Kovar et al., *Phys. Rev. C* **20**, 1305 (1980).
13. M. N. Namboodiri et al., *Nucl. Phys.* **A263**, 491 (1976).
14. D. Glas and U. Mosel, *Nucl. Phys.* **A237**, 429 (1975).
15. S. M. Lee et al., *Phys. Rev. Lett.* **45**, 165 (1980).
16. R. Vandenbosch and J. Lazzarini, *Phys. Rev. C* **23**, 1074 (1981).
17. D. Shapira et al., *Nucl. Instrum. Methods* **163**, 325 (1979).
18. R. Bass, *Phys. Lett.* **47B**, 139 (1974).
19. D. Horn and A. J. Ferguson, *Phys. Rev. Lett.* **41**, 1529 (1978).

REACTION PRODUCTS AT BACKWARD ANGLES FROM $^{28}Si + ^{12}C$

D. Shapira, K. A. Erb
R. Novotny, Y. D. Chan
J. L. C. Ford, Jr., J. C. Peng[1]
J. D. Moses[1]

Numerous experimental studies of collisions between ^{12}C or ^{16}O and various *s-d*-shell nuclei have established that the cross sections for low-lying states populated in the elastic, inelastic, and alpha-transfer channels have the following characteristics at backward angles: (1) enhanced backward-angle cross section,[2] (2) excitation functions which exhibit pronounced resonant-like structures,[3] (3) correlations between the structures in the excitation functions for some but not all of the exit channels.[4] More recent elastic and inelastic scattering data for ^{20}Ne plus ^{12}C measured at ORNL not only display the above characteristics for low-lying inelastic and elastic data,[5] but in addition there is a much larger inelastic yield for large negative Q-values which increases with increasing scattering angle (toward 180°).[6] The excitation function for the total carbon yield has structure that is less pronounced than that in the ground-state excitation function but which is nevertheless correlated with structures of many other exit channels (particularly the evaporation residues).

In order to investigate phenomena similar to those observed in the $^{20}Ne + ^{12}C$ system, we have measured, at backward angles and over a wide energy range, reaction products emitted from $^{28}Si + ^{12}C$ collisions. It is also of interest to see whether spectra with highly damped yields are observed in other exit channels such as those with non-alpha-conjugate nuclei.

Figure 2.13 shows C, N, and O spectra after correcting for the energy loss in the absorber preceding the detector, which stopped the incident Si beam.

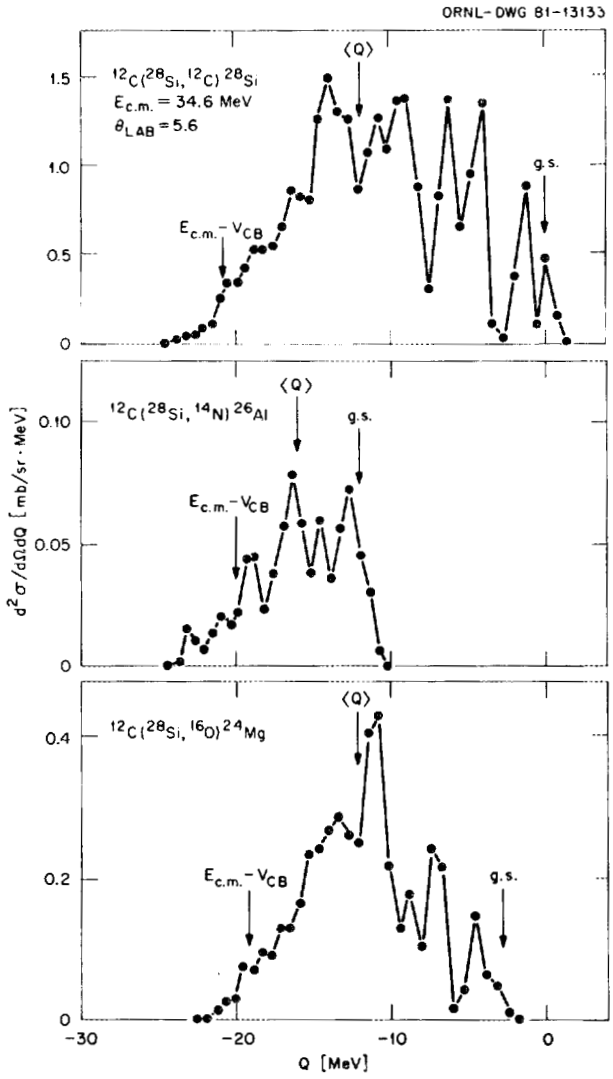


Fig. 2.13. Energy spectra for C, N, and O emitted at backward angles.

Two-body final states of ^{12}C + ^{28}Si, ^{14}N + ^{26}Al, and ^{16}O + ^{24}Mg were assumed in calculating the Q values. The three arrows in these spectra show the energies expected for emission of either ^{12}C, ^{14}N, or ^{16}O in two-body reactions at (1) the Coulomb barrier, (2) the total interaction barrier (Coulomb plus centrifugal with 60% of ℓ grazing), and (3) when both nuclei are emitted in their ground states. For a fixed bombarding energy the energy spectra measured at different angles (in the backward hemisphere) are similar in shape and have the same most probable Q values. The center-of-mass cross sections for the total C, O, and N yields were calculated using this Q value. The resulting angular distributions shown in Fig. 2.14 for the total C, N, and O yields all rise toward 180° with a $1/\sin\theta_{c.m.}$ dependence. In this respect the ^{28}Si + ^{12}C system behaves similarly to the ^{12}C + ^{20}Ne system, and even the data for non-alpha-conjugate exit channels show such a backward-angle behavior. Apparently the cross-section increase at backward angles does not depend on the particular exit channel studied and in particular not on an alpha-conjugate character of the residual nuclei.

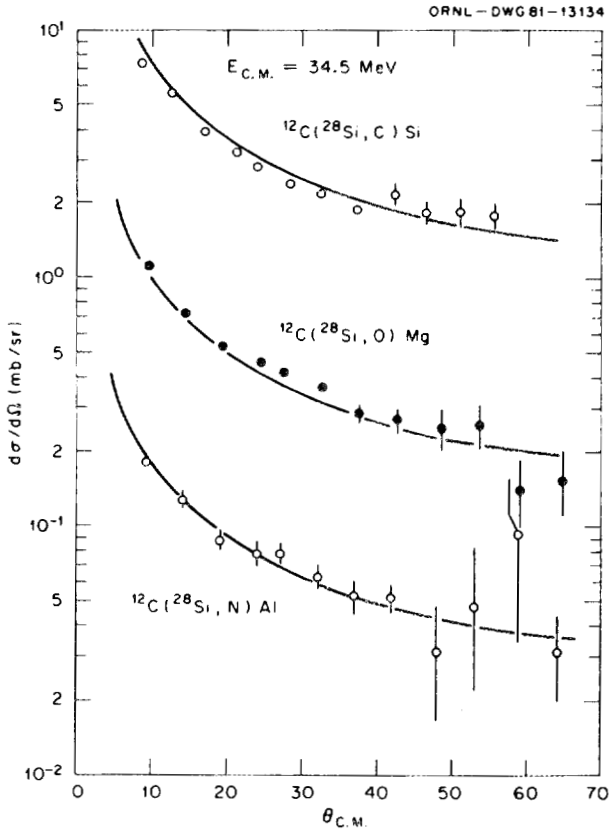


Fig. 2.14. Angular distribution (in the center-of-mass system) for the total yields seen in Fig. 2.13.

The excitation functions for the total C, N, and O yield integrated over the angular range $90 \leqslant \theta_{c.m.} \leqslant 180°$ (by means of the angular distributions of Fig. 2.14) are shown in Fig. 2.15. The excitation functions increase smoothly with bombarding energy without significant structure. This behavior contrasts with that seen in the lighter ^{12}C + ^{20}Ne system, where resonant-like structures were observed in the excitation function for the total carbon yield.

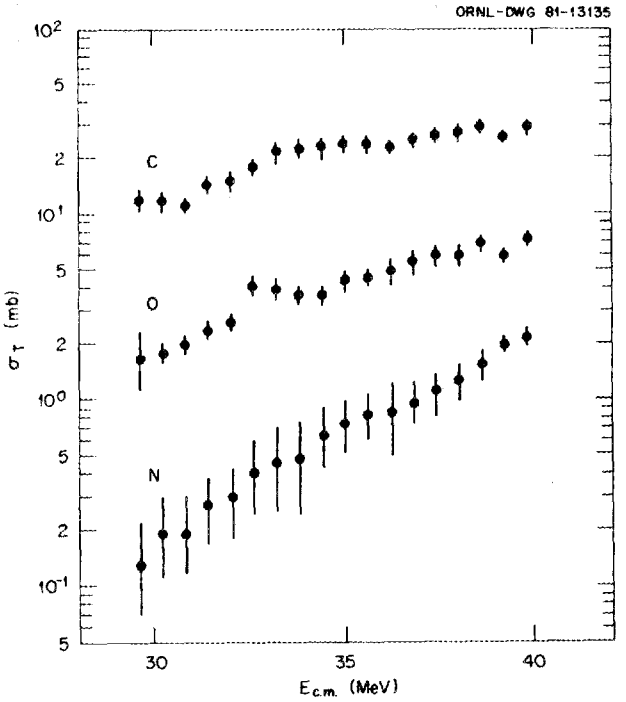


Fig. 2.15. Excitation functions for the C, N, and O yields integrated over the angular range of 90° $\leq \theta_{c.m.} <$ 180°.

What these data (as well as those for the exit channel for boron emission) demonstrate is that the cross-section increase at backward angles is not a phenomenon exclusive to low-lying states in alpha-conjugate exit channels but is a more general process associated with many exit channels and resulting in a very large yield. The energy spectra, which indicate that strong if not complete damping of the energy degree of freedom has occurred, and the damping of the initial linear momentum suggested by the $1/\sin\theta_{c.m.}$ angular distributions are characteristic of an orbiting deep-inelastic-like process.[7]

The behavior observed for the low-lying transitions can also be viewed as part of this general deep-inelastic mechanism. The relationship between such a process and the transparency in the entrance channel can be investigated by comparing the strength of the structures observed in the present $^{28}Si + {}^{12}C$ measurement with corresponding $^{30}Si + {}^{12}C$ data.

1. Los Alamos National Laboratory.

2. P. Braun-Munzinger et al., *Phys. Rev. Lett.* **38**, 944 (1977); S. Kubon et al., *Phys. Lett.* **81B**, 140 (1979).
3. J. Barette et al., *Phys. Rev. Lett.* **40**, 445 (1978); A. Roy et al., *Phys. Rev. C* **20**, 2143 (1979); R. Ost et al., *Phys. Rev. C* **19**, 740 (1979); J. C. Peng et al., *Phys. Rev. Lett.* **42**, 1458 (1979).
4. J. C. Peng et al., *Phys. Lett.* **80B**, 35 (1978); M. Paul et al., *Phys. Rev. Lett.* **40**, 1310 (1978); C. K. Gelbke et al., *Phys. Rev. Lett.* **41**, 1778 (1978); S. M. Lee et al., *Phys. Rev. Lett.* **42**, 429 (1979).
5. J. L. C. Ford, Jr., et al., *Phys. Lett.* **89B**, 48 (1979).
6. D. Shapira et al., *Phys. Rev. Lett.* **43**, 1781 (1979).
7. J. Wylcinski et al., *Phys. Lett.* **47B**, 484 (1973).

STUDY OF DEEP-INELASTIC PROCESSES IN LIGHT-HEAVY-ION COLLISIONS ($A_T + A_P < 80$)

D. Shapira J. L. C. Ford, Jr.
R. Novotny K. A. Erb
Y. D. Chan

In our study of reaction products emitted at backward angles in collisions between ^{27}Al and ^{16}O, ^{20}Ne and ^{12}C, and ^{28}Si and ^{12}C, large yields were observed which are attributed to a deep-inelastic-like process (large damping of energy but no mass equilibration).[1] Deep-inelastic processes have long been associated with a reaction mechanism called orbiting.[2] In this process the projectile and target remain in contact for an extended time period during which the dinuclear system rotates and separates after the projectile swings around the target (negative-angle scattering) and loses much of its kinetic energy. Most phenomenological models employ friction forces as a vehicle for fast energy damping between the projectile and target. Both tangential and radial friction are considered; the relative role of these two components results in a sticking, rolling, or sliding relative motion. A subject of much experimental work[3] is the extraction, from nuclear scattering results, of the strength of the radial and tangential friction forces present during the orbiting process.

The study of deep-inelastic processes in light systems is hampered by the presence of large contributions from other reaction processes in observed energy spectra. At backward angles, however, contributions from quasi-elastic processes are negligible, and, except for a possible fusion-fission yield, only deep-inelastic-like projects due to orbiting can be present. In this way we have been able to make a detailed study of the deep-inelastic process in these light systems. Initially we measured detailed energy and angle dependences of the yield to several outgoing channels in one system ($^{28}Si + {}^{12}C$). This

enables us to establish the macroscopic character of this process. A comparative study of several light systems should help to unravel the microscopic character of this process.

Figure 2.16 shows an energy spectrum of outgoing carbon nuclei (at backward center-of-mass angles) emitted from the $^{28}Si + {}^{12}C$ system for three different bombarding energies. For each bombarding energy a most probable Q value ($\bar{Q}$) and a spectral width can be determined from the measured energy spectrum of each exit channel. The dependence of $\bar{Q}$ on bombarding energy is shown in Fig. 2.17 for the C, N, and O channels. Equating the kinetic energy to the total potential energy of the orbiting nuclei ($V_{Coul} + V_{nuc} + V_{centrifugal}$) produces a linear energy dependence. Neglecting the effect of the nuclear forces, one expects a very simple relationship for the slope of the $\bar{Q}$ vs $E_{c.m.}$ plot for different exit channels. In the extreme sticking (infinite tangential friction) limit one expects almost the same slope for all three channels.[4] The data shown in Fig. 2.17 indicate that the behavior of the C + Si dinuclear system is close to the sticking limit.

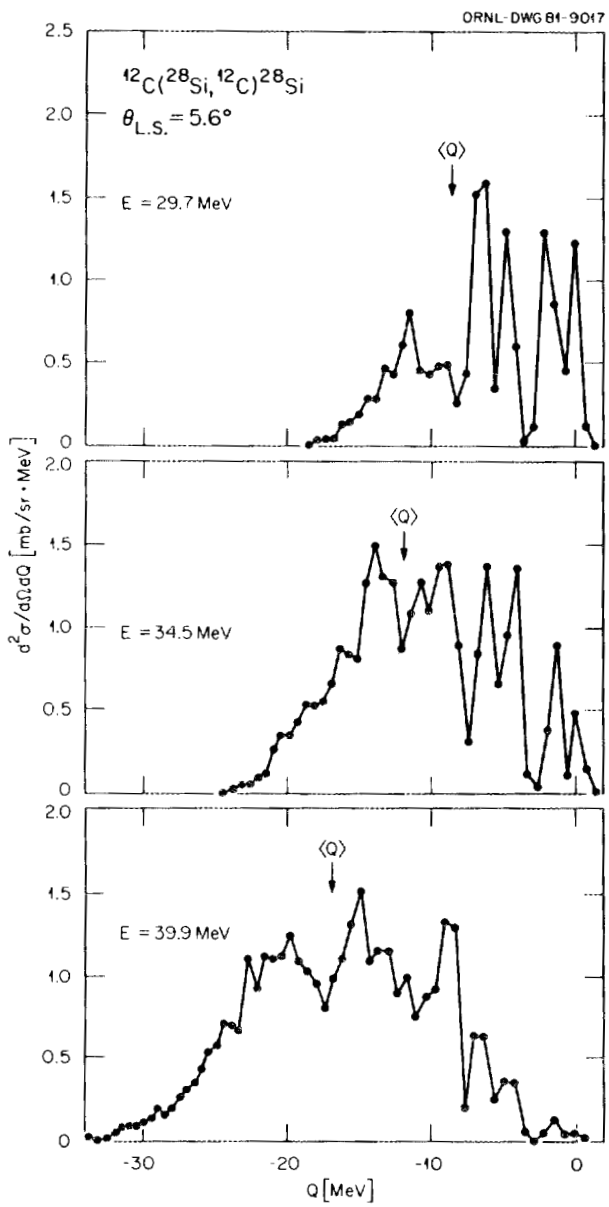


Fig. 2.16. Spectra of carbon products emitted at forward angles in the bombardment of ^{12}C by ^{28}Si shown at three different bombarding (c.m.) energies.

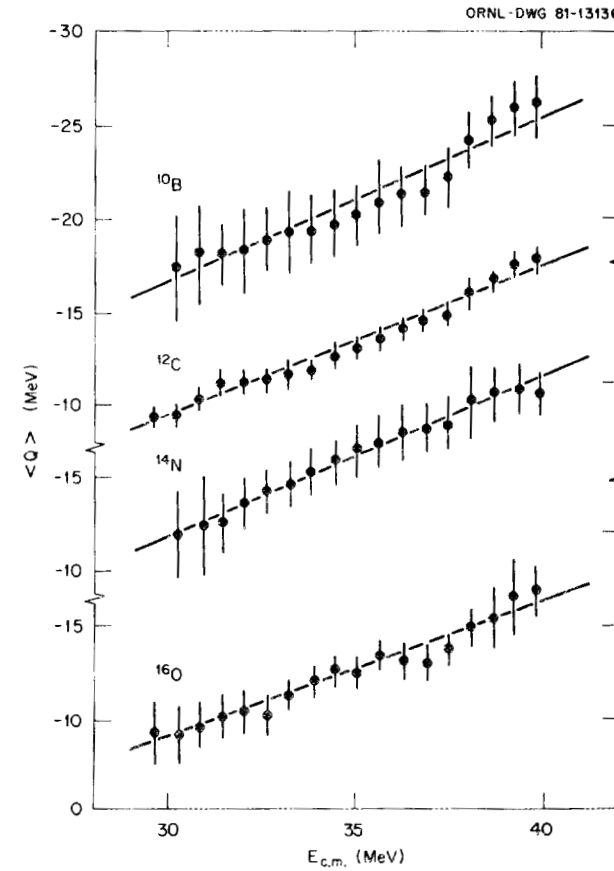


Fig. 2.17. Average Q value as a function of bombarding (c.m.) energy for C + Si, N + Al, B + P, and O + Mg channels.

1. D. Shapira et al., accompanying report; D. Shapira et al., *Phys. Rev. C* **21**, 1824 (1980); D. Shapira et al., *Phys. Rev. Lett.* **43**, 1781 (1979).

2. J. Wilcynski, *Phys. Lett.* **47B**, 484 (1973).
3. U. Shröder et al., *Annu. Rev. Nucl. Sci.* **27**, 465 (1977).
4. P. Braun Munzinger et al., *Phys. Rev. Lett.* **37**, 1582 (1976).

CORRELATED MASS AND CHARGE DISTRIBUTIONS FROM Ne + Al REACTIONS

F. E. Obenshain R. L. Robinson
R. L. Ferguson D. Shapira
F. Plasil A. H. Snell
G. R. Young

Correlated mass and charge distributions from ^{20}Ne + ^{27}Al reactions have been measured[1] at laboratory energies of 167 and 118 MeV for the neon projectile. Previously, measurements of charge and mass distributions in the deep-inelastic region for this system were made by Natowitz et al.,[2] and measurements of the mass distribution were made by Bohne et al.[3] This report is concerned with the production and the subsequent decay of the compound nucleus ^{47}V. The formation of the compound state in heavy-ion reactions is a consequence of total energy damping in the entrance channel. This stage of the reaction is characterized by a totally equilibrated nuclear system with a lifetime that is long compared with that for direct reactions. Since the radial energy damping is complete, the excitation energy and angular momentum of the compound system may be very large, and the nuclear state may decay by particle emission or by fission. However, for the lighter systems this latter mode of deexcitation is small compared with the total fusion cross section.

Over the past several years a time-of-flight (TOF) apparatus has been developed which has the capability of resolving individual masses up to at least $A \cong 65$. For example, with this apparatus we have resolved the individual masses and charges of the systems Ne + Al and Ar + Al.

In addition to the mass and charge distributions of products from Ne + Al reactions we have measured their angular distributions for the two laboratory energies. From this information the production cross section for each isotope has been obtained. The energy and angular dependence of the cross section give a complete picture of the reaction mechanism.

The analysis of these data is based on the assumption that the compound nucleus is formed in statistical equilibrium. The subsequent decay processes are described by statistical evaporation of nucleons and nuclei (mainly ^{4}He). The statistical nuclear model, coupled with the Hauser-Feshbach formula, is used to calculate the isotopic yields.[4,5] The agreement between experiment and calculations is indicative of the validity of this assumption.

The measured isotopic yields for $13 \leqslant Z < 23$ are shown in Fig. 2.18 along with the evaporation-model calculations (CASCADE) for E_{Lab} = 167 MeV. The yield for each isotope was obtained by integration of the angular distribution. In the region considered here the shape of the angular distributions is well described by statistical evaporation of p, n, and ^{4}He from the compound system. For species near the target ^{27}Al, there is some indication that other reaction channels, such as deep-inelastic scattering, may contribute to the cross section.

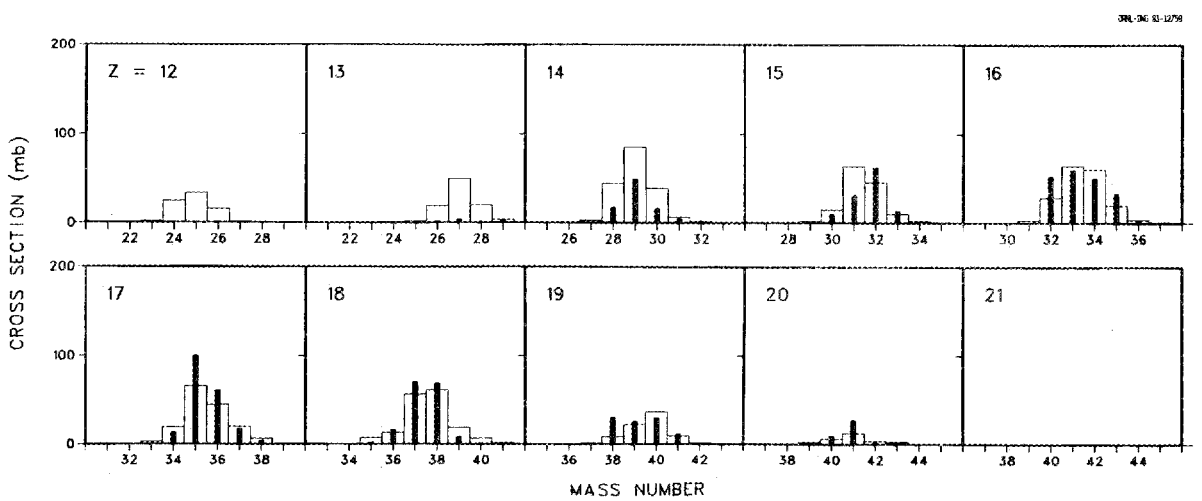


Fig. 2.18. Isotopic yields for 167-MeV Ne + Al. Open bars, measured values; solid bars, evaporation-model calculations.

However, the statistical fluctuations of the experiment are large enough to preclude a precise unfolding of the data and identification of the mechanism.

The composite system ^{47}V has an excess of one neutron (i.e., $N - Z = 1$), and the evaporation-residue formation is centered along an $N - Z = 1$ pathway. Efficient cooling of the compound system occurs by emission of alpha particles. As may be seen from Fig. 2.18, the largest yields occur for removal of one, three, four, and five alpha particles. One exception occurs for $Z = 19$, where $2\alpha + n$ emission is greater than the 2α emission.

The total evaporation-residue cross section for the range $13 \leqslant Z \leqslant 23$ is $\sigma_{ER} = 1035$ mb and corresponds to a critical angular momentum of $42\hbar$. The angular momentum above which the fission barrier is zero in the rotating liquid drop (RLD) is $48\hbar$.

The elastic scattering data at 167 MeV are well described by an optical-model calculation, and from these data we determine a center-of-mass 1/4-point angle of $\theta_{1/4} = 14.8°$. The total reaction cross section is $\sigma_R = 1829$ mb, and the interaction angular momentum is $54\hbar$.

The charge distribution for the 167-MeV case is shown in Fig. 2.19*a*, and the mass distribution is shown in Fig. 2.19*b* along with the CASCADE calculations. The average value of Z is 16, and the distribution has a variance $\sigma_Z^2 = 4.4$. The average mass (Fig. 2.19*b*) is 33, and the variance of this distribution is $\sigma_A^2 = 20.4$. The average values for Z and A again correspond to $N - Z = 1$, in agreement with the previous observations. Both distributions show some structure relating to odd-even effects. The charge distribution has a tendency to have higher yields for even Z, whereas the mass distribution tends to have higher yield for odd A than for even A.

The lower-energy ($E_{lab} = 118$ MeV) data are shown in Fig. 2.20. Reducing the excitation energy from about 114 MeV to about 85 MeV decreases the average number of nucleons evaporated by about 2. The overall effect on the ER distribution is shown in Fig. 2.21. The yield is more concentrated toward the compound nucleus, and, as may be seen in Fig. 2.20, the 2α channel is now dominant compared with $4\alpha + pn$ at the higher energy. The tendency to evaporate $x\alpha$ following the $N - Z = 1$ pathway is the same at this energy as it was at the higher.

The total reaction cross section determined from optical-model calculations and elastic data for several angles is $\sigma_R = 1713$ mb, corresponding to an interaction angular momentum of $44\hbar$. The summation of the ER yield for $13 \leqslant Z \leqslant 23$ gives a cross section $\sigma_{ER} = 1098$ mb, a value slightly higher than at 167 MeV. However, the critical angular momentum for compound-nucleus formation is $35\hbar$.

Since most of the parameters used in the evaporation calculations are obtained from other experiments we simply vary these within acceptable limits to obtain the agreement shown in the figures. An interesting point observed from these comparisons is the lack of agreement in the region near ^{27}Al. According to the work of Wilczynski et al.[6]

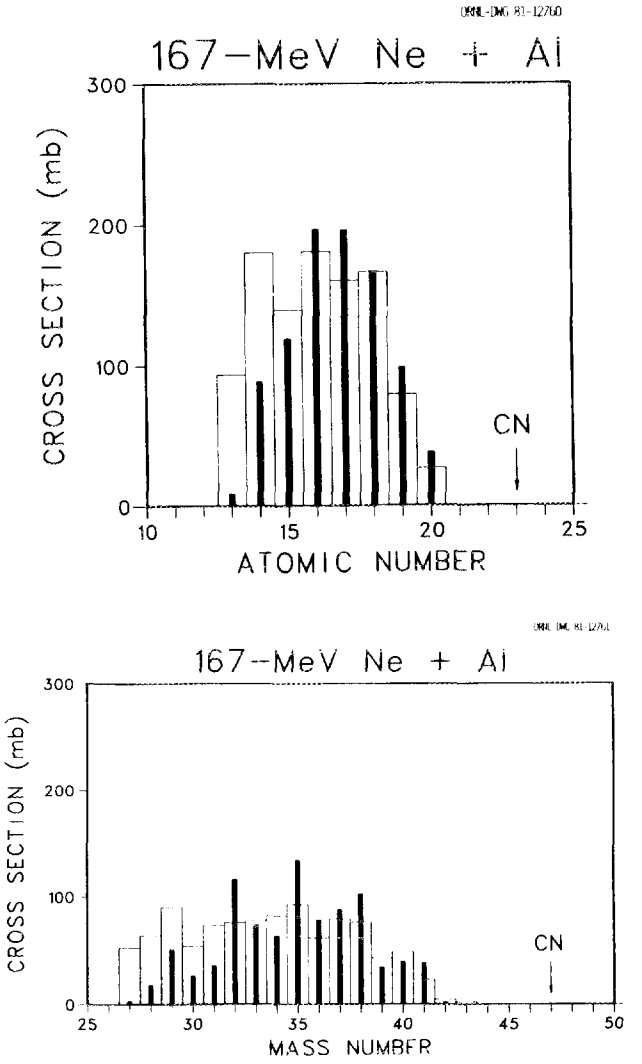


Fig. 2.19. Reaction data for 167-MeV Ne + Al. Open bars, measured values; solid bars, calculations. (*a*) Charge distribution; (*b*) mass distribution.

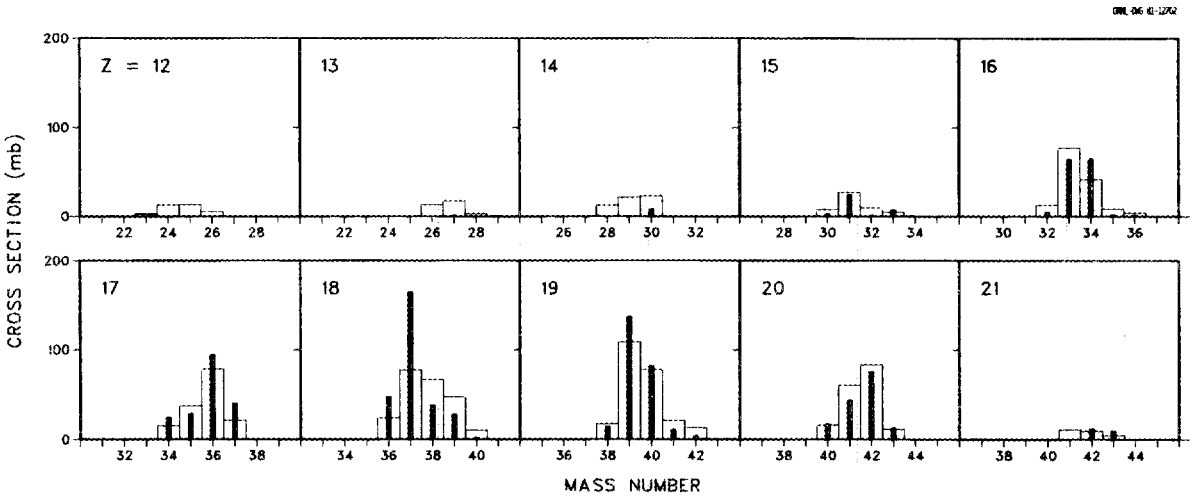


Fig. 2.20. Isotopic yields for 118-MeV Ne + Al. Open bars, measured values; solid bars, calculations.

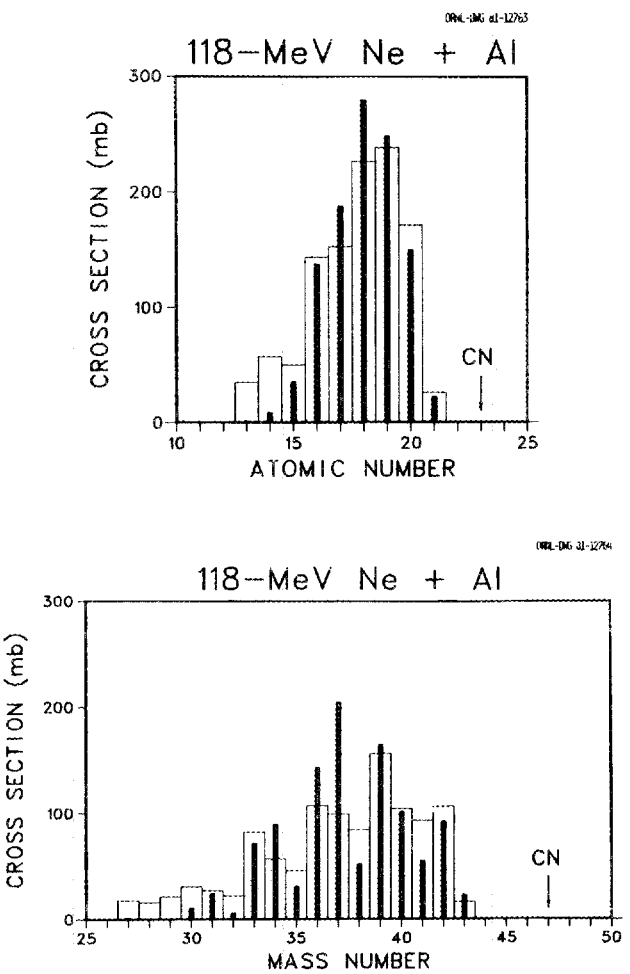


Fig. 2.21. Reaction data for 118-MeV Ne + Al. (*a*) Charge distribution; (*b*) mass distribution.

and Lehr et al.[7] the largest value of angular momentum for which Ne and AL will fuse is $^{28}\hbar$, a value well below what we obtain from the fusion cross section. In order to exhaust the observed cross section they postulate that the excess angular momentum must be removed by particle emission from the projectile before fusion occurs. The names incomplete fusion and massive transfer have been given to this process.

We have carried out evaporation calculations based on this idea by assuming that Ne fuses with Al in the angular momentum range 0 to $28\hbar$ and that O, C, and Be fuse with the target in the angular momentum ranges, $28\hbar$ to $31\hbar$, $31\hbar$ to $35\hbar$, and $35\hbar$ to $41\hbar$ respectively. A summation of the partial cross sections for each of these reaction channels results in a redistribution of some of the ER yield from higher to lower Z and A values. This result is, of course, consistent with the evaporation of particles from much lighter compound systems than ^{47}V, and it does produce a better fit to the data in the lower mass region.

1. R. L. Ferguson et al., Lawrence Berkeley Laboratory report LBL-10688, p. 21 (1980).

2. J. B. Natowitz, M. N. Namboodiri, R. Eggers, P. Gonthier, K. Geoffroy, R. Hanus, C. Towsley, and K. Das, *Nucl. Phys.* **A277**, 477 (1977).

3. W. Bohne, K. Grabisch, H. Morgenstern, and W. Stoffler, International Workshop on Heavy Ion Fusion Reactions, Bad Honnef, 1980.

4. F. Puhlhofer, *Nucl. Phys.* **A280**, 267 (1977).

5. A. Gavron, *Phys. Rev. C* **21**, 230 (1980).

6. J. Wilczynski, K. Siwek-Wilczynska, J. van Driel, S. Gonggrijp, D. Hageman, R. Janssens, J. Lukasiak, and R. Siemssen, *Phys. Rev. Lett.* 45, 606 (1980).

7. H. Lehr, W. Oertzen, W. Bohne, H. Morgenstern, K. Grabish, and F. Puhlhofer, preprint HMI-P 1/80 (1980).

CORRELATED CHARGE AND MASS DISTRIBUTIONS FROM REACTIONS OF ^{56}Fe WITH ^{58}Ni AND ^{64}Ni

H. C. Britt[1] Y. Patin[4]
M. Blann[2] F. Plasil
P. R. Christensen[3] S. Pontoppidan[3]
B. H. Erkkila[1] J. Randrup[5]
R. L. Ferguson R. H. Stokes[1]
A. Gavron[1] F. Videbaek[3]
O. Hansen[3] M. P. Webb[1]
G. R. Young

Correlated charge and mass distributions of projectile-like products have been measured from reactions of 315-MeV ^{56}Fe with ^{58}Ni, 461-MeV ^{56}Fe with ^{58}Ni, and 464-MeV ^{56}Fe with ^{64}Ni. The measurements were made at the LBL Super-HILAC by means of a time-of-flight system combined with a telescope consisting of an ionization chamber and a surface-barrier detector. Single nuclear charge and mass resolution was achieved for all projectile-like products with energy losses between 10 and 120 MeV. The results are presented in Fig. 2.22 for reactions with ^{58}Ni and in Fig. 2.23 for reactions with ^{64}Ni. The data are shown, as a function of energy loss, in terms of the averages and standard deviations of the overall A and $N - Z$ distributions, where A, N, and Z are the mass, neutron, and charge numbers of the reaction products respectively. The coördinates A and $N - Z$ have been chosen to present the results, since they are the nearly normal coordinates of the valley of beta stability. The data of Figs. 2.22 and 2.23 are angle-integrated over an angular range of approximately 6° in the vicinity of the appropriate grazing angle.

The results were compared with the independent-particle transport model of Randrup.[6, 7] In this model, the transport of mass, charge, and energy (as well as linear and angular momentum) is attributed to the stochastic exchange of individual nucleons between the reacting nuclei. Proper account of the Pauli exclusion principle is included in the theory, and the constraint of the underlying time-dependent potential energy surface due to its curvature and alignment in the (A, $N - Z$) coordinate system is of primary importance. The

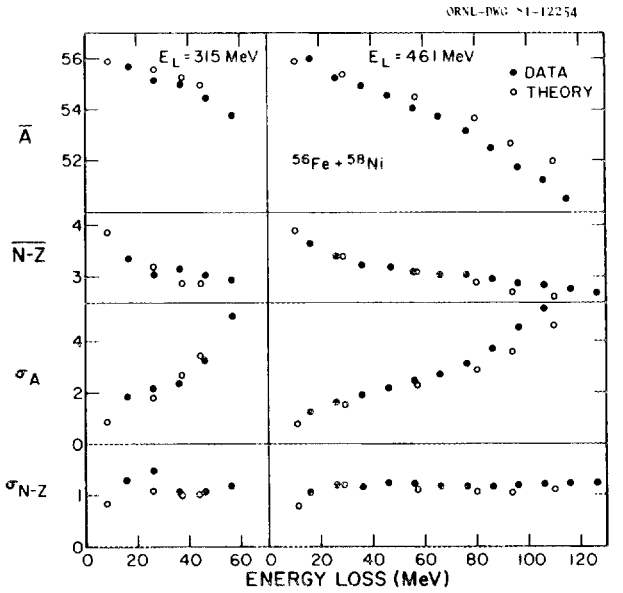


Fig. 2.22. Averages and standard deviations of the overall A and $N - Z$ distributions as a function of energy loss for projectile-like products from reactions of 315- and 461-MeV ^{56}Fe with ^{58}Ni. The theoretical results include effects of particle evaporation (see text).

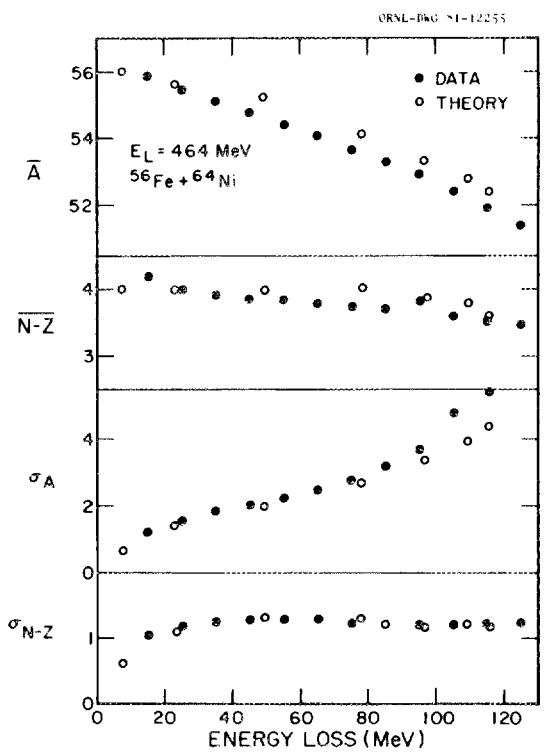


Fig. 2.23. Same as Fig. 2.22 but for reactions between 464-MeV ^{56}Fe and ^{64}Ni.

theoretical results for the average values of A and $N - Z$ (as well as for N and Z) are shown for our cases, as a function of energy loss, in Fig. 2.24. It can be seen that the predictions for reactions with ^{58}Ni differ markedly from those for reactions with ^{64}Ni for values of $\overline{N - Z}$ but not for values of $\bar{A}$.

For comparisons between experiment and theory to be valid, corrections for effects of particle evaporation from the excited reaction products must be made. Since the correction of the experimental data for these effects is likely to be ambiguous, we have chosen to include them in the theoretical predictions. Thus our approach was to apply to the model predictions[6,7] evaporation corrections by means of the computer program JULIAN.[8] For this purpose, we assumed that the available excitation energy is, on the average, divided between the reaction products in proportion to their masses, and we used an appropriate excitation energy distribution for each reaction product. The resulting theoretical predictions, which contain evaporation effects, are compared with the experiments in Figs. 2.22 and 2.23. It can be seen that agreement between experiment and theory is excellent in all respects. It should be noted that the theory contains no adjustable parameters and that the agreement holds at both bombarding energies, as well as for the two different values of N/Z of the target.

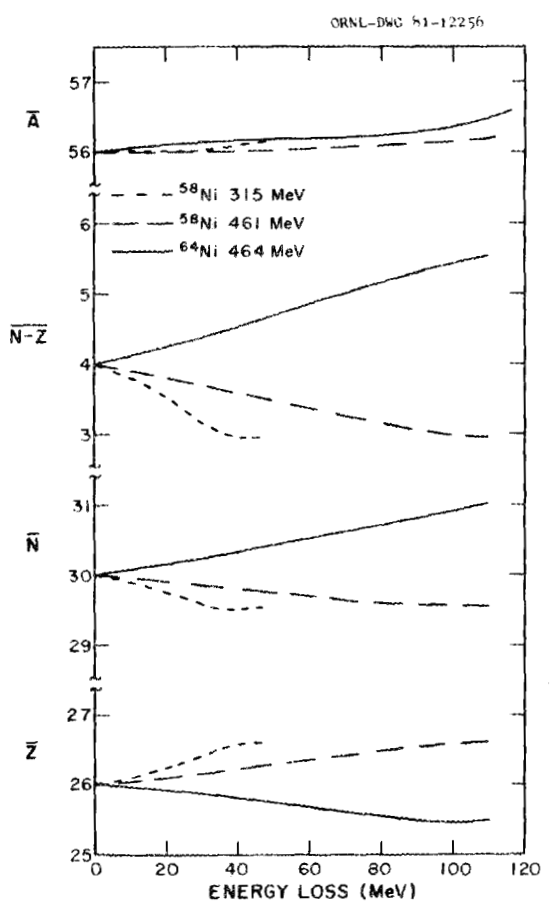


Fig. 2.24. Theoretical results for averages of the overall A, $N - Z$, N, and Z distributions as a function of energy loss. The calculations do not include effects of deexcitation by particle evaporation.

It is interesting to determine whether or not the transfer of protons and neutrons between the reacting nuclei is correlated. This question can be examined by means of the correlation function $\sigma^2(N, Z)/\sigma(N)\sigma(Z)$. This function is equal to unity for completely correlated transfer and to zero for noncorrelated exchange. Theoretical predictions, before particle evaporation (for ^{56}Fe + ^{64}Ni at 464 MeV), range from zero at zero energy loss to 0.7 at 120-MeV energy loss. Effects of particle evaporation raise the value of the calculated correlation function to about 0.9 at 120-MeV energy loss, and the experimental results are in excellent agreement with this value. Thus the experimental observation that, at large energy losses, the exchange of protons and neutrons appears to be fully correlated is due in part to the effects of particle evaporation.

---

1. Los Alamos National Laboratory.
2. Lawrence Livermore National Laboratory.
3. Niels Bohr Institute, Copenhagen, Denmark.
4. PNN, CEA, Bruyères-le-Châtel, France.
5. Lawrence Berkeley Laboratory.
6. J. Randrup, *Nucl. Phys.* **A307**, 319 (1978); **A327**, 490 (1979).
7. W. U. Schröder, J. R. Huizenga, and J. Randrup, *Phys. Lett.* **98B**, 355 (1981).
8. M. Hillman and Y. Eyal, code JULIAN, (unpublished), modified by A Gavron; A. Gavron, *Phys. Rev. C* **21**, 230 (1980).

FISSION BARRIER OF ^{153}Tb[1]

F. Plasil — F. E. Obenshain
R. L. Ferguson — F. Pleasonton
R. L. Hahn[2] — G. R. Young

Fission and evaporation-residue excitation functions have been measured for the systems ^{12}C + ^{141}Pr and ^{20}Ne + ^{133}Cs. Fission cross sections (σ_f) were determined by measurements of coincident fission fragments, and cross sections for evaporation residues (σ_{ER}) were obtained by means of the time-

of-flight method. The σ_f results are shown in Fig. 2.25. In contrast to the σ_f data, σ_{ER} values were obtained at only three energies for each reaction. Since σ_{ER} values are known to vary smoothly with excitation energy and since the evaporation-residue excitation functions are relatively flat in the energy region of interest, the small number of σ_{ER} points did not present serious problems.

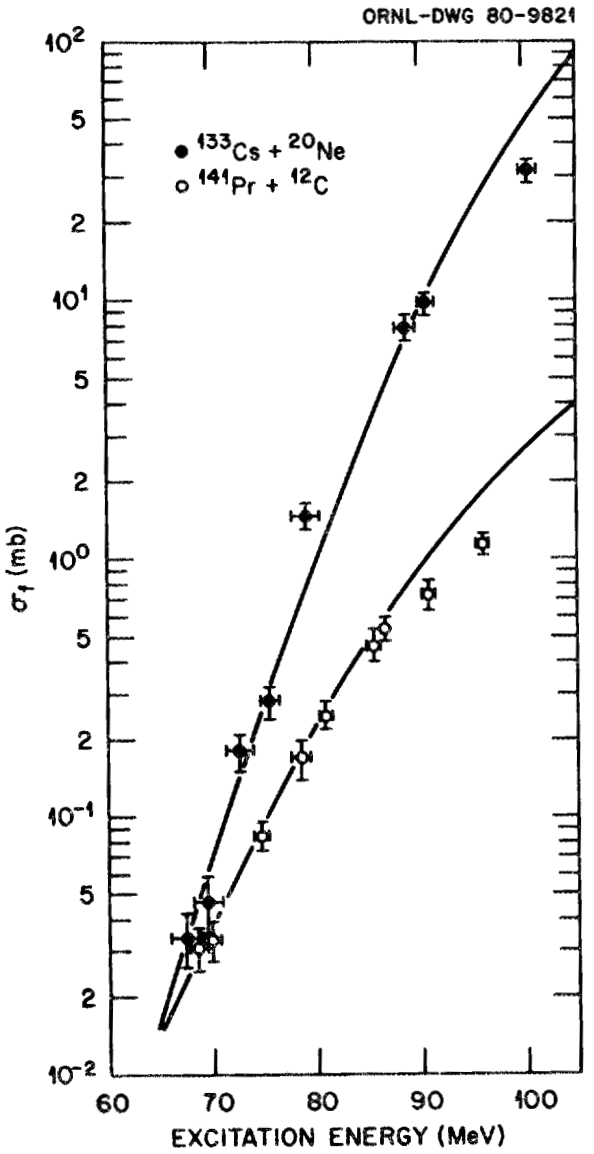


Fig. 2.25. Excitation functions for the fission of the ^{153}Tb compound nucleus produced in reactions of ^{12}C with ^{141}Pr and ^{20}Ne with ^{133}Cs. The circles indicate experimental results. The curves are statistical-model fits to both sets of data with a_f/a_ν = 1.08 and B_f = 28.5 MeV (see text).

Results were analyzed in terms of competition between fission and particle emission on the basis of the statistical model. Angular-momentum-dependent fission barriers (B_f) were used. The angular-momentum dependence of B_f was obtained from the rotating-liquid-drop model.[3] Fits to data were made by means of two adjustable parameters, k and a_f/a_ν, where a_f and a_ν are the level density parameters for fission and for particle emission respectively. The parameter k is defined by $B_f(J) = kB_f^{LD}(J)$, where $B_f^{LD}(J)$ is the liquid-drop barrier[3] at angular momentum J. It was found that values of a_f/a_ν govern primarily the absolute magnitudes of the fission excitation functions, while values of k determine their slope. This is illustrated in Fig. 2.26 for the case of ^{12}C + ^{141}Pr.

The best fits to the data from both reactions were obtained with a_f/a_ν = 1.08 and k = 0.83. These fits are indicated in Fig. 2.25. Our value of k is considerably higher than those determined for similar systems by Beckerman and Blann.[4] The dif-

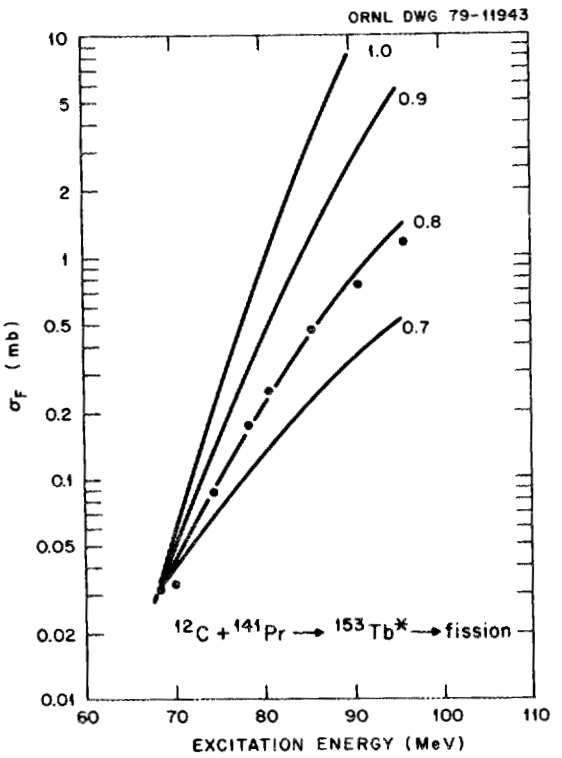


Fig. 2.26. Effect of fission barrier variation on statistical-model fits to the fission excitation function from the ^{12}C + ^{141}Pr reaction. The labels on the curves indicate values of k in the relationship $B_f = kB_f^{LD}(J = 0)$. The corresponding values of a_f/a_ν range from 0.985 for k = 0.7 to 1.245 for k = 1.0.

ference between the two sets of results is mainly due to the facts that our measurements were made down to much lower values of σ_f than those of ref. 4 and that we have chosen to give the greatest weight to the lowest σ_f data points in our analysis.

Extrapolations of $B_f(J)$ values determined in this work to $J = 0$ cannot be justified on theoretical grounds. If, however, we choose to ignore this point, then the fission barrier of ^{153}Tb obtained from our data is 28.5 ± 1.7 MeV. This result is consistent with predictions from recent nuclear mass calculations and with barriers obtained from ^{4}He-induced fission.

1. Published in *Phys. Rev. Lett.* **45**, 333 (1980).
2. Chemistry Division.
3. S. Cohen, F. Plasil, and W. J. Swiatecki, *Ann. Phys.* (N.Y.) **82**, 557 (1974).
4. M. Beckerman and M. Blann, *Phys. Lett.* **68B**, 31 (1977) and *Phys. Rev. C* **17**, 1615 (1978).

MASS AND CHARGE DISTRIBUTIONS FROM REACTIONS BETWEEN ^{86}Kr and ^{124}Sn[1]

M. Blann[2] P. D. Goldstone[3]
H. C. Britt[3] H. H. Gutbrod[4]
B. H. Erkkila[3] F. Plasil
R. L. Ferguson R. H. Stokes[3]

Fragment mass numbers, charges, and kinetic energies were measured by time-of-flight and ΔE-E techniques for reactions between ^{124}Sn nuclei and ^{86}Kr projectiles at laboratory bombarding energies of 440 and 720 MeV. The measurements were performed at the LBL SuperHILAC, and results were obtained at angles ranging from 5 to 25° in 5° intervals. The deeply inelastic events were analyzed in terms of plots of the average mass number ($\bar{A}$) for a given atomic number Z, as a function of Z. From these plots and from evaporation calculations, it was possible to conclude that the available excitation energy is divided between the two primary reaction products in proportion to their masses. This shared excitation energy includes both thermal and deformation energy of the fragments.

Dispersions (expressed as standard deviations) in kinetic energy and mass at fixed values of Z were obtained for strongly damped products. Estimates of the primary dispersions (before deexcitation by particle emission) in fragment excitation, kinetic energy, and mass were made. The statistical evaporation model was used to estimate the broadening due to evaporation. Sample results are presented in Table 2.3 for energy dispersions. From Table 2.3 it can be seen that the dispersions in Q values for the reactions appear to be fairly constant fractions (about 13%) of the Q values and that there is a considerable difference between the primary and final dispersions. The primary mass dispersions at fixed Z were also found to be constant with a standard deviation of only about 1.6–1.7 units (compared with a final measured standard deviation of 2.0–2.4 units). This rather narrow distribution probably reflects the constraints of the underlying potential energy surface, which is due to the narrow width of the valley of beta stability and its alignment in the A-Z plane.

1. Published in *Phys. Rev. C* **19**, 1288 (1979).
2. Nuclear Structure Research Laboratory, Rochester; present address, Lawrence Livermore National Laboratory.
3. Los Alamos National Laboratory.
4. GSI, Darmstadt, and Lawrence Berkeley Laboratory.

REACTIONS OF 142-MeV ^{16}O WITH ^{146}Nd

R. Novotny J. H. Barker[1]
J. R. Beene D. G. Sarantites[2]
M. L. Halbert M. Jääskeläinen[2]
D. C. Hensley R. Woodward[2]

A bombardment of ^{146}Nd with ^{16}O was carried out to measure gamma-ray side feeding patterns in

Table 2.3. Energy dispersions for typical reaction products

Z	A	E_{Kr} (MeV)	Excitation E (MeV)	Q (MeV)	σ_{exp} (MeV)	σ_{prim}[a] (MeV)	σ_Q[b] (MeV)	σ_Q/Q
30	73	440	85 ± 10	−104 ± 10	18	16.5	14	0.13 ± 0.02
30	73	720	230 ± 10	−250 ± 10	55	42	32	0.13 ± 0.01
46	112	440	105 ± 10	−110 ± 10	18	16	18	0.16 ± 0.02
46	112	720	260 ± 10	−265 ± 10	45	30	30	0.11 ± 0.01

[a]Standard deviation of the experimental kinetic energy distribution reduced by estimated spread due to particle evaporation.
[b]σ_{prim} expressed in terms of the Q value.

coincidence with alpha particles. These results, pertaining to the incomplete fusion reaction mechanism, have been published.[3] At the same time the experiment recorded much information on other exit channels. Since the combination of charged-particle telescopes, a Ge(Li) detector, and a gamma-ray multiplicity array can provide unusually complete data, we report here results of a preliminary analysis for some of the other channels.

A 148.8-MeV $^{16}O^{5+}$ beam from the ORIC bombarded a 10.3-mg/cm^2 target of Nd metal enriched to 97.54% in ^{146}Nd. The mean energy in the target was 142 MeV. A Ge(Li) detector at 125° was operated in coincidence with six ΔE-E silicon surface-barrier telescopes. The telescopes were in the same plane as the Ge(Li) detector at −18°, +22.5°, −28°, +38.3°, −57°, and +164°. For each particle-gamma coincidence, the computer recorded on magnetic tape the pulse heights in the Ge(Li) detector and the relevant ΔE and E counters, the time delay between the pulses, and a bit pattern showing which NaI counters of an eight-counter multiplicity array had fired. The event tapes were later scanned with ΔE-E masks appropriate for various charged particles, ultimately producing particle-energy spectra and Ge(Li) spectra associated with each particle type in each telescope. Delay times as long as 300 ns between the telescope signal and the Ge(Li) pulse were accepted, allowing for essentially complete decay of all the isomeric levels. For the even-Z products the characteristic known gamma lines clearly identified the yrast transitions in the various residual nuclei. For odd Z, many lines were visible, but most of them could not be identified with any of the expected products. The NaI information was not examined in these scans; data on gamma-ray multiplicities have not yet been extracted.

Figure 2.27 is a ΔE-E map of the Ge(Li)-coincident particles detected in the 38°

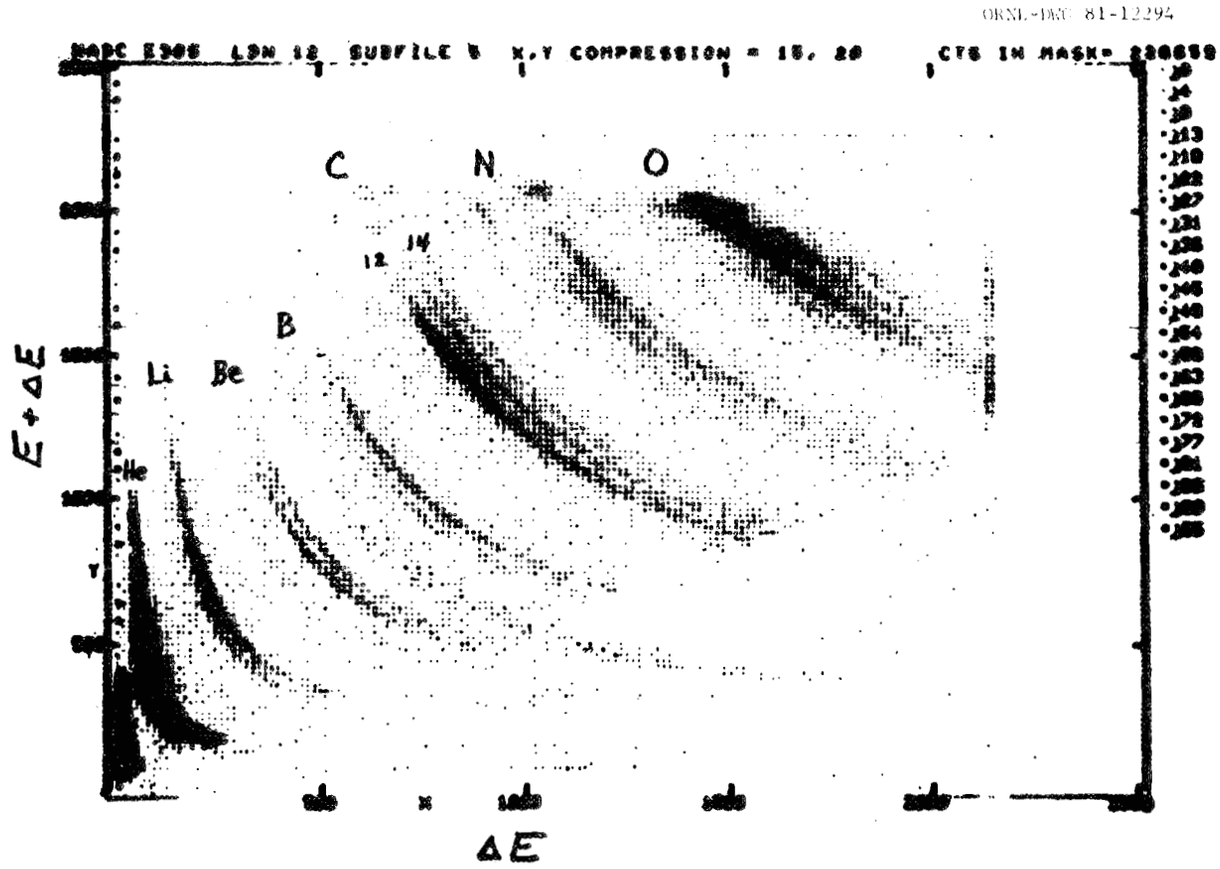


Fig. 2.27. Map of ΔE-E data from the 38.3° telescope in coincidence with Ge(Li) pulses. The signal from the stopping detector (E) was summed with that from the transmission detector (ΔE) before the data pulse-height analysis. The loci of the various products are labeled, with an indication for C of its isotopes.

telescope. The dominant isotopes for each Z are ^{1}H, ^{4}He, ^{7}Li, ^{9}Be, ^{11}B, ^{12}C, ^{15}N, and ^{16}O. Transitions to the few particle-stable levels of ^{13}N and ^{16}N are evident. The $^{15}N/^{14}N$ intensity ration is about 2. At more forward angles, small numbers of F ions and a few Ne ions were observed. Almost no particles with $Z > 3$ were seen at 57 and 164°.

Figure 2.28 shows the energy spectra of the particles emitted at various angles. The arrows mark the Coulomb barrier for a binary division in each case. The heavier particles peak at energies higher than the arrows, indicating that they arise from a process that is not strongly damped. For Li and Be the peak occurs near the Coulomb barrier, but the tail toward higher energies is much stronger than expected for a fully damped situation. The angular correlations fall more steeply than $1/\sin\theta_{c.m.}$ for most of the particles; only low-energy Li is consistent with this angular dependence. One must keep in mind that since a Ge(Li) coincidence was required, these results are biased by $M\gamma$ for each channel. Also, no attempt was made in Fig. 2.28 to correct for the variation of Ge(Li) efficiency due to the different gamma-ray energies for the various channels.

Table 2.4 shows the isotopic composition of the C particles averaged over the energy bins of Fig. 2.28; the composition varies little with particle energy. There is some increase in the ^{12}C fraction at the larger angles. The excitation energy of the ^{150}Sm remaining after the departure of a ^{12}C particle may be deduced from the ^{12}C kinetic energy. The most probable ^{12}C energy corresponds to 20–30 MeV excitation, enough to boil off about two neutrons or

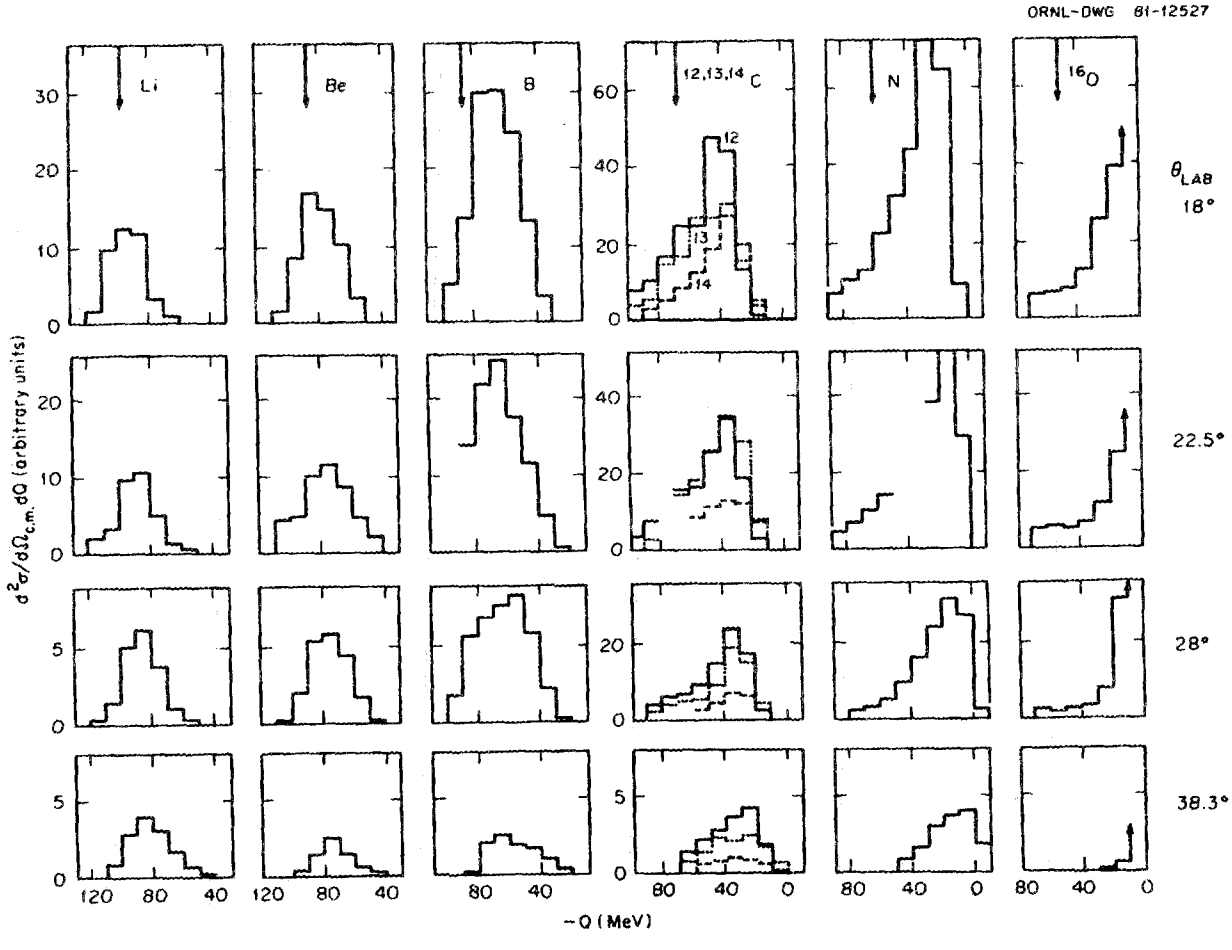


Fig. 2.28. Relative double-differential center-of-mass cross sections for various particles at four angles of emission, as a function of the energy released. The arrow shows the Coulomb barrier for a binary final state including the particular observed particle. The breaks in the 22.5° data are due to a faulty E detector.

Table 2.4. Carbon isotope percentages as a function of angle (These numbers are averaged over the particle energy bins of Fig. 2.28)

θ (deg)	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C
18		40	40	20	
22.5	5	35	31	26	4
28	6	49	30	13	2
38.3		58	30	11	

perhaps three, which should give ^{148}Sm as the most likely product and ^{147}Sm as the next. The results for ^{13}C were analogous. For ^{14}C the Sm excitation energy was somewhat lower, though still adequate for emission of one neutron.

These features are confirmed for ^{12}C and ^{13}C by analysis of the peak intensities in the Ge(Li) spectra as a function of C energy (Fig. 2.29). Moreover, the yields of the Sm isotopes corresponding to loss of one neutron are largest for the high-energy particles, and those arising from loss of several neutrons peak at progressively lower C energies, in a fashion reminiscent of excitation-function data for compound-nucleus evaporation. The arrows in Fig. 2.29 show the maximum C energies at which various numbers of neutrons may separate from the primary Sm product, ^{150}Sm for ^{12}C or ^{149}Sm for ^{13}C. If we recall that each neutron carries several additional MeV as kinetic energy, the data are consistent with the idea that the primary nucleus simply evaporates as many neutrons as it can, depending on the energy not carried off by the carbon particle.

The situation is different with the ^{146}Nd product (the only Nd isotope that could be identified). Here the C energy has little effect. Another mechanism must be important, possible breakup of the ^{16}O projectile into $^{12}C + \alpha$, since ^{146}Nd is also observed in coincidence with alpha particles. Actually, the energy-integrated Nd yield associated with alpha particles is larger than it is for ^{12}C, suggesting that more severe fragmetation of the ^{16}O occurs part of the time. The Nd yields in coincidence with ^{13}C are a factor of about 2 smaller than with ^{12}C; a reduced cross section for ^{13}C might be expected, since breakup of ^{16}O into $^{13}C + {}^{3}He$ is energetically less favorable.

The most significant products in coincidence with alpha particles are isotopes of Dy, as reported

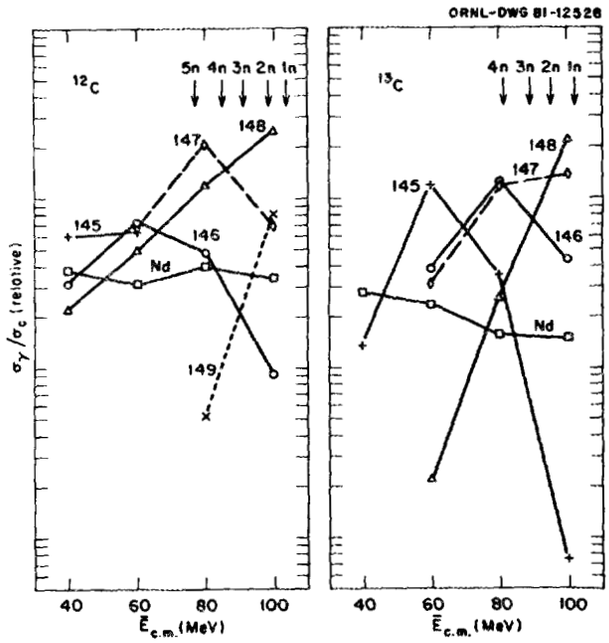


Fig. 2.29. Relative importance of various final Sm or ^{146}Nd nuclei in coincidence with ^{12}C (left) or ^{13}C (right) as a function of center-of-mass particle energy. The ordinate is a weighted average of the yield of the lowest gamma-ray transition as seen in the Ge(Li) spectra in coincidence with C emitted at angles from 18 to 38.3°, normalized to the corresponding particle cross sections from Fig. 2.28. The curves identified by the numbers 145, 146, ... are for ^{145}Sm, ^{146}Sm, ... The arrows show the thresholds for separation of the indicated number of neutrons from the initial nucleus (^{150}Sm for ^{12}C or ^{149}Sm for ^{13}C) without allowance for neutron kinetic energy.

in ref. 3. The ^{146}Nd yield is only about 2% of the Dy. No Sm isotopes associated with alpha particles could be definitely identified. There was some evidence for ^{152}Gd, which could be due to ^{8}Be emission followed by evaporation of two neutrons, but no other isotopes of Gd could be positively identified.

---

1. St. Louis University, St. Louis, MO 63103; present address: South Carolina Electric and Gas Company, Columbia, SC 29218.
2. Washington University, St. Louis, MO 63130.
3. J. H. Barker, J. R. Beene, M. L. Halbert, D. C. Hensley, M. Jaaskelainen, D. G. Sarantites, and R. Woodward, *Phys. Rev. Lett.* **45**, 424 (1980).

ENERGETIC Z = 1, 2 PARTICLES FROM HEAVY-ION-INDUCED REACTIONS

R. L. Robinson
R. L. Auble
C. B. Fulmer
J. B. Ball
F. E. Bertrand
R. L. Ferguson
J. Gomez del Campo
I. Y. Lee
M. J. Martin
G. R. Young
J. R. Wu[1]
J. C. Wells[2]
H. Yamada[3]

In heavy-ion-induced reactions with $E_{proj} > 8$ MeV/amu there is a large emission of energetic Z = 1, 2 particles that cannot be explained by either total fusion or the deeply inelastic collision (DIC) process. An example of this is given in Fig. 2.30.[4] While a number of models have been proposed, the dominant reaction mechanism giving rise to these energetic light particles has not been definitively established. We have continued measurements of these energetic light ions for the purpose of testing the proposed models and with the hope of identifying the dominant mechanism(s). These studies have developed along two principal avenues. First is an investigation of the variation of double-differential cross sections of the inclusive spectra as a function of the projectile energy and target mass. Data analyzed to date are for 8- to 16-MeV/amu ^{12}C and ^{16}O projectiles extracted from the ORIC. Data were also recently obtained with beams of 50- to 150-MeV/amu ^{16}O at the Bevalac and will be analyzed in the near future. Second, for 136- and 194-MeV ^{12}C on ^{60}Ni we have investigated coincident relations of the energetic particles with (1) other light ions, (2) projectile-like fragments (PLF), (3) gamma rays which were used to identify the residual target fragments, and (4) gamma-ray multiplicities. Coincident studies are motivated by the fact that inclusive data alone are not sufficiently sensitive to ascertain the validity of different proposed models.

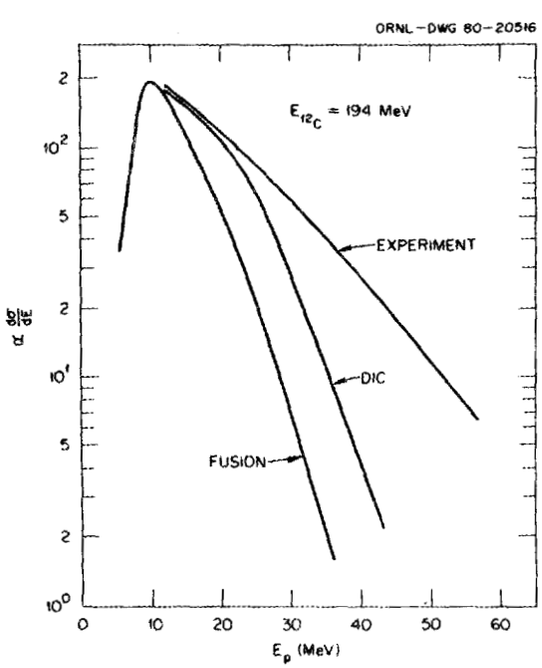


Fig. 2.30. Inclusive proton spectra at 17° for 194-MeV ^{12}C bombardment of ^{60}Ni. The "experimental" line is a smooth fit to the experimental data. The other two curves are calculated for a fusion reaction and for a deeply inelastic collision process as calculated with the program LILITA. They are normalized to the same value of E_p = 12 MeV.

The energetic light ions were detected by charged-particle telescopes each consisting of a 500-or 1000-μ-thick Si ΔE detector and a 5- or 12.7-cm-deep NaI crystal. There were four to eight detector telescopes for the singles measurements. The coincidence measurement utilized four energetic light-ion telescopes at forward angles, a heavy-ion telescope, two Ge(Li) detectors, and four NaI detectors for gamma-ray multiplicity determination.

Forward-angle data from the bombardment of ^{12}C, Fe, and ^{91}Zr with 208-MeV ^{16}O revealed that the cross sections for Z = 1, 2 particles were relatively insensitive to target mass.[5] The variation was less than the $A^{1/3}$ dependence expected for a peripheral reaction. The implication is that either the target is a spectator or the numbers of target nucleons that participate in the reaction are similar for each target.

Double-differential cross sections were measured for 90-, 123-, 156, and 194-MeV ^{12}C bombardment of ^{60}Ni. The exponential decreases with particle energy are comparable at the four projectile energies. The cross sections are similar in magnitude when plotted against $E_{particle}/(E/A)_{beam}$, as shown in Fig. 2.31. Reasonable fits to their dependence on particle energy and angle were obtained by assuming that the particles were emitted by an excited source moving in the direction of the beam. The parameters are the source velocity v_s and temperature T and a normalization factor. Table 2.5 gives the temperatures and velocities required to fit the proton data. These same parameters also give acceptable fits to the differential cross sections for the other Z = 1, 2 particles.

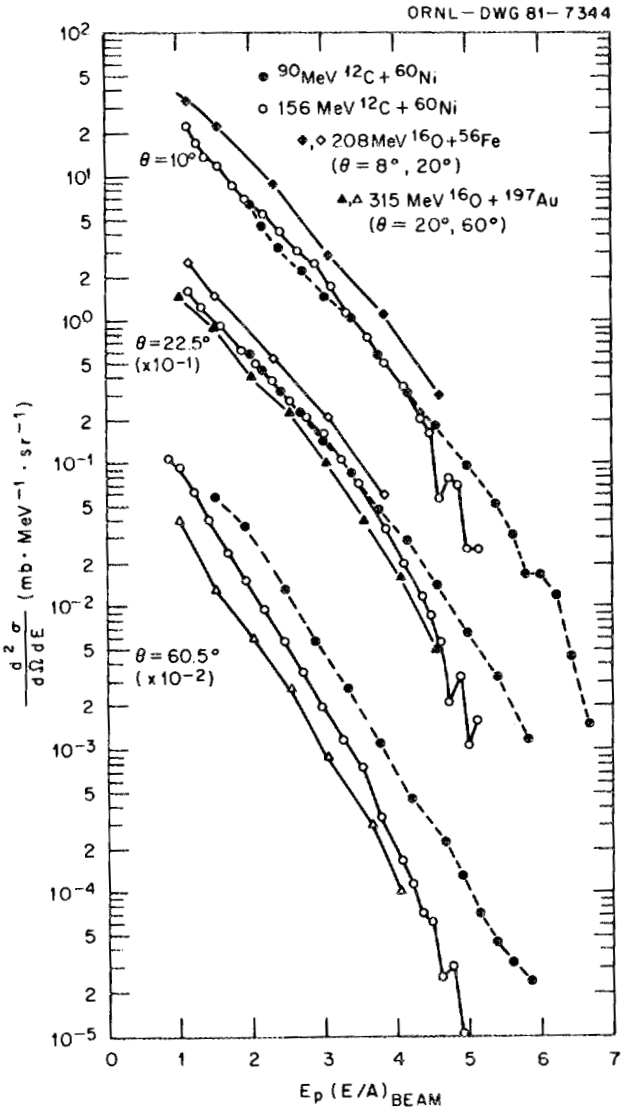


Fig. 2.31. Differential cross sections for protons. They are plotted against the energy of the particles divided by the energy per nucleon in the projectile.

Angular distributions of protons and alpha particles observed in coincidence with $Z = 1$ to 7 particles detected at 17° resulting from 194- and 136-MeV ^{12}C bombardment of ^{60}Ni, with a few curious exceptions, are all strongly peaked within a few degrees of 0. However, alpha-particle angular distributions are narrower (FWHM ≈ 30°) than the proton spectra (≈50°) and in contrast to the proton results are always symmetrical about the beam direction.

The multiplicities of the protons and alpha particles in coincidence with $Z = 1$ to 6 particles observed at 17° are illustrated in Fig. 2.32. The alpha multiplicities show a sudden drop between $Z = 4$ and 5 (not present in the proton results) that can be attributed to alpha particles from breakup of the ^{12}C projectile. The observation of alpha particles in coincidence with $Z \geqslant 5$ particles and protons with $Z = 6$ particles show that some energetic $Z = 1, 2$ particles are not emitted from the projectile in a one-step process. Figure 2.32 shows that for the most energetic protons and alpha particles the multiplicities for the higher Z gates are relatively smaller than for $Z = 1, 2$ gates as compared with

Table 2.5. Temperature and velocity parameters used to fit inclusive proton spectra from the ^{12}C + ^{60}Ni reaction

$E_{^{12}C}$ (MeV)	T (MeV)	v_s/v_p
90	3.5	0.40
123	4.3	0.45
156	5.0	0.50
194	≈5.0	≈0.55

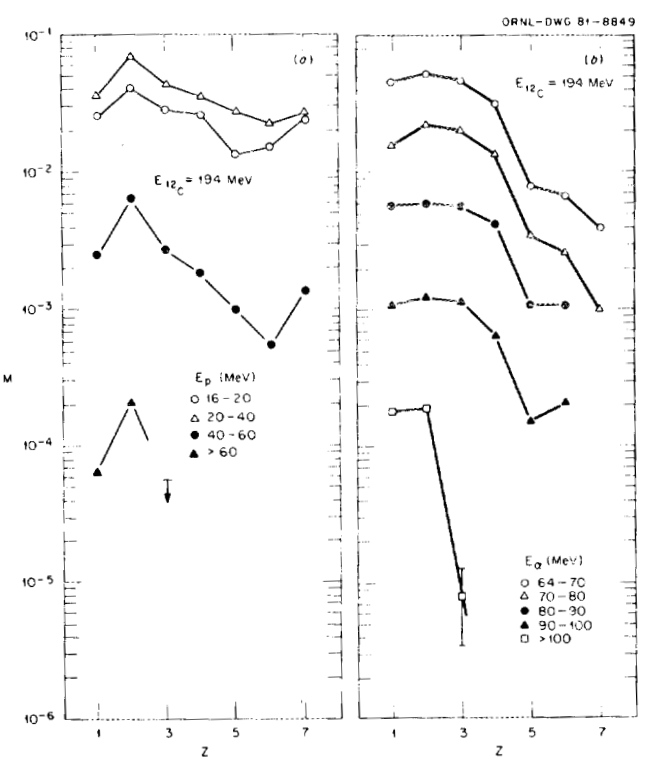


Fig. 2.32. The multiplicities of particles from bombardment of ^{60}Ni with 194-MeV ^{12}C. (*a*) Protons and (*b*) alpha particles in the noted energy bins in coincidence with $Z = 1$ to 6 particles observed at 17°.

the lower-energy light ions. This suggests there is a component of the very energetic light-ion spectra that is not associated with a process in which a projectile-like fragment remains.

Figure 2.33 shows the distribution of residual nuclei in coincidence with slow and fast protons and alpha particles. For three of these plots the crest of the contour mountain is at ^{60}Ni. That is, the average number of nucleons emitted through all processes is approximately equal to that of the projectile. The contour plot obtained through coincidence with lower-energy alpha particles peaks at about ^{56}Fe. Probably additional particles are emitted, since there is more energy available for other processes when the gating particle has less energy. Comparison of these contours with those calculated for total fusion and for deeply inelastic collisions shows they are more like those predicted for total fusion.

There are three observations from the coincident studies that favor the conclusion that energetic light ions observed in coincidence with PLFs are emitted during the collision process and not sequentially: (1) the widths and peak positions of the light-ion angular distributions at most show very weak dependence on the energy of the projectile, on the energy of the emitted light ion, and on the Z of the gating PLF; (2) the experimental angular distribution widths do not agree with the predictions of the program LILITA[4] for the DIC; (3) the multiplicities of energetic light ions obtained when gating on low-energy light ions and on high-energy light ions are generally comparable. Points 1 and 3 indicate that the coincident PLF has no memory of the emisssion of the energetic light ion.

A picture for a major reaction mechanism suggested by comparison with Monte Carlo calculations made with the program LILITA[4] and by features like the narrow widths of the angular distributions and the decrease of the multiplicity of the energetic light particles with increasing Z of the gating particles is one in which the projectile begins to coalesce with the target and, before equilibrium is reached, the fast particle is emitted. The remainder of the projectile is then fused with the target. Evaporation from the compound system returns the compound nucleus to an average mass similar to that of the target. This picture could also account for the success of the phenomenological explanation of the inclusive data that show the cross section can be explained in terms of emission from a source with velocity of approximately one-half of the projectile velocity. This could be the average velocity of the PLF, as it is in the process of fusing, at the time the energetic light ion is emitted.

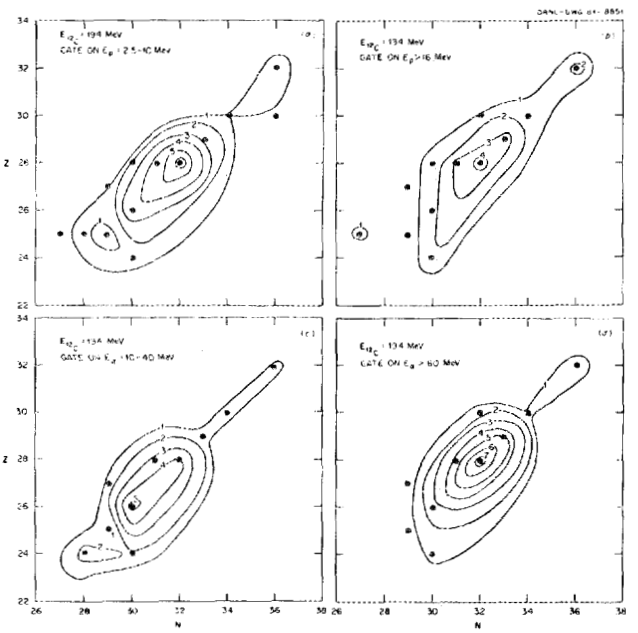


Fig. 2.33. Distribution of residual nuclei resulting from 194-MeV ^{12}C bombardment of ^{60}Ni in coincidence with emitted particles. (*a*) 2.5- to 10-MeV protons, (*b*) >16-MeV protons, (*c*) 10- to 40-MeV alpha particles, and (*d*) >60-MeV alpha particles. The contour lines correspond to percent of all coincident residual nuclei. The locations of the measured points on which these contour lines are based are indicated by solid circles.

1. Present address: Bell Laboratories, Naperville, Ill.
2. Tennessee Technological University, Cookeville.
3. Vanderbilt University, Nashville, Tenn.
4. J. Gomez del Campo, *Proc. of the Symposium on Heavy Ion Physics from 10 to 200 MeV/amu*, ed. J. Barrette and P. D. Bond, July 1979, BNL-51115, vol. 1, p. 93 (1979).
5. C. B. Fulmer, J. B. Ball, R. L. Ferguson, R. L. Robinson, and J. R. Wu, *Phys. Lett.* **100B**, 305 (1981).

NEUTRON EMISSION IN REACTIONS INDUCED WITH CARBON, OXYGEN, AND NEON IONS

J. R. Beene
B. Cheynis
R. L. Ferguson
A. Gavron[1]
K. Geoffroy Young[2]
M. Jääskeläinen[3]
C. F. Maguire[4]
F. E. Obenshain
G. A. Petitt[5]
F. Plasil
D. G. Sarantites[3]
G. R. Young

Neutron emission associated with deeply inelastic (DI) products, with evaporation residues (ER), and with fission fragments (FF) has been

investigated. The systems studied were ^{16}O + Nb, ^{12}C + ^{158}Gd, ^{13}C + ^{157}Gd, and ^{20}Ne + ^{150}Nd. Neutron spectra and angular distributions were obtained by means of eight liquid scintillator detectors deployed around a thin-walled spherical chamber. Surface-barrier detectors were located inside the chamber for the purpose of detecting the coincident ER, FF, and DI products. The ER and FF were identified by means their time of flight relative to the cyclotron rf structure, and DI products were identified in a ΔE-E telescope.

Neutrons Associated with Evaporation Residues

In earlier work, nonequilibrium neutron emission (NNE) associated with ER has been observed for the ^{12}C + ^{158}Gd system at 152 MeV and for the ^{16}O + ^{154}Sm system (also at ^{152} MeV) but not for ^{20}Ne + ^{150}Nd at 175 MeV.[6] These observations indicated that projectile structure influences the probability of NNE. The purpose of the present work was to consider further the effects of projectile structure and to investigate the energy dependence of NNE. Energy spectra and angular distributions of neutrons associated with ER (fusion-like products) were measured from the following reactions: ^{12}C + ^{158}Gd at lab energies of 192, 150, 124, and 103 MeV; ^{13}C + ^{157}Gd at 160, 140, and 110 MeV; and ^{20}Ne + ^{150}Nd at 176 and 239 MeV. Typical neutron spectra shown in Fig. 2.34 for the 150-MeV ^{12}C + ^{158}Gd and 160-MeV ^{13}C + ^{157}Gd cases. It is clear from the figure that there is no significant difference between the spectra obtained from the ^{12}C reactions and those from the ^{13}C reactions. Thus we do not observe a projectile structure effect in this case.

In order to determine quantitatively the extent of NNE, it is necessary to subtract the contribution of evaporated neutrons from the measured spectra. Since there is no unique prescription to do this, we have used two methods which provide us with upper- and lower-limit estimates of NNE. The lower limit for NNE was obtained by ascribing all neutrons below 9 MeV to evaporation and by fitting the low-energy portion of the spectrum with

$$\phi(\varepsilon) = \varepsilon^{0.6} \exp[-\varepsilon/T_{Eq}]. \quad (1)$$

The results of the fits are illustrated in Fig. 2.34. The NNE multiplicity for this case was obtained from the differences between the integrated experimental spectra and the integrals (at various angles) of Eq. (1). The results are shown in Fig. 2.35.

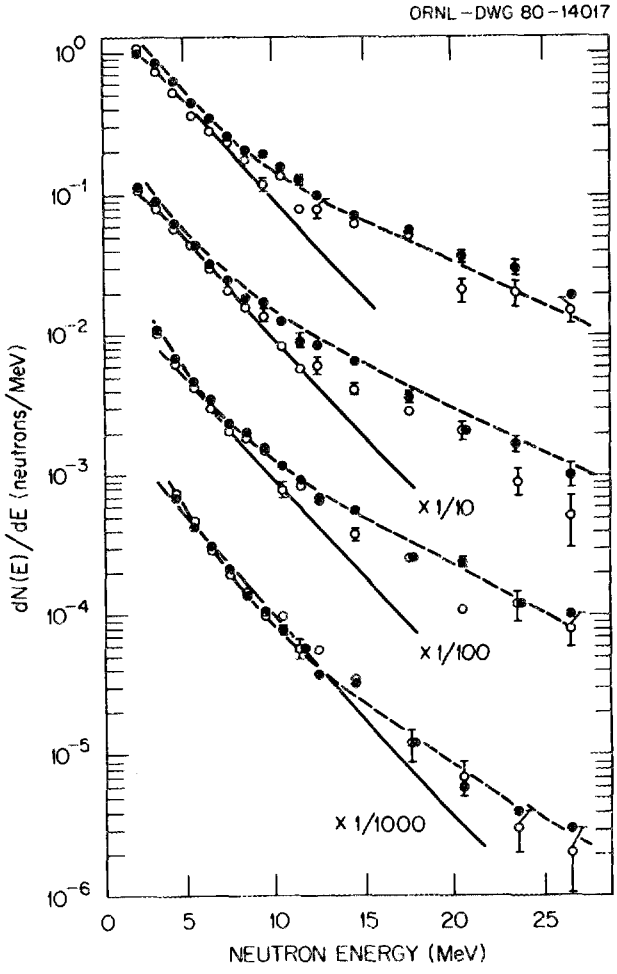


Fig. 2.34. Spectra of neutrons in coincidence with evaporation residues. Open circles: ^{12}C + ^{158}Gd (150 MeV); closed circles: ^{13}C + ^{157}Gd (160 MeV); average angles with respect to the beam (from top to bottom): 15.5, 32.5, 56.5, and 113.5°. The solid line is obtained by fitting the ^{12}C data using Eq. (1). The dashed line is obtained by fitting the ^{13}C data using the two-source model (see text).

The upper limit for NNE was obtained by assuming that, in addition to the evaporation spectrum of Eq. (1), there exists another source of neutrons which has a higher temperature and which moves with a velocity V_{NE} greater than the velocity of the center of mass. We assumed the spectrum from this source to be given by

$$\phi_{NE}(\varepsilon) = \varepsilon \exp[-\varepsilon/T_{NE}]. \quad (2)$$

A three-parameter fit was then performed to spectra at various angles. Equations (1) and (2) were used, and the variable parameters were T_{Eq}, T_{NE}, and V_{NE}. Results of the fits are given in Table 2.6

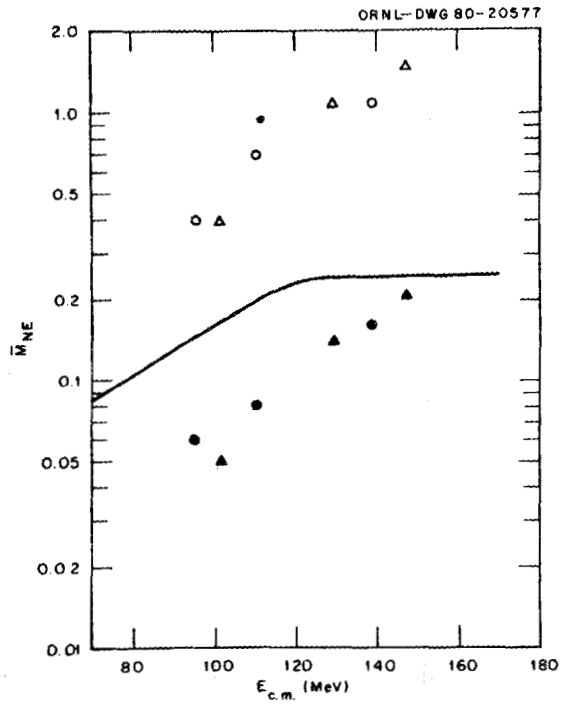


Fig. 2.35. Average nonequilibrium neutron multiplicities. The curve was obtained from the Wilczynski et al. sum-rule model (ref. 8). The open symbols refer to values from Table 2.6 and the closed symbols to values from the lower-limit estimate of NNE (see text). Triangles are for $^{13}C + ^{157}Gd$ and circles for $^{12}C + ^{158}Gd$.

and illustrated in Fig. 2.34. The multiplicities obtained from integration of Eq. (2) are shown in Fig. 2.35.

The absence of differences in NNE between ^{12}C-and ^{13}C-induced reactions is in disagreement with the modified Fermi-jet calculations of Boneh et al.[7] but agrees with the predictions of the sum-rule model of incomplete fusion of Wilczynski et al.[8] Other comparisons with the Wilczynski model have also been favorable. For example, the predicted NNE multiplicity is shown as a function of bombarding energy in Fig. 2.35. As expected, our results, which constitute upper and lower limits, bracket the calculated curve.

Neutrons Associated with Projectile-Like Products in Reactions between C and Gd

We have also investigated NNE associated with inelastic reactions for the systems discussed above. Here we wish to point out only one particularly interesting aspect of our results. It was noted that in cases in which a neutron detector was located at an angle close to the angle of the coincident heavy-ion telescope [in which the projectile-like fragment (PLF) was detected], a "bump" was observed in the neutron spectrum. From the neutron energy associated with the bump, it followed that the

Table 2.6. Parameters from the two-source description of NNE (See text)

Reaction	E^a (MeV)	T_{Eq}^b (MeV)	T_{NE}^c (MeV)	$V_{c.m.}^d$ (cm/ns)	V_B^e (cm/ns)	V_{NE}^f (cm/ns)	$\bar{M}_{Eq}^g$	$\bar{M}_{NE}^h$
$^{13}C + ^{157}Gd$	160	1.60	4.2	0.40	3.98	1.2	7.0	1.5
	140	1.54	3.8	0.35	3.58	1.0	6.3	1.1
	110	1.60	3.7	0.31	2.89	0.8	5.9	0.4
$^{12}C + ^{158}Gd$	194	1.80	4.6	0.39	4.70	1.2	7.0	1.1
	150	1.63	4.2	0.35	3.94	0.9	7.1	1.1
	124	1.57	4.0	0.32	3.36	0.8	6.5	0.7
	103	1.59	4.1	0.29	2.84	0.7	5.8	0.4
$^{20}Ne + ^{150}Nd$	240	1.80	4.1	0.56	3.80	1.1	7.2	0.9
	174	1.92	4.2	0.48	2.90	0.9	7.4	0.4

[a] E: laboratory bombarding energy.
[b] T_{Eq}: temperature parameter in Eq. (1).
[c] T_{NE}: temperature parameter in Eq. (2).
[d] $V_{c.m.}$: c.m. velocity (provided for reference).
[e] V_B: velocity of projectile in the interaction region (provided for reference).
[f] V_{NE}: velocity of moving NNE source.
[g] $\bar{M}_{Eq}$: neutron evaporation multiplicity.
[h] $\bar{M}_{NE}$: NNE multiplicity.

neutrons causing it had velocities similar to those of the projectile-like fragments. The bump was observed only for neutrons coincident with certain specific products (e.g., with $Z = 5$ and 6 products in the $^{12}C + {}^{158}Gd$ case). The observed structure is illustrated in Fig. 2.36 for the case of 124-MeV $^{12}C + {}^{158}Gd$. A possible explanation of the observed structure is that it results from the decay of states in the projectile-like fragment which have excitation energies that lie only slightly (about 100 keV) above the neutron separation energy for the particular nucleus involved. The decay of such states would result in neutron emisssion localized within a narrow cone about the direction of the projectile-like fragment. Due to the low kinetic energy released in the decay, the neutrons would have a narrow velocity distribution centered about the fragment velocity. It is possible to obtain estimates of the constraints on the level widths required by such a picture from estimates of the interaction times involved. From considerations based on rotation frequencies and on the time required for Rutherford trajectories, we estimate the typical interaction

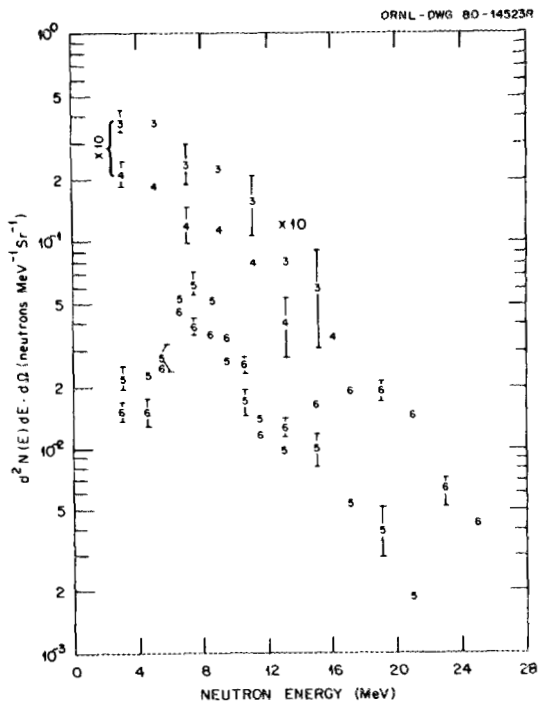


Fig. 2.36. Spectra of neutrons in coincidence with projectile-like fragments having specific values of Z from reactions between 124-MeV $^{12}C + {}^{158}Gd$. The numbers of the data points indicate the nuclear charge of the projectile-like fragment with which the neutrons are in coincidence. Note the peaks in the neutron spectra associated with PLFs having $Z = 5$ and 6.

time in our cases to be of the order of 5×10^{-21} s. If we require that the probablility of decay of the excited state during this time be less than 10%, then the permissible level width is about 15 keV.

We have examined known states with finite neutron widths, involving low kinetic energy release, for all nuclei with $Z = 3$ to 6 and $A = 6$ to 15. Only two levels, one in ^{12}B and the other in ^{14}C, satisfy the conditions stated above. ^{12}B has a state at 3.3884 MeV (cf. $S_n = 3.369$ MeV) with $\Gamma_n < 1.4$ keV, and ^{14}C has a state at 8.3183 MeV (cf. $S_n = 8.1770$ MeV) with $\Gamma_n = 3.4 \pm 0.6$ keV. The fact that suitable states exist only in boron and carbon may explain why the bumps observed are predominantly associated with projectile-like fragments with $Z = 5$ and 6. If the above requirements are relaxed slightly, states in ^{7}Li, ^{8}Li, and ^{10}Be could also lead to peaks in the neutron spectra associated with PLF with $Z = 3$ or 4. Such peaks are, in fact, observed in ^{13}C-induced reactions.

Neutron Emission in Deeply Inelastic Collisions of ^{16}O with ^{93}Nb at 204 MeV[9]

Spectra of neutrons in coincidence with PLFs produced in deeply inelastic collisions of ^{16}O with ^{93}Nb at 204 MeV have been measured at eight angles. The total neutron multiplicity associated with such events was found to be 1.3. From the neutron spectrum obtained in a detector located at 143° with respect to the beam direction (121° with respect to the PLF direction) and from statistical-model calculations, it was possible to deduce that 1.0 ± 0.1 neutron is associated with statistical evaporation from the target-like fragments (TLF). The contribution of neutrons emitted from the TLF was subtracted from the spectra in the other detectors. It was not possible to fit the resulting spectra and angular distributions with statistical neutron emission from the PLFs. In order to fit the experimental results, it was necessary to assume the existence of an additional source of neutrons with a temperature of 1.5 MeV, moving along the beam axis with a velocity of 3.3 cm/ns and emitting neutrons isotropicallly. The neutron multiplicities necessary to reproduce the data were found to be (1) 0.15 ± 0.05 neutron from the PLF (2) 1.0 ± 0.1 neutron from the TLF and (3) 0.15 ± 0.05 neutron emitted by the additional source.

Neutrons Associated with Fission Fragments

Measurements of spectra and of angular distributions of neutrons associated with fission

fragments were made for the reactions $^{12}C + {}^{158}Gd$ at 192 MeV and $^{20}Ne + {}^{150}Nd$ at 176 and 239 MeV. From the data, from evaporation calculations, and from simultaneous measurements of neutrons associated with ER, it is possible to deduce whether the observed neutrons were emitted before fission (from the compound nucleus) or after fission (from the fission fragments). The results are presented in Fig. 2.37 as a function of the critical angular momentum, ℓ_{crit}. Values of ℓ_{crit} were estimated for the fusion reactions from the Bass model.[10] The critical angular momenta and excitation energies are $72\hbar$ and 169 MeV for the $^{12}C + {}^{158}Gd$ case, $79\hbar$ and 135 MeV for the $^{20}Ne + {}^{150}Nd$ reaction at the lower bombarding energy, and $99\hbar$ and 191 MeV for the $^{20}Ne + {}^{150}Nd$ case at the higher energy. From Fig. 2.37 it can be noted that at the two lower values of ℓ_{crit} (and of excitation energy), most neutrons are emitted prior to fission, while at the higher value of ℓ_{crit} most neutrons are emitted after fission. We conclude that the fission process is very rapid at the highest excitation energy and angular momentum. One possible explanation is that in this case, the fission reaction is dominated by "fast fission," a decay mode short-lived relative to compound-nucleus decay.[11]

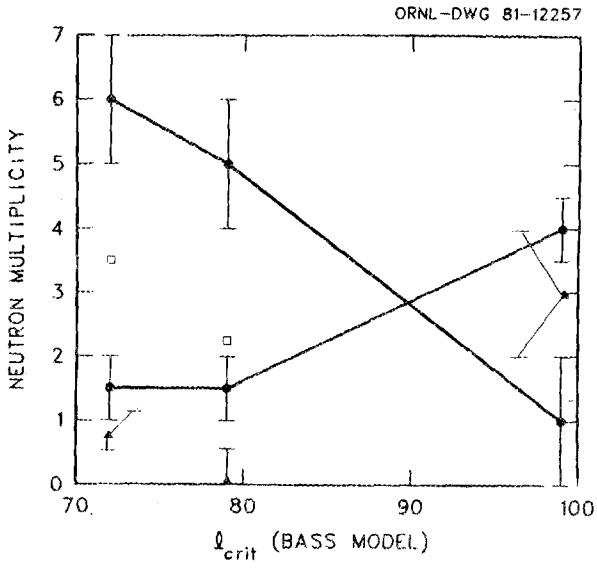


Fig. 2.37. Neutron multiplicities as a function of ℓ_{crit} (ref 10). Closed circles indicate the number of neutrons evaporated before fission. The open circles indicate the number of neutrons evaporated from each fission fragment. The squares indicate statistical-model calculations and the triangles the number of nonequilibrium neutrons preceding fission.

It is also important to point out (see Fig 2.37) that the numbers of prefission neutrons observed at the two lowest values of ℓ_{crit} are much larger than can be expected on the basis of standard statistical-model calculations. The reason for this discrepancy is not understood.

---

1. ORNL and LANL; present address: LANL.
2. Washington University, St. Louis, Mo; present address: Fusion Energy Division, ORNL.
3. Washington University, St. Louis, Mo.
4. Vanderbilt Univesity, Nashville, Tenn.
5. Georgia State University, Atlanta.
6. L. Westerberg et al., *Phys. Rev. C* **18**, 774 (1978); K. Geoffroy Young et al., to be published.
7. Y. Boneh, A. Gavron, and S. Wald, *Proceedings of the VII International Workshop on Gross Properties of Nuclei and Nuclear Excitations* (Hirschegg, Austria, January 15-27, 1979); Y. Boneh and A. Gavron, *Proceedings of the International Symposium on Continuum Spectra of Heavy-Ion Reactions* (San Antonio, Texas, December 3-5, 1979).
8. J. Wilczynski, K. Siwek-Wilczynska, J. van Driel, S. Gonggrijp, D. C. J. M. Hagemann, R. V. F. Jansens, J. Kukasiak, and R. H. Siemssen, *Phys. Rev. Lett.* **45**, 606 (1980).
9. Summary of work published in *Phys. Rev. Lett.* **46**, 8 (1981).
10. R. Bass, *Phys. Rev. Lett.* **39**, 265 (1977).
11. C. Lebrun et al., *Z. Phys.* **A299**, 263 (1981).

ALPHA-PARTICLE EMISSION IN DEEPLY INELASTIC REACTIONS OF 204-MeV ^{16}O WITH ^{93}Nb[1]

G. R. Young
R. L. Ferguson
A. Gavron[2]
D. C. Hensley
C. F. Maguire[3]
F. E. Obenshain
G. A. Petitt[4]
F. Plasil
A. H. Snell
M. P. Webb[2]

One of the central questions in the study of deeply inelastic reactions is the mechanism by which the initial kinetic energy is dissipated during the reaction. Several explanations have been explored, including correlated nucleon exchange, excitation of giant collective modes which act as doorway states, and emission of high-energy light fragments in initial stages of the reaction. Experiments measuring projectile-like-fragment (PLF)–alpha-particle coincidences have provided the particularly interesting conclusion that much of the observed alpha-particle emission was nonstatistical[5,6] and might have arisen from a localized region of excitation, or "hot spot,"[6] which implies high energy density and large rates of energy deposition in one nucleus by the other.

We performed measurements of PLF–alpha-particle coincidences for the reaction 204-MeV ^{16}O + ^{93}Nb in order to study the characteristics of the alpha particles emitted and to test the hypothesis of hot-spot formation for this system.[7] The experiments were performed with ΔE-E telescopes having a gas ionization ΔE section to detect heavy ions (HI) of $Z \geqslant 4$ and silicon ΔE-E telescopes to detect light ions of $Z \leqslant 2$. The heavy-ion telescopes were placed at angles of -12 and $-21°$ with respect to the beam axis, while the light-ion telescopes were placed at several in-plane angles (θ) between -90 and $+90°$ and at various out-of-plane angles. The results obtained on energy-energy correlations of coincident alpha particles and PLFs as a function of alpha-particle detection angle, θ_α, were analyzed to yield an energy-integrated alpha-particle multiplicity, $dM_\alpha/d\Omega_\alpha$, and mean values of the three-body kinematic quantities E_{12} and E_{23}. M_α was computed as

$$\frac{dM_\alpha}{d\Omega_\alpha} = \frac{\int dE_{\mathrm{PLF}}\, dE_\alpha\, Y_c}{(\int dE_{\mathrm{PLF}}\, Y_s)\,(\Delta\Omega_d)} ,$$

where Y_c and Y_s are coincident and singles PLF yields and $\Delta\Omega_d$ is the alpha-particle detector's solid angle. E_{ij} is the relative energy of particles i and j in their common center-of-mass system. Here 1, 2, and 3 refer to PLF, alpha particle, and undetected HI respectively. A constant value of E_{12} for all θ_α would imply that emission of alpha particles by the PLF was the dominant source of alpha particles at all angles.

Figure 2.38 shows the results for $dM_\alpha/d\Omega_\alpha$, $\langle E_{12}\rangle$, and $\langle E_{23}\rangle$ as a function of θ_α. No obvious symmetry of $dM_\alpha/d\Omega_\alpha$ about the direction of the detected PLF (arrow) or undetected target-like fragment (TLF) is seen. Monte Carlo calculations were made by assuming statistical emission of alpha particles from the fully accelerated PLF and TLF. These calculations included energy spectra of PLF and alpha particles and mean multiplicities and angular distributions of alpha particles emitted by the PLF and TLF. Ignoring the angular distribution of the PLF yields the dashed line in Fig. 2.38, which clearly does not correspond to observation. Inclusion of the steeply forward-peaked PLF angular distribution, and thus of resultant biasing of the measurements due to recoil effects, yields the solid lines shown in Fig. 2.38. These calculations were seen to reproduce the general features of the results shown and were found to reproduce also the out-of-plane results, the magnitude and shape of $d^2M_\alpha/dE_\alpha\, d\Omega_\alpha$, and the shape of the PLF angular distribution. These results strongly suggest a statistical picture for the observed anisotropic high-energy alpha-particle emission seen in deeply inelastic reactions.

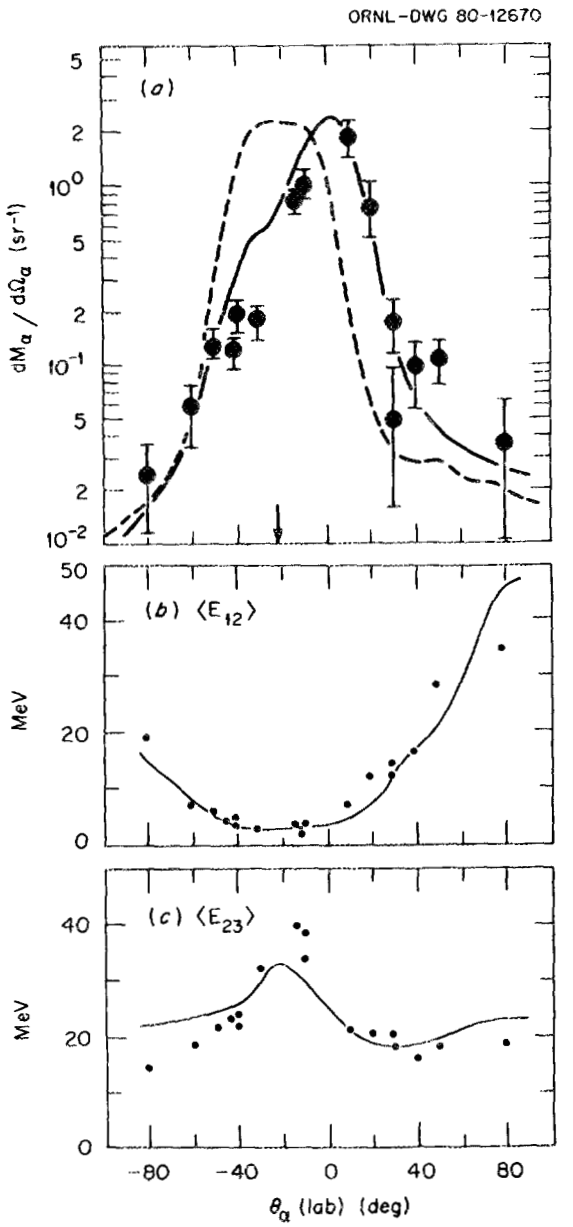


Fig. 2.38. Alpha-particle emission in reaction of 204-MeV ^{16}O with ^{93}Nb. (a) Differential alpha-particle multiplicities, $dM_\alpha/d\Omega_\alpha$, and mean values of *(b)* E_{12} and *(c)* E_{23} for carbon–alpha-particle coincidences at $\theta_{HI} = -21°$. The results of calculations described in the text are given by the dashed line, emission angle of the PLF assumed to be near the HI detector's direction; solid line, measured angular distribution of the PLF taken into account.

1. Summary of paper published in *Phys. Rev. Lett.* **45**, 1389 (1980).
2. Present address: Los Alamos National Laboratory.
3. Vanderbilt University.
4. Georgia State University.
5. C.-K. Gelbke et al., *Phys. Lett.* **71B**, 83 (1977).
6. H. Ho et al., *Z. Phys.* **A283**, 235 (1977).
7. G. R. Young et al., *Phys. Rev. Lett.* **45**, 1389 (1980).

ANALYSIS OF ALPHA EMISSION ASSOCIATED WITH DEEPLY INELASTIC REACTIONS[1]

G. R. Young

In conjunction with our experiments concerning alpha-particle emission from the reaction 204-MeV $^{16}O + ^{93}Nb$, we have made calculations[2] of the expected coincident alpha-particle spectra in deeply inelastic collisions (DIC). These calculations were based on the assumption that all alpha particles were emitted statistically from fully accelerated projectile-like and target-like fragments in the final stage of DIC.

To carry out the calculations, a Monte Carlo computer code was set up and designed to include the following features. The projectile-like fragments (PLFs) and target-like fragments (TLFs) were assumed to share all available mass with Gaussian distributions in mass and charge centered about the projectile and target mass. Two-body kinematics were used to assign a Gaussian excitation energy distribution; the excitation energy was assumed to be shared according to the mass ratio of the PLF and TLF. The initial angular distribution of the PLF was taken from measured values of $d\sigma/d\Omega_{PLF}$. The statistical-model code JULIAN was used to predict multiplicities and energy spectra of neutrons, protons, and alpha particles emitted by the PLF and TLF. These results were input to our Monte Carlo code. Parent-nucleus spin values for the JULIAN calculations were taken from the sticking model. The asymmetry of the light-particle emission relative to the spin vector of the PLF or TLF (which was assumed to be perpendicular to the scattering plane, as expected in a classical orbiting model of deeply inelastic collisions) was taken as $1 + a \sin^2\theta$, that is, an oblate shape. The parameter a was estimated using the JULIAN calculations. A small modification was made to JULIAN to yield angular distribution output in the necessary form to do this.

Calculations were made of the final PLF angular distribution, mass distribution, and energy distribution. The input distributions were then adjusted till the final distributions agreed reasonably well with our measured values. The expected characteristics of the emitted alpha particles were then computed and compared with experiment. The results of this comparison indicated that most of the observed emission was statistical, with a possible small ($\lesssim$20%) discrepancy near 0° (see the preceding report).

We proceeded to make similar calculations for systems investigated earlier by other groups. Calculations of the angular distribution of alpha particles, expressed as a multiplicity $dM_\alpha/d\Omega_\alpha$, were made for the systems 315-MeV $^{16}O + ^{197}Au$[3] and 96-MeV $^{16}O + ^{58}Ni$.[4] Values for PLF primary distributions were determined as described above. Our calculated final distributions were compared with the published PLF final distributions. Since the first system is very asymmetric and the second involves small excitations in its DIC, a model[5] was used to estimate the PLF excitation energy in both cases. The resulting calculated values for $dM_\alpha/d\Omega_\alpha$ are compared with published values in Fig. 2.39 for carbon–alpha-particle coincidences. The results again suggest that much of the observed forward-angle peak in $dM_\alpha/d\Omega_\alpha$ is due to statistical alpha-particle emission.

Calculations have also been made of results on PLF–alpha-particle coincidences for the reactions 65-MeV $^{16}O + ^{27}Al$,[6] 148-MeV $^{14}N + ^{58}Ni$,[7] and 400-MeV $^{40}Ca + ^{40}Ca$.[8] Good agreement between the published experimental results and our calculations was obtained. However, in the case of ^{36}Ar + alpha-particle coincidences measured in ref. 8, it became apparent that the alpha-particle energy spectra calculated with JULIAN are continuous and too broad for this case, in which not many levels with nonzero alpha-particle decay widths are known. Rather, it was imperative to use the excitation energies of known alpha-particle-decaying states in ^{40}Ca to calculate alpha-particle energy spectra that agree with the measured spectra. We are continuing to investigate this effect and also the effect of short-lived ($<10^{-20}$ s) states on the calculated spectra.

1. Part of this summary has been published in *Phys. Rev. Lett.* **45**, 1389 (1980).
2. G. R. Young et al., *Phys. Rev. Lett.* **45**, 1389 (1980).

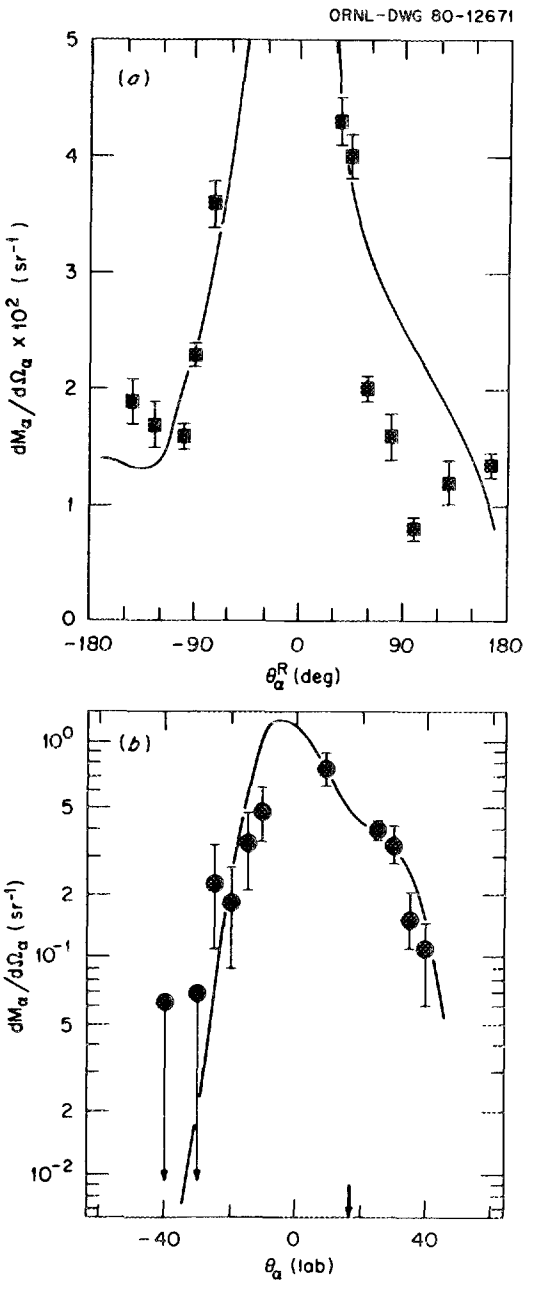


Fig. 2.39. Multiplicities for carbon-alpha-particle coincidences. Solid lines, results of calculations; points, measured values of $dM_\alpha/d\Omega_\alpha$ for (*a*) 92-MeV $^{16}O + {}^{58}Ni$ (ref. 4) and (*b*) 310-MeV $^{16}O + {}^{197}Au$ (ref. 3). The $^{16}O + {}^{58}Ni$ results are given in the rest frame of the recoiling target-like fragment with 0° defined as the beam axis. The $^{16}O + {}^{197}Au$ results are in the laboratory frame. For the latter case, the calculated multiplicity was arbitrarily normalized to the measured cross sections at $\theta_\alpha = 25°$, and a range of three-body Q values from -100 to -60 MeV was used.

3. C.-K. Gelbke et al., *Phys. Lett.* **71B**, 83 (1977).
4. H. Ho et al., *Z. Phys.* **A283**, 235 (1977).
5. L. G. Moretto, Lawrence Berkeley Laboratory report LBL-9130 (unpublished).
6. M. B. Tsang et al., *Phys. Rev. C* **23**, 1560 (1981).
7. R. K. Bhowmik et al., *Phys. Rev. Lett.* **43**, 619 (1979).
8. J. C. Roynette et al., IPN preprint.

AMBIGUITIES IN THE INFERENCE OF PRECOMPOUND EMISSION FROM EXCITATION-FUNCTION ANALYSIS

M. Blann[1] R. L. Ferguson

Many heavy-ion experiments have been performed in which final product yields and/or gamma-ray multiplicities for particular products have been measured. In some cases[2,3] there have been attempts to infer from these measurements the average kinetic energy of deexcitation neutrons emitted and, in turn, to imply evidence for precompound particle emission. We have performed Weisskopf-type statistical-model calculations[4-6] in order to demonstrate that purely statistical decay can yield high average neutron energies under the conditions imposed by analyses such as those referred to above.

Results of our calculations for deexcitation of ^{111}Cd have been published.[7] They show that simply neglecting open evaporation channels other than those studied experimentally can lead to calculated (statistical) energies as large as 60 MeV per neutron at 180 MeV of excitation and, thus, demonstrate that the high energies derived in such analyses imply nothing concerning (nonstatistical) precompound emission. We conclude that inferences concerning nonstatistical behavior of emitted particles should be made with extreme caution when these conclusions are based on measurements of a limited set of the evaporation products of a reaction.

---

1. Lawrence Livermore National Laboratory, Livermore, Calif.

2. D. L. Hillis, O. Christensen, B. Fernandez, A. J. Ferguson, J. D. Garrett, G. B. Hagemann, B. Herskind, B. B. Back, and F. Folkmann, *Phys. Lett.* **B78**, 405 (1978).
3. C. R. Gould, R. Bass, I. V. Czarnecki, V. Hartmann, K. Stelzer, and R. Zitzmann, *Z. Phys.* **A284**, 353 (1978).
4. V. F. Weisskopf, *Phys. Rev.* **53**, 295 (1937).
5. M. Blann, "Overlaid ALICE," report No. COO-3494-32, 1977 (unpublished).

6. F. Plasil, "ORNL ALICE," report No. ORNL/TM-6054, 1977 (unpublished).

7. M. Blann and R. L. Ferguson, *Phys. Rev. C* **19**, 289 (1979).

INCOMPLETE FUSION REACTIONS

J. R. Beene — D. G. Sarantites[2]
M. L. Halbert — K. Geoffroy Young[3]
D. C. Hensley — M. E. Jääskeläinen[2]
J. H. Barker[1] — R. Woodward[2]

It has been known for over 20 years that fast light particles are emitted at forward angles in reactions induced by heavy ions at about 10 MeV per nucleon or higher, but the mechanism producing these particles in fusion-like reactions has only recently become clear. The particles appear to originate from projectile fragmentation at an early stage of the reaction, acting more or less as uninvolved spectators, while the fusion occurs between the remainder of the projectile and the target. This process is known by several names, principally incomplete fusion,[4,5] massive transfer,[6] and breakup fusion.[7] The simple classical picture of ref. 5 seems capable of predicting the main features of the process, particularly the angular momentum dependence. Most of the quantitative information demonstrating the validity of this concept has come from work done in this laboratory in collaboration with the St. Louis group.

The following four papers on incomplete fusion were submitted for publication during the period covered by this report. We give here only a brief statement of the principal results of each one. In all cases the various fusion-like exit channels were identified by coincidences with known gamma transitions characteristic of the corresponding residual nuclei. In all but the last, the angular momenta involved were deduced from measurements of the gamma-ray multiplicity distribution.

Experiment A.[8] The fast forward alpha, ^{8}Be, and ^{12}C particles from fusion-like reactions of ^{153}-MeV ^{16}O with ^{154}Sm were found to be associated with narrow ranges of entrance-channel angular momentum above the critical ℓ value for complete fusion. The ℓ values are highest for the heaviest escaping fragments. The measured range of ℓ values for each particle type is in excellent agreement with the predictions of the model.[5]

Experiment B.[9] In the regime of compound-nucleus evaporation reactions, we have found that the angular momentum deposited in the residual nucleus rises approximately in linear fashion as a function of the energy available for gamma-ray emission. Incomplete fusion was found to limit the deposited angular momentum to about 40 units for ^{12}C- and about 50 units for ^{16}O-induced reactions. With a ^{20}Ne beam, no limit was evident even for deposited angular momenta as high as 60 units. All of these observations are well reproduced by the incomplete-fusion picture of ref. 5. Moreover, for all available heavy-ion fusion data involving emission of fast neutrons and alpha particles,[9–13] the energy at which this process sets in has been successfully correlated with the separation energy of the fast particle from the projectile (plus a Coulomb term for the alpha particles). This suggests again that the fast particles originate from a projectile-like object.

Experiment C.[14] The spectra of neutrons associated with fusion of 153-MeV ^{16}O with ^{154}Sm and 152-MeV ^{12}C with ^{158}Gd (ref. 15) show a nonstatistical high-energy component over a wide range of angles. This component can be well represented by isotropic emission in the rest frame of a hot source ($T \sim 5$ MeV) moving with about half the projectile velocity. This speed is too high for the source to be the fused system or a target-like fragment. These fast neutrons can therefore only originate from a projectile-like object, consistent with the incomplete-fusion picture.

Experiment D.[16] The gamma-ray intensity was measured as a function of spin for the yrast states in noncollective residual nuclei in the reactions ^{146}Nd(^{16}O, αxn)$^{158-x}$Dy in coincidence with (*a*) fast alpha particles at forward angles and (*b*) evaporation alpha particles at a backward angle. The gamma-ray feeding patterns deduced from *b* show that a wide range of entrance-channel ℓ values is populated, as expected for conventional compound-nucleus formation. However, the ℓ values leading to *a* cover only a narrow range (about 9) at high ℓ (about 50). Again, the predictions of the model[5] represent these results very well.

In summary, a considerable body of varied information on fusion accompanied by fast-particle emission has been accumulated and found to paint a unified picture of projectile fragmentation as the source of the fast particles. The methods are largely based on detection of the associated gamma rays. Such data lead directly to characterization of angular-momentum distributions, opening a new dimension in the study of reaction mechanisms that has not heretofore been properly exploited.

1. Oak Ridge Associated Universities Research Participant on sabbatical leave from St. Louis University, St. Louis, Mo., September 1980–February 1981; present address: South Carolina Electric & Gas Company, Columbia.

2. Washington University, St. Louis, Mo.

3. Washington University; present address: Fusion Energy Division, ORNL.

4. T. Inamura, M. Ishihara, T. Fukuda, T. Shimoda, and H. Hiruta, *Phys. Lett.* **68B**, 51 (1977).

5. K. Siwek-Wilczynska, E. H. du Marchie van Voorthuysen, J. van Popta, R. H. Siemssen, and J. Wilczynski, *Phys. Rev. Lett.* **42**, 1599 (1979); *Nucl. Phys.* **A330**, 150 (1979).

6. D. R. Zolnowski, H. Yamada, S. E. Cala, A. C. Kahler, and T. T. Sugihara, *Phys. Rev. Lett.* **41**, 92 (1978).

7. T. Udagawa and T. Tamura, *Phys. Rev. Lett.* **45**, 1311 (1980).

8. K. A. Geoffroy, D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, *Phys. Rev. Lett.* **43**, 1303 (1979).

9. J. R. Beene, M. L. Halbert, D. C. Hensley, R. A. Dayras, K. Geoffroy Young, D. G. Sarantites, and J. H. Barker, *Phys. Rev. C* **23**, 2463 (1981).

10. D. G. Sarantites, J. H. Barker, M. L. Halbert, D. C. Hensley, R. A. Dayras, E. Eichler, N. R. Johnson, and S. A. Gronemeyer, *Phys. Rev. C* **14**, 2138 (1976).

11. D. G. Sarantites, L. Westerberg, R. A. Dayras, M. L. Halbert, D. C. Hensley, and J. H. Barker, *Phys. Rev. C* **17**, 501 (1978).

12. D. G. Sarantites, L. Westerberg, M. L. Halbert, R. A. Dayras, D. C. Hensley, and J. H. Barker, *Phys. Rev. C* **18**, 774 (1978).

13. D. L. Hillis, O. Christensen, B. Fernandez, A. J. Ferguson, J. D. Garrett, G. B. Hagemann, B. Herskind, B. B. Back, and F. Folkmann, *Phys. Lett.* **78B**, 405 (1978).

14. K. Geoffroy Young, D. Sarantites, J. R. Beene, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, *Phys. Rev. C* **23**, 2479 (1981).

15. L. Westerberg, D. G. Sarantites, D. C. Hensley, R. A. Dayras, M. L. Halbert, and J. H. Barker, *Phys. Rev. C* **18**, 796 (1978).

16. J. H. Barker, J. R. Beene, M. L. Halbert, D. C. Hensley, M. E. Jääskeläinen, D. G. Sarantites, and R. Woodward, *Phys. Rev. Lett.* **45**, 424 (1980).

LOCALIZED l WINDOW FROM PARTIAL FUSION REACTIONS ACCOMPANIED BY PROTON, DEUTERON, AND TRITON EMISSION

H. Yamada[1] D. C. Hensley
C. F. Maguire[1] M. L. Halbert
J. H. Hamilton[1] R. L. Robinson
A. V. Ramayya[1] F. E. Bertrand
R. Woodward[2]

Large yields of forward-emitted fast light particles ($Z = 1, 2$) have been observed in heavy-ion-induced nuclear reactions over a wide range of bombarding energy (10–800 MeV/amu) and for various projectiles. It is commonly suggested that the emission occurs at an early stage of the reaction. Especially surprising is the large yield of deuterons (d) and tritons (t),[3] which are generally thought to exist in nuclei only with very low probability. Among the questions raised by these observations are, What is the source of the fast light particles, and what entrance-channel angular momenta contribute to these processes?

We report here the first measurements of gamma-ray multiplicity ($M\gamma$) in coincidence with fast p, d, and t particles detected at ± 20 and $45°$ and with specific transitions from very high spin states ($26\hbar$) in the partial fusion (PF) reaction residual nucleus. By concentrating on the emitted fast p, d, and t, we hoped to avoid contamination of the light-particle spectrum by the evaporation process. The proton spectrum observed[3] in coincidence with specific gamma rays showed a nonevaporation component peaking near 20 MeV which is clearly separated from the evaporation component peaking near 10 MeV. The data shown here provide for the first time direct evidence of a narrow angular-momentum window associated with PF reactions with emitted p, d, or t. Eight small NaI scintillation detectors were used in order to measure the gamma-ray multiplicity.

Average gamma-ray multiplicities were obtained for all the yrast transitions of $^{157-159}$Er observed in the Ge(Li) spectra in coincidence with the light particles. To minimize the evaporation component, the proton energy was required to be above 15 MeV. The values of $M\gamma$ are remarkably constant at about 31 for the three different PF reactions leading to yrast transitions up to $J = 26\hbar$ in ^{158}Er, which is the dominant product (Fig. 2.40). A comparable value of $M\gamma$ is also extracted, although with less precision, for the adjacent odd-mass nuclei ^{157,159}Er. The constancy of the $M\gamma$ with J implies that there is no initial population up to at least spin $26\hbar$.

We deduce the average spin J of ^{158}Er prior to gamma-ray emission to be $54\hbar$ by using the usual relation $J = 2(M\gamma - 4)$. Assuming that each neutron removes $1\hbar$ on the average, we obtain an average transferred spin ℓ_t of $63\hbar$ after partial fusion takes place. The critical angular momentum ℓ_{cr} for the fusion of ^{154}Sm with ^{13}C (the transferred fragment in the pxn reaction) is $57\hbar$, based on the semiempirical formula by Lefort and Ngo.[4] The fact that the value of $\ell_t \approx 63\hbar$ deduced from our experiment is consistent with this value implies that the initial spin population localized near ℓ_{cr} must be

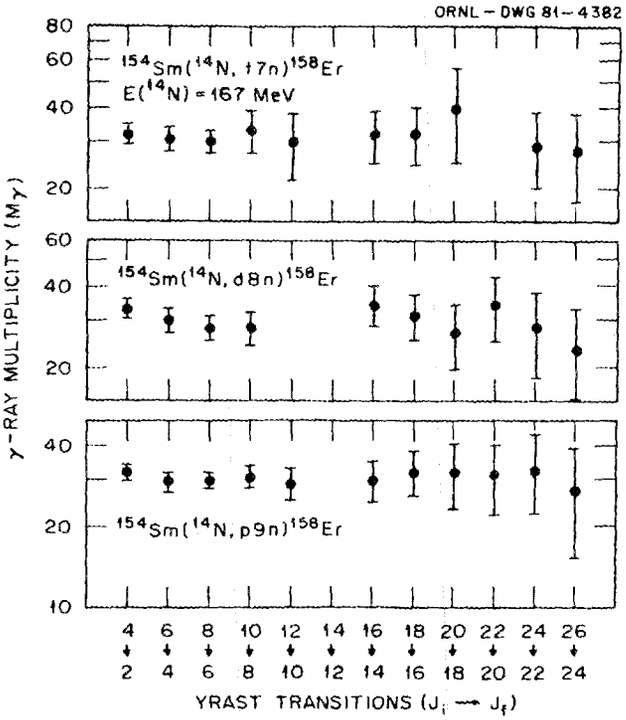


Fig. 2.40. The gamma-ray multiplicities as a function of the yrast transitions in ^{158}Er which are produced by partial fusion reactions accompanied by fast proton, deuteron, and triton emissions.

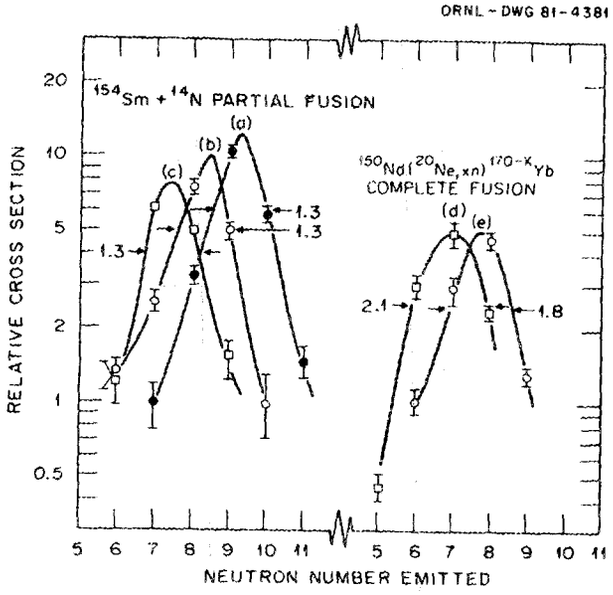


Fig. 2.41. Relative yields of neutron-evaporation residual nuclei following the partial fusion reactions accompanied by proton, deuteron, and triton emissions (*a, b,* and *c* respectively) in comparison with relative yields for complete fusion reactions at 127 and 144 MeV bombarding energies (*d* and *e* from ref. 6). Values of FWHM are indicated.

narrow. Since this result is common to the *p, d,* and *t* channels and also to the three residual isotopes ^{157,158,159}Er, we conclude that only a high and localized range of initial angular momenta participates in these PF reactions. This ℓ window has a lower limit of at least 35$\hbar$ (obtained by adding 9$\hbar$ carried off by the neutrons to the observed limit of 26$\hbar$), a centroid of about 63$\hbar$, and an upper limit of 70$\hbar$ (the fission limit given by the rotating-liquid-drop model).[5]

Additional experimental evidence for the localization is illustrated in Fig. 2.41. Here we plot the relative yields of the PF residual nuclei as a function of the number of emitted neutrons (*a, b, c* in Fig. 2.41). The full width at half maximum (FWHM) of 1.3 deduced for the mass distribution of the PF residues is significantly smaller than the FWHM of about 2.0 observed for the complete fusion reaction of ^{150}Nd(^{20}Ne, *xn*)$^{170-x}$Yb at bombarding energies of 127 and 144 MeV.[6]

The number of emitted neutrons depends on the excitation energy of the fused system. The width of the mass distribution arises in part from the spread of evaporation-neutron energies. The distribution of the initial spin population also causes a spread in the mass distribution, because the thermal excitation energy is counted from the yrast state associated with a particular spin. Since the average excitation energies are about equal for both fused systems, the contributions to the width from neutron evaporation should be the same. Consequently, the difference between the widths is due primarily to the difference in the width of the initial spin populations. The contrast is even more striking if it is realized that there is an additional contribution to the width in the PF residues due to the spread in the light-particle energies.

This signature of the narrow ℓ window in the PF reaction is direct and free from considerations of nuclear structure and gamma-decay processes. This evidence indicates that only high partial waves are involved in the PF reaction, as predicted by the massive transfer[7] (breakup fusion[8]) model.

---

1. Department of Physics and Astronomy, Vanderbilt University, Nashville, Tenn.

2. Department of Chemistry, Washington University, St. Louis, Mo.

3. H. Yamada et al., *Phys. Rev. Lett.* **43**, 605 (1979).
4. M. Lefort and Ch. Ngo, *Ann. Phys.* **3**, 25 (1978); Galin et al., *Phys. Rev. C* **9**, 1018 (1974).
5. S. Cohen, F. Plasil, and W. J. Swiatecki, *Ann. Phys.* **82**, 557 (1974).
6. D. G. Sarantites et al., *Phys. Rev. C* **14**, 3128 (1976).
7. T. Kishimoto and K.-I. Kubo, *Symposium on High Spin Phenomena, Argonne, March 1979*, ANL/PHY-79-4, p. 535.
8. T. Udagawa and T. Tamura, *Phys. Rev. Lett.* **45a**, 1311 (1980).

STUDIES OF THE FISSION ISOMER ^{240m}Am USING LASER TECHNIQUES

C. E. Bemis, Jr. J. P. Young[1]
J. R. Beene S. D. Kramer[2]

The application of the laser-induced nuclear polarization technique, (LINUP) to studies of spontaneous-fission isomerism has been successfully accomplished.[3] A brief description of the prior developmental work and preliminary experiments appeared in the previous issue of this report.[4] The published account[3] of the optical-isomer shift experiments describes our broad-band optical pumping experiments with the fission isomer 0.94-ms ^{240m}Am. Additional broad-band experiments, briefly described below, have been performed with improved experimental techniques and have been analyzed to include the effect of higher-order radial charge moments. Also described below are the recently initiated hyperfine optical pumping experiments designed to provide a direct measure of the nuclear spin for this isomer as well as the nuclear magnetic and spectroscopic quadrupole moments.

Optical-Isomer Shift for ^{240m}Am(SF)

Laser optical pumping of the americium $^8S_{7/2} \rightarrow {}^{10}P_{7/2}$ resonance transition with polarized photons leads to an alignment of the total angular momentum, $\mathbf{F} = \mathbf{I} + \mathbf{J}$, in the atomic ground state. Using circularly polarized photons, σ_+ or σ_-, the ultimate alignment condition corresponds to orienting the system so that the projection M_F of $\mathbf{F}$ on an external quantization axis, the laser beam propagation axis in this case, is a maximum. The optical pumping cycle thus consists of repeated absorptions of circularly polarized photons ($\Delta F = 0, \pm 1$ with $\Delta M_F \equiv {}^+1$ for σ_+) followed by spontaneous radiative decay ($\Delta F = 0, \pm 1$ with $\Delta M_F = 0, \pm 1$). The optical-isomer shift experiments were performed with a laser output line width sufficiently broad (about 30 GHz) to cover the entire hyperfine structure multiplet of the excited $^{10}P_{7/2}$ state. Pressure- and Doppler-broadened absorption profiles for particular hyperfine components are $\lesssim 1$ GHz. With the ultimate alignment condition, $F = F_{max}$ and $M_F = +M_{F\max}$, reached in the optical pumping cycle, subsequent spontaneous-fission decay from the aligned system for $I \geqslant 1$ will be anisotropic, with the preferred fission direction along the laser propagation axis. Anisotropic fission decay is thus a sensitive indicator of the optical resonance condition and was observed from the 0.94 ± 0.04 ms isomer of ^{240m}Am when the laser was tuned to a wavelength of 640.77 ± 0.07 nm (air). This wavelength is 0.26 ± 0.02 nm longer than this same atomic transition in ^{241}Am. This optical-isomer shift result was reported in ref. 3 together with a first-order evaluation of this shift in terms of a difference in nuclear mean square radii, $\delta\langle r^2\rangle$, of 5.1 fm^2 between the fission isomer and the normal ground state. The $\delta\langle r^2\rangle$ result implies a deformation parameter, β_2, of 0.66 ± 0.04 and an intrinsic quadrupole moment, Q_{20}, of 32.7 ± 2.0 b, as previously reported.[3]

Additional broad-band laser optical pumping experiments have since been performed with this isomer with improved laser wavelength stabilization and wavelength scanning, together with higher laser output power and laser power density in the interaction region. These additional experiments, with somewhat better statistical accuracy, corroborate our initial experiment,[3] namely, that the optical-isomer shift, $\Delta\nu_{240m-241}$, is +0.250 ± 0.015 nm. An in-depth analysis of this wavelength shift, which includes higher-order radial charge moments performed with a realistic deformed Fermi charge distribution, has been completed and will be included in a future publication[5] which describes these experiments and results in detail.

Hyperfine Optical Pumping of ^{240m}Am(SF)

We have initiated narrower laser line width experiments, hyperfine optical pumping, to provide a direct measure of the sign and magnitude of the nuclear magnetic moment and in higher order the spectroscopic quadrupole moment. Our Coherent 699-21 actively stabilized single-frequency ring dye laser will be used in these experiments. This laser operates with $\leqslant 1$ MHz laser output line width and thus may optically pump individual members of the hyperfine structure multiplet of the excited $^{10}P_{7/2}$ state in americium. Detailed optical pumping calculations have been performed with the computer program RATES[6] to investigate the time

evolution of the coupled (**I** + **J**) density matrix under the hyperfine pumping conditions for ^{240m}Am. The nuclear density matrix is projected from the coupled matrix and the fission-fragment angular distribution calculated using this nuclear alignment tensor. In hyperfine pumping, the nuclear orientation effects are more complicated and not as large as in the broad-band pumping experiments, where all members of the $^{10}P_{7/2}$ hyperfine multiplet are excited.

The hyperfine pumping effects are illustrated in Fig. 2.42, where the fission-fragment anisotropy, $W(90°)/W(0°)$, with 0° taken as the laser beam propagation direction, is given as a function of laser wavelength. The calculations were performed for nuclear spin $I = 2$ and for nuclear g factor $g_I = +0.56$, which are reasonable choices based on subjective analyses of our broad-band experiments.

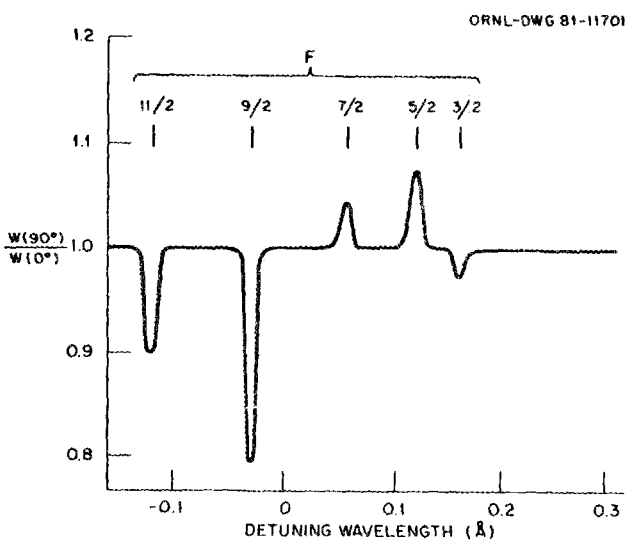


Fig. 2.42. Calculated fission-fragment anisotropy for hyperfine pumping of the $^8S_{7/2} \rightarrow {}^{10}P_{7/2}$ transition in ^{240m}Am. The calculations assume $I = 2$, $g_I = +0.56$ and correspond to the anisotropy expected at 2 ms for a laser power density of 3.5 W/cm^2.

The calculations include a broadened (Doppler plus collisional) hyperfine absorption profile of about 1 GHz and include relaxation effects in both excited $^{10}P_{7/2}$ and ground $^8S_{7/2}$ states. The requisite laser techniques to complete these hyperfine pumping experiments are being developed.

1. Analytical Chemistry Division.
2. Health and Safety Research Division.

3. C. E. Bemis, Jr., J. R. Beene, J. P. Young, and S. D. Kramer, *Phys. Rev. Lett.* 43, 1854 (1979).
4. C. E. Bemis, Jr., J. R. Beene, S. D. Kramer, J. P. Young, and G. S. Hurst, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498, p. 43 (June 1979).
5. C. E. Bemis, Jr., J. R. Beene, J. P. Young, and S. D. Kramer, to be published.
6. J. R. Beene, "RATES: A System of Computer Programs to Perform Optical Pumping Calculations," 1980 (unpublished).

LASER-INDUCED NUCLEAR POLARIZATION OF ISOMERIC STATES OF Fr ISOTOPES

J. R. Beene C. E. Bemis, Jr. J. P. Young[1]

There are other nuclear shape effects that, while less dramatic than the shape isomerism in the actinides, are nevertheless very important. Over the last two years, nuclear theorists have emphasized the importance of small oblate deformation in stabilizing aligned many-particle configurations in the high-spin yrast states of near-spherical nuclei.[2] The high-spin isomers or "yrast traps" that occur in these nuclei are expected to have oblate deformation, and this deformation is expected to increase with increasing spin. We plan to apply the LINUP method to a systematic study of shapes (via isomer shifts and quadrupole moments) as a function of spin for high-spin isomers in selected atomic species near ^{208}Pb and ^{146}Gd; these two regions are especially favorable for these effects.

The initial experiments will be done with francium nuclides. The first optical resonance line (D_2) in Fr has recently been located.[3] and its wavelength measured to be 718 nm. Some straightforward development of laser techniques will be required to do effective optical pumping at this wavelength. Preliminary experiments, including measurements of cross section and recoil range in He from the reaction ^{205}Tl(^{12}C,3n)^{214}Fr at a 67-MeV bombarding energy, have been completed on a pair of millisecond alpha-decaying isomers ($I^\pi = 1^-, 9^-$) in ^{214}Fr. The ease of detecting heavy charged particles, the large alpha-decay anisotropies expected, and the relatively long nuclear half-lives make these isomers an ideal case for use in perfecting the techniques. Subsequent experiments will be performed on higher-spin gamma-decaying isomers in neighboring isotopes. Francium isotopes are especially good cases because of the large number of known high-spin isomers and because the Fr atom, being an alkali has a very large resonant photon absorption

cross section, which allows us to work with nuclear states as short-lived as tens of nanoseconds.

1. Analytical Chemistry Division.
2. K. Matsuyanagi et al., *Nucl. Phys.* **A307**, 253 (1978).
3. L. Liberman et al., *Phys. Rev. A* **22**, 2732 (1980).

SPONTANEOUS-FISSION BRANCHING IN THE DECAY OF ^{259}104[1]

C. E. Bemis, Jr. D. C. Hensley
P. F. Dittner F. Plasil
R. L. Ferguson F. Pleasonton

The alpha decay of ^{259}104 was studied by Ghiorso et al.[2] by means of the ^{249}Cf(^{13}C,3n) and ^{248}Cm(^{16}O,5n) reactions. Two alpha groups have been attributed to the decay of ^{259}104. The reported energies are 8.77 MeV (60%) and 8.86 MeV (40%). The half-life was found to be about 3 s, and decay by spontaneous fission was found not to be prominent. Indirect determinations of the fission branching ratio of ^{259}104 were reported by Dubna workers to be in the range of 0.06–0.12.[3]

In the present study, ^{259}104 was produced in the ^{249}Cf(^{13}C,3n) reaction. The average beam energy at the center of the Cf_2O_3 target was 71.5 MeV. Alpha-decay and spontaneous-fission events were measured during time intervals of 0.2–5.0 s following 5-s bombardments. A combination of helium jet and mechanical wheel was used to transport the products to the semiconductor detectors. Two alpha groups at energies of 8.87 ± 0.02 MeV (about 40%) and 8.77 ± 0.02 MeV (about 60%) were ascribed to the decay of ^{259}104. A total of 69 events constituted these alpha peaks, and the half-life derived from them was 3.0 ± 1.3 s. These results are in agreement with those of ref. 2.

A total of 22 single fission-fragment events were also observed. Large corrections had to be made for the presence of two interfering spontaneous-fission activities; 8 ± 2 fission events were attributed to the long-lived spontaneous-fission activity from ^{256}Md and ^{256}Fm, and 4.8 ± 1.2 fission events were attributed to the decay of ^{256}No. The number of fission events ascribed to ^{259}104 was, thus, 9.2 ± 5.2. This result corresponds to a fission branching ratio of 0.063 ± 0.037, which is in agreement with the indirectly determined results of ref. 3. From the data it was also deduced that the cross section for the production of ^{259}104 in the ^{13}C + ^{249}Cf reaction at 71.5 MeV is about 6×10^{-33} cm^2 and that the cross section for the production of ^{256}No is about 8.3×10^{-32} cm^2.

1. C. E. Bemis, Jr., et al., *Phys. Rev. C* **23**, 555 (1981).
2. A. Ghiorso et al., *Phys. Rev. Lett.* **22**, 1317 (1969); A. Ghiorso in *Proceedings of the R. A. Welch Foundation Conference on Chemical Research XIII, Houston, 1970*, p. 107.
3. G. N. Flerov et al, *Proceedings of the International Conference on Heavy Ion Physics, Dubna, 1971*, Dubna report No. JINR-D7-5769, p. 125 (ORNL-tr-2711); V. A. Druin et al., *At. Energ.* **35**, 259 (1973) [*Sov. At. Energy* **35**, 964 (1974)].

PRODUCTION OF HEAVY ACTINIDES AND ATTEMPTED PRODUCTION OF SUPERHEAVY ELEMENTS IN THE ^{238}U + ^{248}Cm REACTION

R. L. Ferguson M. Schädel[4]
R. L. Hahn[1] K. Sümmerer[4]
E. K. Hulet[2] G. Wirth[4]
R. W. Lougheed[2] G. Herrmann[5]
J. M. Nitschke[3] P. Peuser[5]
W. Brüchle[4] R. Stakemann[5]
H. Gäggeler[4] G. Tittel[5]
J. V. Kratz[4] N. Trautmann[5]

Strongly damped collisions between very heavy ions might be expected to lead to the formation of such highly fissionable products as heavy actinides or superheavy elements if such products could be formed with low excitation energy and angular momentum. In collisions between 6.1–7.5 MeV/u ^{238}U ions and ^{238}U target nuclei, formation of heavy actinides was, in fact, shown[6] to be associated with low-energy tails of the broad excitation energy distributions from the reaction. This reaction was also used[7] in a search for spontaneously fissioning superheavy elements. Upper limits found for superheavy-element formation cross sections were 10^{-32} to 10^{-35} cm^2, depending on the assumed half-life. Substantial enhancements have been predicted[8] for yields of heavy actinides from reactions between ^{238}U ions and target nuclei heavier than ^{238}U. Consequently, we have investigated heavy-actinide production and have searched for superheavy elements with the ^{238}U + ^{248}Cm reaction.

At the UNILAC a metallic ^{248}Cm target, 7 mg·cm^{-2} thick, was bombarded with 7.4-MeV/u^{238}U ions to a fluence of 3×10^{15} particles. Recoiling reaction products were stopped in a copper catcher. Radiochemical procedures were used to separate the products into fractions containing the actinides and any superheavy elements that

follow the chemistry expected for elements 108–117. Alpha and spontaneous-fission decays (and, for the superheavy-element fractions, coincident neutron multiplicities) were observed for several months. These activities were used in the calculation of formation cross sections.

The cross sections for transuranium isotopes from the $^{238}U + ^{248}Cm$ reaction are shown in Fig. 2.43. Cross sections for the $^{238}U + ^{238}U$ reaction[6] are shown for comparison. The observed increases of three to four orders of magnitude from $^{238}U + ^{238}U$ to $^{238}U + ^{248}Cm$ are even larger than those predicted theoretically.[8]

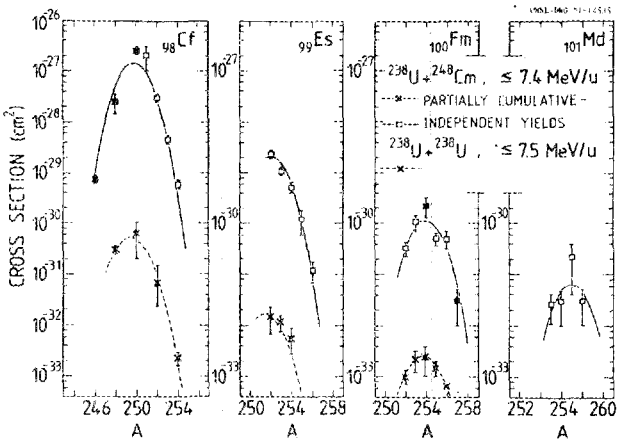


Fig. 2.43. Cross section for the formation of transuranium isotopes in the $^{238}U + ^{248}Cm$ reaction at 7.4 MeV/u incident energy. For comparison, data for the $^{238}U + ^{238}U$ reaction from ref. 6 are given. Gaussian distributions with $\sigma = 1.2$ u for $^{238}U + ^{248}Cm$ and $\sigma + 1.3$ u for $^{238}U + ^{238}U$ are drawn to indicate position and width of the isotope distributions.

After a counting period of 440 days, no events detected with the fission-fragment–neutron-multiplicity counter could be attributed to superheavy-element decay. Samples counted in this detector corresponded to any superheavy elements that are volatile between room temperature and 1020 °C or that form strong bromide complexes in solution. Elements that are volatile below room temperature were condensed on a cryostat and counted with a single surface-barrier detector. Two events, with energies of 61 and 40 MeV, have been detected with this counter but cannot be associated unambiguously with superheavy-element decay. However, these two events were used to calculate the cross sections plotted vs assumed half-life in Fig. 2.44. This figure is to be regarded as representing upper limits for superheavy-element formation cross sections.

It should be noted that our sensitivity to superheavy-element production in the $^{238}U + ^{248}Cm$ experiment was less than was expected because target failures limited the total fluence to an order of magnitude less than that obtained in the $^{238}U + ^{238}U$ experiment.[7] If these target limitations could

ORNL-DWG 81-12536

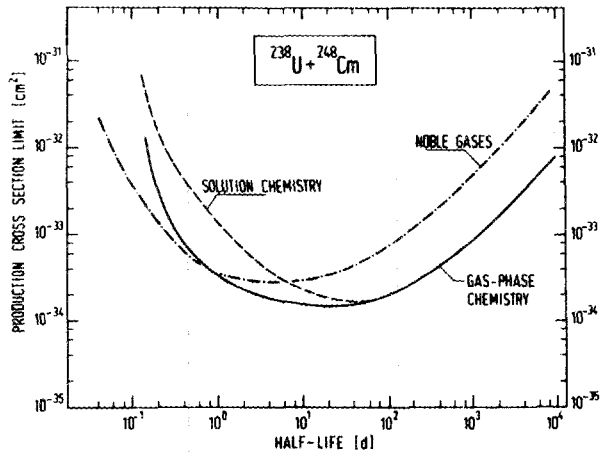


Fig. 2.44. Upper limits for the production cross section of spontaneously fissioning superheavy elements in the $^{238}U + ^{248}Cm$ reaction. The three curves refer to samples obtained from different separation procedures.

be overcome, it would be possible to test the deep-inelastic transfer reaction for production of superheavy elements down to the detection limit of about 10^{-35} cm².

1. Chemistry Division.
2. Lawrence Livermore National Laboratory, Livermore, Calif.
3. Lawrence Berkeley Laboratory, Berkeley, Calif.
4. Gesellschaft für Schwerionenforschung, Darmstadt, FRG.
5. Universität Mainz, Mainz, FRG.
6. G. Schädel, J. V. Kratz, H. Ahrens, W. Brüchle, G. Franz, H. Gäggeler, I. Warnecke, G. Wirth, G. Herrmann, N. Trautmann, and M. Weis, *Phys. Rev. Lett.* **41**, 469 (1978).
7. H. Gäggeler, N. Trautmann, W. Brüchle, G. Herrmann, J. V. Kratz, P. Peuser, M. Schädel, G. Tittel, G. Wirth, H. Ahrens, H. Folger, G. Franz, K. Sümmerer, and M. Zendel, *Phys. Rev. Lett.* **45**, 1824 (1980).
8. C. Riedel and W. Nörenberg, *Z. Phys.* **A290**, 385 (1979).

HIGH—SPIN STATES IN Z = 32 TO 36 NUCLEI

R. L. Robinson
J. H. Hamilton[1]
A. V. Ramayya[1]
A. Y. Ahmed[1]
A. J. Caffrey[2]
A. P. de Lima[1]
E. de Lima[1]
H. Kawakami[1]
H. J. Kim
C. F. Maguire[1]
W. T. Milner
R. B. Piercey[1]
S. Ramavataram[1]
A. C. Rester[3]
R. M. Ronningen[1]
D. L. Sastry[1]
R. O. Sayer[4]
R. Soundranayagam[1]
Z. J. Sun[1]
B. Van Nooijen[1]
J. C. Wells, Jr.[5]
H. Yamada[1]
Z. Z. Zhao[1]

An extensive systematic survey of high-spin states in Z = 32 to 36 nuclei, with particular emphasis on even-even nuclei, has revealed a richness of bands that provides information on multiple independent and highly collective bands. Information is also obtained on single-particle structure and the interplay of this structure with the collectivity of the nucleus.

This multiyear program has been carried out thus far with beams from the ORNL EN tandem. There is now an approved proposal to continue this work with the 25-MV tandem at the HHIRF. With the more exotic projectiles and higher energies it should be possible to study more neutron-deficient nuclei and to study states of higher spins.

The large amount of accelerator time available at the EN tandem made it possible to obtain sufficient statistics to investigate many weaker side bands. Because the beam energies were near the Coulomb barrier, few exit channels resulted from the fused target and projectile, and thus the gamma rays from the nucleus of interest were not usually contaminated with reaction products. To further reduce the confusion which results when gamma rays different reactions are unresolved, different projectile-target combinations were sometimes used to make the same residual nuclei. For the beam energies available from the EN tandem (e.g., 45-MeV ^{16}O), states with spins up to 12 were populated.

The level properties were determined through study of the in-beam gamma rays by a variety of the standard gamma-ray techniques. Level energies and gamma-ray decay paths were extracted from high-resolution singles and gamma-gamma coincident spectra. Spins were based primarily on angular distribution studies, although dependence of gamma-ray yields on beam energy was sometimes employed as a weak argument. Ambiguity in spin assignments was frequently resolved by $\gamma\gamma(\theta)$ or linear polarization measurements. The latter was also used to establish the relative parity of states. Lifetimes were deduced from Doppler shift attenuation measurements.

Although this program has concentrated on even-even nuclei, enough studies have been made of the odd-A and odd-odd nuclei to demonstrate that these too will be fruitful to pursue more thoroughly. Some results for these three classes of nuclei follow.

Even-Even Nuclei

A typical example of the level scheme obtained from an even-even nucleus is given in Fig. 2.45. Moment-of-inertia plots of the yrast levels show a variety of shapes, some backbending strongly, some showing forward bending, and some increasing linearly, as can be explained by a variable moment of inertia (VMI) picture.[6] The $B(E2)$'s of transitions between the yrast members are enhanced over the single-particle estimate, but the degree of enhancement varies strongly. For example, the average $B(E2)$ of the four transitions between the 8^+ and 0^+ levels in ^{68}Ge is 13 spu, whereas for the corresponding transitions in ^{76}Kr it is 96 spu. The variation of $B(E2)$'s with spin shows no singular pattern, as demonstrated by the four examples in Fig. 2.46.

Both the variety of dependences of $B(E2)$'s with spins of the yrast levels and the variety of moment-of-inertia plots suggest that the yrast levels, even at very low spin in some nuclei, are not due to a single collective motion associated with the ground-state band (gsb). In some nuclei there is strong evidence for crossing of the gsb with a band built on an 8^+ level which is attributed to the rotational alignment (RAL) of two $g_{9/2}$ quasi particles. In the case of ^{68}Ge there are two 8^+ bands, which are presumably from RAL of two $g_{9/2}$ protons and two $g_{9/2}$ neutrons. In other nuclei the band crossing is not as evident, but the energy of the higher states is shifted by mixing of states of like spins in the gsb and the 8^+ band. This could explain, for example, the break in the moment of inertia, as observed for ^{78}Kr (Fig. 2.47). The fact that the crossing of the 8^+ band with gsb is seen in some nuclei but not in others can be explained by the differences in energies of the two 8^+ states, one depending on the single-particle excitation plus alignment energies and the other related to the collective nature of the nucleus.

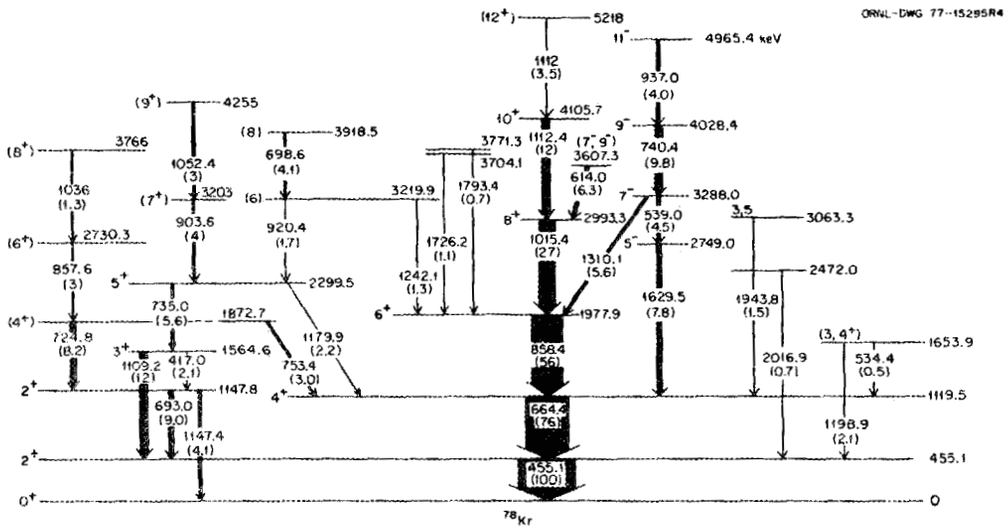


Fig. 2.45. Levels of ^{78}Kr.

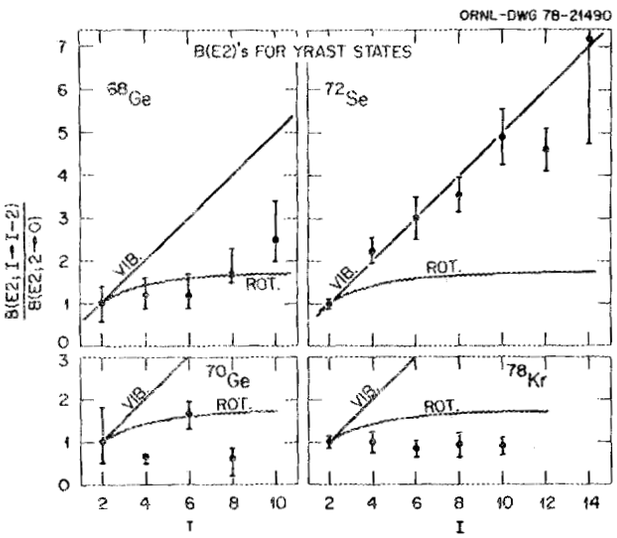


Fig. 2.46. $B(E2)$'s of transitions of the yrast band relative to $B(E2;2 \rightarrow 0)$. Predictions for the vibrational and rotational modes are normalized to the experimental $B(E2;2 \rightarrow 0)$.

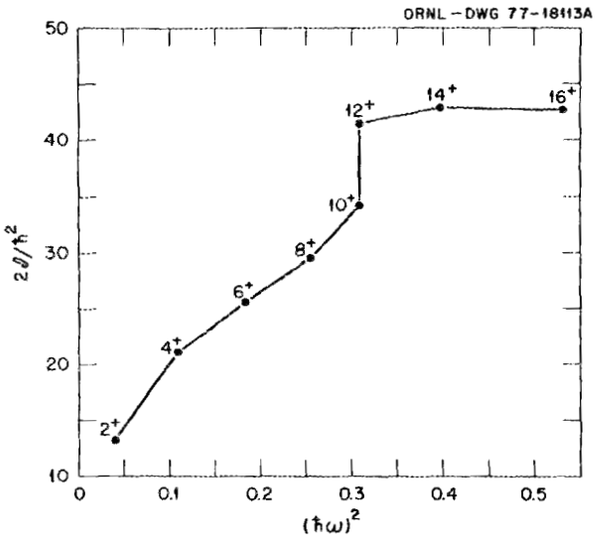


Fig. 2.47. Moment-of-inertia plot for the yrast levels in ^{78}Kr.

Another disturbance of the gsb is attributed to coexistence of the nucleus in two shapes, one shape in the ground state and the other associated with a low-lying 0^+ state which reaches a minimum in energy around $N = 40$ (Fig. 2.48). The properties of the low-lying states in ^{72,74}Se have been explained by band mixing of a near-spherical band built on the 0^+ ground state and a deformed band built on the 0_2^+ state. In ^{74,76}Kr, the energy-level spacings indicate that just the opposite is true, that is, the ground state is deformed and the 0_2^+ state is near spherical.

Odd-parity bands are observed with level spacing patterns similar to that for the gsb, as shown by the example in Fig. 2.49. They are attributed to RAL of a $g_{9/2}$ particle and an odd-parity particle in either a $p_{1/2}$, $p_{3/2}$, or $f_{5/2}$ orbital. In ^{68}Ge, for one of its three odd-parity bands, the 7^- to 5^- energy was compressed, suggesting that the two participating

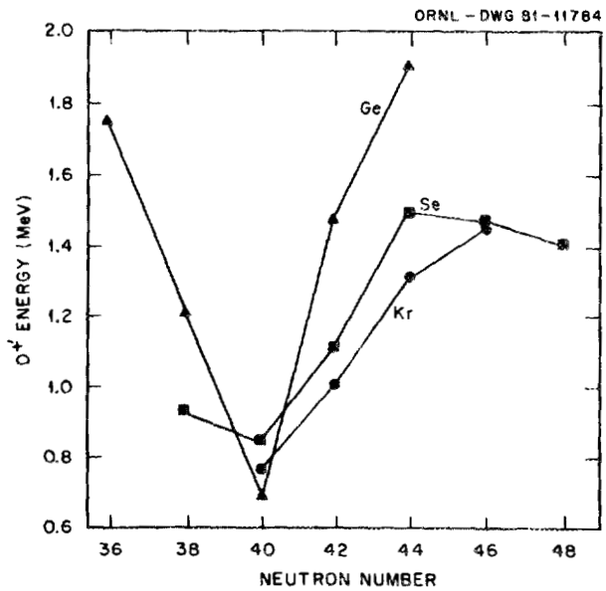


Fig. 2.48. Energies of first excited 0^+ states.

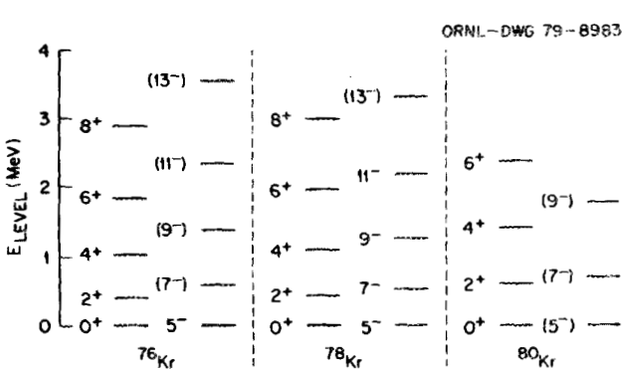


Fig. 2.49. Comparison of the gsb and 5^- band levels in ^{76,78,80}Kr. The energy of the 5^- band head is adjusted to zero.

quasi particles were not fully aligned in the 5^- state. There is no definitive evidence in any nucleus of a band built on a 3^- octupole state.

A limited number of $B(E2)$'s for transitions between members of the odd-parity bands have been obtained. These appear to be larger than that of the corresponding ground-state member, as shown in Table 2.7.

It has been demonstrated that the five bands in ^{68}Ge built on 8^+, 8^+, 5^-, 6^-, and 7^- can all be explained by a two-quasi-particle-plus-rotor model.[7]

An even-parity $\Delta I = 1$ band with spins up to 9^+ has been identified in seven of the nuclei in this mass region. The members decay principally by $\Delta I = 2$ transitions to lower members of the band with large $B(E2)$'s that are comparable to those of transitions within the ground-state band. The weakness of the transitions between levels of the two bands indicates that there is little mixing of the two bands. For example, in ^{76}Kr the $5^+ \rightarrow 3^+$ transition within the $\Delta I = 1$ band has a $B(E2)$ of 101 spu, whereas the transition from this 5^+ level to the 4^+ gsb member has a $B(E2)$ of 3 ± 1 spu. The $\Delta I = 1$ band can very well be characterized as a γ-vibrational band in a deformed nucleus.

Odd-A Nuclei

As an example, we show in Fig. 2.50 the levels obtained for ^{65}Ga. Both collective and single-particle degrees of freedom can be observed. The levels can be divided into four bands, each of which has level spacing suggestive of that of the neighboring even-mass nuclei. Three of the bands may be attributed to coupling of a quasi particle in the $p_{3/2}$, $f_{5/2}$, and $g_{9/2}$ orbitals to core states. However, the energies for states corresponding to the $4^+ \rightarrow 2^+$ core

Table 2.7. $B(E2)/B(E2)_{sp}$ values

Nucleus	Odd-π band		Ground-state band	
	Spin	$B(E2)/B(E2)_{sp}$	Spin	$B(E2)/B(E2)_{sp}$
^{74}Se	$11^- \rightarrow 9^-$	78^{+11}_{-8}	$6 \rightarrow 4$	38 ± 5
	$9^- \rightarrow 7^-$	116^{+46}_{-26}	$4 \rightarrow 2$	81 ± 3
	$7^- \rightarrow 5^-$	64^{+43}_{-18}	$2 \rightarrow 0$	40 ± 2
^{76}Kr	$11^- \rightarrow 9^-$	264^{+242}_{-74}	$6 \rightarrow 4$	89 ± 8
	$9^- \rightarrow 7^-$	281^{+77}_{-50}	$4 \rightarrow 2$	77^{+23}_{-14}
	$7^- \rightarrow 5^-$		$2 \rightarrow 0$	59 ± 7
^{78}Kr	$11^- \rightarrow 9^-$	81 ± 11	$6 \rightarrow 4$	49 ± 11
	$9^- \rightarrow 7^-$	90 ± 30	$4 \rightarrow 2$	59 ± 14
	$7^- \rightarrow 5^-$	130^{+200}_{-80}	$2 \rightarrow 0$	58 ± 7

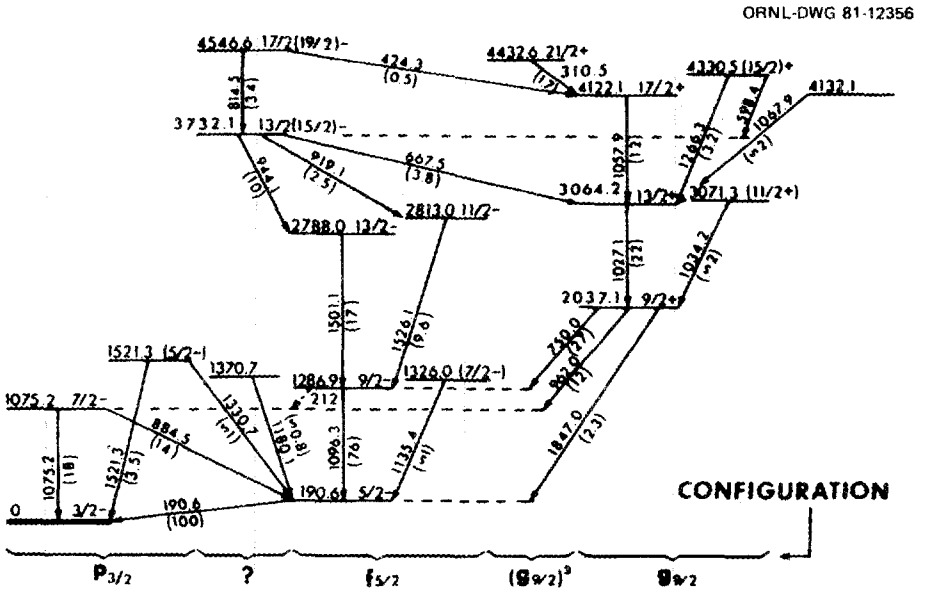


Fig. 2.50. Levels of ^{65}Ga.

state are in poor agreement, indicating that the weak-coupling model may be breaking down as the spin is increased. An alternate explanation is that ^{65}Ga has a triaxial shape. Possibly the $21/2^+$ state is associated with the coupling of three $g_{9/2}$ quasi particles to the core.

Odd-Odd Nuclei

The only cases studied thus far are ^{72,74,76}Br. Figure 2.51 shows the results for ^{76}Br. The most probable value for J_0 is 4. Level spacing indicates (1) perturbation due to the Coriolis interaction, which produces a staggering effect of alternate levels, and (2) the possibility of a band crossing at $J_0 + 4$, the lower-spin levels being members of an RAL band with strong Coriolis decoupling of the odd proton and odd neutron and the higher-spin states being members of a strong-coupled rotational band with less Coriolis decoupling.

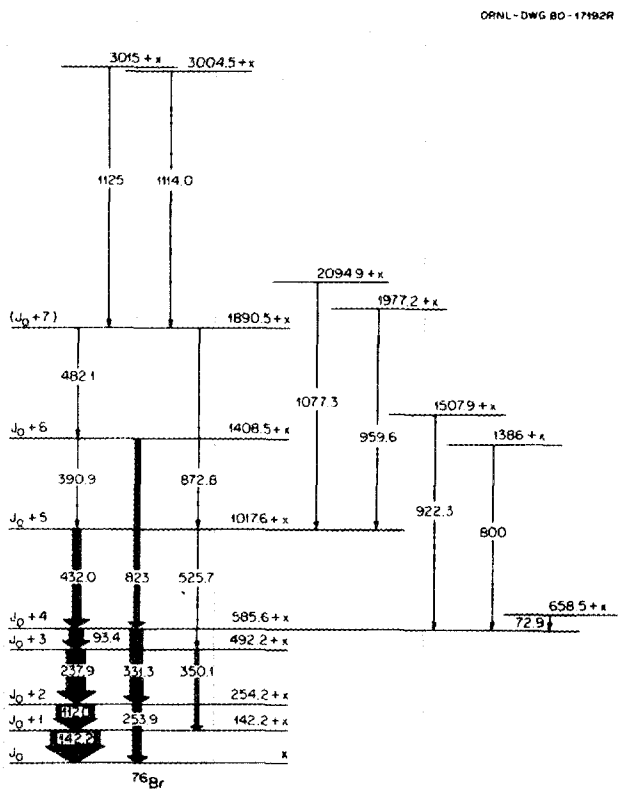


Fig. 2.51. Levels of ^{76}Br.

1. Vanderbilt University, Nashville, Tenn.
2. Johns Hopkins University, Baltimore, Md.
3. Physics Department, University of Florida, Gainesville.
4. UCC-ND Computer Sciences Division.
5. Tennessee Technological University, Cookeville.
6. M. A. Mariscotti, G. Scharff-Goldhaber, and B. Buck, *Phys. Rev.* **178**, 1864 (1969).
7. C. Flaum and D. Cline, *Phys. Rev. C* **14**, 1224 (1976).

ISOMERIC AND HIGH-SPIN STATES OF ^{94}Tc AND THE SEARCH FOR YRAST ISOMERS NEAR N = 50

I. Y. Lee G. R. Young
N. R. Johnson M. W. Guidry[1]
F. K. McGowan S. W. Yates[2]

The discovery of high-spin isomers in nuclei near N = 82 (ref. 3) and in the lead region[4] has prompted intense study of this phenomenon. The nature of the yrast isomers in the Pb region is understood in terms of particle-hole excitation in occupied spherical shell-model orbitals. The attractive proton-neutron interaction for highly aligned high-j orbitals lowers the energies of these states and produces the isomerism.[5] Detailed spectroscopic studies, such as those[6-9] of ^{152}Dy, have led to the conclusion that the light rare-earth isomers also result from the alignment of individual particle spins and have little collectivity.

In a search for high-spin isomers in the $N \sim 50$ region, we have bombarded isotopically enriched ^{76}Ge and ^{78}Se targets with 81-MeV ^{20}Ne beams and ^{89}Y and ^{93}Nb targets with 52- to 63-MeV ^{10}B beams from Oak Ridge Isochronous Cyclotron. The compound nuclei ^{96}Mo, ^{98}Ru, ^{99}Ru, and ^{103}Pd were thus produced. Two large-volume Ge(Li) detectors were used to measure the prompt and delayed gamma rays, by using the cyclotron rf for timing. Five-parameter (γ_1, γ_2, γ-γ TAC, γ_1-rf TAC, and γ_2-rf TAC) coincidence data were recorded to identify isomeric states and to examine prompt gamma-gamma and delayed gamma-gamma coincidences. While a number of known isomers[10] with $t_{1/2} > 2$ ns were identified in isotopes of Ru, Tc, Mo, and Nb, no new high-multiplicity isomers were observed.

In the ^{20}Ne + ^{78}Se reaction, however, we observed a short-lived ($t_{1/2}$ = 4.5 ± 0.6 ns) isomer which had not been assigned previously. This isomer decays by the emission of three gamma rays with energies of 282.9, 690.6, and 1373.4 keV and is presumably not of very high spin. Lederer et al.[11] observed these gamma rays from an isomer with $t_{1/2} \sim 3$ ns produced by the bombardment of ^{92}Mo with 30-MeV alpha particles. They also determined that this isomer must reside in either ^{93}Ru or ^{94}Tc. Häusser et al.[12] recently observed a 2.05-μs isomer in ^{93}Ru but did not report any others.

To confirm the identification of the 4.5-ns activity, we replaced one of the Ge(Li) detectors with a small (1.4-cm^3) intrinsic planar Ge detector (LEPS) to perform an x-ray–gamma-ray coincidence experiment. The gamma rays from this isomer were observed in coincidence with the Tc x rays, thus confirming the assignment of the isomer to ^{94}Tc. The ordering of levels (shown in Fig. 2.52) which deexcite the isomer was made on the basis of the gamma-ray intensities of the prompt and delayed gamma-ray spectra (see Fig. 2.53). While the 1373-keV gamma ray is obviously the lowest-lying in the decay scheme, the 283- and 691-keV transitions have similar intensities and could occur in either order.

With the assumption that the 1373-keV gamma ray represents a transition to the ground state of ^{94}Tc, our prompt gamma-gamma coincidence spectra (see Figs. 2.53 and 2.54) allowed us to construct an yrast sequence of transitions in coincidence with this gamma ray which extends beyond 5 MeV in excitation energy. Again, the level orderings are am-

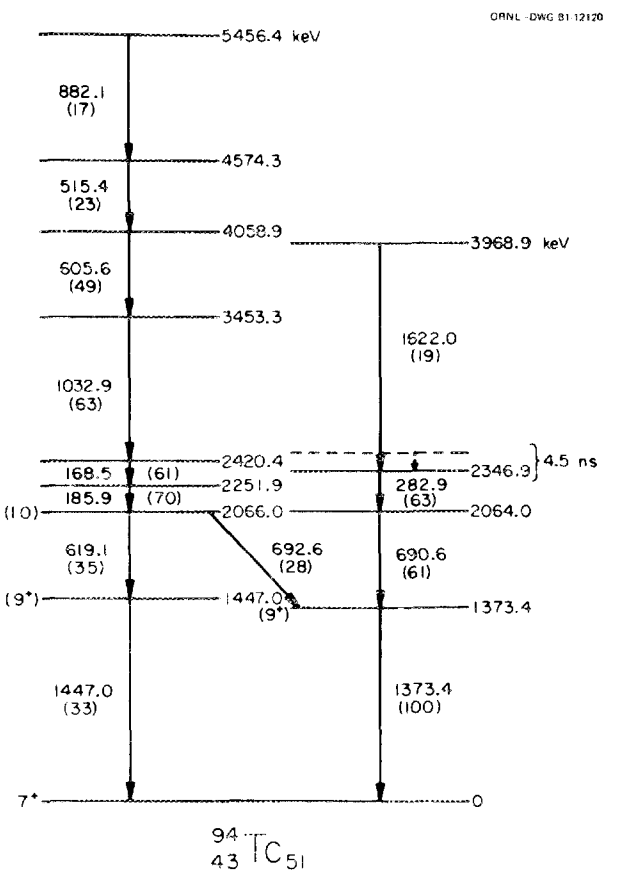


Fig. 2.52. Level scheme of ^{94}Tc showing states populated by the ^{78}Se(^{20}Ne,3$np\gamma$)^{94}Tc reaction. The level and gamma-ray energies are in keV. Prompt gamma-ray intensities, corrected for the angular distribution effect, are shown in parentheses.

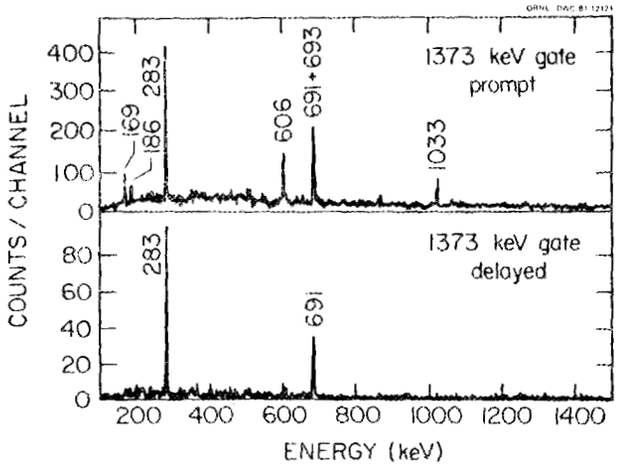


Fig. 2.53. Prompt and delayed (with respect to the beam pulse) gamma-gamma coincidence spectra from the 1373.4-keV gating transition.

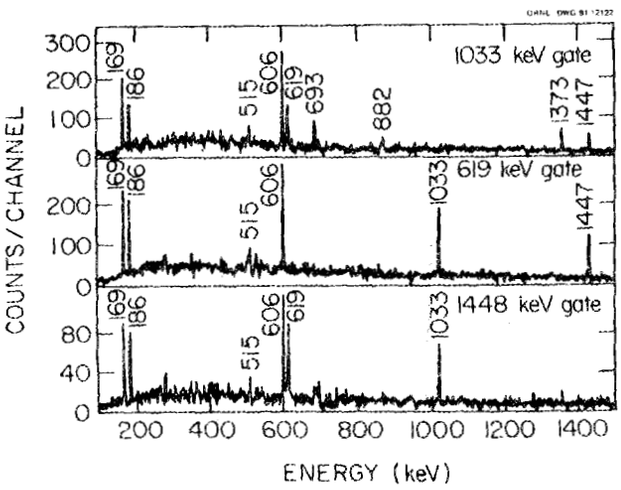


Fig. 2.54. Prompt gamma-gamma coincidence spectra from the 619.1-, 1032.9-, and 1447.0-keV gating transitions.

biguous in some cases, since intensities are the only basis for placement. The observation of all the gamma rays from the ^{94}Tc isomer in prompt coincidence wtih the 1622-keV gamma ray is not unreasonable considering the resolving time ($2\tau \sim$ 8 ns) of our coincidence system, but it could also suggest that the isomer decays be an unobserved isomeric transition, as indicated by the dashed level in Fig. 2.52. In our low-energy spectra we see a 49-keV gamma ray which decays with a ~5-ns half-life, but none of the ^{94}Tc gamma rays are observed in coincidence with this gamma ray. We must therefore conclude that the question of an unobserved isomeric transition remains unresolved.

The anisotropies of the gamma rays of ^{94}Tc were determined from prompt gamma-ray intensities measured at 0 and 90° relative to the beam direction. Only the 168-, 185-, 619-, and 1622-keV transitions showed dipole character. Spectral complications in the 690-keV region did not allow us to obtain a good measurement for the 691- to 693-keV doublet. Because of ambiguities in level ordering and the limited angular distribution data, we have avoided unwarranted speculation on spin and parity assignments. The $7^+[\pi(1g_{9/2})^1\nu(2d_{5/2})^1]$ ground state of ^{94}Tc could imply a spin of 13 (or 15, if an unobserved isomeric transition were present) for the isomer. In analogy to other nuclei in this region, this isomer is probably of single-particle origin.

1. University of Tennessee, Knoxville.
2. University of Kentucky, Lexington.
3. J. Pedersen, B. B. Back, F. M. Bernthal, S. Bjørnholm, J. Borggreen, O. Christensen, F. Folkmann, B. Herskind, T. L. Khoo, M. Neiman, F. Puhlhofer, and G. Sletten, *Phys. Rev. Lett.* **39**, 990 (1977).
4. D. Horn, O. Häusser, T. Faestermann, A. B. McDonald, T. K. Alexander, J. R. Beene, and C. J. Herrlander, *Phys. Rev. Lett.* **39**, 389 (1977).
5. A. Faessler, M. Plosajczak, and K. R. S. Devi, *Phys. Rev. Lett.* **36**, 1028 (1976).
6. T. L. Khoo, R. K. Smither, B. Haas, O. Häusser, H. R. Andrews, D. Horn, and D. Ward, *Phys. Rev. Lett.* **41**, 1027 (1978).
7. J. C. Merdinger, F. A. Beck, T. Burski, C. Gehringer, J. P. Vivien, E. Bozek, and J. Styczen, *Phys. Rev. Lett.* **42**, 23 (1979).
8. B. Haas, H. R. Andrews, O. Häusser, D. Horn, J. F. Sharpey-Schafer, P. Taras, W. Trautmann, D. Ward, T. L. Khoo, and R. K. Smither, *Phys. Lett.* **84B**, 178 (1979).
9. P. Kleinheinz, *Proc. Symp. on High-Spin Phenomena in Nuclei, March 15-17, 1979, Argonne National Laboratory*, ANL/PHY-7904, p. 125.
10. *Table of Isotopes*, 7th ed., ed. C. M. Lederer and V. S. Shirley, Wiley, New York, 1978.
11. C. M. Lederer, J. M. Jaklevic, and J. M. Hollander, *Nucl. Phys.* **A169**, 489 (1971).
12. O. Häusser et al., REPT AECL-6083, 22 (1978).

HIGH-SPIN ISOMERS IN THE $N = 85$ REGION[1]

G. R. Young — D. Cline[4] — R. Ledoux[3]
C. Baktash[2] — D. Elmore[4] — C. L. Lister[2]
P. A. Butler[3] — R. Fridieu[3] — J. Srebrny[4]
D. Horn[2]

The discovery by Pedersen et al.[3] of an island of high-spin isomers in the region $82 < N < 88$ stimulated considerable experimental activity to classify these new isomers, driven in part by the hope they might be the sought-for "yrast traps"

suggested by Bohr and Mottelson.[6] Since Pedersen et al. only determined lifetimes and mean multiplicities of isomers formed in various heavy-ion reactions, we began a series of experiments to identify the specific nuclides displaying isomerism and to establish their level structure.

In the first experiments, carried out at the University of Rochester tandem Van de Graaff, the reactions ^{122}Sn(^{32}S,xn)$^{154-x}$Dy and ^{124}Te(^{32}S,xn)$^{156-x}$Er were studied at various bombarding energies using a recoil catcher apparatus (Fig. 2.55). This permitted recording (in spite of very strong prompt-gamma background) delayed discrete line spectra coming from the decay of isomers produced. Lifetimes were measured with reference to the prompt radiation detected in the NaI(Tl) detectors. On the basis of these results, the reactions ^{141}Pr(^{14}N,4n)^{151}Dy, ^{144}Sm(^{12}C,4n)^{152}Er, and ^{144}Sm(^{12}C,3n)^{153}Er were studied using the BNL tandem Van de Graaff and conventional Ge(Li) gamma-ray spectroscopy techniques, including excitation functions and prompt and delayed gamma-gamma coincidences using dc and pulsed beams.[7,8]

The level scheme deduced for ^{151}Dy is shown in Fig. 2.56. Two isomers were found, with spin, excitation, and $B(E2)$ values of $41/2^{(-)}$, 4903.9 keV, 10 ± 3 W.u. and 49/2, 6032.1 keV, 0.77 ± 0.04 W.u. respectively. The $B(E2)$ values show these transitions are retarded by one or two orders of magnitude with respect to typical collective transi-

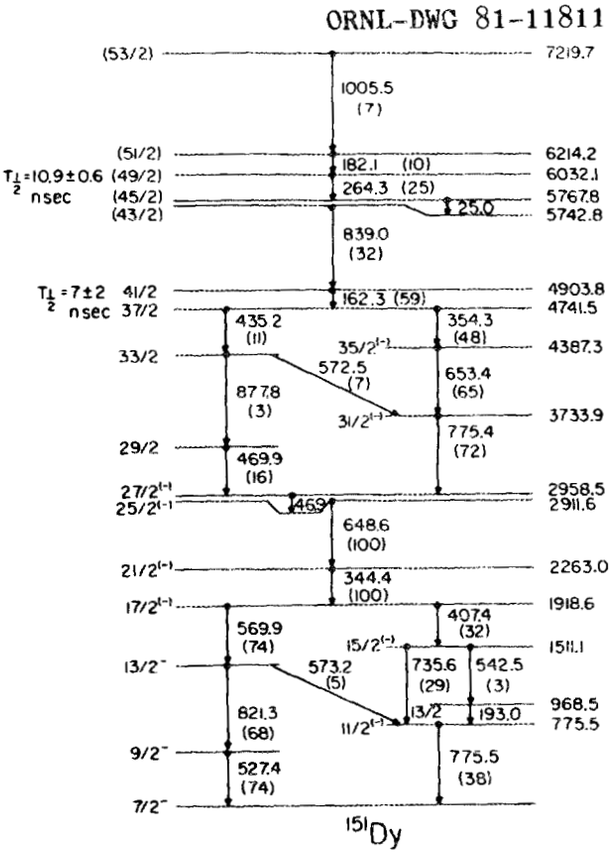


Fig. 2.56. Decay scheme of ^{151}Dy constructed from the data collected in this work. Spin assignments are firm up to the first isomer, at 4904 keV, and tentative above this point. The figures in parentheses indicate the intensity of the gamma-ray transition in the 75-MeV ^{14}N + ^{141}Pr in-beam experiment.

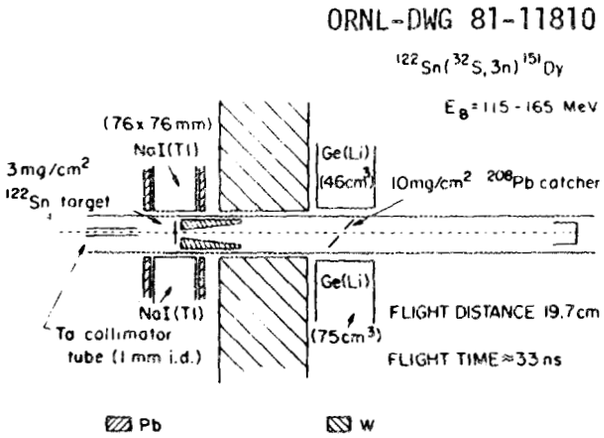


Fig. 2.55. Experimental apparatus used in the Rochester isomer search. The NaI(Tl) counters near the target detect prompt radiation, which was used to generate "time of formation" signals. The Ge(Li) detectors downstream are shielded from prompt radiation and measure delayed radiation emitted from nuclei which have recoiled onto the Pb catcher foil.

tions in the rare-earth region. Indeed, a single-particle nature is suggested. A plot of excitation energy vs $J(J+1)$ for the yrast states exhibits an irregular pattern clustered about a line corresponding to a moment of inertia $2\mathscr{I}/\hbar^2 = 138$ MeV^{-1}, 18% greater than the rigid-sphere value. Such a pattern was shown by Bohr and Mottelson[9] to be characteristic of the alignment of single-particle orbits along a symmetry axis.

The decay scheme for ^{151}Dy is seen roughly to repeat, for the states between $27/2^{(-)}$ and (45/2), the pattern found for the low-lying states from $7/2^-$ (g.s.) to $27/2^{(-)}$. Since the nucleus $^{146}_{64}$Gd$_{82}$ can be regarded as a doubly magic core, it is tempting to ascribe the low-lying structure to the three valence neutrons in a $(\nu f_{7/2})_J^3$ configuration for the states from $7/2^-$ up to $15/2^-$ and to $(\nu f_{7/2}{}^2 \otimes \nu h_{9/2})_J$ for states along the parallel branch up to $21/2^-$. Break-

ing a $(\pi h_{11/2}{}^2)_{J=0}$ core pair to $(\pi h_{11/2}{}^2)_{J=10}$ requires about 2.9 MeV. Coupling this to the above neutron configurations then provides an explanation for the repetition of the low-lying pattern above $27/2^-$. Detailed calculations by Cerkaski et al.,[10] which use an axially symmetric oblate Woods-Saxon single-particle potential with $\beta_2 = -0.16$ and $\beta_4 = 0.03$, were found to give rough agreement with the observed level structure. The foregoing considerations and similar ones for ^{152,153}Er (ref. 8) all point to an explanation of the high-spin isomers observed in terms of single-particle excitations built upon spherical cores.

1. Summary of papers published in *Phys. Rev. C* **20**, 605 (1979) and *Phys. Rev. C* **23**, 1047 (1981).
2. Brookhaven National Laboratory.
3. Massachusetts Institute of Technology.
4. University of Rochester.
5. J. Pedersen et al., *Phys. Rev. Lett.* **39**, 990 (1977).
6. A. Bohr and B. R. Mottelson, *Phys. Scr.* **10A**, 13 (1974).
7. C. J. Lister, G. R. Young, D. Cline, J. Srebrny, D. Elmore, P. A. Butler, R. Ledoux, and R. Fridieu, *Phys. Rev. C* **20**, 605 (1979).
8. D. Horn, C. J. Lister, C. Baktash, and G. R. Young, *Phys. Rev. C* **23**, 1047 (1981).
9. A. Bohr and B. R. Mottelson, *Nuclear Structure*, Benjamin, New York, 1975, vol. 2, pp. 43–44, 72 ff., 80ff.
10. M. Cerkaski, J. Dudek, P. Rozmej, and Z. Szymanski, *Nucl. Phys.* **A315**, 269 (1979).

A HIGH-SPIN ISOMER IN ^{148}Tb

J. R. Beene — D. G. Sarantites[2]
M. L. Halbert — L. Westerberg[2,3]
D. C. Hensley — K. Geoffroy Young[2,4]
J. H. Barker[1] — J. Jastrzebski[5]

A persistent theme of nuclear research over the last several years has been the investigation of effects of large angular momentum on the structure of nuclei. Recently the study of high-spin isomeric yrast states has been one of the most active aspects of this field. Yrast isomers are interesting and important for many reasons. Their existence often implies pronounced irregularities in the yrast line and, consequently, potentially interesting nuclear structure effects as a function of spin.[6,7] Furthermore the isomers can be a powerful aid in spectroscopic investigations, making possible studies of discrete nuclear states to very high spins,[8] as well as making feasible accurate determination of static and dynamic nuclear moments, which are of great importance in a clear understanding of their structure (see, for example, refs. 9 and 10).

A major impetus to this field was provided by the systematic experimental survey by Pedersen et al.[11] of a large number of nuclei which resulted in the discovery of an island of isomers near $N = 82$ and $Z \sim 64$.

Evidence has been presented of an effective proton-shell closure at $Z = 64$,[12,13] at least for neutron numbers not very far from the $N = 82$ closed shell. Thus ^{146}Gd appears as a double-closed-shell nucleus, and the island of isomers in this vicinity is analogous to the similar island near ^{208}Pb. Recent deformed independent particle model calculations[14–17] have cast considerable light on the characteristics of the high-spin isomeric states in both regions. As in the spherical-shell model, high angular momenta are generated by aligning spins of individual particles, but at moderate spins the nucleus begins to acquire a net oblate deformation with a symmetry axis along the spin direction. The resulting deformation energy is believed to account for a major part of the effective interaction which must be introduced into spherical-shell-model calculations at moderate spins. At higher spins it becomes increasingly important as the deformation increases. The calculated deformations, for which there is now experimental support,[18] are larger and become important at lower spins in the Gd region than in the Pb region. More experimental information at high spin in a variety of nuclei near ^{146}Gd is needed if these calculations are to be further tested and improved.

We report here on an investigation of the yrast-level scheme of the $N = 83$, $Z = 65$ nucleus ^{148}Tb up to spin about 30. Data from a number of experiments were used to construct a level scheme for ^{148}Tb. Initial experiments employed the ^{142}Nd(^{16}O,$\alpha p5n$) reaction at 127.5 and 155.5 MeV in an experimental configuration similar to that of ref. 11, with the GeLi detectors and an array of NaI detectors shielded from prompt radiation by a Pb tunnel. The NaI array provided a measure of the delayed-gamma multiplicity. In subsequent experiments with the same reaction at 154.5 MeV, conversion electrons in the range from about 200 to about 1000 keV from the decay of the isomer were detected in a 3-mm-thick Si(Li) detector placed at the focus of a well-shielded magnetic lens.[19] Experiments to characterize the prompt decay and to obtain better gamma-gamma coincidence data were carried out using 140.4-MeV ^{16}O on ^{138}La and 151.3-MeV ^{32}S on ^{120}Sn. In the latter case extensive $E\gamma$-$E\gamma$-time data were collected using four Ge(Li)

detectors. It may be mentioned that this was the first use of a sulfur beam from the ORIC.

The initial ^{16}O on ^{142}Nd bombardment was undertaken as a survey to search for high-spin isomers by looking for products with delayed multiplicity, M_D, greater than about 10. The most promising case was a group of lines having M_D about 13 and resulting from the decay of an about 1-μs isomer. The isomer was shown to have $Z = 65$ from the conversion electron data (via the K binding energy) and $A = 148$ based on excitation functions and daughter activities, thus completing the identification of ^{148}Tb. This assignment has since been confirmed by other groups,[20,21] who studied some of the lower transitions in ^{148}Tb.

The level scheme shown in Fig. 2.57 was constructed on the basis of gamma-gamma coincidence data. Level ordering is based primarily on prompt-feeding data. However, prompt feeding for levels placed above the 5.6-MeV level was very weak. Thus, above this point, ambiguity remains, and ordering is based on other evidence (e.g., observation of crossover transitions). Spin assignments are based on conversion coefficient data (Fig. 2.58) and angular distribution data. The half-life of the isomer tentatively assigned as $I^\pi = 26^+$ was determined to be 840 ± 40 ns from data obtained in the $^{32}S + {}^{120}Sn$ bombardment. The half-life of the 11^- isomer was determined to be 19.6 ± 1.1 ns, in good agreement with other measurements.[20,21] There is some evidence for another isomer with $T_{1/2} \sim 20$ to 40 ns in the decay scheme, possibly the $19^{(-)}$ state at 4.8 MeV.

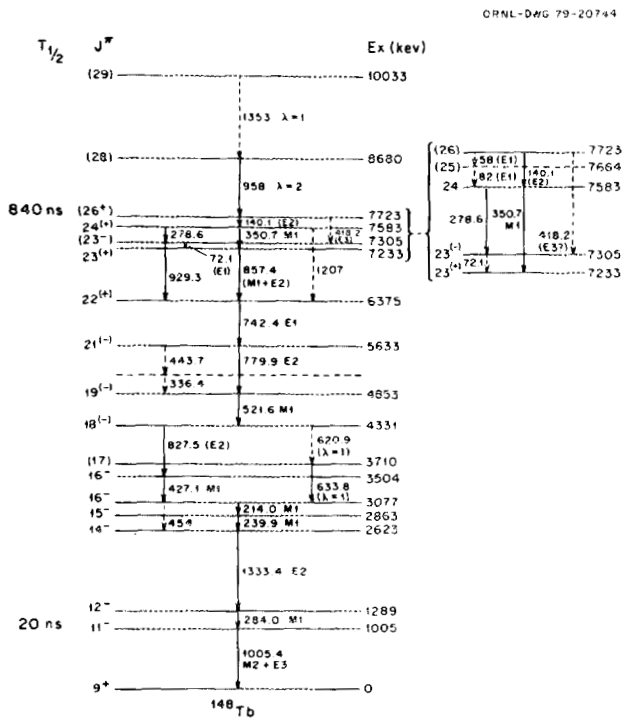


Fig. 2.57. Partial level scheme of ^{148}Tb deduced from the present results. Level energies are given relative to the 9^+ level. Placement of transitions marked with solid lines was established by gamma-gamma coincidences. Placement of the dashed transitions is based mainly on energy differences.

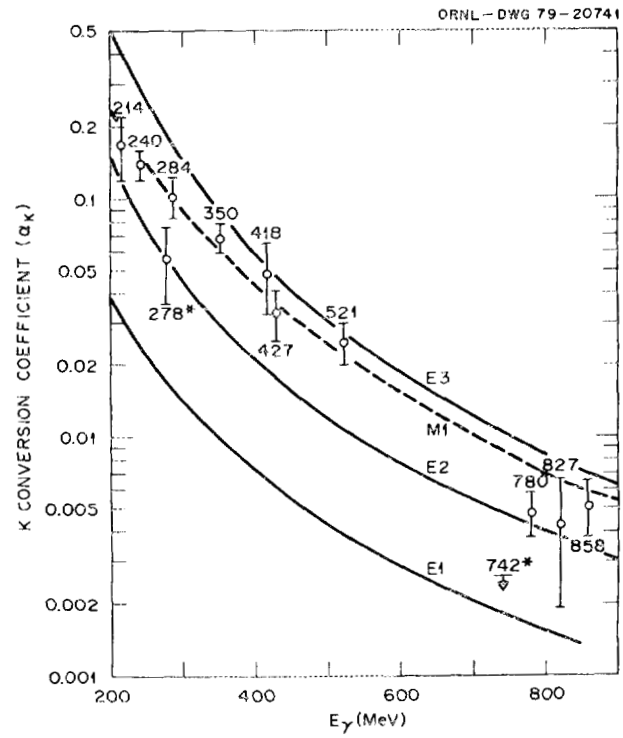


Fig. 2.58. Conversion electron data for ten delayed transitions plotted as a function of the energy of the corresponding gamma ray.

No direct evidence exists from either our angular distribution or conversion coefficient data concerning the multipolarity of the 140-keV transition. The delayed yield of 140-keV gamma rays [30 ± 6 relative to $I_\gamma(284) = 100$] argues strongly against an $M2$ or higher multipolarity. An $M2$ assignment, which implies $\alpha \sim 6.5$, would require $I_\gamma(140) \lesssim 13$. Even if our intensity measurements were in error, an unusually large $B(M2) \sim 3$ W.u. would be required to account for the observed half-life. The corresponding transition strengths for re-

maining possible multipolarities, deduced from the measured $T_{1/2}$ of the 7723-keV level and the 140-keV gamma yield, are $B(E1) \sim 3 \times 10^{-8}$ W.u., $B(M1) \sim 2.9 \times 10^{-6}$ W.u., and $B(E2) \sim 0.08$ W.u. The tentative placement of the 58- and 82-keV transitions parallel to the 140-keV transitions, together with the very large $E1$ retardation required, argues against an $E1$ assignment for the 140-keV transition. Evidence that the 58- and 82-keV transitions are involved in the decay of the 840-ns ^{148}Tb isomer comes from their identification in gamma-gamma coincidence with several of the strong lower-lying lines in the ^{148}Tb spectrum. The coincidence data gated by the 140-keV transition were not of sufficient quality to establish whether these transitions were or were not in coincidence with this line. The $E1$ assignments are the only ones consistent with the observed I_γ for these low-energy transitions. An $M1$ or higher multipolarity assignment would imply a conversion coefficient at least 10 times greater at 58 keV. The relative ordering of the 82- and 58-keV transitions is not established. An $M1$ assignment to the 140-keV transition cannot be ruled out entirely, but it would imply an unusually large retardation factor (3×10^5) and require that a possible 490-keV $E2$ transition connecting the 7723 and 7233-keV levels have a strength $B(E2) \lesssim 5 \times 10^{-5}$ W.u. We therefore consider the $E2$ assignment as most probable.

The placement of the 418.3-keV gamma and its assignment as an $E3$ transition are the most tentative of those involving the primary decay of the isomer, being based entirely on level energy differences and on the fact that the experimental α_K is consistent with $E3$.

Support for the inclusion of the three low-energy $E1$ transitions (58-, 82-, and 72-keV) in the level scheme is provided by the observation of the total delayed (>100 ns) Tb K x-ray yield. The level scheme without inclusion of these low-energy transitions predicts too low an x-ray yield, while their inclusion is consistent with the data.

Within the context of the empirical spherical-shell-model approach of Blomqvist,[12,22] a likely configuration for a spin 26 isomer in ^{148}Tb near 7.7 MeV would be $[\pi(h_{11/2}^3\ d_{5/2}^{-1}\ g_{7/2}^{-1})_{39/2}\ \nu i_{13/2}]_{26-}$. The 140-keV transition to a spin 24 state then could be analogous to the $(d_{5/2}^{-1}g_{7/2}^{-1})_{6-}$ to $(d_{5/2}^{-2})_{4+}$ transition in ^{144}Sm [which has $B(E2) = 0.18$ W.u. compared with $B(E2) = 0.08$ for the ^{146}Tb $26 \rightarrow 24$ transition], and the 418-keV $E3$ transition can be interpreted naturally as a transition to a $[\pi(h_{11/2}^3\ d_{5/2}^{-1}\ g_{7/2}^{-1})_{39/2}\ \nu f_{7/2}]$ state, since $B(E3) = 58 \pm 20$ W.u. for the 418-keV decay, not very different from the $B(E3) = 36$ W.u. for the "$i_{13/2}$" $\rightarrow f_{7/2}$ transition in ^{147}Gd (the "$i_{13/2}$" state has a large $f_{7/2} \times 3^-$ admixture).

While this interpretation is appealing, it does contradict our (somewhat uncertain) parity assignments above spin 18. The deformed-independent-particle calculations would suggest that a state involving alignment of particle and hole angular momenta, such as that suggested above, would be extremely unlikely to form an yrast state—and in particular an isomeric state. Furthermore it would seem almost certain that neutron excitations should be important at such high excitation energies. These calculations[16,17] would suggest that candidates for yrast states in this spin and excitation energy region would be states like

$$[\pi(d_{5/2}^{-1}\ h_{11/2}^2)_{21/2,23/2}\ \nu(d_{3/2}^{-2}\ f_{7/2}\ h_{9/2}\ i_{13/2})_{29/2}]_{23+,26+},$$

$$[\pi(d_{5/2}^{-2}\ h_{11/2}^3)_{27/2}\ \nu(d_{3/2}^{-1}\ f_{7/2}\ i_{13/2})_{21/2,23/2}]_{24+,23+}, \text{ or}$$

$$[\pi(d_{5/2}^{-2}\ h_{11/2}^3)_{27/2}\ \nu(d_{3/2}^{-2}\ f_{7/2}\ h_{9/2}\ i_{13/2})_{29/2}]_{28-}$$

(where the configuration is understood to develop continuously into these states as the deformation goes to zero). Of these, the most likely to form isomers from the point of view of the calculation would probably be the 25^+ and the 28^- state, in disagreement with out level scheme.

---

1. St. Louis University, St. Louis, Mo.; present address: South Carolina Electric & Gas Company, Columbia.
2. Washington University, St. Louis. Mo.
3. Present address: Institute of Physics, University of Uppsala, Box 530, S-75121 Uppsala, Sweden.
4. Present address: Fusion Energy Division.
5. Institute for Nuclear Research, Swierk, Poland; visitor 1977–78 at University of Indiana, Bloomington.

6. A. Bohr and B. R. Mottelson, *Phys. Scr.* **10A**, 13 (1974).
7. K. Neergaard, V. V. Pashkevich, and S. Frauendorf, *Nucl. Phys.* **A262**, 61 (1976).
8. T. L. Khoo, R. K. Smither, B. Haas, D. Häusser, H. R. Andrews, D. Horn, and D. Ward, *Phys. Rev. Lett.* **41**, 1027 (1978).
9. D. Horn, O. Häusser, T. Faestermann, A. B. McDonald, T. K. Alexander, J. R. Beene, and C. J. Herrlander, *Phys. Rev. Lett.* **39**, 389 (1977).
10. O. Häusser, P. Taras, W. Trautmann, D. Ward, T. K. Alexander, H. R. Andrews, B. Haas, and D. Horn, *Phys. Rev. Lett.* **42**, 1451 (1979).
11. J. Pedersen, B. B. Back, F. M. Bernthal, S. Bjørnholm, J. Borggreen, O. Christensen, F. Folkmann, B. Herskind, T. L. Khoo, M. Neiman, F. Puhlhofer, and G. Sletten, *Phys. Rev. Lett.* **39**, 990 (1977).

12. P. Kleinheinz, *Symposium on High-Spin Phenomena in Nuclei, Argonne National Laboratory, March 15–17, 1979*, ANL PHY-79-a4, p. 125 (unpublished).

13. P. Kleinheinz, R. Broda, P. J. Daly, S. Lunardi, and M. Ogawa, *Z. Phys.* **A290**, 279 (1979).

14. K. Matsuyanagi, T. Døssing, and K. Neergård, *Nucl. Phys.* **A307**, 253 (1978).

15. G. Andersson, S. E. Larsson, G. Leander, P. Moller, S. G. Nilsson, I. Ragnarsson, S. Åberg, and R. Bengtsson, *Nucl. Phys.* **A268**, 205 (1976).

16. M. Cerkaski, J. Dudek, P. Romej, and Z. Szymanski, *Nucl. Phys.* **A315**, 269 (1979).

17. T. Døssing, K. Neergård, and H. Sagawa, *Proc. Intern. Conf. on Nuclear Behavior at High Angular Momentum* (Strasbourg, 1980).

18. O. Häusser, M.-E. Mahnke, J. F. Sharpey-Schafer, M. L. Swanson, P. Taras, D. Ward, H. R. Andrews, and T. K. Alexander, *Phys. Rev. Lett.* **44**, 132 (1981).

19. L. Westerberg, D. G. Sarantites, R. Lovett, J. T. Hood, J. H. Barker, C. M. Currie, and N. Mullani, *Nucl. Instrum. Methods* **145**, 295 (1977).

20. R. Broda, M. Behar, P. Kleinheinz, P. J. Daly, and J. Blomqvist, *Z. Phys.* **293**, 135 (1979).

21. N. C. Singhal and M. W. Johns, *Can. J. Phys.* **57**, 358 (1979).

22. J. Blomqvist, *Symposium on High-Spin Phenomena in Nuclei, Argonne National Laboratory, March 15–17, 1979*, ANL PHY-79-4, p. 155 (unpublished).

ENERGY-ENERGY CORRELATION MEASUREMENTS IN THE GAMMA-RAY CONTINUUM

I. Y. Lee
S. A. Hjorth[2]
Th. Lindblad[2]
L. L. Riedinger[3]
R. O. Sayer[4]
D. R. Haenni[1]
N. R. Johnson
W. T. Milner
R. L. Robinson
G. R. Young
S. W. Yates[5]

In the gamma-ray decay of compound nuclei formed in heavy-ion-induced fusion reactions, only the low-spin ($I < 30$) transitions show up as discrete gamma-ray lines; transitions from states with higher spin form a continuum. We have performed experiments on the gamma-ray continuum in order to determine nuclear high-spin ($30 < I < 60$) properties such as effective moments of inertia and feeding lifetimes. Recently a method has been proposed[6] by which it is possible to obtain the true collective moment of inertia from gamma-ray energy-energy correlation data.

Using this method, we have studied ^{126}Ba and ^{132}Ce formed in ^{110}Pd(^{20}Ne,4n) and ^{116}Cd(^{20}Ne,4n) reactions. In the experiments the continuum gamma rays were detected in coincidence by three 12.7 × 12.7 cm NaI detectors, and two 25.4 × 25.4 cm NaI total-energy detectors were used for reaction-channel selection. Data were recorded only when at least two small NaI detectors and one large detector intercepted gamma rays. By putting a proper lower limit on the total energy, we could exclude other reaction channels (such as 5n and 6n). Events corresponding to neutrons were eliminated by using a time-of-flight method. In the data analysis the experimental two-dimensional energy-energy spectra were first unfolded to remove the effects of detector response (such as from the Compton and escape events); then a subtraction method[6] was applied to extract the correlated spectra. Figure 2.59 shows a spectrum for ^{126}Ba.

The main feature of the spectrum in Fig. 2.59 is the presence of a valley along the diagonal ($E_{\gamma 1} = E_{\gamma 2}$) up to 1.4 MeV. The highest spin state known from discrete line spectroscopy[7] is the 18$^+$ state with $E_\gamma = 0.95$ MeV. Therefore the present result establishes the collective rotational behavior of this nucleus to a region considerably higher than can be reached by the discrete-gamma-ray studies. Furthermore, from the width W of the valley, we can extract the collective moment of inertia $\mathscr{I}_c$:

$$2\mathscr{I}_c/\hbar^2 = 16/W , \qquad (1)$$

and the nuclear rotation frequency ω can be derived from the gamma-ray transition energy E_γ:

$$\hbar\omega = E_\gamma/2 . \qquad (2)$$

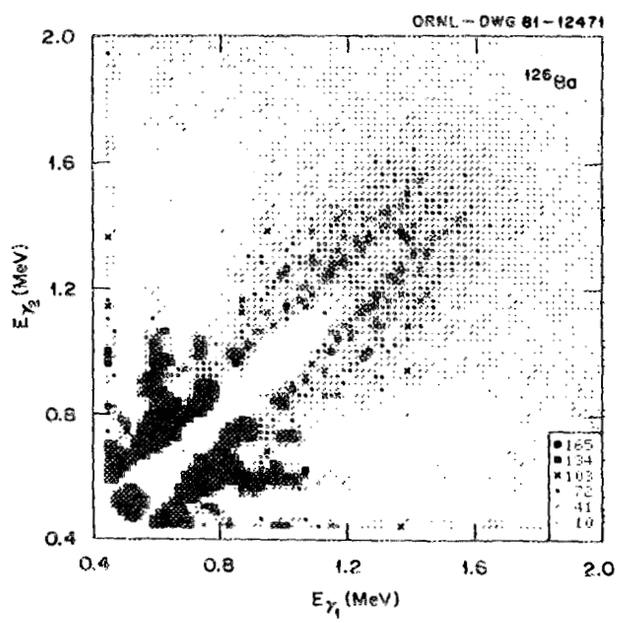


Fig. 2.59. Energy-energy correlation spectrum for ^{126}Ba.

The moment of inertia as a function of the square of the rotation frequency is shown in Fig. 2.60 for ^{126}Ba and ^{132}Ce. For both nuclei, we observe an initial increasing of the moment of inertia until $(\hbar\omega)^2 = 0.15$ MeV^2. This is followed by a reduction of the moment of inertia, and afterward it stays constant up to 0.4 MeV^2.

1. Present address: Texas A&M University, College Station.
2. Present address: Research Institute of Physics, Stockholm, Sweden.
3. University of Tennessee, Knoxville.
4. Computer Sciences Division.
5. University of Kentucky, Lexington.
6. O. Andersen, J. D. Garrett, G. B. Hagemann, B. Berskind, D. L. Hillis, and L. L. Riedinger, *Phys. Rev. Lett.* **43**, 687 (1979).
7. C. Flaum, D. Cline, A. W. Sunyar, O. C. Kistner, Y. K. Lee, and J. S. Kim, *Nucl. Phys.* **A264**, 291 (1976).

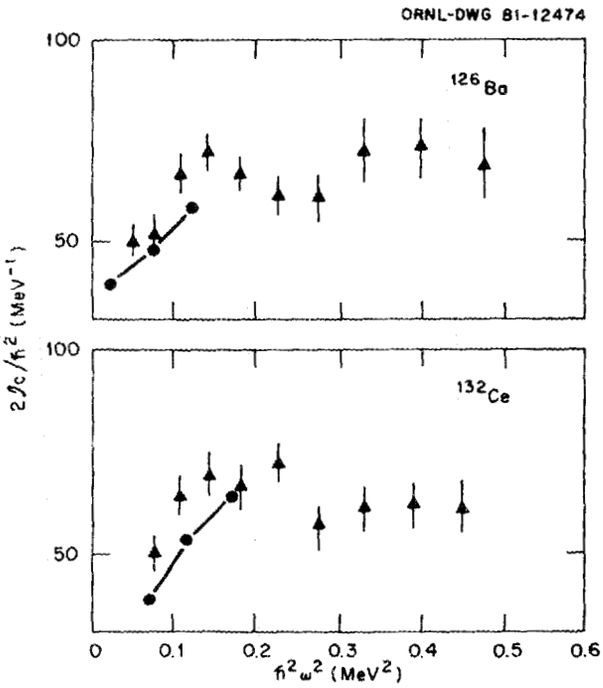


Fig. 2.60. Collective moment of inertia of ^{126}Ba and ^{132}Ce. The circular points represent results from discrete-line data; the triangular points represent results from present work.

BACKBENDING OF THE MOMENT OF INERTIA ABOVE THE KNOWN SPIN LIMIT IN ^{156}Er

H. Yamada[1]
A. Ahmed[1]
J. D. Cole
M. L. Halbert
J. H. Hamilton[1]
D. C. Hensley
M. Herath-Banada[1]
S. Hjorth[2]
C. F. Maguire[1]
R. B. Piercey[1]
A. V. Ramayya[1]
R. L. Robinson

A possible nuclear shape transition from prolate to oblate deformation induced by rotational alignment, which is expected to occur above spin 40, is a very interesting subject to be investigated. In the near-spherical nuclei ^{152}Dy and ^{154}Er, the observation that the yrast excitation energies increased as $(\hbar^2/2\mathcal{J})\ I(I+1)$ above spin 14 has been taken as resulting from the alignment of the spins of the individual nucleons. In deformed nuclei such as ^{156}Er and ^{160}Yb, discrete states are known only up to spin 32. Although the failure of discrete-gamma-ray measurements above spin 32 is attributed to the existence of many parallel bands built on quasiparticle states which smear out the individual gamma transitions, we expect that discrete-gamma-ray measurements can be extended to higher spins by using some special angular momentum filter.

A special reaction useful for selecting essentially only the high-spin population is the partial-fusion reaction (PFR) accompanied with emission of fast light particles. The reaction mechanism has been shown to be associated with peripheral collisions.[3,4] The PFR is characterized by a narrow spin population localized near the critical angular momentum (about 63$\hbar$) for fusion. These characteristics of the PFR provide the following special advantages for gamma-ray spectroscopy: (1) Only very high-spin states are populated. This allows one to focus on effects associated with this narrow spin window. This also implies that few gamma-decay paths are involved, which helps to clean up the continuum gamma-ray background. (2) The PFR of 167-MeV ^{14}N leads to $\overline{M}_\gamma = 31$, whereas the complete fusion of 200-MeV ^{40}Ar leads to $\overline{M}_\gamma = 27$ only. The PFR

populates the high-spin states more efficiently. (3) The distribution in mass of the evaporation residues is narrow, as shown in ref. 4, and a reasonably accurate mass identification can be made directly from the PFR light-particle energies. (4) The cross section for the PFR is relatively large (about 500 mb), and our efficiency for collecting the PFR products is nearly 80%, using a forward annular telescope. (5) The often serious problem arising from Doppler-shift effects in the gamma-ray energies measured by the Ge(Li) detector is largely avoided with the use of ^{14}N, a "light" heavy ion.

We combined a gamma-ray energy-energy correlation method[5] with the PFR technique, using three large collimated NaI detectors, a Ge(Li) detector, and a forward annular light-particle detector telescope. The reaction used was ^{154}Sm[^{14}N,(p, d, or t)xn]^{158}Er at a bombarding energy of 167 MeV. In Fig. 2.61 we show a gamma-ray energy-energy correlation map taken in coincidence with the fast light particles. In this experiment we obtained a total of about 3 million particle-gamma-gamma coincidence events where the more usual gamma-gamma correlation studies with complete-fusion reactions generally require at least 50 million events. But because the fast light particle coincidence requirement improves the peak-to-background ratio by more than an order of magnitude, the quality of the "background"-subtracted data is comparable to that obtained with the usual technique. The map in Fig. 2.61 is mainly associated with ^{158}Er, since the cross section for producing ^{158}Er is at least two times those for producing ^{157,159}Er and since other reaction channels were not observed in the coincidence Ge(Li) spectra.

The map shows valleys and bridges along the diagonal, particularly those associated with the known first and second back bends in ^{158}Er near 0.5 and 0.9 MeV. There is one clear bridge located at 0.7 MeV, but there are no back bends associated with ^{158}Er between the first and second ones already mentioned. We find that the 0.7-MeV bridge is not correlated with known ^{158}Er transitions and feel that this bridge probably is associated with either ^{157}Er or ^{159}Er, although back bends have not been observed in the odd-A nuclei ^{157,159}Er, probably due to blocking effects.

Two features of the correlation map are worth pointing out. First, a broad accumulation of correlated events between 0.9 and 1.4 MeV seen in the ^{124}Sn(^{40}Ar,4n)^{160}Er complete-fusion reaction[6] is not seen in our data, possibly because only very high initial spins are populated. Second, there are likely additional bridge structures near 1.1 and 1.2 MeV. If these are associated with additional back bends in ^{158}Er, they would be for spins greater than $32\hbar$ and would suggest that there is continued alignment of high-j orbitals, in other words, that collective rotations perpendicular to the symmetry axis continue on up to at least $\hbar\omega$ = 0.6 MeV.

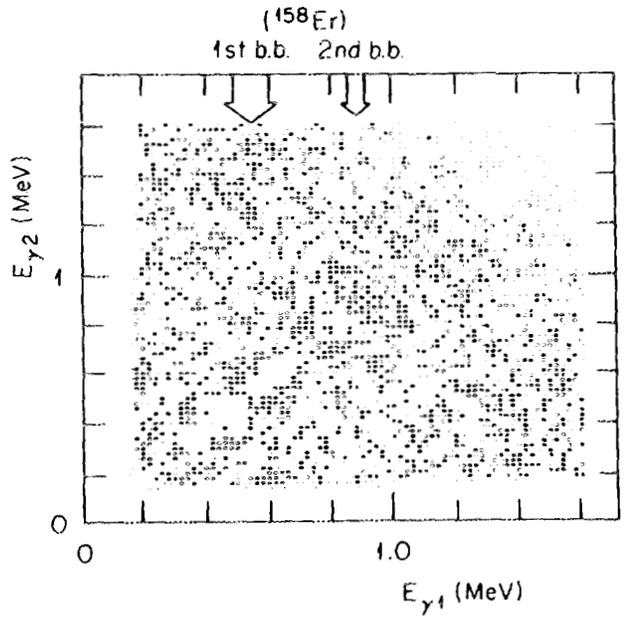


Fig. 2.61. Gamma-ray energy-energy correlation map obtained in coincidence with fast light particles (p, d, and t). The clear valley along the diagonal is crossed by bridges, two of which are associated with known back bending in ^{158}Er near 0.5 MeV (first) and 0.9 MeV (second). There are additional bridges at 0.7, 1.1, and 1.2 MeV.

---

1. Vanderbilt University.
2. On leave from Research Institute of Physics, S10405 Stockholm 50, Sweden.
3. H. Yamada et al., *Phys. Rev. Lett.* **43**, 687 (1979).
4. H. Yamada et al., *Bull. Am. Phys. Soc.*, April 1981; to be published; ORNL annual report 1980.
5. O. Anderson et al., *Phys. Rev. Lett.* **43**, 687 (1979).
6. M. A. Deleplanque et al., *Phys. Rev. Lett.* **45**, 172 (1980).

LIFETIMES OF ROTATIONAL STATES IN ^{154}Sm

N. R. Johnson M. W. Guidry[1]
R. J. Sturm[2] E. Eichler[3]
R. O. Sayer[4] D. C. Hensley
N. C. Singhal[5]

Measurements of the lifetimes of collective nuclear states provide detailed information on the nuclear shape corresponding to those states. A particularly interesting region for such studies is the beginning of the rare-earth nuclei, where the addition of only a few particles precipitates a rapid transition from spherical to deformed structure, with a small region of vibrationally soft nuclei lying between. In the present work we have made lifetime measurements for $I \leqslant 10$ in the ground-state rotational band of the nucleus ^{154}Sm, and we discuss the results in the light of the fact that ^{154}Sm lies on the deformed edge of this transition region. These measurements were carried out by the Doppler-shift recoil-distance (plunger) method. The method, apparatus, and data analysis techniques are described[6-8] in detail elsewhere.

Two different experiments were performed. In the first, a beam of 145.8-MeV ^{40}Ar ions from the Oak Ridge Isochronous Cyclotron was used to produce Coulomb excitation in the ^{154}Sm target, and measurements of the shifted and unshifted peak intensities were made at a series of relatively large target-stopper distances to establish the lifetimes of the 4^+ and 6^+ members of the ground band. The second experiment was carried out with a 152.8-MeV ^{40}Ar beam, and here we looked primarily at close target-stopper separations to determine the lifetimes of the 6^+, 8^+, and 10^+ ground-state-band members. In both cases, the target was a 0.95-mg/cm^2 metallic samarium foil enriched to 99.54% in mass 154.

Figure 2.62 shows plots of the corrected ratios R for the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions in ^{154}Sm, while Fig. 2.63 shows similar plots for the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, and $10^+ \rightarrow 8^+$ transitions measured in a separate experiment. The ratio R is defined by $R = I_u/(I_u + I_s)$, where I_u and I_s are the intensities of the unshifted and shifted peaks corrected for efficiency, solid angle, feeding from higher states, and alignment attenuation effects by the method described in refs. 6–8 and embodied in the computer program ORACLE.[8] In Table 2.8 we show a summary of the half-life and $B(E2)$ values obtained from the data in Figs. 2.62 and 2.63.

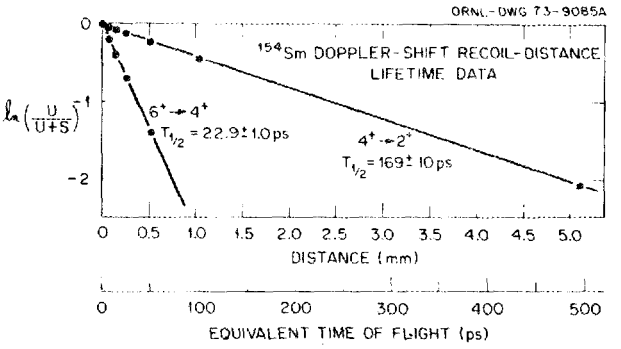


Fig. 2.62. Plots of ratios of unshifted to sum of unshifted and shifted gamma-ray intensities as a function of target-stopper separation for the $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions in ^{154}Sm. These data were recorded following Coulomb excitation of the target nuclei with a 152.8-MeV ^{40}Ar Beam.

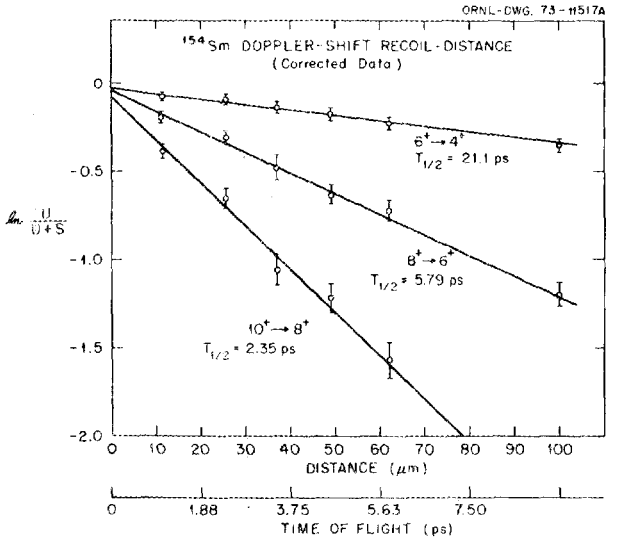


Fig. 2.63. Plots of ratios of unshifted to sum of unshifted and shifted gamma-ray intensities as a function of target-stopper separation for the $6^+ \rightarrow 4^+$, $8^+ \rightarrow 6^+$, and $10^+ \rightarrow 8^+$ transitions in ^{154}Sm. The data were recorded following Coulomb excitation of the target nuclei with a 145.8-MeV ^{40}Ar beam.

The results presented in column 6 of Table 2.8 are suggestive of a rotor exhibiting a slight increase (less than 5%) in the intrinsic quadrupole moment as the collective angular momentum is increased from 0 to 10 units. Within the error limits these ratios are very near to unity, but the trend as one moves to the higher-spin states in ^{154}Sm is toward increasing values for the experimental-to-theoretical $B(E2)$ ratio. This trend is also evident in

Table 2.8. Lifetimes and $B(E2)$ Values for ^{154}Sm

Transition	E (keV)	$T_{1/2}$ (ps)	α_T[a]	$B(E2)_{exp}$ (e^2b^2)	$B(E2)_{exp}/B(E2)_{rot}$ Present experiment	Diamond et al. ref. 11	Weighted average
2 → 0	88.89		4.928	0.879 ± 0.002[b]	1.00[c]	1.00[c]	1.00[c]
4 → 2	184.8	169 ± 10[d]	0.2738	1.21 ± 0.07[d]	0.97 ± 0.06	0.94 ± 0.03	0.95 ± 0.03
6 → 4	276.9	22.9 ± 1.0[d]	0.0727	1.46 ± 0.06[d]	1.06 ± 0.05[f]	0.99 ± 0.04	1.02 ± 0.03
		21.2 ± 1.1[e]		1.52 ± 0.05[e]			
8 → 6	358.9	5.82 ± 0.38[e]	0.0327	1.57 ± 0.10[e]	1.09 ± 0.07	1.03 ± 0.11	1.07 ± 0.06
10 → 8	430.2	2.37 ± 0.18[e]	0.0194	1.60 ± 0.12[e]	1.08 ± 0.11		1.08 ± 0.11

[a]Total internal conversion coefficient from refs. 9 and 10.
[b]Weighted average value from (α,α') experiments of refs. 12–16.
[c]Normalized to unity for the 2 → 0 transition.
[d]From experiment with 152.8-MeV ^{40}Ar beam.
[e]From experiment with 145.8-MeV ^{40}Ar beam.
[f]Average value from the two measurements.

the weighted averages of our values and those of Diamond et al.,[11] as shown in column 8.

The 90-neutron nuclei ^{150}Nd, ^{152}Sm, ^{154}Gd, and ^{156}Dy are known to exhibit considerable enhancement of $B(E2)$ values over the rotational prediction for 6^+ through 10^+ members of the ground-state bands. The most frequently applied interpretation of this effect is that of centrifugal stretching in these β-soft isotones. Therefore the present results on ^{154}Sm suggest a significant increase in nuclear rigidity arising from adding two neutrons to the $N = 90$ nucleus ^{152}Sm. For example, the ratio $B(E2)\text{exp}/B(E2)_{tot}$ for the 8 → 6 transition is about 1.3 for ^{152}Sm but only about 1.09 for ^{154}Sm. However, our data also suggest that the nucleus ^{154}Sm is still slightly soft against centrifugal distortion when compared with nuclei lying further into the deformed region. A detailed account of the present work was published recently.[17]

1. University of Tennessee, Knoxville.
2. Max Kade Foundation Fellow from the University of Marburg, Germany.
3. Deceased.
4. Computer Sciences Division.
5. Vanderbilt University Postdoctoral Fellow assigned to Oak Ridge National Laboratory. Present address: Ontario Hydroelectric, Toronto, Canada.

6. N. R. Johnson, R. J. Sturm, E. Eichler, M. W. Guidry, G. D. O'Kelley, R. O. Sayer, D. C. Hensley, N. C. Singhal, and J. H. Hamilton, *Phys. Rev. C* **12**, 1927 (1975).
7. M. W. Guidry, R. J. Sturm, N. R. Johnson, E. Eichler, G. D. O'Kelley, N. C. Singhal, and R. O. Sayer, *Phys. Rev. C* **13**, 1164 (1976).
8. R. J. Sturm and M. W. Guidry, *Nucl. Instrum. Methods* **138**, 345 (1976).
9. R. S. Hager and E. C. Seltzer, *Nucl. Data* **A4** 397 (1968).
10. O. Dragoun, Z. Plajner, and F. Schmutzler, *Nucl. Data* **A9**, 119 (1971).
11. R. M. Diamond, G. D. Symons, J. L. Quebert, K. H. Maier, J. R. Leigh, and F. S. Stephens, *Nucl. Phys.* **A184**, 481 (1972).
12. H. Shaw and J. S. Greenberg, *Phys. Rev. C* **10**, 263 (1974).
13. H. Fischer, D. Kamke, H. J. Kittling, E. Kuhlmann, H. Plicht, and R. Schormann, *Phys. Rev. C* **15**, 921 (1977).
14. T. K. Saylor, J. X. Saladin, I. Y. Lee, and K. A. Erb, *Phys. Lett.* **42B**, 51 (1972).
15. H. J. Wollersheim, W. Wilcke, Th. W. Elze, and D. Pelte, *Phys. Lett.* **48B**, 323 (1974).
16. C. E. Bemis, P. H. Stelson, F. K. McGowan, W. T. Milner, J. L. C. Ford, R. L. Robinson, and W. Tuttle, *Phys. Rev. C* **8**, 1934 (1973).
17. N. R. Johnson, M. W. Guidry, R. J. Sturm, E. Eichler, R. O. Sayer, D. C. Hensley, and N. C. Singhal, *Phys. Rev. C* **22**, 2416 (1980).

MEASUREMENTS OF THE REDUCED TRANSITION PROBABILITIES IN ^{152,154,156,158,160}Gd WITH ^{136}Xe PROJECTILES

I. Y. Lee — N. R. Johnson
T. T. Sugihara[1] — M. W. Guidry[2]
E. L. Robinson[3] — R. M. Diamond[4]
F. S. Stephens[4]

At the beginning of the rare-earth region, the nuclei change from nearly spherical to highly deformed shapes. The stable gadolinium isotopes span this region and are, therefore, very suitable for studying the transition from noncollective to collec-

tive nuclei. By using heavy ions as projectiles, high-spin states can be excited with large cross sections, and the large recoil velocity of the target nuclei makes it possible to measure the lifetimes of the short-lived states.

We have performed Coulomb excitation measurements on five even-even Gd isotopes from ^{152}Gd to ^{160}Gd. The experiments were carried out using the ^{136}Xe beam from the LBL SuperHILAC. The scattered ^{136}Xe particles were detected in nine solid-state detectors arranged in a 3 × 3 array which covered 60 to 95° in θ and 60° in ϕ. The decay gamma rays are detected (in coincidence with the particles) in a Ge(Li) detector at −30°, which is the average recoil direction. The use of a thin target, the coincidence requirement, and the placement of the Ge(Li) detector in the recoil direction are all necessary to reduce the Doppler broadening of the gamma-ray lines. Figure 2.64 shows the Doppler-shift-corrected gamma-ray spectrum of ^{158}Gd. The highest spin states observed are 12$^+$ for ^{152}Gd, 16$^+$ for ^{154}Gd, 18$^+$ for ^{156}Gd, 18$^+$ for ^{158}Gd, and 20$^+$ for ^{160}Gd. The gamma-ray yields were analyzed using the Coulomb excitation program of Winther and deBoer. In the calculation, $E2$ and $E4$ matrix elements between all the levels in the ground-state band were included. Using the rotational values derived from the known values of $M(E2, 0 \rightarrow 2)$ and $M(E4, 0 \rightarrow 4)$, we can reproduce the experimental yields of ^{156,158,160}Gd. However, for ^{152,154}Gd a gradual increase and then a leveling off of the $E2$ matrix element as a function of spin are needed to reproduce the results. This increase is about 25% from 2$^+$ to 12$^+$ states for ^{152}Gd and about 10% from 2$^+$ to 16$^+$ states for ^{154}Gd. This is consistent with the picture that these two nuclei stretch as a function of spin but are stabilized by shell effects at a deformation comparable to that of a deformed rare-earth nucleus.

Lifetime measurements were carried out using the Doppler-broadened line-shape method with an ^{136}Xe beam and thick targets of ^{156,158,160}Gd. Gamma rays were detected at 0° in singles with a Ge(Li) detector. Figure 2.65 shows the spectrum for ^{160}Gd. From the known slowing-down time, the angular distribution of the recoil nuclei, and the excitation function of the states, the lifetimes can be extracted from the line shapes. Table 2.9 gives the lifetimes determined from the experiment and the

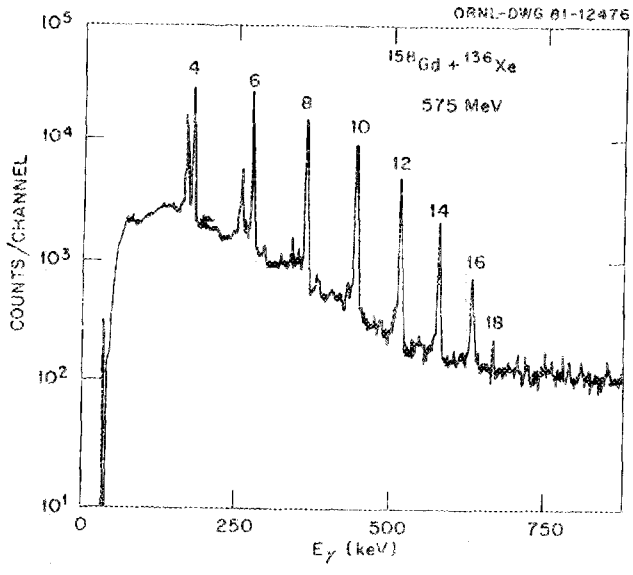


Fig. 2.64. Gamma-ray spectrum of ^{158}Gd after Doppler-shift correction.

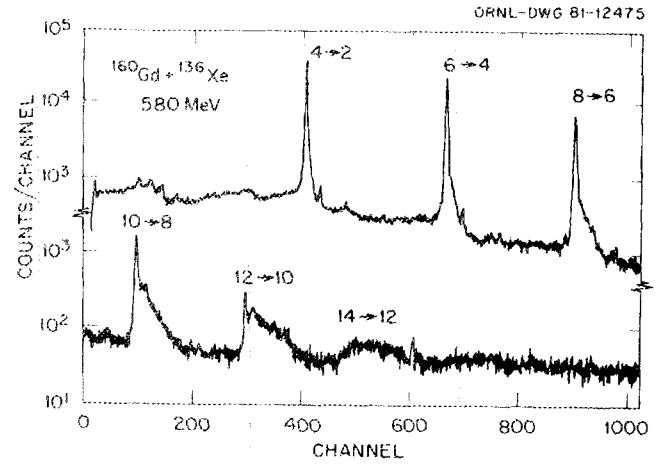


Fig. 2.65. Spectrum showing the line shapes of ^{160}Gd.

Table 2.9 Lifetimes of Gd isotopes derived from Doppler-broadened line-shape analysis

Isotope	I	τ_{exp} (ps)	τ (ps)	τ /τ
^{152}Gd	8	6.0 (1.0)	6.60	1.10 (20)
	10	2.4 (0.4)	2.78	1.16 (20)
	12	1.7 (0.3)	1.51	0.89 (16)
^{154}Gd	10	2.5 (0.4)	2.69	1.08 (17)
	12	1.2 (0.2)	1.28	1.07 (18)
^{160}Gd	8	7.5 (1.5)	8.68	1.15 (23)
	10	3.2 (0.5)	3.07	0.96 (15)
	12	1.2 (0.2)	1.40	1.16 (19)

comparison with the rotational values derived from $M(E2, 2^+ \rightarrow 0^+)$. These results show that the 8^+, 10^+, and 12^+ states of ^{156,158,160}Gd follow the rotational model, in agreement with the gamma-ray yield results.

1. Present address: Texas A&M University, College Station.
2. University of Tennessee, Knoxville.
3. University of Alabama, Birmingham.
4. Lawrence Berkeley Laboratory.

HIGH-SPIN STATES IN ^{160}Yb

L. L. Riedinger[1] D. R. Haenni[2]
S. A. Hjorth[3] N. R. Johnson
I. Y. Lee W. K. Luk[1]
R. L. Robinson

The yrast line of rotational nuclei has been surveyed rather well up to $I = 20$ in most cases and up to $I = 28$ in a few. One finds sudden rearrangement of the angular-momentum-carrying modes in the form of the first back bend ($I \sim 12$) and, in a few cases, the second back bend ($I \sim 28$). It is of interest to study the yrast and near-yrast region at higher spins to see what other rearrangements take place. Is pairing depleted after the second back bend? Will other particles be rotationally aligned? Are shape changes imminent? To try to answer these questions, we have worked to study discrete lines in rotational bands in regions at or beyond $I = 30$. Techniques more sophisticated than those in vogue five years ago are necessary to perform spectroscopy measurements on the weak transitions on a high background in (HI,xn) measurements. We have developed multidetector arrays to emphasize those reactions that produce the high spins.

At first, five, and then seven, Ge counters have been used in our recent measurements. The high multiplicities of these reaction products often result in three or more Ge counters firing in the coincidence mode, giving a large number of Ge-Ge pairs to be analyzed in order that a level scheme can be constructed. A selection of the reaction product is performed by requiring that a large total gamma-ray energy be detected in two large NaI counters, one a 25 × 25 cm crystal located below the reaction plane and the other a 22 × 30 cm detector placed above. The coincidence data are sorted in a specialized program[4] where the channel number of the individual Ge detector is gain-shifted event by event on analysis, so that one 2048 × 2048 coincidence matrix containing all Ge-Ge pairs is attained.

A multidetector array containing five Ge counters was used to study ^{160}Yb by the (^{20}Ne,4n) reaction at 107 MeV bombarding energy. Detailed spectroscopy on this nucleus had recently been performed[5] by using the ^{16}O,3n) reaction. That work led to the assignment of the yrast line up to $I = 28$ and five side bands up to $I \sim 23$. The yrast line was known to exhibit a sharp back bend at $\hbar\omega = 0.28$ MeV [resulting in an angular momentum alignment gain (i) of 10.5$\hbar$] and a partially completed second back bend (up bend) at $\hbar\omega = 0.41$ MeV with unknown alignment gain. The side bands uniformly exhibited band crossings at $\hbar\omega \sim 0.35$ MeV, although the crossings were not completed, and thus the gains in alignment are not known. The yrast and two of the side bands are shown in Fig. 2.66. In order to clearly identify the quasi particles (q.p.) responsible for the crossings, higher spin states must be known.

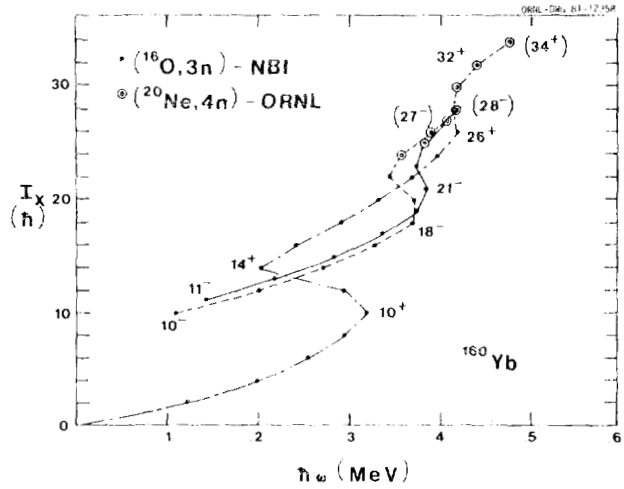


Fig. 2.66. Plot of I_x vs $\hbar\omega$ for the yrast (dot-dashed line) band in ^{160}Yb, in addition to side bands 1 (dashed line) and 2 (solid). The circled points resulted from ORIC work, while the others were first assigned in the NBI measurements and observed also in the ORIC experiment.

The larger ℓ_{max} of the ^{20}Ne-induced reaction (compared with the ^{16}O-induced study) resulted in a very large increase in the observed intensities of the high-spin states, as shown in Fig. 2.67. This allowed identification of higher spin states in several of the bands, as shown in Fig. 2.66. Tentative assignment

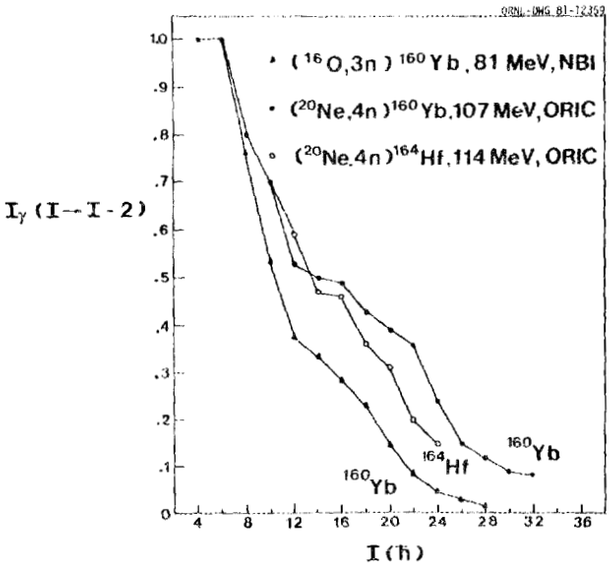


Fig. 2.67. Relative gamma-ray intensities observed in three different measurements. The values are normalized to 1.0 for the 4 → 2 transition.

of the $I = 34$ yrast state means that one or two transitions in the four-quasi-particle band after the second back bend have been observed. The alignment gain in this crossing will be discussed in the following contribution.

The two negative-parity side bands have crossings at $\hbar\omega_c \sim 0.35$ MeV, and our new data demonstrate that there occurs an approximately 6.5 $\hbar$ increase in I_x, the angular momentum along the rotation axis. This crossing frequency and i value agree well with what is expected for the rotation alignment of a pair of $i_{13/2}$ neutrons, not those in the lowest two orbits (call them A and B, $i \cong 10\hbar$) but those in the next two orbits (B and C, $i \cong 6\hbar$). The AB pair is responsible for the first yrast back bend, but the A is blocked in the two side bands, since they are composed of $i_{13/2}$ neutron level A in combination with the $h_{9/2}$ neutron levels. The characteristic ω_c and i for this BC crossing are 0.36 MeV/$\hbar$ and $6\hbar$, in agreement with the data presented here. These calculations were performed in the formalism of the cranked shell model, as discussed by Bengtsson and Frauendorf[6] and by Riedinger et al.[5,7]

1. University of Tennessee, Knoxville.
2. Present address: Texas A&M University, College Station.
3. Present address: AFI, Stockholm, Sweden.

4. H. Ower, University of Tennessee and ORNL.
5. L. L. Riedinger, O. Andersen, et al., *Phys. Rev. Lett.* **44**, 568 (1980).
6. R. Bengtsson and S. Frauendorf, *Nucl. Phys.* **A327**, 139 (1979).
7. L. L. Riedinger, *Nucl. Phys.* **A347**, 141 (1980).

NEW YRAST BANDS IN ^{162,164}Hf

L. L. Riedinger[1] H. Ower[1]
M. P. Fewell D. R. Haenni[2]
J. S. Hattula[3] S. A. Hjorth[4]
I. Y. Lee N. R. Johnson

The $N = 90$ nuclei ^{160}Yb (ref. 5) and ^{158}Er (ref. 6) both exhibit second yrast back bends at $\hbar\omega = 0.41$ MeV. Theoretical calculations[7,8] suggest that the alignment of $h_{11/2}$ protons is responsible for that crossing, but then an oscillation of the strength of this crossing with proton number should be evident. To search for this effect in light Hf ($Z = 72$), we have begun measurements on the virgin nuclei ^{162,164}Hf (no known excited states). A multidetector array involving seven Ge counters was used in these measurements. The reactions used were ^{148}Sm(^{20}Ne,4n) ^{164}Hf at 114 MeV and ^{144}Sm(^{22}Ne,4n) ^{162}Hf at 123 MeV. The beam energies were varied by use of degrader foils for an excitation function on these previously unknown final products.

The ^{164}Hf data are quite good, rich in side-band information. However, only the analysis of the yrast line is reported here. The first back bend in ^{164}Hf is quite sharp, similar to ^{160}Yb. After this back bend these two S bands are quite similar up to $I = 20$. The extreme similarity in these two yrast lines is surprising, in view of the different N, Z, and deformation. The two yrast lines begin to diverge at $I = 22$, after which the second back bend occurs in ^{160}Yb but notably not in ^{164}Hf (at least up to $I = 28$). The close similarities of these two cases up to $I = 20$ suggest that the divergence beyond $I = 20$ is due to the interaction of the two-quasi-particle (q.p.) and four q.p. bands in the second back bend of ^{160}Yb. This interaction is evidently much smaller (or absent?) in ^{164}Hf, and so one can view the smooth S band in ^{164}Hf as a good estimate of the reference two-q.p. configuration to which one can compare the four q.p. configuration of ^{160}Yb. Performing this comparison yields an alignment gain of $6.7\hbar$ in the second backbend, in good agreement with the predicted i for $h_{11/2}$ proton alignment.[7]

Our more recent measurement on ^{162}Hf has yielded data not as clean as those for ^{164}Hf (life becomes more difficult farther from the line of stability) but still of high enough quality to construct the yrast band. The deformation is less (first 2^+ = 284 keV in ^{162}Hf, 211 in ^{164}Hf) for ^{162}Hf, but the first back bend begins once again at I = 123 and is again quite sharp (see Fig. 2.68). In contrast to the oscillating nature of the sharpness of the first back bend closer to stability in this region, we observe very similar and quite sharp back bends in these three nuclei. It is possible that the wave functions of the ground and S bands in these nuclei of small deformations are sufficiently different in a consistent manner, giving small interaction and sharp back bends. This story of uniformity does not hold, of course, for the second back bend.

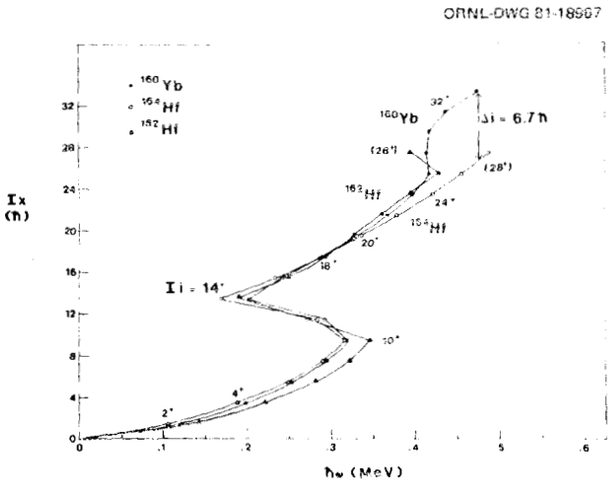


Fig. 2.68. Plot of I_x vs $\hbar\omega$ for the yrast bands in ^{160}Yb, ^{162}Hf, and ^{164}Hf. The highest-spin transition in each case is tentative.

After the first crossing, the S band of ^{162}Hf is similar to the others at I = 18, but then it rises faster than that of ^{160}Yb. The assignments up to the 862-keV $26^+ \rightarrow 24^+$ transition are fairly definite, and the next transition may be the 790-keV line, a doublet with that of $24 \rightarrow 22$. This tentative assignment would dictate a very sharp second back bend and would indicate that the two-q.p.–four-q.p. interaction at $\hbar\omega \sim 0.4$ MeV is decreasing systematically for Z = 68, 70, and 72 respectively. The difference in ^{162}Hf and ^{164}Hf is striking and requires detailed cranked-shell-model calculations to find if the alignment of $h_{11/2}$ protons can explain the variation. These calculations[7] suggest that a crossing of $h_{9/2}$ neutrons is also possible at similar frequencies; such a crossing would be expected to be more neutron-number-dependent, and so it is important to see which effect can explain these new data.

---

1. University of Tennessee, Knoxville.
2. Present address: Texas A&M University, College Station.
3. Visitor from University of Jyvaskyla, Finland.
4. Present address: AFI, Stockholm, Sweden.
5. L. L. Riedinger, O. Andersen, et al., *Phys. Rev. Lett.* **44**, 568 (1980).
6. I. Y. Lee et al., *Phys. Ref. Lett.* **38**, 1454 (1977).
7. R. Bengtsson and S. Frauendorf, *Nucl. Phys.* **A327**, 139 (1979).
8. A. Faessler and M. Ploszajczak, *Phys. Lett.* **76B**, 1 (1978).

MOMENTS OF INERTIA OF QUASI-PARTICLE BANDS

S. Frauendorf[1] L. L. Riedinger[1]

In the spectroscopy of high-spin states, there are three types of parameters to measure. The frequencies of band crossings and the alignment gains which result in these crossings are two such quantities discussed in the previous two contributions. The third quantity is the collective moment of inertia.

The total angular momentum along the x (rotation) axis, I_x, can be written as the sum of a part from alignment of quasi particles (q.p.) along the rotation axis, i, and a part from rotation of the nonaligned core, R:

$$I_x = i + R.$$

The rotational angular momentum can be written in terms of a collective moment of inertia, which seems to vary with frequency and can thus be parameterized by the expansion

$$I_x = i + \omega(\mathscr{I}_0 + \mathscr{I}_1\omega^2) ,$$

where $\mathscr{I}_0$ and $\mathscr{I}_1$ are VMI-type parameters.[2,3,4] For K = 0 bands the total angular momentum is along the x axis, and so $I_x = I + 1/2$. The simplest definition of a moment of inertia is then

$$\mathscr{I}_b^{(1)} = \frac{I_x}{\omega} = \frac{i}{\omega} + (\mathscr{I}_0 + \mathscr{I}_1\omega^2) .$$

This is half the usual effective moment of inertia plotted in the back-bending graph, $2\mathscr{I}/\hbar^2 = (4I - 2)E_\gamma$, for an $I \rightarrow I - 2$ transition. Such a plot is

made for the new data reported by Walus[5] on ^{166}Yb in Fig. 2.69. A large increase in $\mathscr{I}_b^{(1)}$ occurs at the back bend, since the aligned angular momentum increases from a very small value in the ground band to a rather large quantity in the S band. After the back bend, i is approximately constant, and so the first term in the above equation decreases with increasing ω, causing the characteristic droop in $\mathscr{I}_b^{(1)}$. The effect of the term in i can be eliminated by defining a moment of inertia based upon second differences:

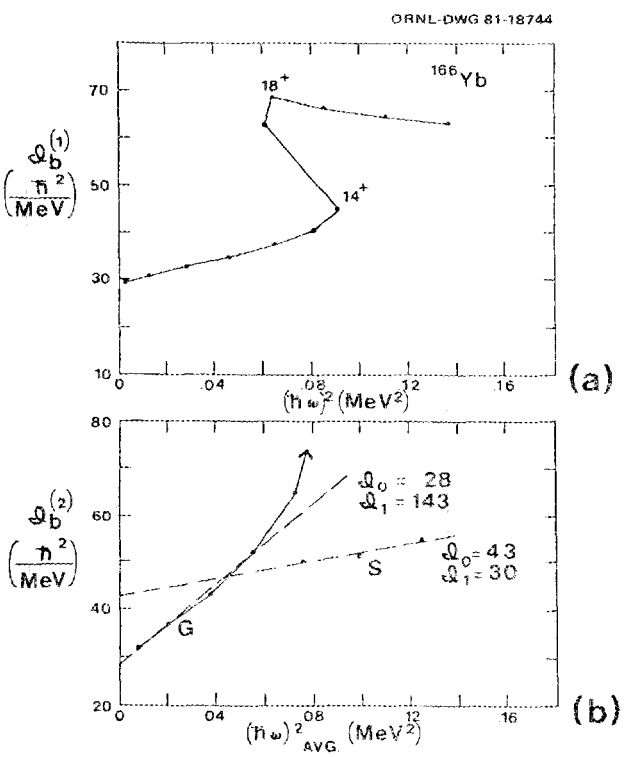
$$\mathscr{I}_b^{(2)} = \frac{dI_x}{d\omega} = \mathscr{I}_0 + 3\,\mathscr{I}_1\omega^2 \ .$$

For $K = 0$ bands, $\hbar\omega$ is half of the transition energy, and so experimental estimates of $\mathscr{I}_b^{(2)}$ can be deduced from $\Delta I/\Delta\omega$ for two consecutive rotational transitions in a band. The experimental values for ^{166}Yb are displayed in Fig. 2.69*b*.

In Fig. 2.69*a*, one can easily observe the different behavior of the moment of inertia with rotational frequency in the ground vs the S bands. While $\mathscr{I}_b^{(1)}$ increases constantly with ω^2 in the ground band, this quantity is more constant in the S band. This is more easily seen in Fig. 2.69*b*, where the parameter $\mathscr{I}_1$ expresses this difference: $\mathscr{I}_1$ is 4.5 times larger in the ground band than in the S band. In addition, one notices a larger value of $\mathscr{I}_0$ for the S band by extrapolating to $\omega = 0$.

Figure 2.70 presents a summary of $\mathscr{I}_0$ and $\mathscr{I}_1$ values extracted from experimental data in this way for ground and S bands in a number of light rare-earth nuclei. In order to extract reasonable values for an S band, one must know experimentally three or four rotational transitions after the completion of the band crossing. This excludes from this systematic representation many back-bending cases, especially if the crossing has the nature of a weak up bend.

The trend for Fig. 2.70 is clear: in all cases $\mathscr{I}_0$ is larger and $\mathscr{I}_1$ smaller for the S band compared



2.69. Moments of inertia for the yrast band in ^{166}Yb. (*a*) Plot of $\mathscr{I}_b^{(1)} = I_x/\omega$ vs $(\hbar\omega)^2$; (*b*) plot of $\mathscr{I}_b^{(2)} = dI/d\omega$. G and S refer to the ground and S bands respectively. The data of Walus (ref. 5) are used for the states of highest spins.

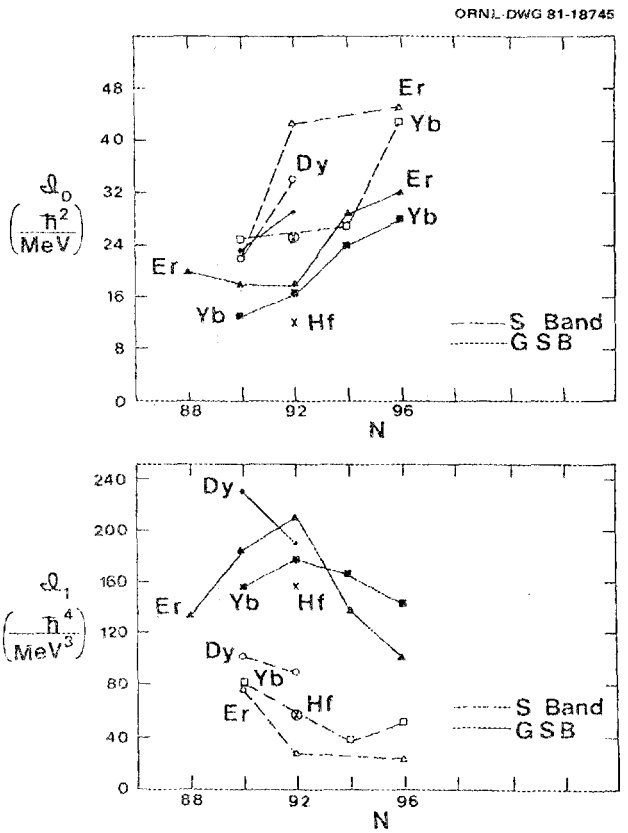


Fig. 2.70. Values of the moment of inertia parameters, $\mathscr{I}_0$ and $\mathscr{I}_1$, for some back-bending nuclei. Dark symbols and lines, ground-state bands; open symbols, S bands. These values are extracted from experimental transition energies, as demonstrated in Fig. 2.69*b*.

with the ground band. Furthermore, $\mathscr{I}_0$ and $\mathscr{I}_1$ values extracted from a one-q.p. band in ^{161}Yb (ref. 3) are intermediate to the 0 and two-q.p. values for $N = 90$ and 92 in Fig. 2.70. An increase in the number of quasi particles evidently increases the deformation ($\mathscr{I}_0$ increases) and decreases the degree to which $\mathscr{I}$ varies with frequency ($\mathscr{I}_1$ decreases). This is a new correlation which must be calculated theoretically from basic models. In a loose way, $\mathscr{I}_1$ can be viewed as the coefficient of the "stretching" term in the moment of inertia. This is not necessarily a physical stretching but more an increase due to a gradual decrease in the pairing correlations, prompted by the nuclear rotation. The trend shows consistently less "stretching" for S bands compared with ground bands.

Of interest, then, is to extract $\mathscr{I}_0$ and $\mathscr{I}_1$ from a four-q.p. aligned band. We observed two rotational transitions after the second yrast back bend in ^{160}Yb, as shown in Fig. 2.68. This leads to one point in the $\mathscr{I}_b^{(2)}$ vs ω^2 plot, which of course is insufficient for extracting $\mathscr{I}_0$ and $\mathscr{I}_1$ for this four-q.p. band. Studies of higher spins beyond the second back bend in ^{160}Yb (and other cases) are important for learning the behavior of the collective moment of inertia in certain four-q.p. bands at high frequencies.

1. University of Tennessee, Knoxville.
2. R. Bengtsson and S. Frauendorf, *Nucl. Phys.* **A327**, 139 (1979).
3. L. L. Riedinger, Nobel Symposium on High Spin States, to be published in *Physica Scripta.*
4. S. Frauendorf, Nobel Symposium on High Spin States, to be published in *Physica Scripta.*
5. W. Walus, Nobel Symposium on High Spin States, to be published in *Physica Scripta.*

LIFETIME MEASUREMENTS IN ^{162}Dy

M. W. Guidry[1] I. Y. Lee
N. R. Johnson R. M. Diamond[2]
F. S. Stephens[2]

We have used multiple Coulomb excitation and Doppler-broadened line shape (DBLS) methods to study the nucleus ^{162}Dy. The Coulomb excitation measurements utilized 1-mg/cm^2 targets and 595-and 623-MeV ^{136}Xe beams with gamma rays detected in coincidence with scattered particles. By using multiplicities determined from an NaI array, expected systematics, and variation of intensity with particle scattering angle and incident energy, levels in the ground band have been assigned through spin 20 (spins 14–20 were not known before). They are displayed in Table 2.10.

Thick targets were used in the DBLS measurements, and gamma rays were detected in singles mode. Line-shape fitting yielded the mean lives displayed in Table 2.10, and they are seen to be rotational within experimental error. These data represent another of several examples demonstrating the remarkable ability of the rotational model to correctly predict transition probabilities at high spin, even when energy levels systematically deviate from the rotational model.

Table 2.10. Measured lifetimes and energies of transitions in ^{162}Dy in comparison with predictions of a rotational model

I	E_γ (MeV) for $I \to I-2$	τ (ps) DBLS[a]	τ (ps) Rotor
2+	0.0807		3164.9
4+	0.1850		187.6
6+	0.2829		24.7
8+	0.3728	5.9 ± 0.5	6.18
10+	0.4538	2.1 ± 0.2	2.28
12+	0.527	1.1 ± 0.1	1.07
14+	0.592	0.65 ± 0.07	0.59
16+	0.649		0.37
18+	0.693		0.27
20+	(0.718)		0.22

[a]Doppler-broadened line shape.

This behavior can be understood on the basis of a Coriolis antipairing compression of energy levels, which has only a small effect on transition probabilities.

1. University of Tennessee, Knoxville.
2. Lawrence Berkeley Laboratory.

HIGH-SPIN PROPERTIES OF ^{164}Er

N. R. Johnson
I. Y. Lee
L. L. Riedinger[3]
A. C. Kahler[3]
R. S. Simon[5]
P. Colombani[5]
R. M. Diamond[5]
R. D. Hichwa[6]
S. W. Yates[1]
E. Eichler[2]
M. W. Guidry[3]
D. Cline[4]
P. A. Butler[5]
F. S. Stephens[5]
R. M. Ronningen[6]
J. H. Hamilton[6]
E. L. Robinson[7]

In the last progress report from the ORNL Physics Division we[8] detailed our findings on the multiple band crossings in ^{164}Er. Since that time, our extensive studies on this nucleus have been completed, and all of our results now appear[9-11] in the published literature.

The high-spin states in ^{164}Er were studied by using conventional gamma-ray spectroscopy techniques following the reactions ^{150}Nd(^{18}O,4$n\gamma$) and ^{164}Dy(α,4$n\gamma$), as well as by measuring the gamma-ray yields and the Doppler-broadened line shapes following Coulomb excitation with ^{136}Xe ions. Based on the results of all these measurements, we derived the level scheme shown in Fig. 2.71. In addition to the information on the ground, rotation-aligned, and γ-vibrational bands shown in our last report,[8] this scheme includes two well-developed negative-parity bands as well as an even-spin band with unassigned parity. These results are in basic agreement with those recently reported by Kistner et al.[12]

We found the existence of back-bending in the positive-parity yrast sequence, the even-spin sequence of the γ band, and the odd-spin sequence of

ORNL-DWG 79-15125

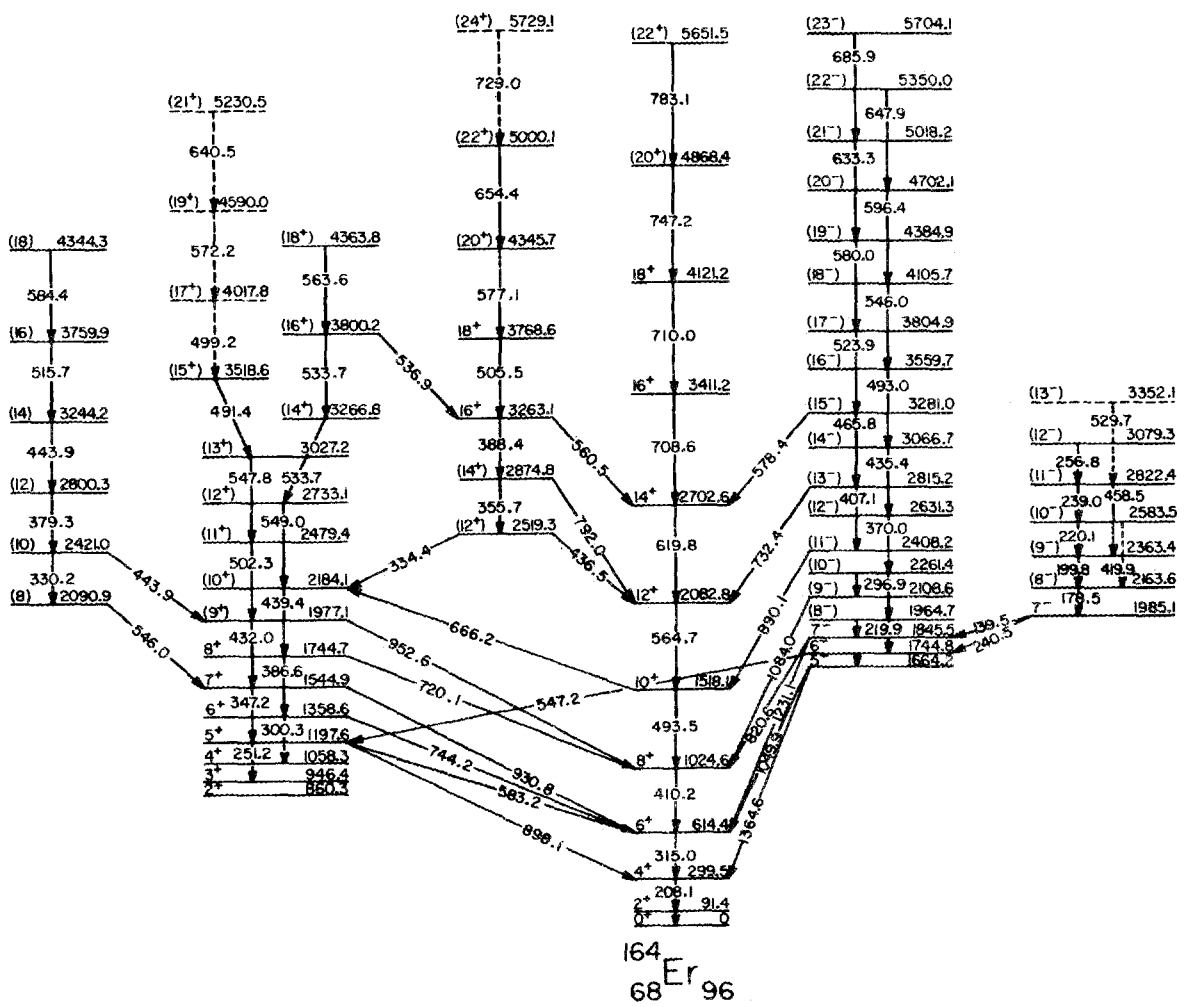


Fig. 2.71. Level scheme of ^{164}Er determined from Coulomb excitation, ^{150}Nd(^{18}O,4n)^{164}Er, and ^{164}Dy(α,4n)^{164}Er reactions.

the γ band. This back-bending behavior of the positive-parity yrast sequence is demonstrated to result from the intersection of the ground band, seen to spin 22^+, with an even-spin "superband," having a large moment of inertia, which is observed from spins 12^+ to 24^+. The observed interaction between this yrast superband and the γ band demonstrates that this band possesses only even-spin members for $I \geqslant 12^+$. We have found additional even-spin (yrare even) and odd-spin (yrast odd) superbands which possess large moments of inertia and lie about 0.5 MeV above the lowest superband. The interaction of these bands with the γ band was observed. Although the evidence is weak, the data also imply that the ground-state and yrare even-spin bands intersect at $I \cong 24$. The observed level energies and gamma-ray branchings are consistent with the three superbands having a constant 45-keV interaction matrix element with the ground-state and γ bands. The level energies of the two negative-parity bands are observed to behave differently; namely, the 7^- band behaves like a good rotor while the 5^- band exhibits an odd-even staggering characteristic of a rotation-aligned band.[13,14] In fact, rotation-alignment-model calculations show good agreement with all of the observed properties discussed here.

A summary of the $B(E2)$ values deduced from both the Coulomb excitation yields and the Doppler-broadened line shape measurements is given in Table 2.11. We see no strong evidence for deviation from a good rotational picture, contrary to the earlier findings of Kearns et al.[15] They reported that, for the $12^+ \rightarrow 10^+$ transition, there was more than a 30% deviation between experiment and theory. Our data in Table 2.11 are consistent with a picture of interacting rotational bands with an interaction matrix element $\cong$ 45 keV. In particular, the $B(E2)$ values for the unperturbed ground band are in agreement with the rigid-rotor relation, that is, with a constant intrinsic quadrupole moment, while the excitation of the γ band is consistent with the prediction of the rigid-triaxial-rotor model with asymmetry $\gamma = 12.7°$.

1. University of Kentucky, Lexington.
2. Deceased.
3. University of Tennessee, Knoxville.

Table 2.11. Lifetimes and $B(E2)$ values for states in ^{164}Er

Transition $I \rightarrow I-2$	Mean life, τ_{exp} (ps)	$B(E2; I \rightarrow I-2)$ $(e \cdot b)^2$ Doppler-broadened line shape	Multiple Coulomb excitation	Previous work	Rigid rotor
		Ground band			
$4^+ \rightarrow 2^+$				$\pm$ 0.14[a]	1.57
$6^+ \rightarrow 4^+$					1.73
$8^+ \rightarrow 6^+$	3.69 $\pm$ 0.18	1.86 $\pm$ 0.09		1.78 $\pm$ 0.13[b]	1.81
$10^+ \rightarrow 8^+$	1.46 $\pm$ 0.09	1.91 $\pm$ 0.12	1.70 $\pm$ 0.16	1.96 $\pm$ 0.12[b]	1.85
$12^+ \rightarrow 10^+$	0.8 $\pm$ 0.06	1.75 $\pm$ 0.13	1.89 $\pm$ 0.19	1.19 $\pm$ 0.09[b]	1.89
$14^+ \rightarrow 12^+$			2.33 $\pm$ 0.32		1.91
$16^+ \rightarrow 14^+$			1.52 $\pm$ 0.28[c]		1.93
		Superband			
$16^+ \rightarrow 14^+$			$\leqslant$2.8		
		γ band			
$12^+_\gamma \rightarrow 10^+_\gamma$			1.5 $\pm$ 0.7		1.59
$14^+_\gamma \rightarrow 12^+_\gamma$			1.9 $\pm$ 0.9[c]		1.62

[a]Ref. 16—lifetime measurement by a microwave technique.

[b]Ref. 15—Doppler-broadened line shape measurement.

[c]Gamma ray unresolved from weaker transition between next two higher members of the collective band. This quoted $B(E2)$ value was extracted by assuming that the weaker transition from the higher transition was correctly calculated using a $B(E2)$ value given by the rotational model.

4. University of Rochester, Rochester, N.Y.
5. Lawrence Berkeley Laboratory, Berkeley, Calif.
6. Vanderbilt University, Nashville, Tenn.
7. University of Alabama, Birmingham.
8. N. R. Johnson, D. Cline, S. W. Yates, F. S. Stephens, L. L. Riedinger, and R. M. Ronningen, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978,* ORNL-5498, P. 37 (June 1979).
9. N. R. Johnson, D. Cline, S. W. Yates, F. S. Stephens, L. L. Riedinger, and R. M. Ronningen, *Phys. Rev. Lett.* **40**, 151 (1978).
10. S. W. Yates, I. Y. Lee, N. R. Johnson, E. Eichler, L. L. Riedinger, M. W. Guidry, A. C. Kahler, D. Cline, R. S. Simon, P. A. Butler, P. Colombani, F. S. Stephens, R. M. Diamond, R. M. Ronningen, R. D. Hichwa, J. H. Hamilton, and E. L. Robinson, *Phys. Rev. C* **21**, 2366 (1980).
11. I. Y. Lee, D. Cline, R. S. Simon, P. A. Butler, P. Colombani, M. W. Guidry, F. S. Stephens, R. M. Diamond, N. R. Johnson, and E. Eichler, *Phys. Rev. Lett.* **37**, 420 (1976).
12. O. C. Kistner, A. W. Sunyar, and E. der Mateosian, *Phys. Rev. C* **17**, 1417 (1978).
13. F. S. Stephens and R. S. Simon, *Nucl. Phys.* **A183**, 257 (1972).
14. C. Flaum and D. Cline, *Phys. Rev. C* **14**, 1224 (1976).
15. F. Kearns, G. Varley, G. D. Dracoulis, T. Inamura, J. C. Lisle, and J. C. Wilmott, *Nucl. Phys.* **A278**, 109 (1977).
16. I. Ben-Zvi, A. E. Blaugrund, Y. Dar, G. Goldring, J. Hess, M. W. Sachs, E. Z. Skurnik, and Y. Wolfson, *Nucl. Phys.* **A117**, 625 (1968).

REDUCED $M1$, $E1$, $E2$, AND $E3$ TRANSITION PROBABILITIES FOR TRANSITIONS IN $^{156-160}$Gd AND $^{160-164}$Dy

F. K. McGowan W. T. Milner

Direct $E2$ and $E3$ Coulomb excitation of 2^+ and 3^- states in $^{156-160}$Gd and $^{160-164}$Dy has been measured by means of gamma-ray spectroscopy. Vibrational-like 2^+ and 3^- states were identified in each nucleus. The $B(E\lambda,0 \rightarrow J = \lambda)$ for excitation of each state and information on the reduced transition probabilities for the different decay modes of these states have been extracted from the data. The occurrence of a rather low-lying $K = 2$ γ-vibrational-like band is a systematic feature of the even-A deformed nuclei. The observed nuclear structure properties of the $2'^+$ member in $^{156-160}$Gd and $^{160-164}$Dy are remarkably similar, namely, the $B(E2,0 \rightarrow 2')$, the large value of $\delta = (E2/M1)^{1/2}$ for the $2'^+ \rightarrow 2^+$ transition, and the branching data for decay of the $2'^+$ state. On the other hand, the $K = 0$ vibrational-like states are highly variable, and usually the $B(E2,0 \rightarrow 2)$ values are at least an order of magnitude less than the $B(E2,0 \rightarrow 2')$ values. The pairing interaction of the IBA Hamiltonian provides a good description of these general features. The displacement of the $K,J^\pi = 0,2^+$ state above the $K,J^\pi = 2,2^+$ increases with increasing pairing interaction, and the $B(E2,0 \rightarrow 2)$ for excitation of the $K,J^\pi = 0,2^+$ state decreases. This behavior seems to be a systematic feature of the even-A deformed nuclei in the rare-earth region. In general, the interacting boson approximation (IBA) model provides a detailed quantitative description of the level energies and of the $E2$ transition probabilities. In ^{156,158}Gd the properties of the two excited $K = 0^+$ bands cannot be reproduced simultaneously by the present IBA calculations. These intruder states are presumably associated with other low-lying degrees of freedom. Work in the direction to extend the IBA model to include other modes of excitation is in progress.[1]

A microscopic description of octupole vibrational states explains satisfactorily the general features of the distribution of the $B(E3)$ strength and the energy intervals within rotational bands. In particular, the agreement between experimental data and the calculations[2] provides further evidence of the strong Coriolis coupling between the states of the octupole quadruplet in the deformed nuclei. The Coriolis coupling is of major importance for interpretation of the reduced $E1$ transition probabilities for transitions connecting members of the octupole quadruplet with $K^\pi = 0^+$ bands. The reduced $E1$ matrix elements $\langle 0^+ \mid M'(E1;-K) \mid K^- \rangle$ with $K = 0$ and 1 extracted from our data have a characteristic feature; namely, the ratio of the $E1$ matrix element M' with $\Delta K = 1$ to that with $\Delta K = 0$ is very small (10^{-1} to 10^{-3}). Extreme caution must be exercised in making K assignments for octupole states based on experimental $B(E1)$ branching ratios and the Alaga-rule prediction.

---

1. F. Iachello, private communication, 1979, and in *Structure of Medium-Heavy Nuclei, 1979,* The Institute of Physics, London, 1980, pp. 161–68.
2. K. Neergård and P. Vogel, *Nucl. Phys.* **A145**, 33 (1970) and private communication.

INTERACTING BOSON APPROXIMATION MODEL ANALYSIS OF $E2$ TRANSITION PROBABILITIES FOR TRANSITIONS IN $^{166-170}$Er

F. K. McGowan

The $B(E2)$ values[1] for the different decay modes of the 2^+ states in $^{166-170}$Er are compared with theoretical predictions from the IBA model. These

calculations were done using the IBA computer code[2] PHINT. The interation parameters in the IBA Hamiltonian were adjusted to fit typically 14 state energies in each nucleus. In the calculations of the transition probabilities, the parameters E2SD and E2DD in the $E2$ transition operator were adjusted to reproduce the experimental $B(E2,0 \rightarrow 2)$ values for excitation of the 2^+ members of the ground-state and γ-vibrational-like bands. Values of the parameters for the IBA calculations are given in Table 2.12. The average deviation between experimental and theoretical energies is 8.9 keV for a fit to 13 state energies in ^{170}Er. The values of the parameters in Table 2.12 correspond to a truncation of the total number of bosons to 14. Actually, the total numbers of bosons are 15, 16, and 17 for $^{166-170}$Er respectively. To test the influence of the truncation on the predictions, a calculation for ^{170}Er was also done with the total number of bosons truncated to $N = 11$. The results are indistinguishable from those for $N = 14$.

The results of the calculations are given in Table 2.13. It is evident from Table 2.13 that the $B(E2)$ values for the $2 \rightarrow 2$ and $2 \rightarrow 4$ transitions from the decay of the $K,J^\pi = 2,2^+$ state are reproduced reasonably well by the IBA predictions. The breaking of the SU(3) symmetry by the pairing interaction in the IBA Hamiltonian plays a crucial role in giving a quantitative account of the $B(E2)$ values for decay of the $K,J^\pi = 0,2^+$ state to the ground-state band. The experimental $B(E2)$ values for excitation of this 2^+ state are at least an order of

Table 2.12. Values of the parameters used in the IBA calculations
(These parameters correspond to the variable names in program PHINT for the IBA Hamiltonian expressed interms of the "multipole expansion")

Nucleus	PAIR (keV)	ELL (keV)	QQ (keV)	E2SD (eb)	E2DD (eb)
^{166}Er[a]	16.51	18.33	−17.92	0.1478	−0.1156
^{168}Er[a]	21.50	19.20	−18.80	0.1468	−0.1300
^{170}Er[a]	1.06	17.08	−21.23	0.1482	−0.1367
^{170}Er[b]	1.37	14.83	−27.28	0.1812	−0.1988

[a]Total number of bosons truncated to 14.
[b]Total number of bosons truncated to 11.

Table 2.13. Experimental and IBA-predicted $B(E2)$ values

	Initial state		Final state		$B(E2,J_i \rightarrow J_f)$ ($10^{-50}e^2$cm^4)	
Nucleus	K_i,J_i^π	E (keV)	K_f,J_f^π	E (keV)	Exp	IBA
^{166}Er	$2,2^+$	785.9	$0,0^+$	0	2.80 ± 0.16	2.80
			$0,2^+$	80.6	5.39 ± 0.29	4.27
			$0,4^+$	265.0	0.42 ± 0.04	0.27
	$0,2^+$	1159	$0,0^+$	0	0.084 ± 0.012	0.084
			$0,2^+$	80.6	0.096 ± 0.020	0.132
			$0,4^+$	265.0		0.29
			$2,2^+$	785.9	0.45 ± 0.09	2.75
^{168}Er	$2,2^+$	821.1	$0,0^+$	0	2.62 ± 0.16	2.62
			$0,2^+$	79.8	4.77 ± 0.29	3.97
			$0,4^+$	264.1	0.28 ± 0.03	0.24
	$0,2^+$	1261	$0,0^+$	0	< 0.13	0.047
^{170}Er	$2,2^+$	934	$0,0^+$	0	2.04 ± 0.12	2.04
			$0,2^+$	78.6	3.68 ± 0.26	3.25
			$0,4^+$	260	0.22 ± 0.03	0.20
	$0,2^+$	960	$0,0^+$	0	0.16 ± 0.02	0.27
			$0,2^+$	78.6	0.28 ± 0.06	0.47
			$0,4^+$	260	0.95 ± 0.15	1.01

magnitude smaller than the $B(E2)$ values for excitation of the $K,J^\pi = 2,2^+$ state and thus provide a comprehensive test of the IBA predictions.

The IBA prediction of the $B(E2)$ for excitation of the $K,J^\pi = 0,2^+$ state in ^{168}Er is consistent with the upper limit of the $B(E2,0 \rightarrow 2)$ for excitation of a state at 1261 keV [1276 keV from the (n,γ) reaction]. An extensive test of the IBA predictions for a complete set of states with $J < 6$ below 2 MeV excitation in ^{168}Er from the (n,γ) reaction and for the $B(E2)$ branching ratios has already been reported by Warner et al.[3] The IBA model provides a detailed quantitative description of the level energies and of the $E2$ transition branching ratios. One feature pointed out by Warner et al. in the predictions and in the data is the dominant strength of $E2$ transitions from the β-vibrational-like band to the γ-vibrational-like band compared with those to the ground-state band. This feature appears to be present in the decay of the 2^+ state at 1159 keV in ^{166}Er. However, the $B(E2)$ for the 373-keV transition in ^{166}Er is 6 times smaller than the IBA prediction. Discrepancies[4] of this magnitude were also observed in the comparison of the experimental and IBA-predicted $B(E2)$ values for corresponding decay modes of the $K,J^\pi = 0,2^+$ state at 1517 keV in ^{158}Gd.

In general, the IBA model provides a detailed quantitative description of the level energies and of the $E2$ transition probabilities for decay of 2^+ states. The displacement of the $K,J^\pi = 0,2^+$ state above the $K,J^\pi = 2,2^+$ increases and the $B(E2,0 \rightarrow 2)$ for excitation of the $K,J^\pi = 0,2^+$ state decreases with increasing pairing interaction in the IBA Hamiltonian. This characteristic feature occurs in several even-A nuclei in the rare-eath region ($^{156-160}$Gd, $^{160-164}$Dy, and $^{166-170}$Er). A knowledge of $B(E2)$ values provides a more comprehensive test of the IBA model predictions than branching ratio data [relative $B(E2)$ values] do.

1. F. K. McGowan, W. T. Milner, R. L. Robinson, P. H. Stelson, and Z. W. Grabowski, *Nycl. Phys.* **A297**, 51 (1978).
2. Olaf Scholten, unpublished.
3. D. D. Warner, R. F. Casten, and W. F. Davidson, *Phys. Rev. Lett.* **45**, 1761 (1980).
4. F. K. McGowan and W. T. Milner, *Phys. Rev. C* **23**, 1926 (1981).

COULOMB EXCITATION STUDY OF ^{182,184,186}W ISOTOPES

Ph. Hubert[1] C. Roulet[2]
H. Sergolle[2] P. Colombani[2]
J. M. La Grange[2] J. Vanhorenbeeck[3]
N. R. Johnson

Multiple Coulomb excitation is a well-adapted technique for the study of collective properties in rare-earth and actinide nuclei excited to high spin. Here, we have applied the method to the transitional nuclei ^{182,184,186}W by using a 340-MeV ^{84}Kr beam from the ALICE accelerator in Orsay.

Deexcitation gamma rays intercepting a Ge(Li) detector at 22° to the beam were measured in coincidence with Kr projectiles scattered into two silicon detectors positioned at 93 and 122°. The extracted gamma-ray yields were then compared with the theoretical calculations performed with the use of $E2$ and $E4$ matrix elements in the Winther-deBoer code.[4] The summary of $B(E2)$ information given in Table 2.14 shows that the three nuclei ^{182}W, ^{184}W and ^{186}W behave in a rotational fashion, at least up to spins of 10 or 12 in their ground bands. A complete account of this work appears in ref. 9.

An interesting point arises in the comparison of the behavior of the yrast lines of ^{182,184,186}W with those of all the known tungsten isotopes of mass 180 and lighter. All of the latter group show either back-bending or up-bending, whereas the mass 182, 184, and 186 tungsten nuclei give no indication of such up to spins 10–12.

Pertinent to the above consideration is the recent work of Faessler et al.[10] They have carried out microscopic calculations and find that the back-bending effect in this region is in every case primarily due to the $i_{13/2}$ neutrons (not the $h_{9/2}$ protons). They point out that the occurrence of back-bending in ^{180}W but not in ^{182}W is probably associated with changes in the Nilsson energy levels as a result of variations in hexadecapole deformations. However, it is interesting to consider the possibility that ^{182}W may back bend at somewhat higher spin. The case here is somewhat analogous to that of ^{182}Os and ^{184}Os, which show back-bending at spins of 10^+ and 14^+ respectively. It would thus seem of some importance to attempt the excitation of higher spin states in ^{182,184,186}W by the use of heavier

Table 2.14. Experimental $B(E2)$ values and the corresponding rotational values for ^{182,184,186}W

Nucleus	I_i	I_f	$B(E2)_{exp}$	$B(\ 2)$	$B(E2)_{exp}/B(E2)_{Rot}$
^{182}W	2	0	0.84 ± 0.01[a]	0.84	1
	4	2	1.16 ± 0.08[b]	1.20	1.00 ± 0.07
	6	4	1.32 ± 0.07	1.32	1.00 ± 0.06
	8	6	1.47 ± 0.10	1.38	1.06 ± 0.08
	10	8	1.49 ± 0.12	1.42	1.05 ± 0.09
	12	10	1.11 ± 0.28	1.44	0.77 ± 0.20
^{184}W	2	0	0.76 ± 0.01[c]	0.76	1
	4	2	1.03 ± 0.07[b]	1.08	0.95 ± 0.07
	6	4	1.18 ± 0.08	1.20	0.98 ± 0.07
	8	6	1.51 ± 0.13	1.25	1.20 ± 0.10
	10	8	1.82 ± 0.34	1.29	1.41 ± 0.26
^{186}W	2	0	0.68 ± 0.01[c]	0.68	1
	4	2	1.93 ± 0.09[b]	0.97	0.96 ± 0.09
	6	4	1.15 ± 0.09	1.07	1.07 ± 0.09
	8	6	1.19 ± 0.11	1.12	1.06 ± 0.10
	10	8	1.17 ± 0.30	1.15	1.02 ± 0.26

[a]Ref. 5.
[b]Ref. 6.
[c]Average value from ref. 7 and 8.

projectiles. This should give some clarification on how the addition of neutron pairs shifts the critical $i_{13/2}$ (9/2 + [624]) orbital with respect to the Fermi levels in these nuclei.

1. Centre d'Etudes Nucléaires de Bordeaux-Gradignan, Gradignan, France.
2. Institut de Physique Nucléaire, Orsay, France.
3. Université Libre de Bruxelles, Belgium.
4. A. Winther and J. deBoer, p. 303 in *Coulomb Excitation*, ed. K. Alder and A. Winther, Academic Press, New York, 1966.
5. C. E. Bemis, P. H. Stelson, F. K. McGowan, W. T. Milner, J. L. C. Ford, R. L. Robinson, and W. Tuttle, *Phys. Rev. C* **8**, 1934 (1973).
6. W. T. Milner, F. K. McGowan, R. L. Robinson, P. H. Stelson, and R. O. Sayer, *Nucl. Phys.* **A177**, 1 (1971).
7. I. Y. Lee, J. X. Saladin, C. Baktash, J. E. Holden, and J. O'Brien, *Phys. Rev. Lett.* **33**, 383 (1974).
8. R. G. Stokstad and B. Persson, *Phys. Rev.* **170**, 1072 (1968).
9. Ph. Hubert, C. Roulet, H. Sergolle, P. Colombani, J. M. La Grange, J. Vanhorenbeeck, and N. R. Johnson, *Nucl. Phys.* **A321**, 213 (1979).
10. A. Faessler, M. Ploszajczak, and K. R. Sandhya Devi, *Nucl. Phys.* **A301**, 382 (1978).

INTERPRETATION OF THE 21-ns ISOMER IN ^{190}Hg AS $(\nu i_{13/2})^2$ FROM A *G*-FACTOR MEASUREMENT

S. A. Hjorth[1] I. Y. Lee
J. R. Beene C. Roulet[2]
D. R. Haenni Noah R. Johnson
Felix E. Obenshain G. R. Young

The first back bend found in many deformed nuclei in the mass region A = 150 to 208 is explained as an alignment of a pair of $i_{13/2}$ neutrons (see, e.g., Stephens[3]). However, published level schemes of $^{190-196}$Hg and ^{194}Pt exhibit a low-lying isomeric 10^+ level, while the 12^+ level is shown at somewhat higher excitation.[4-7] Such a level sequence does not arise naturally in the $(\nu i_{13/2})^2$ configuration, and the first 10^+ level in $^{190-196}$Hg and in ^{194}Pt has therefore been explained as a $(\pi h_{11/2})_{10+}^{-2}$ state.[4,6,8] A measurement of the nuclear g factor should easily distinguish between these possibilities in a model-independent way. This is true because the g factor for a $\pi h_{11/2}$ excitation is close to unity, whereas the g factor of an $i_{13/2}$ neutron is about −0.2.

In the present experiment, 94-MeV ^{14}N ions from the Oak Ridge Isochronous Cyclotron were used to produce ^{190}Hg nuclei in a 0.114-mm-thick annealed foil of ^{181}Ta which was mounted in a target chamber between the pole tips of a magnet. Pulse heights from three Ge(Li) detectors (located at 0 and at $\pm 135°$) and the times relative to the cyclotron beam bursts were stored in list mode on magnetic tape. The time of arrival of a beam burst was obtained from a device[9] containing a thin plastic scintillator inserted in a path of the beam. In this way, data were recorded in the same detector geometry for the three field settings $B = 0$ and $B = \pm 2.0$ T.

In the measurement with no magnetic field the time distributions observed in all three detectors are consistent with a purely exponential decay. By fitting the time distributions with an exponential decay curve plus a constant background, we obtain $t_{1/2} = 21 \pm 2$ ns for the isomeric state in ^{190}Hg. This value agrees with that of 24 ± 3 ns reported by Lieder et al.[5]

In measurements with field up and field down, the time distributions were fitted with an expression of the form

$$I_\gamma(t,\theta) = N\{1 + A_2P_2[\cos(\theta - \omega_L t - \delta)]\}\exp(-\lambda t) ,$$

with nearly the same values of the angular distribution coefficient A_2, Larmor frequency ω_L, and beam bending angle δ. The beam bending angle was calculated to be 8.5° by using the measured magnetic field strength along the beam path. The normalized decay spectra were used to form the ratio

$$R(t) = \frac{I_\gamma(t, 135°) - I_\gamma(t, -135°)}{I_\gamma(t, 135°) + I_\gamma(t, -135°)} ,$$

upon which final fits to ω_L were performed for the two cases $B = \pm 2.0$ T. As shown in Fig. 2.72, good fits corresponding to $g = -0.21 \pm 0.02$ with $A_2 = 0.18$ for $B = +2.0$ T and $A_2 = 0.16$ for $B = -2.0$ T were obtained. The main contribution to the experimental uncertainty in the g factor comes from the normalization procedure. The uncertainty produced by the fitting procedure and the corrections due to diamagnetic screening and Knight shifts are much smaller.

The only seniority 2 excitations that can be responsible for a low-lying 10^+ level in ^{190}Hg arise from the $(\pi h_{11/2})^{-2}$ and $(\nu i_{13/2})^2$ configurations. The widely differing values of the gyromagnetic ratios

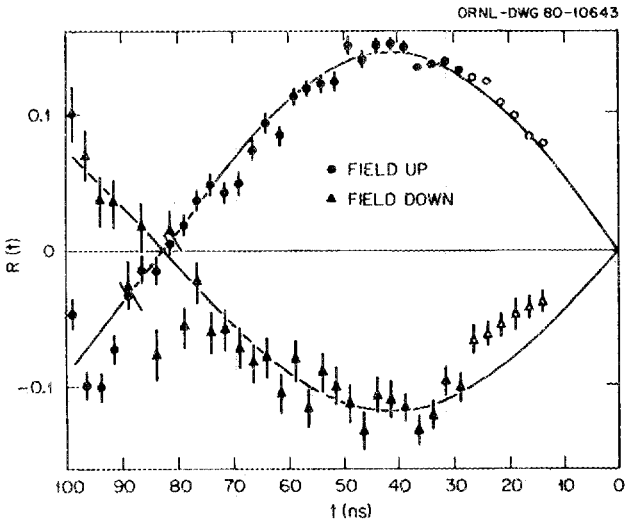


Fig. 2.72. Spin rotation ratio $R(t)$ in ^{190}Hg as a function of time relative to the center of the prompt peak. The figure displays the data for field up and field down as solid round and triangular symbols respectively. The curves are fits to the data described in the text. The data for $t = 30$ ns are affected by prompt events and are excluded from the fits. This is indicated by open symbols in the figure.

for these two configurations (cf. the discussion above) let us uniquely establish the configuration of the isomer as $(\nu i_{13/2})^2$.

In the previously accepted level scheme of ^{190}Hg the 21-ns isomer was identified[5] with the 10^+ state at 2468 keV, and the structure of the state was considered[5] to be $(\pi h_{11/2})^{-2}$ based on the half-life and the small 10^+-to-8^+ level spacing. The spacing between the 12^+ and 10^+ levels of the $(\nu i_{13/2})^2$ configuration should be considerably smaller than the spacing between any pair of lower spin $(\nu i_{13/2})^2$ states, while in the previous level scheme the 12^+-to-10^+ spacing is more than three times the 8^+-to-10^+ spacing. Our result is most easily understood if a 12^+ state exists very close to the 10^+ state, with the 12^+-to-10^+ transition so low in energy that it has not yet been observed. The 21-ns isomer should then be identified with this 12^+ state rather than with the 10^+ state. Further, both the energies and spins of the levels in the yrast band above spin 10^+ should be adjusted to accommodate this unobserved low-energy transition.

Using the value $B(E2;12^+ \rightarrow 10^+) = 2921\ e^2\text{fm}^4$ measured[10] in ^{198}Hg and the 21-ns half-life determined in our work, we estimate the energy of the 12^+-t-10^+ transition in ^{190}Hg to be 12 keV. Such a low-energy transition could easily have escaped

detection in previous work. Also, using the $B(E2;10^+ \rightarrow 8^+)$ value from ^{198}Hg, we estimate the half-life of the 10^+ state in ^{190}Hg to be shorter than 2 ns, supporting our suggestion that the 10^+ state is not the isomer in ^{190}Hg. Furthermore, in nearby isotopes of platinum and lead the $(\nu i_{13/2})^2$ isomerism is well established, with the 12^+-to-10^+ spacings ranging between 3.1 and 60 keV. It is likely that the same type of isomer exists in the mercury isotopes.

In conclusion, our measurement of the g factor of the 21-ns isomer in ^{190}Hg clearly demonstrates that the isomerism is due to the $\nu i_{13/2}$ orbital. The result is contrary to the commonly accepted assignment of the isomer as $(\pi h_{11/2})^{-2}$. Further, it suggests the existence of a hitherto unobserved 12^+ level close to the 10^+ state. Similar situations are likely to exist in $^{192-196}$Hg and in ^{194}Pt.

---

1. On leave from the Research Institute of Physics, Stockholm, Sweden.

2. Present address: Etudes et Productions, Schlumberger, Clamar, France.

3. F. S. Stephens, *Rev. Mod. Phys.* **47**, 43 (1975).

4. D. Proetel, R. M. Diamond, and F. S. Stephens, *Nucl. Phys.* **A231**, 301 (1974).

5. R. M. Lieder, H. Beuscher, W. F. Davidson, A. Neskakis, and C. Mayer Boricke, *Nucl. Phys.* **A248**, 317 (1975).

6. A. W. Sunyar, G. Scharff-Goldhaber, and M. McKeown, *Phys. Rev. Lett.* **21**, 237 (1968).

7. S. A. Hjorth, A. Johnson, Th. Lindblad, L. Funke, P. Kemnitz, and G. Winter, *Nucl. Phys.* **A262**, 328 (1976).

8. T. Inamura, Y. Tendow, S. Nagamiya, and A. Hashizume, *J. Phys. Soc. Jpn.* **32**, 1163 (1972).

9. C. Roulet, G. Albouy, G. Auger, M. P. Bourgarel, J. C. David, J. M. Lagrange, B. Monsanglant, M. Pautrat, H. Richel, H. Sergolle, and J. Vanhorenbeeck, *Nucl. Instrum. Methods* **125**, 29 (1975).

10. C. Gunter, H. Hubel, A. Kleinrahm, D. Mertin, B. Richter, W. D. Schneider, and R. Tischler, *Phys. Rev. C* **15**, 1298 (1977).

COULOMB EXCITATION OF STATES IN ^{191,193}Ir AND A TEST OF THE PARTICLE-ASYMMETRIC-RIGID-ROTOR-MODEL DESCRIPTION OF THESE STATES

F. K. McGowan — N. R. Johnson
I-Y. Lee — W. T. Milner
M. W. Guidry[1] — C. Roulet[2]
R. M. Diamond[3] — F. S. Stephens[3]
J. X. Saladin[4] — A. A. Hussein[4]

The Os and Pt nuclei are in the shape-transition region (prolate-to-oblate shape transition). Several different collective models have accounted for properties of their lowest-lying states with varying degrees of success. These models range from the asymmetric rigid rotor through various rotation-vibration models about triaxial and axial shapes to the gamma-unstable model and the interacting-boson-approximation model.

Lee et al.[5] Coulomb-excited the ground-state band up to $J^\pi = 10^+$ and the γ-vibrational-like band up to $J^\pi = 8^+$ in $^{192-196}$Pt with ^{136}Xe projectiles. The observed gamma-ray yields imply $B(E2)$ values which follow the asymmetric-rigid-rotor-model predictions. This contradicts microscopic collective-model calculations of potential energy surfaces which predict considerable γ softness (shallow deformation potentials). An analysis[6] of unique parity spectra based on high-j negative-parity orbitals in adjacent unstable odd-A nuclei with the rigid-triaxial-rotor-plus-particle model reveals γ values in the range $20° < \gamma < 35°$.

We have observed Coulomb excitation of states in ^{191,193}Ir up to $J = 17/2$ with 617-MeV ^{136}Xe ions from the SuperHILAC and 160-MeV ^{40}Ar ions from the ORIC. At the University of Pittsburgh, Coulomb-excitation measurements from the reaction (α,α') have been done with the EN tandem. Figure 2.73 shows the states from Coulomb excitation of ^{191}Ir with ^{40}Ar ions and the gamma-ray transitions from the decay of these states. The backscattered ^{40}Ar ions were detected in a solid-state annular

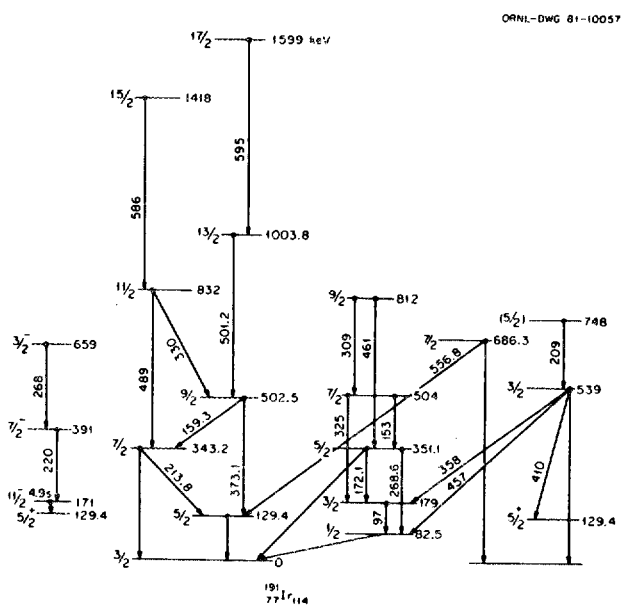


Fig. 2.73. Level diagram of states and transitions observed by Coulomb excitation of ^{191}Ir with 160-MeV ^{40}Ar ions.

detector which extended from 154 to 171°. Gamma rays in coincidence with backscattered ^{40}Ar were detected in three Ge(Li) detectors located at θ_γ = 0, 55, and 90° with respect to the ion beam. Isotopically enriched targets 1.0 mg/cm^2 on 20-μin. Ni (0.51 × 10^{-6} m) were prepared by sputtering with the SPUTTERBELL (focused-ion-beam sputtering system). Most of the states in Fig. 2.73 are grouped into two rotational-like bands based on the 3/2$^+$ ground state and the 1/2$^+$ first excited state.

The original motivation of this experiment was to test the particle-asymmetric-rigid-rotor-model[7] description of the positive-parity states in ^{191,193}Ir. In the meantime, Iachello[8] has suggested that dynamical supersymmetries may be present in the level spectra of complex nuclei. This suggestion was based on the analysis of the energy-level spectra of the pair of nuclei ^{192}Pt and ^{191}Ir, in which the states of the combined system of bosons and fermions can be simultaneously classified within the same group-theoretical framework.

So far, we have compared the experimental gamma-ray yields with the predictions of the particle-asymmetric-rigid-rotor model. The Coulomb-excitation yields are calculated using the program of Winther and deBoer. For the input of the program, we use the experimental level energies and a set of theoretical $E2$ matrix elements. The latter were obtained from calculations using the particle-triaxial-rigid-rotor-model program.[9] The deformation parameters ε and γ were adjusted to give the best agreement between theoretical and experimental excitation energies. The average deviation between experimental and theoretical energies is 30 keV for a fit to 14 state energies in ^{191}Ir with ε = 0.168, γ = 24.5°, and $E(2+)$ = 200 keV. These parameters are very close to those for the $A-1$ core ^{190}Os, namely, ε = 0.157, γ = 22.0°, and $E(2+)$ = 187 keV. This choice of deformation parameters in the calculations reproduces the $B(E2)$ values deduced from light-ion Coulomb excitation of the 5/2$^+$ and 7/2$^+$ members of the 3/2$^+$ band and the 1/2$^+$ and 3/2$^+$ members of the 1/2$^+$ band. The input to the calculations of Coulomb-excitation probabilities involved 20 states and 120 $E2$ matrix elements. Thirteen of these $E2$ matrix elements were fixed by results deduced from light-ion direct $E2$ Coulomb excitation and nuclear spectroscopic information for the decay modes of these states. The remaining $E2$ matrix elements were taken from the particle-asymmetric-rigid-rotor-model calculations.

Figure 2.74 shows the comparison between the experimental and calculated results from Coulomb excitation of ^{191}Ir by 160-MeV ^{40}Ar. The gamma-ray yields for transitions within the rotational-like band based on the 3/2$^+$ ground state are presented in Fig. 2.74 relative to the gamma-ray yields for the 7/2$^+$ → 3/2$^+$ transition. The summation implies the sum of the yields for each transition observed at θ_γ = 0, 55, and 90°. The overall agreement of the particle-asymmetric-rigid-rotor-model predictions with the experimental results is quite good. Figure 2.75 shows the comparison between the experimental and calculated results for the transitions from decay of the K_i, J_i^π = 7/2,7/2$^+$ state at 686.3 keV. Again the particle-asymmetric-rigid-rotor-model predictions are in good agreement with the data. In fact, the model prediction of $\delta \cong [T(E2)/T(M1)]^{1/2}$ =

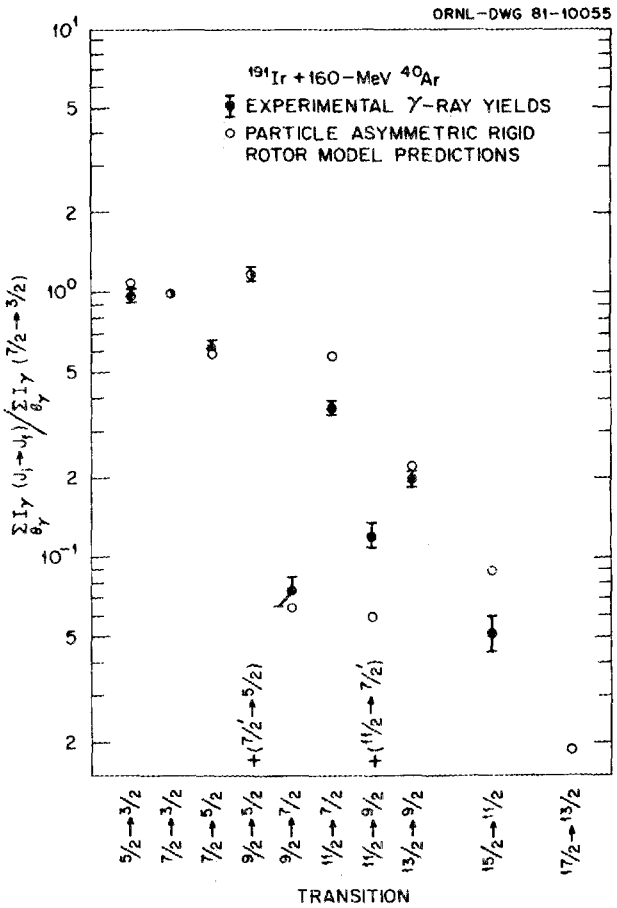


Fig. 2.74. Comparison of the experimental gamma-ray yields with the predictions of the particle-asymmetric-rigid-rotor model for transitions within the rotational-like band based on the 3/2$^+$ ground state of ^{191}Ir.

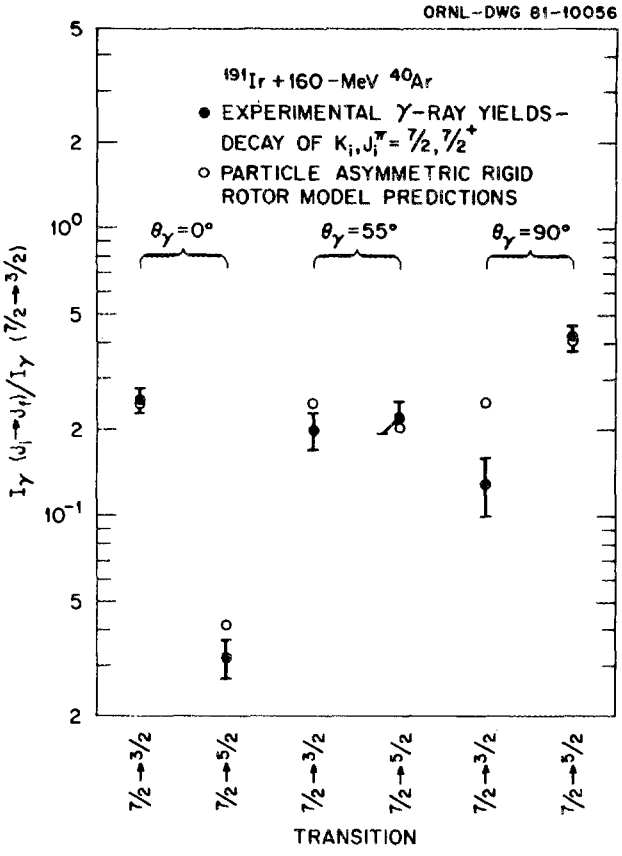


Fig. 2.75. Comparison of the experimental and calculated results for the transitions from the decay of the $KJ^\pi = 7/2,7/2^+$ state at 686.3 keV in ^{191}Ir.

-1.05 for the $7/2 \to 5/2$ transition gives an excellent account of the observed angular distribution for this transition. The agreement between the experimental gamma-ray yields and the model predictions is satisfactory for transitions within the $1/2^+$ rotational-like band and for transitions between the $1/2^+$ and $3/2^+$ rotational-like bands (not shown).

The states observed from Coulomb excitation of ^{193}Ir and the gamma-ray transitions from the decay of these states are nearly identical to the results from ^{191}Ir.

---

1. University of Tennessee, Knoxville.
2. Institut de Physique Nucléaire, Orsay, France.
3. Lawrence Berkeley Laboratory, Berkeley, Calif.
4. University of Pittsburgh, Pittsburgh. Pa.
5. I. Y. Lee, D. Cline, P. A. Butler, R. M. Diamond, J. O. Newton, R. S. Simon, and F. S. Stephens, *Phys. Rev. Lett.* **39**, 684 (1977).
6. J. Meyer-Ter-Vehen, *Nucl. Phys.* **A249**, 111, 141 (1975).
7. Ch. Vieu, S. E. Larsson, G. Leander, I. Ragnarsson, W. DeWieclawik, and J. S. Dionisio, *Z. Phys.* **A290**, 301 (1979).
8. F. Iachello, *Phys. Rev. Lett.* **44**, 772 (1980).
9. Computer code supplied by G. Leander of the Lund Institute, Sweden. Present addres: UNISOR, Oak Ridge National Laboratory.

COULOMB EXCITATION OF ROTATIONAL STATES IN ^{243}Am AND GROUND-STATE QUADRUPOLE MOMENT

C. E. Bemis, Jr. W. T. Milner
F. K. McGowan R. L. Robinson
J. L. C. Ford, Jr. P. H. Stelson

Precision Coulomb-excitation measurements on a series of even-Z–even-A targets which spanned a major portion of the actinide deformed region ($230 \leqslant A \leqslant 252$) were performed and completed during the period 1970–75.[1–4] These previously reported measurements were used to systematically determine transition moments and equilibrium deformations from analyses of the excitation probabilities within the ground-state rotational bands[1–3] and to investigate the nature of higher-lying states of vibrational-like character for these nuclides.[4] Measurements for the odd-A target ^{243}Am were completed with those of the even-A targets, but a comprehensive analysis for ^{243}Am was not performed at that time. The results of the complete analysis for ^{243}Am are included here.

The spectrum of 17-MeV ^{4}He ions scattered from an isotopically pure target of ^{243}Am at a laboratory angle of 150° is shown in Fig. 2.76. The target, about 30 μg/cm^2 of ^{243}Am on a target backing of 1.27×10^{-4}-cm-thick Ni, was prepared using an electromagnetic isotope separator. The experiment was performed at the Oak Ridge EN tandem Van de Graaff using a split-pole magnetic spectrometer equipped with a position-sensitive proportional detector in the focal plane. Further experimental details may be found in ref. 2.

In addition to the elastic scattering from the $5/2^-$ ground state and the inelastic scattering from the previously known $7/2^-$ and $9/2^-$ ground-band rotational states, two additional inelastic peaks at excitation energies of 162.3 and 238 keV are observed. We have assigned these unknown states in ^{243}Am as the $11/2^-$ and $13/2^-$ members of the $5/2^-[523\downarrow]$ ground-state rotational band, as indicated in Fig. 2.76. These states may be Coulomb-excited via two-step $E2$ processes in a manner similar to the excitation of the 4^+ members of the

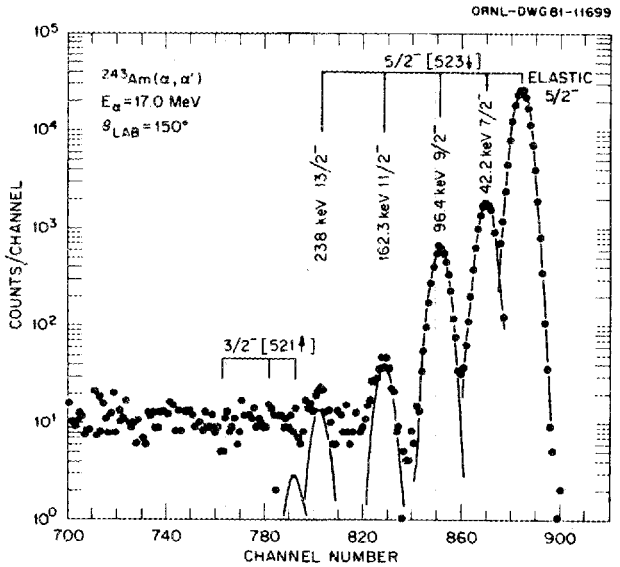


Fig. 2.76. Elastically and inelastically scattered 17-MeV ^{4}He ions from ^{243}Am at a laboratory angle of 150°. Peak positions for observed members of the 5/2⁻[523↓] ground-state rotational band are indicated, together with those expected from the first few members of the unobserved 3/2⁻[521↑] band.

ground-band rotational states in the actinide even-even nuclei. A two-parameter linear least-squares fit to the energies of these rotational states, $I = 5/2$ through 13/2, with the rotational energy expression

$$E = E_0 + A[I(I + 1)] + B[I(I + 1)]^2$$

yields rotational energy constants $A = 6.17$ keV and $B = -3.72$ eV. The small magnitude of the B term, comparable to that for neighboring even-even nuclei, indicates that these states are not noticeably Coriolis-admixed with other states of different single-particle character. These configurations include the 3/2⁻[521 ↑] and 7/2⁻[514 ↓] states known[5] in ^{243}Am at band-head energies of 267 and about 933 keV respectively. Excitation of members of these bands was not observed in our experiments above a detection limit which corresponded to a transition probability, $B(E2,5/2^- \rightarrow I)$, of $\lesssim 7 \times 10^{-3}$ e^2b^2, approximately 0.5 times the single-particle transition probability. The expected locations for the first few members of the 3/2⁻[521 ↑] band are also shown in Fig. 2.76.

Experimental excitation probabilities for members of the ground-state rotational band were determined relative to the elastic scattering peak and compared with calculated Coulomb-excitation cross sections to extract the transition matrix elements. The calculations were performed with the semiclassical $E2$ coupled-channels code of Winther and de Boer, modified to include $E1$, $E3$, and $E4$ excitations. Our calculations included all possible reduced $E2$ and $E4$ matrix elements connecting the observed 5/2⁻, 7/2⁻, 9/2⁻, 11/2⁻, and 13/2⁻ members and the unobserved 15/2⁻ and 17/2⁻ members of the ground-state band. The calculations were performed in the "rigid rotor" limit applicable to a pure rotational spectrum, as justified by the convergence of the rotational energy expression and the magnitude of the fourth-order term, $B = -3.72$ eV, and its comparison with the second-order term, $|B/A| = 6.0 \times 10^{-4}$. Absence of $E2$ excitations to states of differing single-particle character, as would be promoted by the particle-rotational coupling or Coriolis interactions, also justifies the use of the "rigid rotor" relationship, which specifies all intraband reduced matrix elements in terms of the intrinsic electric multipole moments, $Q_{\lambda 0}$, of order λ.

The experimental excitation probabilities for the ground-state band are adequately reproduced by the calculations when only $E2$ excitations are considered with an intrinsic quadrupole moment of 12.02 ± 0.09 eb. Although $E4$ excitations are a feature of Coulomb excitation in the actinide region and may be observed in competition with two-step $E2$ processes, our results are consistent with $Q_{40} \equiv 0$. The even-even actinides near neutron number $N = 148$ also exhibit this effect.[2] Our experimental reduced transition probabilities, $B(E2,5/2^- \rightarrow I)$, for the excitation of the 7/2⁻ and 9/2⁻ are 6.89 ± 0.10 e^2b^2 and 2.38 ± 0.04 e^2b^2.

An estimate[6] of the ground-state spectroscopic quadrupole moment for ^{243}Am, 4.9 eb, was made in 1956 from observations of the optical hyperfine structure. From our Coulomb-excitation experiments, we deduce a somewhat smaller ground-state spectroscopic quadrupole moment of 4.29 ± 0.03 eb by using the projection relation

$$Q = Q_{20} \frac{3K^2 - I(I + 1)}{(I + 1)(2I + 3)}$$

with the intrinsic quadrupole moment $Q_{20} = 12.02 \pm 0.09$ eb. Further details of these experiments on ^{243}Am are being prepared for a brief publication.

1. J. L. C. Ford, Jr., P. H. Stelson, C. E. Bemis, Jr., F. K. McGowan, R. L. Robinson, and W. T. Milner, *Phys. Rev. Lett.* 27, 1232 (1971); F. K. McGowan, C. E. Bemis, Jr., J. L. C.

Ford, Jr., W. T. Milner, R. L. Robinson, and P. H. Stelson, *Phys. Rev. Lett.* **27**, 1741 (1971).

2. C. E. Bemis, Jr., F. K. McGowan, J. L. C. Ford, Jr., W. T. Milner, P. H. Stelson, and R. L. Robinson, *Phys. Rev. C* **8**, 1466 (1973).

3. W. T. Milner, C. E. Bemis, Jr., and F. K. McGowan, *Phys. Rev. C* **16**, 1686 (1977).

4. F. K. McGowan, C. E. Bemis, Jr., W. T. Milner, J. L. C. Ford, Jr., R. L. Robinson, and P. H. Stelson, *Phys. Rev. C* **10**, 1146 (1974).

5, Y. A. Ellis, *Nucl. Data Sheets* **19**, 103 (1976); *Nucl. Data Sheets*, to be published.

6. T. E. Manning, M. Fred, and F. S. Tomkins, *Phys. Rev.* **102**, 1108 (1956).

PRECISION MASS MEASUREMENTS UTILIZING BETA END POINTS

D. M. Moltz — K. S. Toth
F. T. Avignone III[1] — H. Noma[1]
B. G. Ritchie[1] — B. D. Kern[2]

One of the more fundamental measurements in nuclear spectroscopy is the determination of total energies and energy distributions for particles emitted in radioactive decay. At ORNL, we have been involved in a systematic study of alpha-decaying nuclei in the medium-weight mass region with $65 \leqslant Z \leqslant 82$ (see refs. 3 and 4 for summaries of this work). The investigation has yielded both half-life and alpha-decay-energy information for proton-rich nuclides far from stability. These energy data are useful not only for comparisons with mass-formula predictions but also for obtaining estimates of nuclear masses. If the alpha-decay energies can be connected via a series of β^+-decay energies to a stable nucleus, then one has ground-state masses for extremely neutron-deficient isotopes. At the present time, the amount of such beta-decay data is rather sparse. To remedy this situation we have begun a program involving the precise measurements of β^+-decay end points for isotopes mass-separated at the UNISOR facility.

To account for spectral distortions caused by solid-state detectors, a basic Monte Carlo approach[5,6] has been successfully used to predict gamma-ray and negatron spectra. Additional work, however, was necessary to extend these calculations to positron spectra, which are further distorted by sum interferences with the annihilation radiation. Corrections were calculated with the Monte Carlo technique for 15 allowed positron spectra with end points ranging from 2.5 to 10 MeV. The detector dimensions, 1.6 cm in diameter and 0.7 cm thick, used in the calculations corresponded to those of the intrinsic Ge detector in our possession. The major effect of the annihilation radiation interference (ΔE_o) was to shift the end point up in energy from 182 keV at 2.5 MeV to 204 keV at 9 MeV. The shift was fitted by the quadratic polynomial

$$\Delta E_o = 0.1572 + 0.0115E_o - 0.0007E_o^2 , \quad (1)$$

where E_o is the correct end point energy.

A stringent test of both our fitting routine of the Kurie plots and the Monte Carlo calculations was performed by measuring the ^{27}Si end point. Silicon-27 was produced in the ^{27}Al(p,n) reaction with about 11.4-MeV protons accelerated in the Oak Ridge EN tandem and then transported to a beta-gamma coincidence station by a helium-jet system for analysis. A continuous counting-collection cycle was utilized to measure both singles and 511-keV conicidence spectra of the ground-state-to-ground-state decay. The singles spectrum gave an end point of 3983 ± 11 keV, and the coincidence spectrum yielded an end point of 3980 ± 30 keV, where the errors are strictly statistical. Application of Eq. (1) results in a positron distortion correction of 191 keV, which when subtracted yields 3792 and 3789 keV for the final end points for ^{27}Si, in excellent agreement with the accepted value of 3787.0 ± 1.3 keV.[7]

To begin our β^+ end-point measurements, we selected the light rubidium isotopes, our choice being predicated on the ease of extracting rubidium from the UNISOR integrated-target ion source and on the availability of direct mass measurements,[8] which could then be used as a check of our measurements. Thus ^{76}Rb, ^{77}Rb, and ^{78}Rb were produced in ^{60,62}Ni(^{20}Ne, pxn) reactions induced by ^{20}Ne ions accelerated in the ORIC. Coincidence measurements were made with the intrinsic Ge detector and a Ge(Li) gamma-ray detector; singles spectra were accumulated simultaneously in a multispectrum mode for half-life information.

An example of our data is given in Fig. 2.77, where we show a Kurie plot of the singles β^+ spectrum for ^{76}Rb. Since the separator ion source produces no krypton and strontium and since ^{76}Kr does not emit β^+ particles, the measured spectrum is completely attributable to ^{76}Rb. The end point deduced from these data was 4582 ± 11 keV. End points deduced from spectra in coincidence with the annihilation radiation peak and the $2^+ \rightarrow 0^+$ (424-keV) ^{76}Kr transition were 4585 ± 40 and 4584 ± 42 keV respectively. The agreement between the coincidence and singles data indicates that there is no

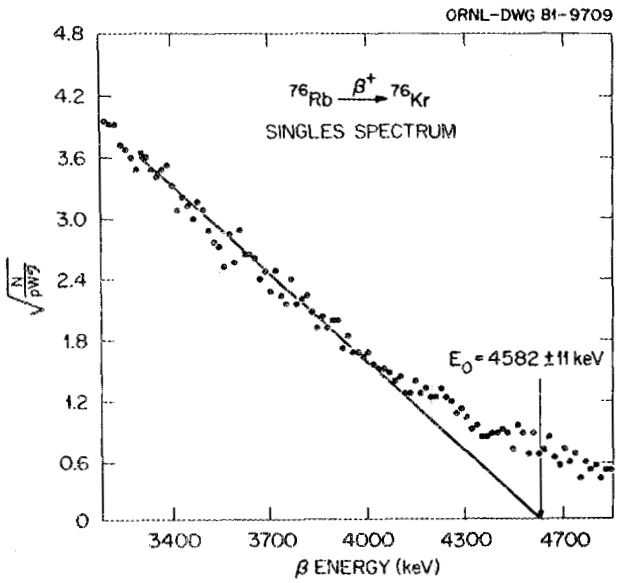


Fig. 2.77. High-energy singles β^+ spectrum arising from the decay of ^{76}Rb.

beta decay to the ^{76}Kr ground state. Because the $4^+ \rightarrow 2^+$ (612-keV) ^{76}Kr transition was not seen, most of the decay must proceed to the 424-keV 2^+ level, and the 76Rb ground state is probably 2^+, as suggested in ref. 9. After correcting the end point by using Eq. (1) and taking into account the 424-keV gamma-decay energy, a $Q_{E.C.}$ value of 5835 ± 42 keV was obtained.

For ^{77}Rb, it was possible to determine end points in coincidence with five different gamma rays in ^{77}Kr. These measurements, together with the singles end point, yielded a $Q_{E.C.}$ of 5102 ± 25 keV. This value agrees with one earlier measurement, 5180 ± 390 keV,[10] but not with another, 4882 ± 150 keV.[11]

In Fig. 2.78 we compare the ^{78}Rb singles spectrum with the one gated by the supposed $2^+ \rightarrow 0^+$ 455-keV ^{78}Kr gamma ray. It is evident that the end points differ by much more than 455 keV. Although the singles statistics in the high-energy portion of the spectrum are extremely poor, we were able to deduce an end point of about 6060 keV; this energy is to be compared with that derived from the spectrum gated by the 455-keV gamma ray, namely, 3150 ± 110 keV. The indication is that the earlier proposed decay scheme (see, e.g., ref. 12) is incorrect and that the 455-keV gamma ray is probably not the $2^+ \rightarrow$ ground-state transition. Recent unpublished work of Rehfield and Moore[13] supports our data. They suggest that a $0^+ \rightarrow 0^+$ isospin-forbidden beta transition connects the ^{78}Rb and ^{78}Kr ground states. Their more accurate end point for this transition is 6221 ± 20 keV.

Table 2.15 summarizes the ^{76}Rb, ^{77}Rb, and ^{78}Rb electron-capture Q values and compares mass excesses deduced from indirect measurements (present

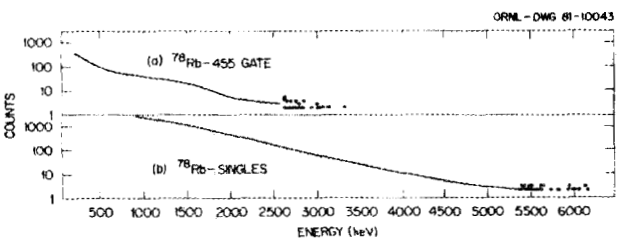


Fig. 2.78. Positron spectra observed in the decay of ^{78}Rb. (*a*) Gated by 455-keV gamma ray; (*b*) singles data.

Table 2.15. $Q_{E.C.}$ and mass excess values (In keV)

	A = 78	A = 77	A = 76
$Q_{E.C.}$ of Rb isotope	7242 ± 20[a]	5102 ± 25[b]	5835 ± 42[b]
Mass excess of Kr isotope[c]	−74150 ± 8	−70236 ± 30	−69100 ± 200[d]
Derived Rb mass excess, $M_{(Kr)} + Q_{E.C.(Rb)}$	−66908 ± 22	−65134 ± 39	−63265 ± 205
Direct mass measurement mass excess[e]	−67076 ± 64	−65037 ± 105	−60668 ± 151
Difference from direct measurements	168	−97	−2597

[a]Ref. 13.
[b]This work.
[c]Ref. 7.
[d]Based on data in ref. 14.
[e]Ref. 8.

work and refs. 13 and 14) with values derived from direct mass measurements.[8] Note the large discrepancy, about 2.6 MeV, for $A = 76$. It is not clear at this time where the problem lies. One possible explanation could be that the ^{76}Kr mass has been measured[14] only indirectly by observing delayed protons from ^{77}Kr decay.

We plan to examine the ^{76}Rb and ^{76}Kr question further and also to extend measurements to ^{75}Rb. Our efforts will then be directed toward the utilization of a new apparatus which couples a He gas-jet system to the existing UNISOR ion source (see description elsewhere in this report) to begin end-point investigations in the rare-earth region.

---

1. University of South Carolina, Columbia.
2. University of Kentucky, Lexington.
3. K. S. Toth, "α-Decay Studies in the Lead Region," *Int. Symp. on Future Directions in Studies of Nuclei Far from Stability, Vanderbilt University, September 1979,* North Holland, 1980, p. 71.
4. K. S. Toth, "α-Decay Systematics for Elements with $50 < Z < 83$," *Sixth Int. Conf. on Atomic Masses, Michigan State University, September 1979,* Plenum Press, New York, 1980, p. 409.
5. T. A. Girard and F. T. Avignone III, *Nucl. Instrum. Methods* **154**, 199 (1978).
6. F. T. Avignone III, L. P. Hopkins, and Z. D. Greenwood, *Nucl. Sci. Eng.* **72**, 216 (1979).
7. A. H. Wapstra and K. Bos, *At. Data Nucl. Data Tables* **19**, 175 (1977).
8. M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, T. Touchard, and H. Wollnik, *Phys. Rev. C* **19**, 1504 (1979).
9. D. D. Bogdanov, I. Voboril, A. V. Dem'yanov, V. A. Karnaukhov, and L. A. Petrov, *Izv. Akad. Nauk SSSR, Ser. Fiz.* **39**, 2029 (1975).
10. L. Westgaard, K. Aleklett, G. Nyman, and E. Roeckl, *Z. Phys.* **A275**, 127 (1975).
11. Ya. Liptak and W. Habernicht, *Izv. Akad. Nauk SSSR, Ser. Fiz.* **39**, 501 (1975).
12. J. A. Velandia, W. I. Holmes, and G. G. J. Boswell, *J. Inorg. Nucl. Chem.* **34**, 401 (1972).
13. D. M. Rehfield and R. B. Moore, submitted to *Phys. Rev. C*, 1981).
14. J. A. Hardy, J. A. MacDonald, H. Schmeing, T. Faestermann, H. R. Andrews, J. S. Geiger, R. L. Graham, and K. P. Jackson, *Phys. Lett.* **63B**, 27 (1976).

IDENTIFICATION OF ^{144}Tb AND ^{145}Tb; LEVELS IN THE $N = 81$ NUCLEUS ^{145}Gd

K. S. Toth D. C. Sousa[1]
C. R. Bingham[2] A. C. Kahler[3]
D. R. Zolnowski[3]

For the past several years we have been making a systematic study[4] of the decay properties of nuclei around the $N = 82$ shell to learn more about their low-lying levels, states whose structure should be describable in terms of a single-particle formalism. In particular, we have investigated[5] isomerism in ^{145}Gd and ^{147}Dy and have examined their levels and those of other $N = 81$ nuclei as a function of Z. The nucleus ^{145}Gd is especially interesting, since there is evidence now that ^{146}Gd exhibits properties characteristic of a doubly magic nucleus. States in ^{145}Gd have been studied via ^{145}Gd^m decay[5] and in-beam gamma-ray experiments.[6] These studies, however, have identified only two excited states at energies below 2.3 MeV, while one would expect, on the basis of shell-model predictions, a greater density of levels.

To obtain more information concerning ^{145}Gd, we undertook a search for ^{145}Tb in concert with our decay studies[7,8] of neutron-deficient holmium isotopes made in ^{10}B bombardments of ^{144}Sm. [Terbium nuclides are produced copiously in ^{144}Sm(^{10}B,αxn) reactions.] Ions of ^{10}B^{3+} were accelerated in the Texas A&M University cyclotron and used to bombard targets of samarium oxide enriched in ^{144}Sm. These targets consisted of oxide layers deposited onto thin aluminum backing foils. In two separate experiments, the energies of the ^{10}B ions extracted from the cyclotron were about 101 and 129 MeV. However, because the particles first were intercepted by the aluminum foils, the maximum energies incident on the target were about 96 and 125 MeV respectively. Incident energies were further varied by using additional aluminum absorbers. The overall energy range covered in the two experiments was from 75 to 125 MeV.

Figures 2.79 and 2.80 show portions of gamma-ray spectra (about 200 to 1200 keV) measured at 96 and 125 MeV respectively. The 96-MeV ^{10}B energy was the lowest one investigated where the gamma rays eventually assigned to ^{145}Tb were clearly observed. In Fig. 2.79, ^{145}Tb transitions are labeled by energy only; other peaks that could be identified are labeled by isotope as well. The evidence that these gamma rays do in fact represent ^{145}Tb decay is as follows: (1) the strongest transitions, at 257.6, 537.1, 572.4, 987.7, and 1109.7 keV, were all found to be in coincidence with gadolinium K x rays; (2) each of these transitions was also observed to be in coincidence with three or more of the others; (3) the relative intensities of these transitions remained approximately constant as the bombarding energy was varied between 96 and 125 MeV; and (4) each transition was found to decay with essentially the same half-life, namely, 30 ± 3 s.

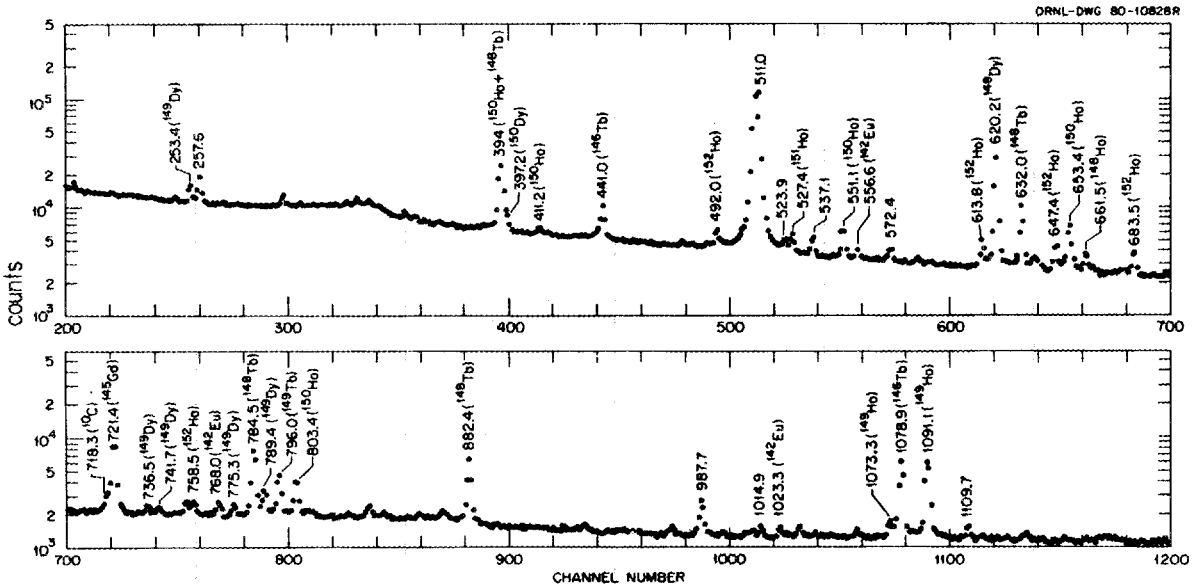


Fig. 2.79. Portion of a gamma-ray spectrum obtained in 96-MeV ^{10}B bombardments of ^{144}Sm. The spectrum represents the first 30 s of counting accumulated following 1-min irradiation cycles. Transitions assigned to ^{145}Tb are labeled by energy only. Other gamma-ray peaks in the spectrum that could be identified are labeled by energy and isotope.

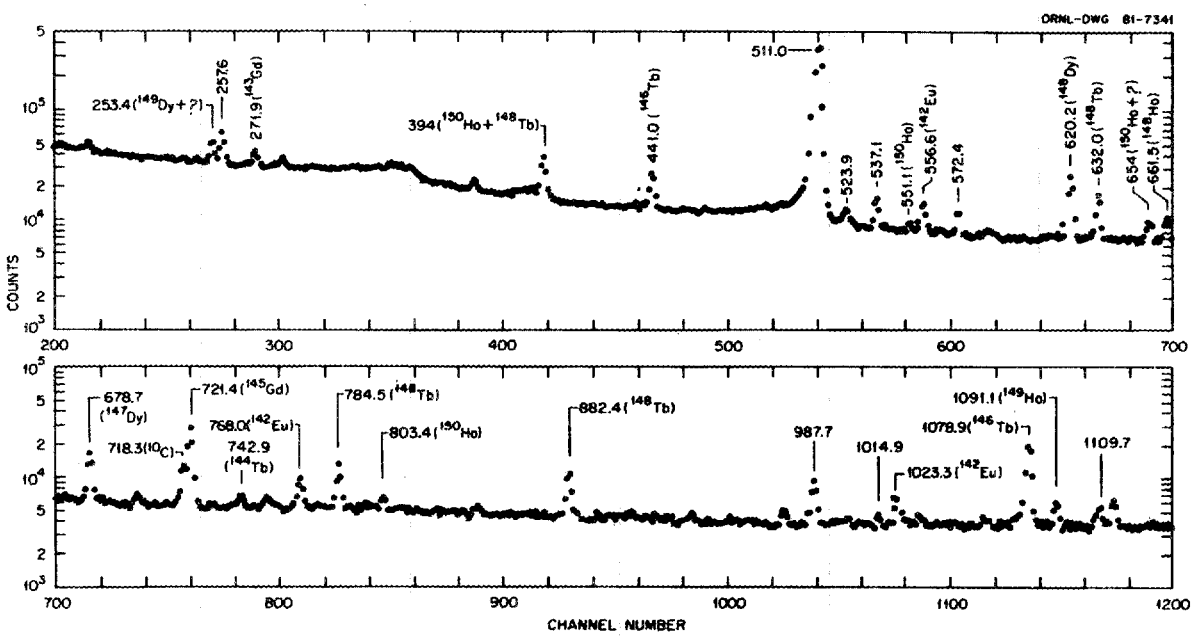


Fig. 2.80. Portion of a gamma-ray spectrum obtained in 125-MeV ^{10}B bombardments of ^{144}Sm. The spectrum represents 20 s of counting accumulated following 20-s irradiation cycles. Transitions assigned to ^{145}Tb are labeled by energy only. Other gamma-ray peaks in the spectrum that could be identified are labeled by energy and isotope. Note the 742.9-keV gamma ray, which is assigned to the decay of ^{144}Tb.

The observed ^{145}Tb gamma rays were placed in a decay scheme as shown in Fig. 2.81. The 27.3- and 748.7-keV states were known[5] from ^{145}Gd^{m} decay; the other four excited levels were proposed on the basis of our singles and coincidence gamma-ray measurements. The first three levels in ^{145}Gd represent (see, e.g., ref. 5) the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ neutron hole states, while the next highest state, 1014.9 keV, is probably due to the $d_{5/2}$ neutron orbital. The remaining levels shown in Fig. 2.81 (together with other so-far-unobserved states) can be accounted for by the coupling of these neutron hole orbitals to the 1579-keV 3^- and 1971-keV 2^+ levels[9,10] in the ^{146}Gd core.

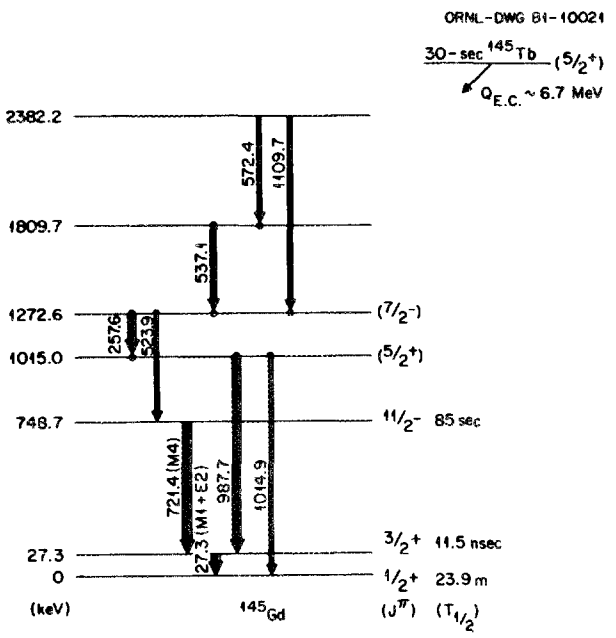


Fig. 2.81. Proposed ^{145}Tb decay scheme.

From the systematics of neighboring $N = 80$ isotones, the ground-state spin of ^{145}Tb is most likely $5/2^+$, since the isotones ^{147}Eu through ^{139}Pr all have $5/2^+$ ground states. In addition, the isotopes ^{147}Tb and ^{149}Tb have the same spins and parity. An $11/2^-$ spin might also be a possibility, since in ^{147}Tb and ^{149}Tb these proton orbitals are both low-energy isomeric states. It is unlikely that the ^{145}Tb species we observe is $11/2^-$ for the following reason. In the work of ref. 6, two intense transitions of energies equal to 1553.5 and 1684.1 keV were observed to depopulate a 13/2 state at 2302.0 keV and a 15/2 level at 2432.8 keV respectively. In our decay work these transitions were not observed. Thus the spin of the ^{145}Tb parent is likely to be $5/2^+$ rather than $11/2^-$.

The spectrum measured at 125 MeV is shown in Fig. 2.80. Once again the ^{145}Tb gamma rays are labeled by energy, while other identifiable peaks are labeled both with energy and isotope. One of the latter peaks, 742.9 keV, is assigned to the new isotope ^{144}Tb. The assignment is based mainly on two facts: (1) the gamma ray is in coincidence with gadolinium K x rays and (2) its energy corresponds to the known[11] 2^+ (first excited state) $\rightarrow 0^+$ (ground state) transition in ^{144}Gd. In addition, the gamma ray was first observed at a ^{10}B energy of 114 MeV, approximately 20–25 MeV above the threshold for the production of ^{145}Tb. The difference is close to the expected increase in energy needed to evaporate another neutron in this proton-rich region of the periodic chart. A decay analysis of the 742.9-keV gamma ray yielded a half-life of 5 ± 1 s for ^{144}Tb. We were unable to observe the 959.3-keV $3^- \rightarrow 2^+$ and 1001.4-keV $4^+ \rightarrow 2^+$ ^{144}Gd transitions.[11] The indication is that the spin of ^{144}Tb is 1, as is the case for the other $N = 79$ doubly odd isotones.

---

1. Eastern Kentucky University, Richmond.
2. University of Tennessee, Knoxville.
3. Texas A&M University, College Station.
4. K. S. Toth, "Investigation of Nuclei near $N = 82$ and $Z = 64$ via Radioactive Decay of High-Spin Isomers," *Symp. on High-Spin Phenomena in Nuclei, Argonne National Laboratory, March 1979,* ANL report ANL-PHY-79-4 (October 1979), p. 413.
5. K. S. Toth, C. R. Bingham, E. Newman, H. K. Carter, and W.-D. Schmidt-Ott, *Phys. Lett.* **56B**, 29 (1975); A. E. Rainis, K. S. Toth, and C. R. Bingham, *Phys. Rev. C* **13**, 1609 (1976).
6. J. Kownacki, J. Ludziejewski, Z. Sujkowski, H. Arnold, and H. Ryde, *Nucl. Phys.* **A236**, 125 (1974).
7. K. S. Toth, C. R. Bingham, D. R. Zolnowski, S. E. Cala, H. K. Carter, and D. C. Sousa, *Phys. Rev. C* **19**, 482 (1979).
8. K. S. Toth, C. R. Bingham, H. K. Carter, B. G. Ritchie, D. C. Sousa, and D. R. Zolnowski, *Phys. Rev. C* **20**, 298 (1979).
9. P. Kleinheinz, S. Lunardi, M. Ogawa, and M. R. Maier, *Z. Phys.* **A284**, 351 (1978).
10. M. Ogawa, R. Broda, K. Zell, P. J. Daly, and P. Kleinheinz, *Phys. Rev. Lett.* **41**, 289 (1978).
11. M. A. J. Mariscotti et al., *Nucl. Phys.* **A311**, 295 (1978).

CONTRADICTION OF THE REPORTED ANOMALY IN ALPHA-DECAY RATES OF LEAD ISOTOPES

K. S. Toth
Y. A. Ellis-Akovali
D. M. Moltz
C. R. Bingham[1]
H. K. Carter[2]
R. L. Mlekodaj[2]
E. H. Spejewski[2]
M. A. Ijaz[3]
J. Lin[4]
D. C. Sousa[5]

A rather regular behavior as a function of neutron number is observed for the reduced widths of alpha-decay transitions which connect ground states of doubly even isotopes. These *s*-wave transitions have reduced widths that are largest for parent nuclei with a few nucleons beyond a closed shell and then decrease as the next shell is approached. In contrast, the *s*-wave widths of ^{186,188,190,192}Pb have been reported[6] to behave anomalously. Their widths were found[6] to increase by a factor of 30 between ^{186}Pb ($N = 104$) and ^{192}Pb ($N = 110$) instead of decreasing in value as the neutron number approached 126. This unusual behavior has not been reproduced by theoretical calculations.[7,8]

In ref. 6 the alpha-decay branching ratios were obtained by comparing alpha-particle and K x-ray counting rates. The determination of an electron-capture-plus-positron (E.C. + β^+) decay strength from K x-ray intensities entails a number of corrections. To obtain more reliable alpha-branching ratios, we undertook the investigation of the E.C. + β^+ decay properties of these neutron-deficient lead nuclei.

The isotopes ^{192}Pb, ^{190}Pb, and ^{188}Pb were produced in ^{180}W(^{16}O,xn) reactions by bombarding a W_2O_3 target, enriched in ^{180}W to 92.6%, with ^{16}O ions accelerated in the Oak Ridge Isochronous Cyclotron. Reaction products were mass-separated by using the UNISOR on-line facility, collected onto an automated tape system, and transported to counting stations for radioactive assay. Singles and coincidence gamma-ray data were accumulated simultaneously with two large-volume Ge(Li) detectors. Also, the production yields for ^{192}Pb and ^{190}Pb were large enough to allow us to obtain conversion-electron data by using a Si(Li) detector. With these data, E.C. + β^+ decay schemes were constructed. For the determination of branching ratios, singles gamma-ray and alpha-particle spectra were measured with the Ge(Li) and Si(Au) detectors placed in calibrated geometries. The alpha-decay strengths were calculated from the measured intensities of the alpha groups of ^{188,190,192}Pb. The E.C. + β^+ strengths were obtained from the intensities of prominent gamma-ray transitions utilizing the proposed decay schemes. The alpha-decay branches were then determined from the two decay strengths.

The ^{192}Pb and ^{190}Pb investigations are now complete (see refs. 9 and 10 respectively). Herein we discuss our initial ^{188}Pb data and then consider the partial alpha half-lives for all three nuclei within the framework of alpha-decay-rate systematics for elements with $Z \geqslant 78$.

A 145-MeV ^{16}O bombarding energy was used to produce the $A = 188$ isobars. The alpha spectrum was dominated by the single group known to belong to ^{188}Pb alpha decay. Its energy was determined to be 5980 ± 5 keV, in agreement with earlier measurements.[11-13] In the gamma-ray spectrum, thallium K x rays were found to be down in intensity by factors of about 10 and 20 with respect to mercury and gold K x rays. This small production yield for ^{188}Pb is due probably to an increased amount of charged-particle emission from the neutron-deficient compound system added to the poorer efficiency of the separator ion source for lead as compared with the other two elements. The low yield accounts for the fact that only two gamma rays of about equal intensity, 185.0 and 758.2 keV, could be definitely assigned to the E.C. + β^+ decay of ^{188}Pb. (The remaining gamma rays are mainly due to the decays[14] of ^{188}Tl, ^{188}Hg, and ^{188}Au.) The two transitions were assigned to ^{188}Pb because they were seen in coincidence with thallium K x rays and because they decayed with a half-life of 22 ± 2 s, in agreement with published values.[11,12] In both the ^{192}Pb and ^{190}Pb E.C. + β^+ decay schemes there are two strong transitions: (1) ^{192}Pb (ref. 9) 1195.4 ($E1$) and 167.5 ($M1$ + $E2$) keV and (2) ^{190}Pb (ref. 10) 942.2 ($E1$) and 151.2 ($M1$ + $E2$) keV. These transitions connect 1^+ and 1^- levels, respectively, with the 2^- low-spin isomeric base states in ^{192}Tl and ^{190}Tl. We therefore suggest that the ^{188}Pb 758.2- and 185.0-keV gamma rays represent the analogous $E1$ and $1 + E2$ transitions in ^{188}Tl.

The ^{192}Pb and ^{190}Pb decay schemes are displayed in Fig. 2.82, together with a partial scheme for ^{188}Pb which shows the proposed placement of the 758.2- and 185.0-keV transitions. This placement is in accord with the fact that the two gamma rays were not observed in coincidence with one another. Their total intensities per 100 E.C. + β^+ decays, indicated in the figure, were determined by assuming no other gamma transitions proceeding to the base state and a direct E.C. + β^+ feeding of less than 1% to this level (based on a log ft value greater than 8.5 for a unique first-forbidden beta transition). With these assumptions, the alpha-branching ratio was calcu-

ORNL-DWG- 80-15342

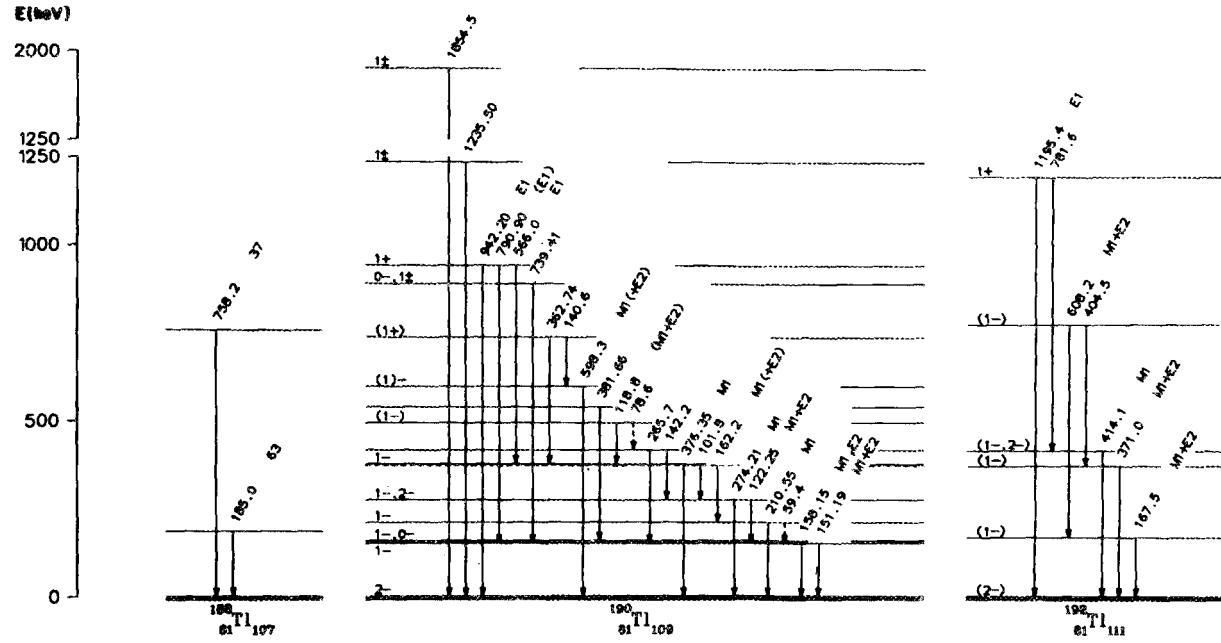


Fig. 2.82. Decay schemes for ^{192}Pb (ref. 9) and ^{190}Pb (ref. 10) shown together with the proposed partial scheme for ^{188}Pb.

lated to the (22 ± 7)%. If other transitions to the base state exist, then this ratio would be smaller. From the intensity of the $K\alpha_1$ x-ray peak, the alpha branch was deduced to be about 15%. This lower value has a large uncertainty; it may, however, indicate the presence of unidentified gamma-ray transitions. Several small peaks were found to decrease in intensity with time in a manner that could tag them as being due to ^{188}Pb decay. Their weak intensities, however, precluded the possibility of determining their half-lives accurately. Also, they could not be observed in coincidence with either the thallium K x rays or the 185.0- and 758.2-keV transitions. If they belong to ^{188}Pb, then their contribution could make the calculated and experimental K x-ray intensities in better agreement with one another.

In discussing alpha-decay rates, we will consider them within a theoretical context so that relative probabilities can be obtained. In the formalism[15] used, a reduced width, δ^2, is defined by the equation $\lambda = \delta^2 P/h$, where λ is the decay constant, h is Planck's constant, and P is the penetrability factor calculated for the alpha particle to tunnel through a barrier.

Decay energies and partial half-lives are needed to compute alpha-decay reduced widths. In Table 2.16 we compare these quantities for ^{188,190,192}Pb as obtained in our current investigations with data reported in refs. 6, 11–13, and 16. Large discrepancies can be noted in the case of the ^{188}Pb and ^{190}Pb alpha branches. The new branches increase the corresponding widths by factors of 7 and 4.5. Contrastingly, our width for ^{192}Pb, 0.049 MeV, is much less than the value of 0.094 MeV calculated from the earlier data. Here the discrepancy is due primarily to the fact that the nuclide's half-life is 3.5 min, rather than 2.3 min as reported by Le Beyec et al.[11] and used in ref. 6.

Figure 2.83 shows s-wave reduced widths for nuclei with Z from 78 to 100 plotted as a function of N. One sees the regularity of the reduced widths as a function of neutron number with the extremely sharp break at $N = 126$. This discontinuity has been shown to be a shell-structure effect. A less pronounced minimum is also observed for the subshell

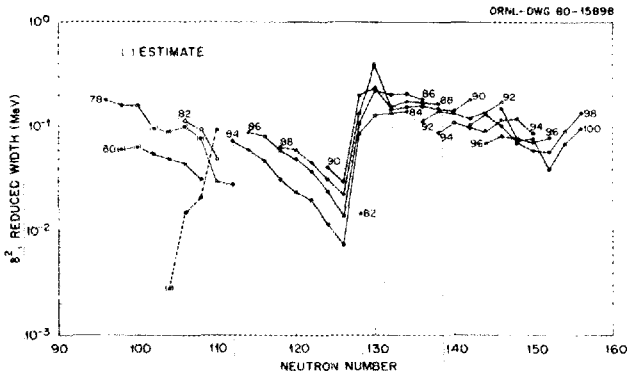


Fig. 2.83. Reduced widths for *s*-wave alpha transitions plotted as a function of *N* for isotopes with *Z* from 78 to 100. The dashed line connects widths for ^{186,188,190,192}Pb calculated from earlier data (note that the ^{186}Pb value is an estimate). The open points for $Z = 82$, connected by the full line, are widths for ^{188,190,192}Pb calculated from our experimental results.

closure at $N = 152$. The reported lead anomaly is indicated by the dashed line in Fig. 2.83, which connects the ^{186,188,190,192}Pb widths calculated from the earlier data summarized in Table 2.16. The widths for ^{188,190,192}Pb computed from our data are shown by the open points. It is clear that, in contradiction to the conclusions made in ref. 6, they have a dependence on N which is similar to that observed for other elements.

To verify this contradiction, the present study needs to be extended to ^{186}Pb and to the recently identified[13] new isotope ^{184}Pb. (Note that the ^{186}Pb width listed in Table 2.16 and shown in Fig. 2.83 is based[6] on an estimated rather than a measured alpha branch.) Given the low production yield for ^{188}Pb in ^{16}O irradiations of ^{180}W, it would not be practical to investigate ^{184,186}Pb with the same (or a similar) target-projectile combination. Instead, we plan to utilize ^{40}Ca beams from the 25-MV tandem to produce the two lead nuclides in (^{40}Ca,4*n*) reactions on ^{148,150}Sm. For completeness we will also obtain data of better quality on the E.C. + β^+ decay of ^{188}Pb by producing the isotope in the ^{152}Sm(^{40}Ca,4*n*) reaction.

1. University of Tennessee, Knoxville.
2. UNISOR, Oak Ridge, Tenn.
3. Virginia Polytechnic Institute, Blacksburg.

Table 2.16. Alpha-decay properties of ^{192}Pb, ^{190}Pb, ^{188}PB, and ^{186}Pb

Isotope	Property	Current investigations[a]	Earlier data	Reference
^{192}Pb	E_α (keV)	5112 (5)	5110[b]	16
	$T_{1/2}$ (min)	3.5 (1)	2.3 (5)	11
	α branch	5.7×10^{-5} (10)	6.9×10^{-5} (24)	6
	δ^2 (MeV)	$0.049^{+0.014}_{-0.012}$	0.094	
^{190}Pb	E_α (keV)	5577 (5)	5580 (10)	11
	$T_{1/2}$ (min)	1.2 (1)	1.2 (2)	11
	α branch	9.0×10^{-3} (20)	2.1×10^{-3} (7)	6
	δ^2 (MeV)	$0.094^{+0.036}_{-0.028}$	$0.021^{+0.017}_{-0.010}$	
^{188}Pb	E_α (keV)	5980 (5)	5980 (10)[c]	11
	$T_{1/2}$ (s)	22 (2)	24.5 (15)[d]	12
	α branch	0.22 (7)	3.3×10^{-2} (11)	6
	δ^2 (MeV)	$0.114^{+0.051}_{-0.041}$	$0.015^{+0.009}_{-0.007}$	
^{186}Pb	E_α (keV)		6320 (20)[e]	11
	$T_{1/2}$ (s)		8 (2)[f]	11
	α branch		4.8×10^{-2}[g]	6
	δ^2 (MeV)		0.028	

[a]Data for ^{192}Pb, ^{190}Pb, ^{188}Pb are taken from ref. 9, ref. 10, and the present study respectively.

[b]Other value: 5060 (30) keV (ref. 11).

[c]Other values: 5975 (15) keV (ref. 12) and 5990 (15) KeV (ref. 13).

[d]Other value: 26 (2) s (ref. 11).

[e]Other value: 6332 (10) keV (ref. 13).

[f]Other value: 4.79 (5) s (ref. 13). This half-life yields a δ^2 of 0.0047.

[g]Estimate from expected (ref. 11) cross sections for the production of ^{186}Pb in heavy-ion-induced reactions.

4. Tennessee Technological University, Cookeville.
5. Eastern Kentucky University, Richmond.
6. P. Hörnshoj, P. G. Hansen, B. Jonson, H. L. Ravn, L. Westgaard, and O. B. Nielsen, *Nucl. Phys.* **A230**, 365 (1974).
7. F. Dickmann and K. Dietrich, *Z. Phys.* **271**, 417 (1974).
8. I. Tonozuke and K. Harada, in *Proceedings of the International Conference on Nuclear Structure, Tokyo, 1977*, ed. T. Marumori, Physical Society of Japan, Tokyo, 1978, p. 431.
9. K. S. Toth, M. A. Ijaz, C. R. Bingham, L. L. Riedinger, H. K. Carter, and D. C. Sousa, *Phys. Rev. C* **19**, 2399 (1979).
10. Y. A. Ellis-Akovali, K. S. Toth, C. R. Bingham, H. K. Carter, and D. C. Sousa, *Phys. Rev. C* **23**, 480 (1981).
11. Y. Le Beyec, M. Lefort, J. Livet, N. T. Porile, and A. Siivola, *Phys. Rev. C* **9**, 1091 (1974).
12. P. Hönrshoj, P. G. Hansen, B. Jonson, A. Lindahl, and O. B. Nielsen, *Phys. Lett.* **43B**, 377 (1973).
13. U. J. Schrewe et al., *Phys. Lett.* **91B**, 46 (1980).
14. J. D. Cole, Ph.D. thesis, Delft University of Technology, The Netherlands, 1978.
15. J. O. Rasmussen, *Phys. Rev.* **113**, 1593 (1959).
16. A. Siivola, Dubna report P7-3202 (1967), p. 89.

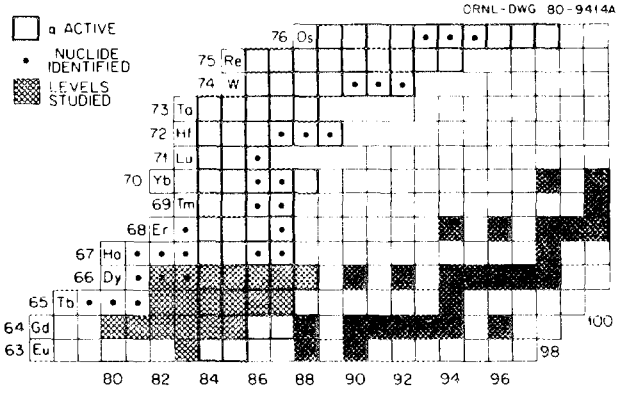


Fig. 2.84. Portion of the periodic chart under investigation. Dots mark isotopes we have identified, while cross-hatched squares represent nuclei whose level structures we have investigated. Missing squares for lutetium, hafnium, tantalum, tungsten, and rhenium indicate isotopes which have *not* been identified as yet.

STUDIES NEAR $N = 82$; EVIDENCE FOR A SHELL CLOSURE AT $Z = 64$

K. S. Toth — H. K. Carter[2]
C. R. Bingham[1] — D. C. Sousa[3]

In the study of nuclei far from stability, radioactive decay becomes a major mechanism with which to obtain nuclear structure information. The program described here deals with the investigation of short-lived nuclei near the $N = 82$ closed shell. Highly neutron-deficient isotopes were produced in compound-nuclear reactions by bombarding enriched rare-earth targets with energetic heavy ions ranging from ^{10}B to ^{20}Ne. Product nuclei knocked out of the thin targets by the incoming projectiles were thermalized in helium gas. The products were then pumped out of the reaction chamber together with the helium and transported through a Teflon capillary to a shielded area suitable for gamma-ray, x-ray, and alpha-particle counting.

The program has been twofold in purpose: (1) the study of alpha-decay energies and partial alpha half-lives for elements with $64 \leqslant Z \leqslant 76$ and (2) the investigation of low-lying levels in nuclei around the $N = 82$ closed shell. Figure 2.84 shows the region of the periodic table being studied. Solid squares indicate beta-stable nuclei, squares enclosed in heavy borders represent alpha-active nuclides, and cross-hatched squares show the nuclei whose level structures we have investigated. The intent has always been to obtain particular pieces of information concerning specific nuclei. However, due to the wide range of nuclides involved, one result has been the accumulation of half-life and decay-energy systematics for neutron-deficient nuclei with $144 \leqslant A \leqslant 172$. A total of 27 new isotopes have been identified; these are marked by dots in Fig. 2.84. Much of the work has been summarized recently in three review articles.[4-6] Herein we discuss those portions of our data which indicate a shell closure at $Z = 64$.

The first evidence for a closure at gadolinium ($Z = 64$) came from an examination of alpha-decay energies in the rare-earth region. For a given element, alpha-decay energies increase with decreasing neutron number. Discontinuities in this monotonic trend appear at 154, 128, and 84 neutrons as a consequence of the shell closures at 152, 126, and 82 neutrons respectively. In an analogous way the energies for a given N increase smoothly with increasing atomic number. In the rare earths, however, a plot of E_α vs N (see Fig. 2.85) reveals a discontinuity at $Z = 64$; while the normal spacing between adjacent even-Z nuclides is about 0.5 MeV, the difference between dysprosium ($Z = 66$) and gadolinium is about 1.1 MeV. The increased gap shows the additional stability of the $Z = 64$ configuration.

Another set of results which relates to the $Z = 64$ closure deals with alpha-decay rates. In alpha decay, half-lives for transitions between ground states of double even nuclei are taken to represent unhindered decays. The reduced widths (or transition probabilities) of these so-called s-wave alpha decays are considered to be standard. They exhibit regular trends as a function of N and Z. They are largest for nuclei with two or four particles beyond

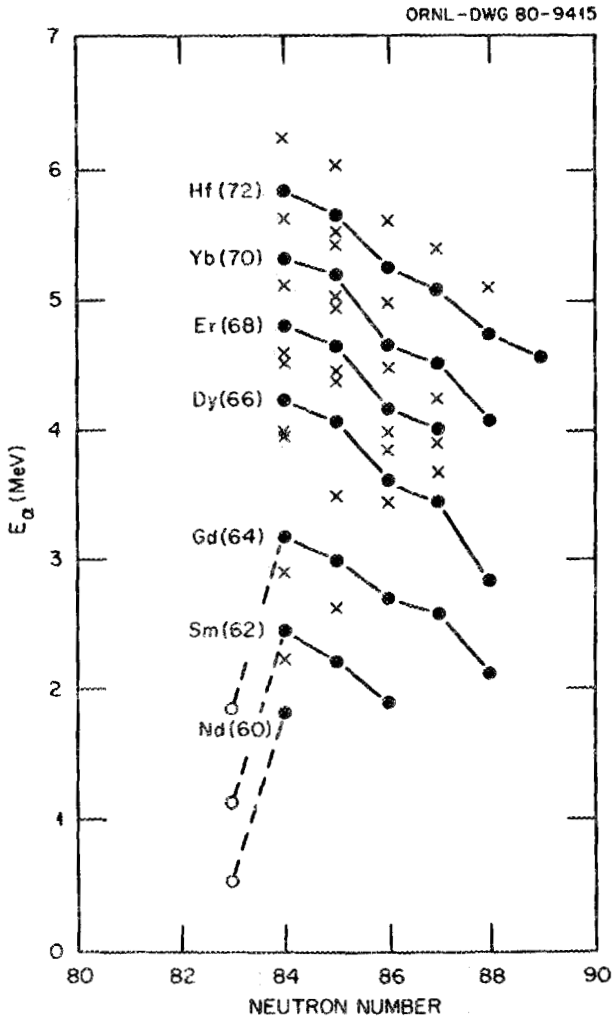


Fig. 2.85. Alpha-decay energies plotted as a function of neutron number for isotopes in the rare-earth region. Only even-Z elements have been labeled and their points connected.

a closed shell. After a sharp minimum at the shell, the widths increase once again in value as the next closure is approached. The trends can be understood in terms of the shell model; namely, the probability amplitude for the formation of an alpha particle is related to the magnitude of the single-particle wave functions at the surface. For closed shells these states are more tightly bound, and the result is a sharp decrease in the alpha-decay rate.

The discontinuity in alpha-decay energies at $Z = 64$ mentioned above was reproduced by calculations[7] which used the BCS method to take into account correlations between protons outside the $Z = 50$ shell. The authors also utilized their wave functins to calculate alpha reduced widths for $N = 84$ even-even nuclei. The calculations showed a significant dip at $Z = 64$ between the $g_{7/2} + d_{5/2}$ and $h_{11/2}$ proton orbitals. However, the data available at that time indicated[7] a general constancy in widths with a dramatic reduction at ^{150}Dy ($Z = 66$). Our investigations of alpha-decay rates showed that the ^{150}Dy alpha-decay branching ratio was in error; it is 36% rather than 18% as earlier data had indicated. Based on new experimental data the alpha-decay rates for $N = 84$ nuclei show (see Fig. 2.86) that the experimental alpha widths agree with the calculations[7] and that a shell closure exists at $Z = 64$.

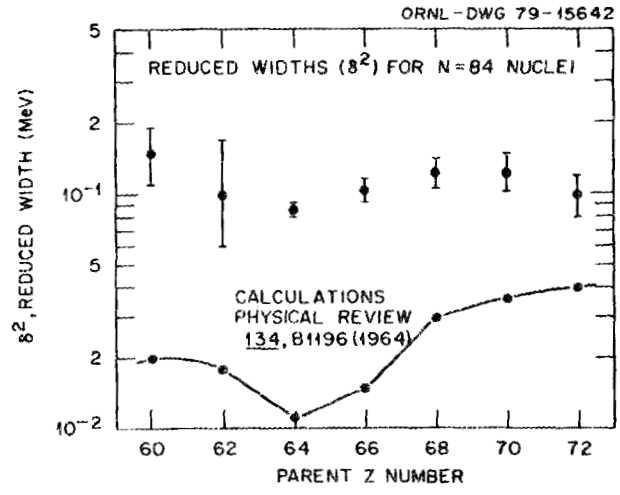


Fig. 2.86. Reduced widths for $N = 84$ even-A alpha emitters. BCS calculations of Macfarlane et al. (ref. 7) are also shown.

The first 2^+ states in a group of singly closed even-even nuclei lie at approximately equal excitations. If, however, one nucleus of these is doubly magic, then this excitation energy becomes substantially higher. Energy systematics for the lowest 2^+, 4^+, 6^+, and 3^- states in $N = 82$ isotones (^{134}Te to ^{148}Dy) are summarized in Fig. 2.87. Information concerning ^{146}Gd and ^{148}Dy levels is taken from our data on the decay of ^{146}Tb and ^{148}Ho and from recent in-beam gamma-ray work (see, e.g., ref. 8). General trends in Fig. 2.87 are that the 2^+, 4^+, and 6^+ states, up to ^{144}Sm, increase gradually in energy as Z increases, while the 3^- level drops precipitously. At ^{146}Gd, the 3^- is the first excited state, while the 2^+ excitation increases sharply from its energy in ^{144}Sm. In ^{148}Dy the 2^+ level drops in energy and, once again, is the first excited state. Its excitation of 1677 keV is close to the 2^+ energy in ^{144}Sm, namely, 1660 keV. The unusually high energy of the 2^+ level in

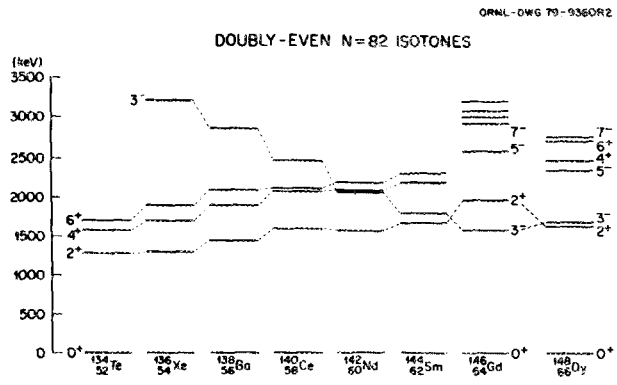


Fig. 2.87. Systematics of low-lying 2^+, 4^+, 6^+, and 3^- levels in doubly even $N = 82$ nuclei.

^{146}Gd and the fact that its first excited state is 3^- provide additional evidence for a closure at $Z = 64$.

Based on three different types of experiments there is now a compelling indication that 64 protons represent a closed configuration. This progress should stimulate new shell-model calculations in this mass region wherein an $N = 82$ plus $Z = 64$ core is assumed rather than the usual $N = 82$ plus $Z = 50$ closure.

---

1. University of Tennessee, Knoxville.
2. UNISOR, Oak Ridge, Tenn.
3. Eastern Kentucky University, Richmond.
4. K. S. Toth, "Investigation of Nuclei near $N = 82$ and $Z = 64$ via Radioactive Decay of High-Spin Isomers," *Symp. on High-Spin Phenomena in Nuclei, Argonne National Laboratory, March 1979,* ANL report No. ANL-PHY-79-4 (October 1979), p. 413.
5. K. S. Toth, "α-Decay Studies in the Lead Region," *Int. Symp. on Future Directions in Studies of Nuclei Far from Stability, Vanderbilt University, September 1979,* North Holland, 1980, p. 71.
6. K. S. Toth, "α-Decay Systematics for Elements with $50 < Z < 83$," *Sixth Int. Conf. on Atomic Masses, Michigan State University, September 1979,* Plenum Press, New York, 1980, p. 409.
7. R. D. Macfarlane, J. O. Rasmussen, and M. Rho, *Phys. Rev.* **134**, B1196 (1964).
8. P. J. Daly et al., *Z. Phys.* **A298**, 173 (1980).

ENERGY LOSS AND STRAGGLING OF 7.3-MeV-PER-NUCLEON ^{84}Kr IONS

R. L. Hahn[1] R. L. Ferguson
K. S. Toth F. Plasil

A preliminary discussion of energy-loss measurements by time of flight for 7.3-MeV/amu ^{84}Kr ions traversing foils of nickel, aluminum, and titanium was presented previously.[2] In particular, a discrepancy of about 20% was noted between the data and the calculated energy losses of Northcliffe and Schilling.[3] Detailed analysis of the data has yielded values of the stopping powers and straggling parameters for ^{84}Kr in these materials.[4]

Stopping Powers

Stopping powers, $S(E)$, are usually extracted from energy-loss measurements done with thin foils. In such a foil, ΔE is small, so that one expects $S(E)$ to vary slowly and linearly with energy about some mean energy, E_o:

$$dE/dx \equiv S(E) = S(E_o) + b(E - E_o). \qquad (1)$$

The energy loss, ΔE, occurring in the foil is then obtained by integrating Eq. (1) over the thickness of the foil, from O to ΔR, so that

$$S(E_o) = (\Delta E/\Delta R)[\tfrac{1}{2} b\, \Delta R/\tanh(\tfrac{1}{2} b\, \Delta R)], \qquad (2)$$

where the mean energy in the foil is $E_o = E_i - \frac{1}{2}\Delta E$. For a thin foil, the term in square brackets, $[F]$, is about 1, so that

$$S(E_o) = \Delta E/\Delta R. \qquad (3)$$

Bimbot et al.[5] have extended this method to thick foils and large energy losses of up to 80 MeV by arguing that Eqs. (1) and (2) should apply to any energy regime where the stopping power varies linearly with energy; for the beams that they consider, they show that $F \approx 1$, so they use Eq. (3) to evaluate $S(E_o)$. If, however, Eq. (1) represents only the linear term in a Taylor expansion about E_o and if the energy loss is large, so that higher-order terms in $E - E_o$ cannot be neglected, then Eqs. (2) and (3) will in general not be valid.

To test these ideas, we have used Eq. (3) to extract $S(E_o)$ values from our data (for the ^{84}Kr energies used, $b = -0.012$ and $F \leqslant 1.001$). These derived data are shown in Fig. 2.88. For Ni, $S(E_o)$ is seen to change slowly, $\lesssim 5\%$, as E_o changes from 7.20 to 6.39 MeV/amu. Figure 2.88 also compares the derived stopping powers with the values calculated after Steward[6] (St.) and by Hubert et al.[7] (H.F.). The latter calculations are, in the main, based on the average trends of $S(E_o)$ vs E determined by Bimbot et al.[5] but take into account the variations with energy of the effective-charge parameter, which reflects changes in the charges on the projectile and target atoms.

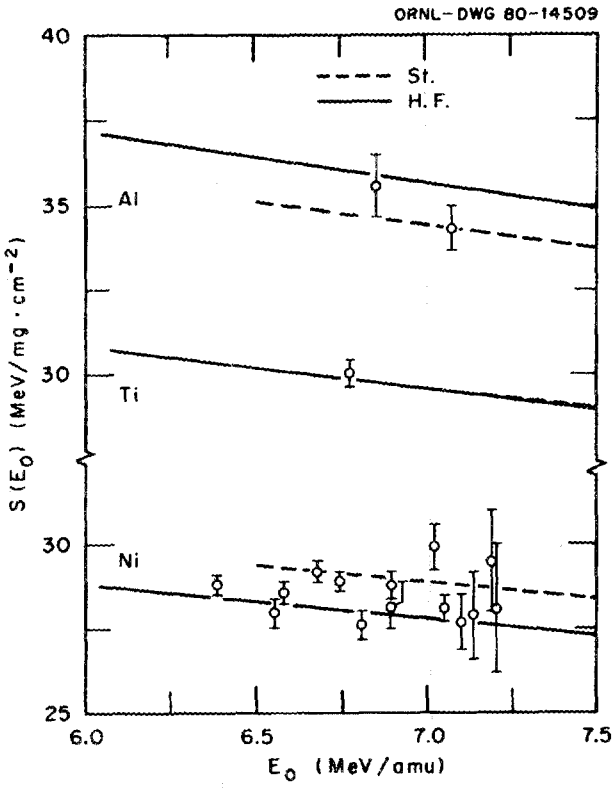


Fig. 2.88. Stopping powers, $S(E_0)$, derived from the energy-loss data. Calculated values are derived from Steward (St., ref. 6) and Hubert et al. (H.F., ref. 7).

It is seen that both St. and H.F. predict slow, linear variations of $S(E_0)$ with energy that do follow the general trends of our data for nickel. However, fluctuations in our data points and the error bars assigned to them do not allow us to choose between the H.F. and St. predictions. We stress that the quality of the data in Fig. 2.88 is not very different from that presented in ref. 5. Thus we conclude that while the approach of Bimbot et al. of using Eqs. (1)–(3) appears to be reasonable for absorbers in which large energy losses of 1–2 MeV/amu occur, it is not obvious that precise values of $S(E_0)$ can be derived from such measurements. It appears that the heuristic value of using Eqs. (1)–(3) lies in compiling and comparing data for different projectile-target combinations and in generating stopping powers[7] for beams and energy regions for which no measurements have as yet been done.

Straggling

Beam straggling, which is due to the statistical nature of the slowing-down process, was shown by Bohr[8] for light ions to vary with the square root of either the absorber thickness or the energy loss. More recent treatments[9] have considered the case of heavy ions, taking into account the additional facts that the stopping power, the charge distribution (charge straggling), and the charge-exchange cross section all change as the energy of the ion decreases in its passage through the absorber. Schmidt-Böcking and Hornung[9] have derived a semiempirical formula for the straggling,

$$\alpha\ (\text{keV}) = K(\Delta E^n)\ \frac{S(E_i - \Delta E)}{S(E_i)} \left(\frac{Z_p Z_T}{Z_p^{1/3} + Z_T^{1/3}}\right)^{1/2}, \qquad (4)$$

where ΔE is in units of MeV and K is a normalization constant. As noted above, the value of n should equal 0.50; its value in ref. 9 is 0.53, obtained from a fit of Eq. (4) to data for $\lesssim 1$ MeV/amu Cl ions slowing down in argon-methane. To plot data for different ions in the same absorber, Schmidt-Bocking and Hornung[9] defined a reduced straggling parameter

$$\alpha^{\text{red}}\ (\text{keV}) = \alpha\ \frac{S(E_i)}{S(E_i - \Delta E)} \left(\frac{Z_p^{1/3} + Z_T^{1/3}}{Z_p}\right)^{1/2}, \qquad (5)$$

so that

$$\alpha^{\text{red}}\ (\text{keV}) = K(\Delta E^n) Z_T^{1/2}. \qquad (6)$$

For energy losses from less than 1 to 60 MeV, they found $K = 14$ for the gaseous absorber argon-methane.

Table 2.17 lists the straggling parameters measured in the present work. We note here that the

Table 2.17. Measured straggling for energetic ^{84}Kr ions

Foil	ΔE^a (MeV)	$\alpha_T{}^b$ (MeV)	α^c (MeV)
None	0	2.72 ± 0.41	
Ni	19.15 ± 0.14	3.62 ± 0.16	2.39
	45.8	4.68	3.82
	73.5	5.79	5.11
	87.0	6.03	5.38
	129.3	7.28	6.75
	159.4	7.78	7.29
Ti	95.2	5.42	4.69

[a] ΔE = measured energy loss.
[b] α_T = measured total straggling, as full width at half maximum, including effects of beam spread and detector resolution.
[c] α = net straggling.

observed straggling, even for energy losses as large as 129 and 159 MeV, is $\lesssim 8$ MeV. These data thus indicate the magnitude of the beam spread to be expected when solid absorbers are used in nuclear physics experiments with energetic Kr ions.

The net straggling data of Table 2.17 have been compared with Eq. (4). The stopping powers used in this comparison were interpolated from the values calculated by Hubert et al.[7] Figure 2.89 presents the data plotted in terms of α^{red}, Eq. (5); the line in the figure represents Eq. (6). It is seen that Eqs. (4)-(6) fit the data very well, with n = 0.50 and with $K = 45 \pm 1$ and 40, respectively, for Ni and Ti (the data for Al are not included in the figure because of the observed nonuniformity of the foils). However, we note that the α^{red} parameterization of ref. 9 does not adequately take into account the variation with absorber, Z_T, since the Ni and Ti data do not fall on one universal curve.

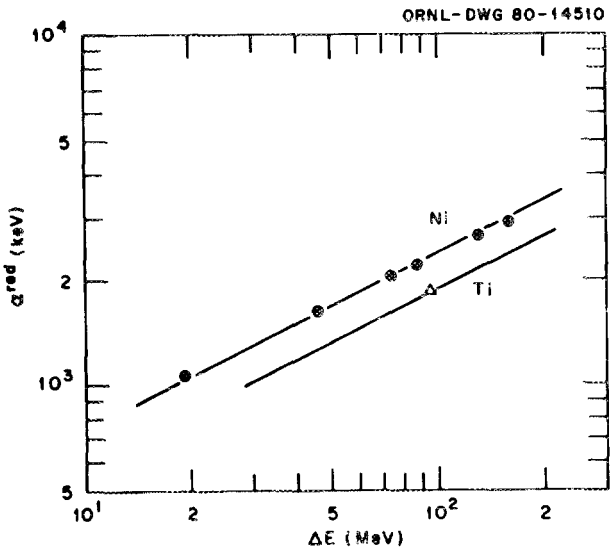


Fig. 2.89. Variation of straggling parameter, α^{red}, with energy loss, ΔE. Data points are given by

$$\alpha^{red} = \alpha \frac{S(E_i)}{S(E_i - \Delta E)} \left(\frac{Z_p^{1/3} + Z_T^{1/3}}{Z_p} \right)^{1/2} ,$$

where α is the measured net straggling. The curves are calculated from $\alpha^{red} = KZ_T^{1/2}\,\Delta E^{1/2}$. For Ni, K = 45; for Ti, K = 40.

These experimental results on energy losses, stopping powers, and straggling and the comparisons made with theory not only are of interest in terms of the physics of electronic stopping but are very pertinent to considerations of the use of beam degrader foils at accelerators. The discrepancies between the Northcliffe and Schilling[3] predictions and the data for ions as heavy as ^{84}Kr are noteworthy because of the widespread use of the N.S. tables in nuclear physics experiments.

---

1. Chemistry Division
2. R. L. Hahn, K. S. Toth, R. L. Ferguson, and F. Plasil, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498, p. 68 (June 1979).
3. L. C. Northcliffe and R. F. Schilling, *Nucl. Data* **A7**, 233 (1970).
4. R. L. Hahn, K. S. Toth, R. L. Ferguson, and F. Plasil, *Nucl. Instrum. Methods* **180**, 581 (1981).
5. R. Bimbot, S. Della Negra, D. Gardes, H. Gauvin, A. Fleury, and F. Hubert, *Nucl. Instrum. Methods* **153**, 161 (1978).
6. P. G. Steward, University of California report No. UCRL-16127 (1968) (unpublished).
7. F. Hubert, A. Fleury, R. Bimbot, and D. Gardes, *Ann. Phys.* (Paris) **5S**, 1 (1980).
8. N. Bohr, *K. Dan. Vidensk. Selsk. Mat.-Fys. Medd.* **18**, No. 8 (1948).
9. H. Schmidt-Böcking and H. Hornung, *Z. Phys.* **A286**, 253 (1978).

THE ^{12}C(p, n) ^{12}N REACTION AT 120, 160, AND 200 MeV

J. Rapaport[1]
T. Taddeucci[1]
C. Gaarde[2]
C. D. Goodman[3]
C. C. Foster[3]
C. A. Goulding[4]
D. Horen
E. Sugarbaker[5]
T. G. Masterson[5]
D. Lind[5]

In the last few years, a number of authors[6] have attempted to express the nucleon-nucleon interaction at intermediate energies in terms of an effective nucleon-nucleon interaction in DWIA. Using phase shifts derived from free nucleon-nucleon scattering they have developed energy- and momentum-dependent effective t matrices for the isoscalar, isospin, and spin-isospin components of the interaction including knockout and exchange. The present experiment was undertaken in order to test this energy and q dependence.

The ^{12}C(p,n) ^{12}N reaction was studied at incident proton energies of 120, 160, and 200 MeV. Angular distributions were measured out to about 35°. The measurements were made using the beam swinger[7] at the Indiana University Cyclotron Facility. Excitations leading to the ground ($J^\pi = 1^+$, $T = 1$) and 0.96-MeV ($J^\pi = 2^+$, $T = 1$) states of ^{12}N were investigated. Transition densities were calculated using Cohen-Kurath[8] wave functions. Theoretical

cross sections were calculated with (σ_{DW}) and without distortion (σ_{PW}) (i.e., $V = W = V_{SO} = 0$). The ratio $N(E, q)$ between σ_{DW} and σ_{PW} can be considered as a measure of distortion effects, which are dependent upon both energy and momentum transfer.

The transition density for the $0^+ \rightarrow 1^+$ excitation is known to involve only a spin density. Furthermore, the ratio $|t^c_{\sigma\tau}/t^c_{\tau}|^2$ is almost constant for small q in the energy range 100–200 MeV. Hence it is expected that the cross section for this GT transition should be nearly independent for small q transfers. This can be seen in Fig. 2.90, where $\sigma_{PW}(q)$ deduced by dividing the experimentally measured cross section by $N(E, q)$ is plotted vs q. For small q, one sees that σ_{PW} is essentially the same for the 120-, 160-, and 200-MeV data. It can be shown that the cross section extrapolated to $q = 0$ can be related to the GT beta-decay matrix element.

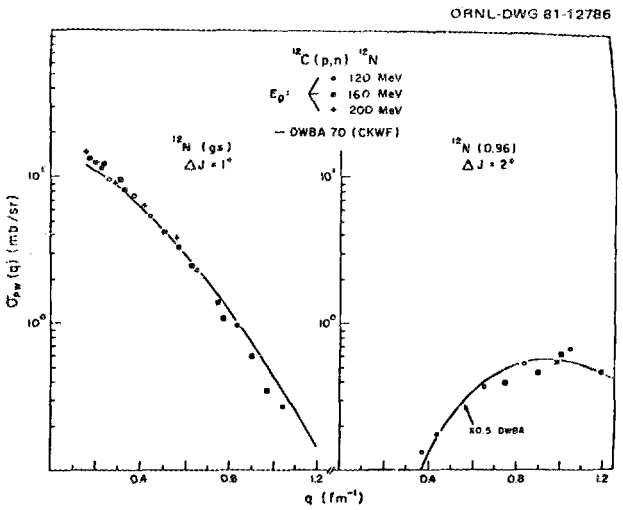


Fig. 2.90. Plane-wave cross sections for the ^{12}C(p,n) ^{12}N ground and 0.96-MeV states calculated from the measured cross sections at 12.0, 160 and 200 MeV. The solid lines represent DWBA 70 plane-wave calculations using Cohen-Kurath wave functions. The $\Delta J = 2$ PW calculation has been multiplied by 0.5 (see text).

The fact that the plane-wave cross sections for different E are essentially the same for a given q is in excellent agreement with the predicted E and q dependence of $t_{\sigma\tau}$, which shows[6] that $t_{\sigma\tau}(E, q)$ is almost independent of E for $q \lesssim 1$ fm^{-1}. The measured cross sections are in excellent agreement with DWBA 70 calculated cross sections using the Cohen-Kurath wave functions and the predicted strength of $t_{\sigma\tau}$.

Similar results are also shown for the $0 \rightarrow 2^+$ transition to the 0.96-MeV state in ^{12}N. For this transition, inclusion of the isovector-tensor interaction is very important. This transition can proceed by either $L = 2$, $S = 0$ or $L = 2$, $S = 1$. Calculations indicate that $S = 1$ dominates. Note that the calculated cross sections using the Cohen-Kurath wave functions had to be multiplied by a factor of 0.5 to get agreement with the data.

---

1. Ohio University, Athens.
2. The Niels Bohr Institute, Copenhagen, Denmark.
3. Indiana University, Bloomington.
4. Univeristy of Texas–Los Alamos National Laboratory, Los Alamos, N. Mex.
5. University of Colorado, Boulder.
6. See, e.g., F. Petrovich, p. 115 in *The (p,n) Reaction and the Nucleon,Nucleon Force,* ed. C. D. Goodman et al., Plenum, New York, 1980; W. G. Love, ibid., p. 23; W. G. Love and M. A. Franey, to be published.
7. C. D. Goodman et al., *IEEE Trans. Nucl. Sci.* **26,** 2248 (1979).
8. S. Cohen and D. Kurath, *Nucl. Phys.* **73,** 1 (1965); T. S. H. Lee and D. Kurath, *Phys. Rev. C* **21,** 293 (1980).

SEARCH FOR ISOBARIC ANALOGS OF *M*1 STATES AND GIANT SPIN-FLIP RESONANCES IN THE ^{208}Pb(*p,n*) REACTION

D. J. Horen
C. D. Goodman[1]
C. C. Foster[1]
C. A. Goulding[2]
T. G. Masterson[3]
M. B. Greenfield[2]
J. Rapaport[4]
D. E. Bainum[5]
E. Sugarbaker[3]
F. Petrovich[6]
W. G. Love[7]

The ^{208}Pb$(p,n)^{208}$Bi reaction has been studied at $E_p = 120$ and 160 MeV using the beam swinger[8] at the Indiana University Cyclotron Facility with a 70-m flight path. The 0° time-of-flight spectra were dominated by two nearly degenerate resonances with $E_x = 15.6$ MeV and $E_x = 15.2$ MeV (IAS), which were shown to have $L = 0$ angular distributions. The 15.6-MeV resonance was identified as the giant GT resonance, since the ratio of its cross section relative to that of the IAS at 160 MeV was enhanced by about a factor of 2 over the ratio at 120 MeV. This is in excellent agreement with the predicted[9] increase in the ratio $|V_{\sigma\tau}/V_{\tau}|^2$ between 120 and 160 MeV.

The observed location of the GT resonance is in good agreement with predictions made by Ikeda.[10]

However, the observed strength represents only about 40% of the sum rule and has triggered several theoretical efforts to explain this.

The spectra at 4–5° are dominated by a peak corresponding to $E_x = 21.5$ MeV. Since the cross section for exciting this resonance tracks with that of the GT as a function of E_p, this resonance can be classified as an $L = 1$, $S = 1$, $T = 1$ excitation (i.e., isovector spin-dipole). The width of this resonance is $\Gamma = 10 \pm 3$ MeV, and it could be composed of components with $J^\pi = 0^-$, 1^-, and 2^-. These results can be used to predict the energy of excitation of the spin-dipole resonance in ^{208}Pb.

Additional weak resonances were observed at $E_x = 2.8$, 22.9, and 24.6 MeV. The 2.8-MeV resonance was found to behave as an $L = 1$, $S = 1$ excitation and is probably a $J^\pi = 2^-$, $h_{9/2}i_{13/2}^{-1}$ proton-particle–neutron-hole state. The 22.9- and 24.6-MeV resonances have $L = 0$. The former is thought to be the IAS of previously observed[11,12] $M1$ states in ^{208}PB.

These results have been published.[13]

1. Indiana University, Bloomington.
2. Florida A&M University, Tallahassee.
3. University of Colorado, Boulder.
4. Ohio University, Athens.
5. Emporia State University, Emporia, Kans.
6. Florida State University, Tallahassee.
7. University of Georgia, Athens.

8. C. D. Goodman et al., *IEEE Trans. Nucl. Sci.* **NS-26**, 2248 (1979).
9. W. G. Love, p. 23 in *The (p,n) Reaction and the Nucleon-Nucleon Force*, ed. C. D. Goodman et al., Plenum, New York 1980.
10. K. Ikeda, *Prog. Theor. Phys.* **31**, 434 (1964).
11. D. J. Horen et al., *Phys. Rev. Lett.* **38**, 1344 (1977).
12. S. Raman, p. 193 in *Neutron Capture Gamma-Ray Spectroscopy*, ed. R. E. Chrien and W. R. Kane, Plenum, New York, 1979.
13. D. J. Horen et al., *Phys. Lett.* **95B**, 27 (1980).

OBSERVATION OF GIANT PARTICLE-HOLE RESONANCES IN ^{90}Zr$(p,n)^{90}$NB

D. E. Bainum[1] D. J. Horen
J. Rapaport[2] C. C. Foster[3]
C. D. Goodman[3] M. B. Greenfield[4]
C. A. Goulding[4]

The Indiana University beam-swinger facility[5] has been utilized with a 62-m flight path to study the reaction ^{90}Zr$(p,n)^{90}$Nb at $E_p = 120$ MeV. At small angles (i.e., $\theta \approx 0°$), the time-of-flight spectra are dominated by the IAS ($E_x = 5.1$ MeV) and giant Gamow-Teller (GT) ($E_x = 8.7$ MeV) resonances, which have $L = 0$ angular distributions. Another peak at $E_x = 17.9$ MeV is found to be described by an $L = 1$ angular distribution.

The cross section of the GT resonance relative to that of the IAS resonance in the 120-MeV spectra is enhanced by about a factor of 5 with respect to the same ratio observed[6] at $E_p \approx 45$ MeV in accordance with theoretical predictions.[7] Love[7] and Petrovich[7] have shown that the effective nucleon-nucleus interaction can be expressed in terms of nucleon-nucleon interaction. Of the various components of the latter, they[7] have shown that at small momentum transfer (i.e., $q \approx 0$) the isovector interaction is dominated by the central isospin (V_τ) and spin-isospin ($V_{\sigma\tau}$) terms, whose magnitudes are a function of E_p. In the energy region $E_p \approx 100$ to 300MeV (at $q \approx 0$), $V_{\sigma\tau}$ is nearly flat, while V_τ is decreasing. Hence one expects to observe an enhancement of transitions which proceed by a $\sigma\cdot\sigma\ \tau\cdot\tau$ interaction over those which proceed by $\tau\cdot\tau$ in this energy domain.

The results have been published.[8] Important findings were: (1) The total GT strength represented only about 40% of the sum rule (i.e., $\Sigma GT = 3(N - Z)$. (2) An $L = 1$ transition was observed at $E_x = 17.9$ MeV.

1. Emporia State University, Emporia, Kans.
2. Ohio University, Athens.
3. Indiana University, Bloomington.
4. Florida A&M Unviersity, Tallahassee.

5. C. D. Goodman, C. C. Foster, M. B. Greenfield, C. A. Goulding, D. A. Lind, and J. Rapaport, *IEEE Trans. Nucl. Sci.* **26**, 2248 (1979).
6. R. R. Doering, Aaron Galonsky, D. M. Peterson, and G. F. Bertsch, *Phys. Rev. Lett.* **35**, 1691 (1975).
7. See, e.g., W. G. Love, pp. 30 and 42 in *The (p,n) Reaction and the Nucleon-Nucleon Force*, ed. C. D. Goodman et al., Plenum, New York, 1980; F. Petrovich, ibid., p, 135.
8. D. E. Bainum, J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, and C. A. Goulding, *Phys. Rev. Lett.* **44**, 1751 (1980).

ENERGY SYSTEMATICS OF THE GIANT GAMOW-TELLER RESONANCE AND A CHARGE-EXCHANGE DIPOLE SPIN-FLIP RESONANCE

D. J. Horen
C. D. Goodman[1]
D. E. Bainum[2]
C. C. Foster[1]
C. Gaarde[3]
C. A. Goulding[4]
M. B. Greenfield[4]
J. Rapaport[5]
T. Taddeucci[5]
E. Sugarbaker[6]
T. Masterson[6]
S. M. Austin[7]
A. Galonsky[7]
W. Sterrenburg[7]

We have used the beam swinger[8] at the Indiana University Cyclotron Facility with protons of incident energy between 100 and 200 MeV to study the energy systematics of the giant Gamow-Teller resonance and an $L = 1$, $S = 1$ resonance. The neutron flight paths were 60–70 m, and data were taken at 2.5° intervals out to about 15°. Targets studied included ^{90,92,94}Zr, ^{112,116,124}Sn, ^{169}Tm, and ^{208}Pb. Neutron time-of-flight spectra at 4.3° for $E_p = 200$ MeV (near a maximum[9,10] in the differential cross section for $L = 1$) are shown in Fig. 2.91. At this energy the IAS is only weakly excited. The locations of the GT and $L = 1$ resonances (and IAS where observable) are indicated in the figure.

In Fig. 2.92 we have plotted vs $(N - Z)/A$ the energy differences between the giant GT and $L = 1$ resonances, respectively, and the IAS. The energies of the GT (and IAS where observable) resonances have been determined from 0° spectra and those for the $L = 1$ from the 4.3° spectra. The uncertainties for $E_{GT} - E_{IAS}$ are less than 0.4 MeV, and those for $E_{L=1} - E_{IAS}$ are estimated to be 1 MeV. As can be seen from Fig. 2.92, to first order both energy differences can be represented by linear functions of $(N - Z)/A$ which have about the same slope. We find the energy differences in MeV:

$$E_{GT} - E_{IAS} = -30.0(N - Z)/A + 6.7,$$

$$E_{L=1} - E_{IAS} = -33.0(N - Z)/A + 13.6 .$$

The energy differences for ^{116}Sn and ^{124}Sn are in good agreement with calculations of Gaponov and Lyntostanski,[11] who have used the theory of finite Fermi systems with a spin-isospin constant of $g_0' = 1.0$. However their predicted values for the Zr isotopes are high by about 2 MeV. The calculated energies for the IAS resonances agree well with experimental values. Hence the discrepancy between

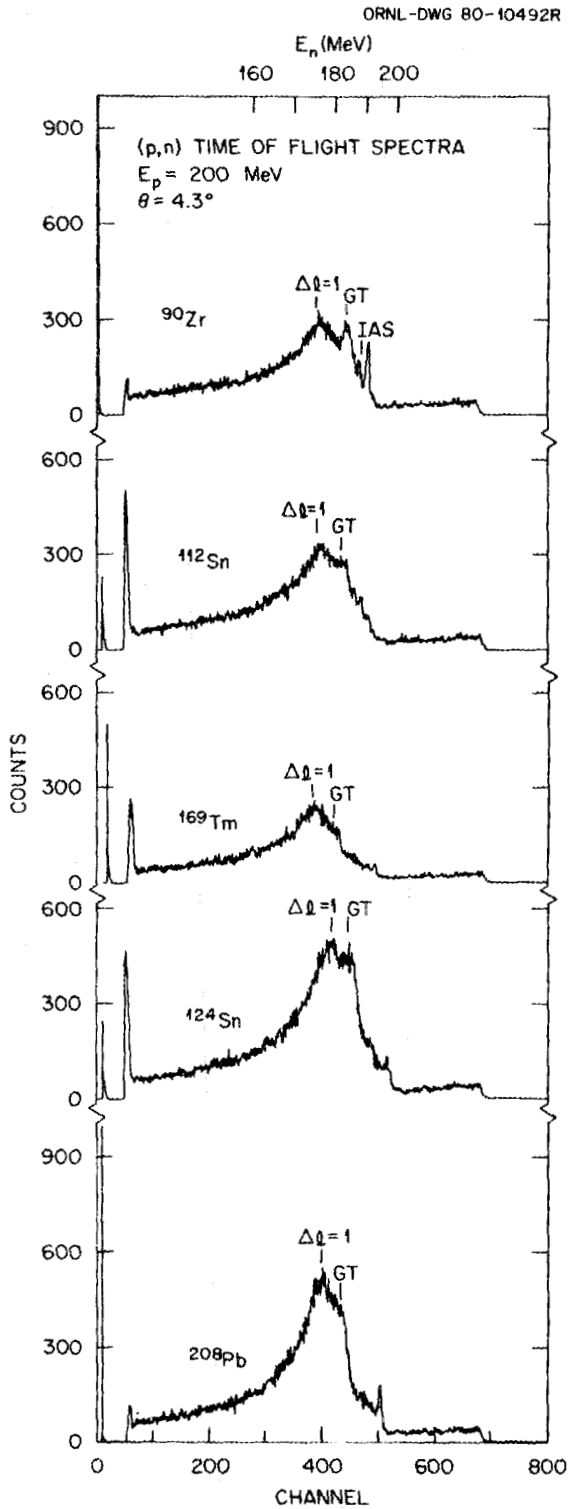


Fig. 2.91. Time-of-flight spectra at 4.3° for the (p,n) reaction at E_p = 200 MeV for targets of ^{90}Zr, ^{112}Sn, ^{169}Tm, ^{124}Sn, and ^{208}Pb.

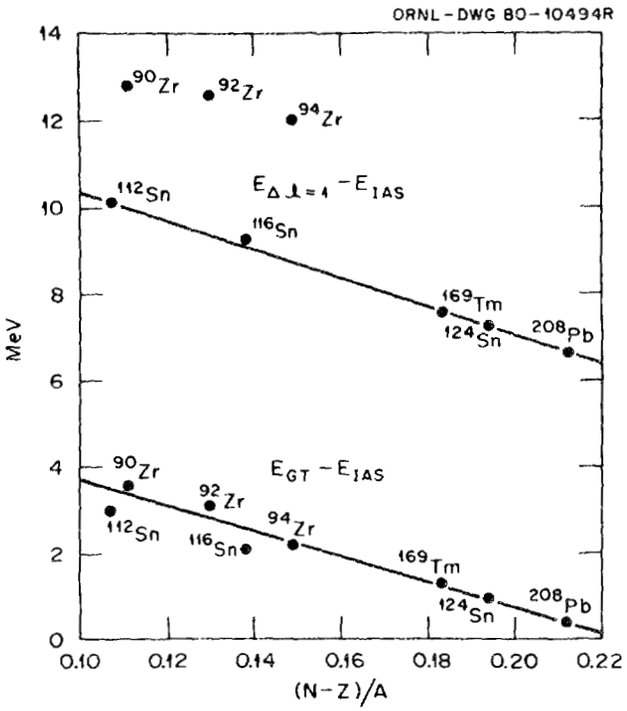


Fig. 2.92. Plots of $E_{GT} - E_{IAS}$ and $E_{\Delta L=1} - E_{IAS}$ $(N - Z)/A$.

the calculated and measured $E_{GT} - E_{IAS}$ for the Zr isotopes indicates a problem with the calculated values of E_{GT}.

A striking feature in Fig. 2.92 is that the values of $E_{L=1} - E_{IAS}$ for the three Zr isotopes lie about 3 MeV above the curve formed by the other elements. Since at present there are no detailed calculations of an $L = 1$, $S = 1$ resonance available for the Zr isotopes, one can only speculate as to the reasons for this. One reason might be that the distribution of strength among the J components for the Zr isotopes differs from that for other elements. Or possibly it is because there are fewer particle-hole pairs which can participate in the Zr isotopes, which would have the tendency to give a greater weighting to the higher-energy transitions which make up the collective state.

This work has been published.[12]

1. Indiana University, Bloomington.
2. Emporia State University, Emporia, Kans.
3. The Niels Bohr Institute, Copenhagen, Denmark.
4. Florida A&M University, Tallahassee.
5. Ohio University, Athens.
6. University of Colorado, Boulder.
7. Michigan State University, East Lansing.

8. C. D. Goodman et al., *IEEE Trans. Nucl. Sci.* **NS-26**, 2248 (1979).
9. D. E. Bainum et al., *Phys. Rev. Lett.* **44**, 1751 (1980).
10. D. J. Horen et al., *Phys. Lett.* **95B**, 27 (1980).
11. Yu. V. Gaponov and Yu. S. Lyutostanski, *Yad. Fiz.* **16**, 484 (1972) [*Sov. J. Nucl. Phys.* **16**, 270 (1973)]; *Yad. Fiz.* **19**, 62 (1974) [*Sov. J. Nucl. Phys.* **19**, 33 (1974)].
12. D. J. Horen et al., *Phys. Lett.* **99B**, 383 (1980).

EXCITATION OF GIANT RESONANCES BY INELASTIC SCATTERING OF 200-MeV PROTONS[1]

F. E. Bertrand — J. Tinsley[3]
E. E. Gross — D. K. McDaniels[3]
D. J. Horen — L. W. Swenson[4]
J. R. Wu[2] — R. Liljestrand[5]

Giant multipole resonances, the so-called "new" giant resonances, have been studied using inelastic scattering of electrons and a wide variety of hadrons. While hadronic probes provide clear excitation of giant resonance peaks, positive identification of the resonance multipolarity is often lacking. This comes about since angular distributions from inelastic hadron scattering are often not strongly characteristic of momentum transfer. The use of 200–400 MeV protons for giant resonance studies offers several advantages over probes previously used. The most notable advantage lies in the clearly characteristic angular distribution shapes for neighboring momentum transfers. For example, according to DWBA calculations, the difference between a "pure" $L = 2$ giant resonance and an $L = 2 + 4$, even for as little as 10–20% $L = 4$ EWSR depletion, is very large. Another interesting aspect of 200-MeV proton inelastic scattering is the very large small-angle cross section predicted for Coulomb excitation of the giant dipole resonance (GDR). Although it is assumed that the GDR is excited in inelastic proton scattering, direct evidence for GDR excitation has heretofore not been provided. Furthermore, at forward angles spin-flip excitations, such as $M1$ states, may be observed.

Protons of 200 MeV from the TRIUMF accelerator were inelastically scattered from about 60-mg/cm^2 targets and detected in the focal plane of the MRS, a broad-range magnetic spectrograph faciltiy.[6] Typical spectra covered an excitation energy range of about 40 MeV for a single field setting of the spectrograph. We have measured the spectrograph response and beam quality at zero degrees using a reduced-intensity beam and find no spurious background that would affect our results.

At the smallest angles studied, observations were made using blank target frames; no deleterious background was observed. The energy resolution was typically 900–1100 keV (FWHM), although some data on low-lying states were taken with about 450 keV (FWHM) resolution. Measurements were made every 2° between 4 and 20°. Our measurements of proton scattering cross sections from hydrogen using a CH_2 target agree to within 5% with phase-shift values.[7]

Data have been obtained for ^{60}Ni, ^{90}Zr, ^{120}Sn, ^{208}Pb, and ^{238}U. Figure 2.93 shows spectra from ^{90}Zr and ^{120}Sn at angles which should provide maximum cross sections for $L = 1, 2$, and 3 excitations. The broad peaks which are obvious in the high-excitation-energy continua arise from excitation of various multipolarity giant resonances.

At 4°, a large peak is observed which is located at the excitation energy of the GDR. The solid curve shown on the 4° data is the GDR shape and energy from (γ,n) measurements,[8] with magnitude fitted to our data. The GDR accounts for virtually the entire observed peak at 4°. The excellent agreement between the (γ,n) and (p,p') spectra provides a clear demonstration of inelastic proton excitation of the GDR. The GDR cross sections at 4° are 27 ± 5 mb/sr and 25 ± 4 mb/sr, respectively, for ^{90}Zr and ^{120}Sn. The GMR is located at nearly the same energy as the GDR, but DWBA calculations indicate that the GMR cross section is at least an order of magnitude smaller than that of the GDR at 4°. Since the $E1$ cross section drops rapidly with increasing angle, the $E0$ cross section becomes increasingly more important at larger angles.

An interesting aspect of the 4° ^{90}Zr spectrum is the presence of a narrow peak at 9.1 ± MeV. This peak is not observed in larger-angle spectra. We suggest that this peak may arise from excitation of $M1$ states in ^{90}Zr. Recent (e,e') measurements[9] report $M1$ states located at 9.371, 9.000, and 8.233 MeV in ^{90}Zr. In addition, a state tentatively identified as $M1$ has been observed[10] at 8.3 ± 0.4 MeV in the (p,n) reaction of ^{90}Zr. The cross section obtained in the (p,n) measurement[11] for the isobaric analog of this $M1$ state is about 4 mb/sr, which would imply a (p,p') cross section of about 10 mb/sr, in good agreement with our measurement of 7.2 ± 2.0 mb/sr. It is clear that we have not shown conclusively that the 9.1-MeV peak arises from ex-

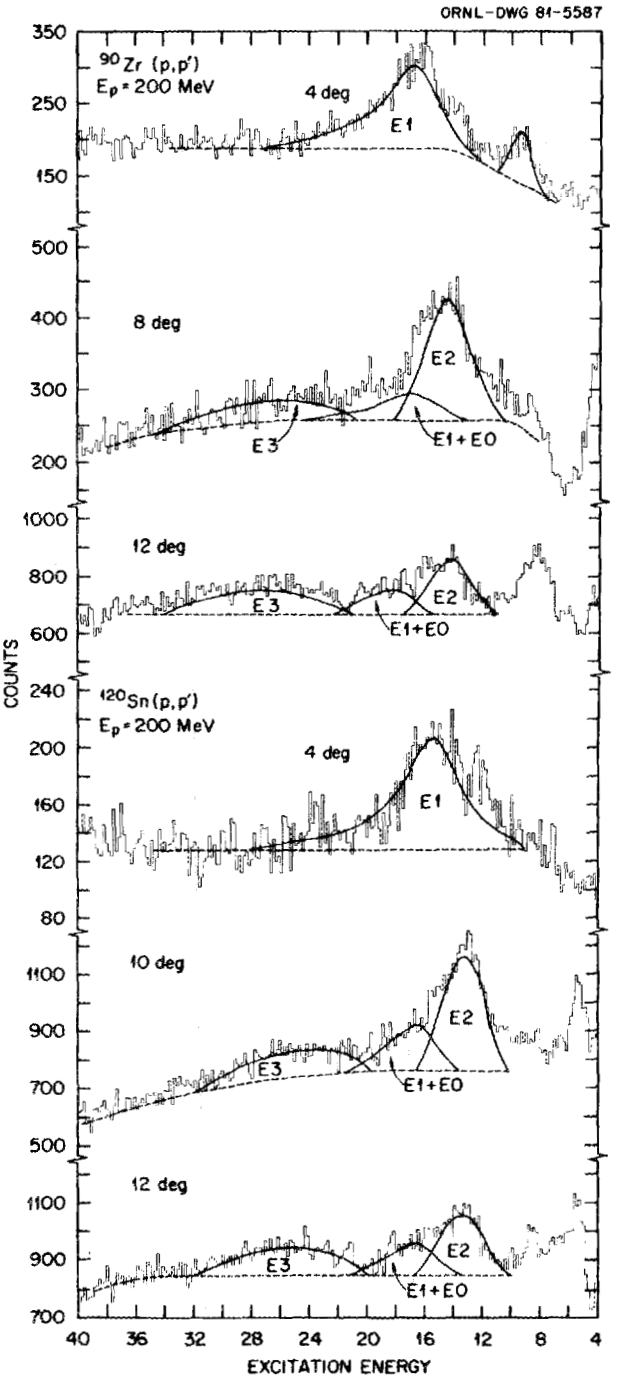


Fig. 2.93. Spectra from inelastic scattering of 200-MeV protons from ^{90}Zr and ^{120}Sn. The multipolarities shown for the resonances are discussed in the test. The dashed line shows the shape and magnitude assumed for the nuclear continuum underlying the resonance peaks.

citation of an $M1$ state. However, considering the poor resolution of the (p,p') and (p,n) measurements, the agreement among the three measurements certainly provides strong suggestion of an $M1$ assignment for the peak. No similar state is seen in our ^{120}Sn 4° spectrum, nor has an $M1$ state been reported from other measurements on ^{120}Sn.

The 8 and 10° spectra shown in Fig. 2.93 were obtained at a maximum for the $L = 2$ angular distribution for ^{90}Zr and ^{120}Sn respectively. The solid curve, taken from the shape and location of the GQR as determined from (α,α') measurements,[12] provides excellent agreement with the present data. In the 12° spectra, broad peaks seen somewhat less clearly at 8 and 10° are observed at 25 ± 1 and 27 ± 1 MeV in ^{120}Sn and ^{90}Zr respectively. The widths (FWHM) of the peaks are, respectively, 8 ± 1 and 9 ± 1 MeV for ^{120}Sn and ^{90}Zr. We interpret these peaks as arising from excitation of the $3\hbar\omega$ GOR ($E3$).

Figure 2.94 shows angular distributions for the GQR and GOR peaks. The uncertainties shown on the measured cross sections arise mostly from the uncertainty in the assumptions made for the shape and magnitude of the nuclear continuum underlying the resonance peaks. The comparisons on Fig. 2.94 show that the GQR cross sections are well described by the $L = 2$ DWBA calculation. The sensitivity of our results to higher-multipole contributions in the GQR peak is shown by the dashed curve, which results from a mixture of only 5% of the $L = 4$ EWSR with the $L = 2$ angular distribution. Clearly, the GQR peak contains very little, if any, contribution from excitation of a $2\hbar\omega$ $E4$ giant resonance. This statement only indicates that there is no major $L = 4$ strength within the GQR peak shown in Fig. 2.93. A $2\hbar\omega$ $E4$ resonance may be many MeV wide and thus may escape detection in the present experiment.

From the DWBA calculations we derive an EWSR depletion for the GQR of 30% ± 8 in ^{90}Zr and 35% ± 6 in ^{120}Sn. These values are low by about a factor of 2 when compared with values[13] from other inelastic reactions.

The measured angular distribution for the peak labeled $E3$ in Fig. 2.93 agrees with the $L = 3$ DWBA calculation and does not agree at all with the $L = 4$ or $L = 2$ calculation. These results provide definitive evidence for the existence of the $3\hbar\omega$ giant octupole resonance. Within the limitation discussed above, our results for the GOR, when compared with the DWBA calculations, yield 14% ± 3 and 18% ± 4 $T = 0$, $E = 3$ EWSR depletion for ^{120}Sn and ^{90}Zr respectively.

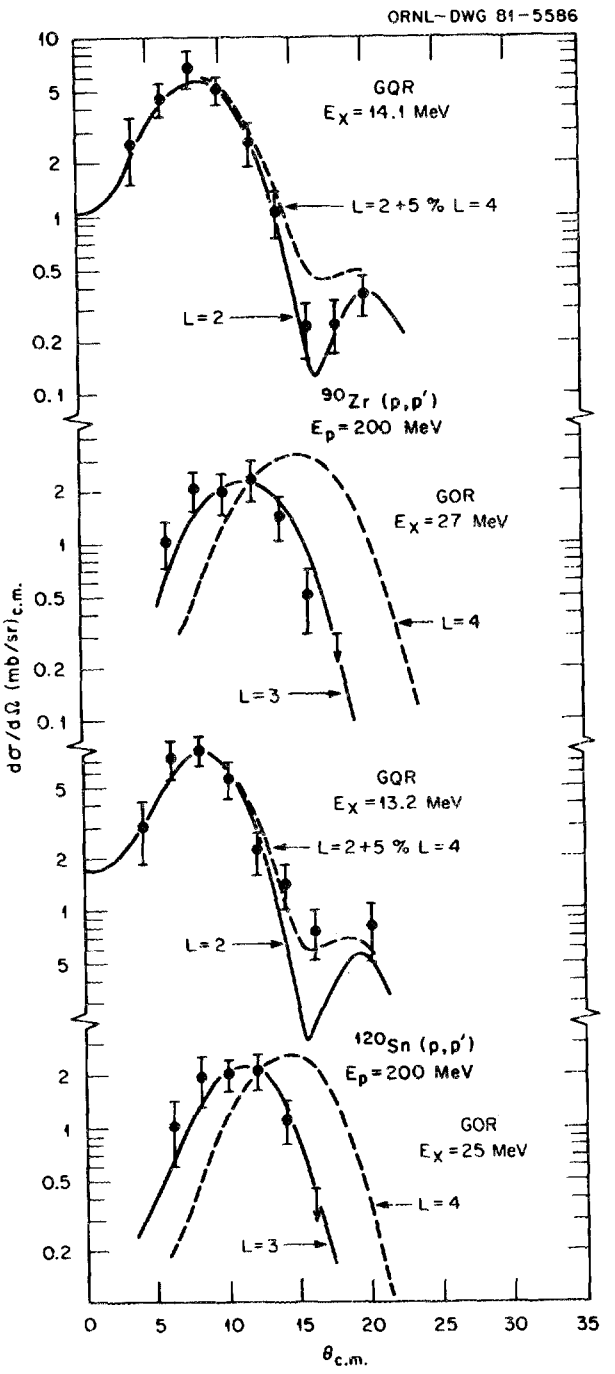


Fig. 2.94. Angular distributions for the GQR and GOR compared with DWBA calculations (solid and dashed curves).

1. Further report of this work to be published in *Physics Letters*.

2. Bell Laboratories, Naperville, Ill.
3. University of Oregon, Eugene.
4. Oregon State University, Corvallis.
5. University of Alberta, TRIUMF, Vancouver, B.C. V6T 2A3.
6. TRIUMF Annual Report, 1977, p. 82. Further details can be found on pp. 4–46 of the TRIUMF Users Manual.
7. R. A. Arndt et al., *Phys. Rev. C* **9**, 555 (1978).
8. B. L. Berman and S. C. Fultz, *Rev. Mod. Phys.* **47**, 713 (1975).
9. D. Meuer et al., *Nucl. Phys.* **A349**, 309 (1980).
10. D. E. Bainum et al., *Phys. Rev. Lett.* **44**, 1751 (1980).
11. J. Rapaport et al., private communication.
12. F. E. Bertrand et al., *Phys. Rev. C* **22**, 1832 (1980).
13. F. E. Bertrand, *Annu. Rev. Nucl. Sci.* **26**, 457 (1976).

GIANT MULTIPOLE RESONANCES FROM INELASTIC SCATTERING OF 152-MeV ALPHA PARTICLES[1]

F. E. Bertrand — A. D. Bacher[3]
G. R. Satchler — G. T. Emery[3]
D. J. Horen — W. P. Jones[3]
J. R. Wu[2] — D. W. Miller[3]
A. ven der Woude[4]

Giant resonance spectra have been measured for ^{208}Pb, ^{120}Sn, ^{90}Zr, ^{58}Ni, and ^{46}Ti using inelastic scattering of 152-MeV alpha particles. In addition to some low-lying states, the spectra were analyzed to yield separate peaks for the giant quadrupole resonance and giant monopole resonance, except in ^{46}Ti, where no evidence was found for a giant monopole resonance. The results for the monopole resonance when compared with distorted-wave Born-approximation calculations show that about 100% (±20%) of the $T = 0$, $L = 0$ energy-weighted sum rule is depleted for nuclei with $A > 90$. For ^{58}Ni, only 40% of the monopole sum rule is found. The excitation energy of the giant monopole resonance follows the systematic trend $\sim 80 \times A^{-1/3}$ MeV. The data are also compared with folding-model calculations using Tassie transition densities and an effective interaction derived from elastic data. Good agreement was obtained for low-lying quadrupole and octopole excitations, but this model yields considerably too little cross section for the monopole resonance. This probably indicates a deficiency in the Tassie-model breathing-mode transition density.

1. Summary of published paper, *Phys. Rev. C* **22**, 1832 (1980).
2. Bell Laboratories, Naperville, Ill.
3. Indiana University, Bloomington.
4. Kernfysisch Versneller Instituut, Groningen, The Netherlands.

THE FISSION PROBABILITY OF ^{239}U AT HIGH EXCITATION MEASURED WITH THE ^{238}U(α,^{3}Hef) REACTION[1]

J. R. Wu[2] — F. E. Bertrand
J. R. Beene — E. E. Gross
C. E. Bemis, Jr. — D. J. Horen
W. P. Jones[3]

The fission probability of ^{239}U has been measured as a function of excitation energy using the ^{238}U(α,^{3}Hef) reaction with $E_\alpha = 152$ MeV. The ^{3}He spectrum in coincidence with fission exhibits a broad peak near the incident beam velocity. The fission probability has been measured over a wide excitation-energy range for ^{239}U and is found to agree with that obtained from the ^{238}U(n,f) reaction. These measurements indicate that the ^{3}He particle is produced predominantly near the beam velocity and behaves as a spectator, while the neutron is transferred to the target, forming a compound nucleus. The wide range of excitation energies which can be investigated in a single experiment, without appreciable interference from other reaction processes, makes the (α,^{3}He) reaction a useful tool for fission probability measurements.

1. Summary of paper to be published in *Physical Review*.
2. Bell Laboratories, Naperville, Ill.
3. Indiana University Cyclotron Facility, Bloomington.

FISSION DECAY OF THE GIANT QUADRUPOLE RESONANCE IN ^{238}U[1]

E. E. Gross — F. E. Bertrand
J. R. Beene — D. J. Horen
C. E. Bemis, Jr. — J. R. Wu[2]
W. P. Jones[3]

We have measured the fission probability of ^{238}U excited by 152-MeV α-particle inelastic scattering. The excitation region studied extended from threshold to 30 MeV. Alpha particles scattered from an 800-μg/cm^2 ^{238}U foil at 11.5° lab [a maximum in the giant quadrupole resonance (GQR) angular distribution] and at 17.5° lab (a GQR minimum) were detected in ΔE (3500 μ) – E (5000 μ) Si surface-barrier telescopes. Both telescopes subtended angles of 1° horizontally and 2° verti-

cally. Coincident fission fragments were detected in position-sensitive gas proportional counters. One fragment detector was centered on the ^{238}U recoil direction (74° lab for alpha particles scattered at 11.5° lab) and subtended 25° horizontally and 1° vertically. The second fission-fragment detector was located antiparallel to the ^{238}U recoil direction and subtended a 25% larger solid angle.

Triple coincidences between two fission fragments and inelastically scattered alpha particles were recorded simultaneously with prescaled alpha-particle singles. A giant resonance peak appeared in the 11.5° lab alpha singles spectrum located at 11.0 MeV with a width of about 5 MeV (FWHM), which we attribute to the GQR. The GQR was unobserved in the 17.5° alpha singles data. In the triple-coincidence alpha-particle spectrum at 11.5°, we observe an enhancement of the fission probability at 10.4 MeV with a width of about 1.5 MeV (FWHM), while no such enhancement is evident in the 17.5° triple-coincidence data.

Due to the unique nuclear alignment properties of fission induced by inelastic alpha-particle scattering, our coincidence measurements are only sensitive to fission of the $K = 0$ component of the GQR in the deformed ^{238}U. Here, K is the projection of the nuclear spin I ($I = 2$ for GQR) on the symmetry axis of the nuclear density distribution. The unique alignment in our experiments, with the recoil axis taken as the axis of quantization, corresponds to $m = 0$ in the plane-wave limit. We deduce a fission probability for the GQR of 0.25 ± 0.10, while that for the underlying nuclear continuum is found to be 0.21 ± 0.08. Thus the GQR shows no special inhibition or preference for fission decay over that for the nuclear continuum or giant dipole resonance ($\Gamma_f/\Gamma \sim 20\%$). Our fission probability measurements and deduced properties of the ^{238}U $E0$ and $E2$ resonances are best understood under the assumption of preservation of the K quantum number during the fission process. This K preservation has not been observed in compound-nuclear fission studies. A possible inference from this contrasting behavior is that the quadrupole oscillation, which is strongly and directly excited in the present reaction, might couple more directly to the fission mode of the nucleus than do the more complex states excited in compound-nuclear reactions.

1. Summary of published paper: *Phys. Lett.* **99B**, 213 (1981).

2. Bell Laboratories, Naperville, Ill.
3. Indiana University Cyclotron Facility, Bloomington.

THE REACTION $\pi^+ + d \rightarrow p + p$ AT 20 TO 65 MeV

B. G. Ritchie[1] J. R. Wu[2]
R. D. Edge[1] M. Blecher[3]
D. J. Malbrough[1] K. Gotow[3]
B. M. Preedom[1] R. L. Burman[4]
F. E. Bertrand R. Carlini[4]
E. E. Gross M. E. Hamm[4]
F. E. Obenshain M. J. Leitch[4]
M. A. Moinester[5]

The reaction $\pi^+ + d \rightarrow p + p$ represents the simplest pion absorption process which can occur; hence the reaction has been of great interest in studies of pion-nucleon and pion-nucleus interactions. It has also been suggested that the reaction may be used to probe the high angular momentum components of the deuteron ground-state wave function and to test conservation laws through the method of detailed balance. As a consequence of these diverse and fundamental phenomena, the reaction has been intensively studied for nearly three decades.

Accurate measurements of the energy dependences of the reaction angular distribution and total cross section are of particular importance in understanding the mechanisms associated with this reaction. As experimental technologies and techniques have improved, more precise determinations of the integral and differential cross sections have been made at many energies. The advent of higher-quality and higher-intensity pion beams provided by the low-energy beam line at LAMPF has led to the present study of the $\pi^+ - d$ reaction. We report new measurements at 20^-, 25^-, 30^-, 35^-, 40^-, and 65-MeV pion beam energies and thus extend our previous work[6] to higher and to lower energies.

The present status of the $\pi^+ + d \rightarrow 2p$ total-cross-section data unde 200 MeV is summarized in Fig. 2.95. Our new high-precision measurements confirm the general trend of the earlier measurements. Also shown on the figure are three calculations which all fail, in different ways to quantitatively account for the entire excitation function. This disagreement between theory and experiment has spurred us to extend our measurements up to and beyond the 3/2, 3/2 resonance, thereby providing an entire excitation function by

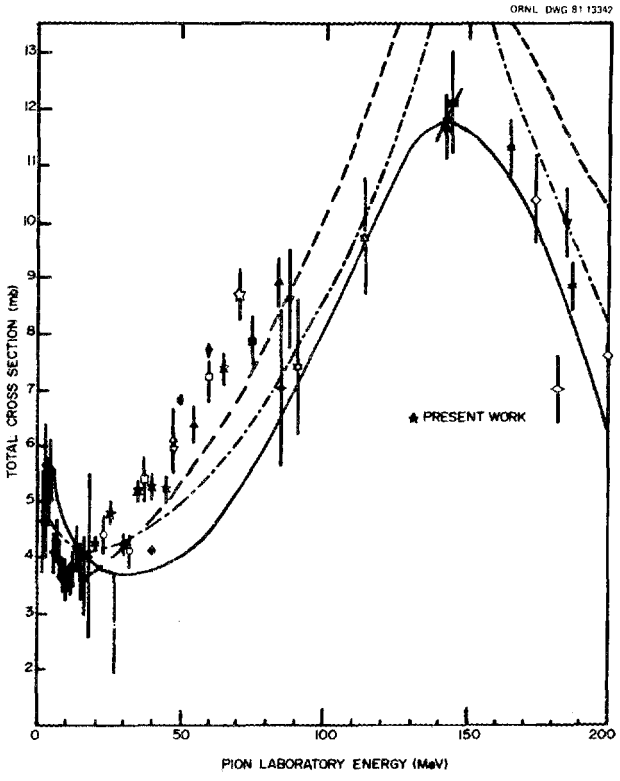


Fig. 2.95. Total cross section for the reaction $\pi^+ + d \rightarrow p + p$ below 200 MeV. The present measurements are indicated by ★. The calculations are those of Chai and Risha (ref. 7), Cheon (ref. 8), and Maxwell, Weise, and Brock (ref. 9).

the efforts of a single group. Hopefully, such a set of data will be more consistent than the present assembly of data and allow a more convincing test of theory.

1. Department of Physics and Astronomy, University of South Carolina, Columbia.
2. Bell Laboratories, Naperville, Ill.
3. Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg.
4. Los Alamos National Laboratory, Los Alamos, N. Mex.
5. Department of Physics and Astronomy, Tel Aviv University, Ramat-Aviv, Israel.
6. B. M. Preedom et al., *Phys. Rev. C* **17**, 1402 (1978).
7. J. Chai and D. O. Riska, *Nucl. Phys.* **A338**, 349 (1980).
8. I. T. Cheon, *Phys. Lett.* **90B**, 342 (1980).
9. O. V. Maxwell, W. Weise, and M. Brock, *Nucl. Phys.* **A348**, 388 (1980).

POSITIVE-PION–NUCLEUS ELASTIC SCATTERING AT 20 MeV

F. E. Obenshain
F. E. Bertrand
M. Blecher[1]
R. L. Burman[2]
R. D. Edge[3]
K. Gotow[3]
E. E. Gross
M. Hamm[2]
N. W. Hill[4]
M. J. Leitch[1]
M. A. Moinester[5]
B. M. Preedom[3]
R. P. Redwine[6]
J. R. Wu

We have measured positive-pion–nucleus elastic scattering at 20 MeV from the targets ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb. These measurements were performed at the low-energy pion (LEP) channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). The data presented here are the first measurements of the elastic scattering at such a low energy, and they may be compared with earlier measurements at 30, 40, and 50 MeV to obtain a rather complete description of the energy and mass dependence of the scattering in this low-energy region. At higher energies the pion-nucleus interaction is dominated by the strong absorption occurring near the $\pi - N$ resonance, but at the lower energies the mean free path is much longer, and the pion interaction may extend into the nuclear interior.

The angular distributions shown in Fig. 2.96 were obtained with plastic scintillator detectors. At this energy and for our targets, the elastically scattered pions are easily resolved from the nonelastically scattered ones. To ensure identification of the pions in the forward direction, an event required the detection of the pion and a subsequent decay muon within the same detector. All of the angles shown in Fig. 2.96 were obtained by moving the set of ten detectors twice, keeping the two at 90 and 100° fixed. The momentum spread in the beam was 2%, and no substantial improvement in the quality of the data was obtained by reducing the momentum spread to 1%.

The absolute cross sections were obtained using the number of incident pions measured with a π-μ dE/dx detector. The detector counted the number of muons resulting from pion decays in the beam line and was calibrated at a reduced beam intensity by a direct counting of the incident pions.

The data shown in Fig. 2.96 were analyzed with a nonlocal optical-model potential in the t-matrix

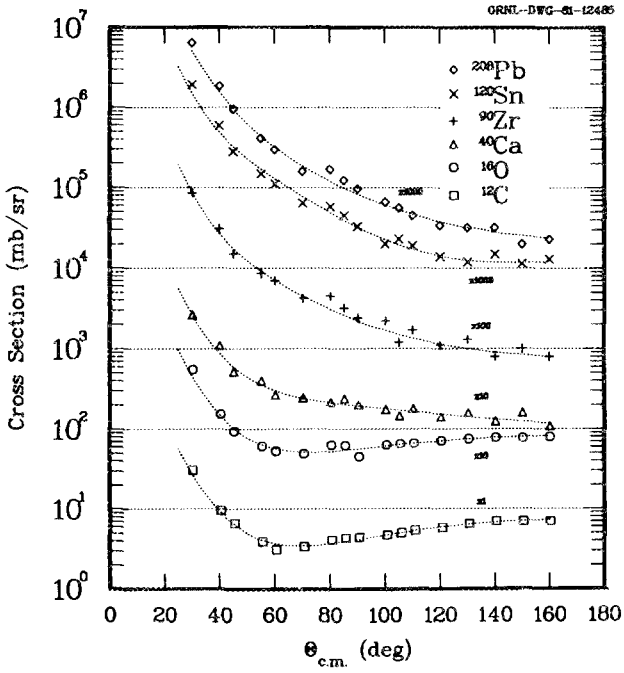


Fig. 2.96. Elastic scattering data for 20-MeV pions from ^{12}C, ^{16}O, ^{40}Ca, ^{90}Zr, ^{120}Sn, and ^{208}Pb are shown by the symbols, and the optical-model fit is shown by the curve.

formulation. The t matrix is

$$t[E(k), \mathbf{q}, \mathbf{q}'] \propto b_0(E) \frac{(k^2 + \alpha_0^2)^2}{(\alpha_0^2 + q^2)(\alpha_0^2 + q'^2)} + b_1(E) \frac{(k^2 + \alpha_1^2)^2}{(\alpha_1^2 + q^2)(\alpha_1^2 + q'^2)} ,$$

where E, k are the on-shell energy and momentum, q, q' are the off-shell initial and final momenta, and $\alpha_{0,1}$ are the range parameters for the πN interaction (we take them to be equal). The s- and p-wave parameters b_0 and b_1 were varied in order to obtain a minimum in χ^2. A variation of the range parameter α from about 300 to about 700 does not significantly change the values of b_0 and b_1 obtained. The formulation becomes the same as Kisslinger's for $\alpha \to \infty$. Table 2.18 shows a comparison of the real and imaginary parts of b_0 and b_1 for α = 500 and infinity for each of the nuclei studied. The curves shown in Fig. 2.96 are those obtained from the minimization of χ^2 for the case α = 500 and with an appropriate set of nuclear parameters taken from electron scattering. The statistical errors associated with each data point are approximately the size of the symbol used.

Table 2.18. Optical-model parameters determined by fitting the data shown in Fig. 2.96

Target α	Re b_0	Im b_0	Re b_1	Im b_1
^{12}C 500	−4.38	−1.48	5.48	−0.11
∞	−5.05	0.16	5.36	−1.87
^{16}O 500	−4.53	2.27	5.25	−1.36
∞	−4.37	2.86	4.49	−2.72
^{40}Ca 500	−4.60	3.11	4.93	−2.31
∞	−4.55	3.71	4.79	−2.23
^{90}Zr 500	−1.46	1.79	6.01	0.43
∞	−1.92	2.31	6.55	0.10
^{120}Sn 500	−2.83	3.68	6.86	−0.51
∞	−5.65	3.47	7.05	0.07
^{208}Pb 500	−1.35	4.07	3.37	+0.61
∞	−5.04	6.35	−2.41	−4.48

In Fig. 2.97 we show a plot of the parameter Im b_0 as a function of energy for each of the nuclei ^{16}O, ^{40}Ca, ^{90}Zr, and ^{208}Pb. The values at 30, 40, and 50 MeV were taken from previous work.[7,8] As can be seen from the figure, the absorptive s-wave parameter increases rather dramatically at 20 MeV compared with the other three energies. The curve is a theoretical prediction.[9] It is thought that this effect is related to the pion-nucleus penetrability at this energy.

Stricker, Carr, and McManus[10] have determined the parameters for an optical-model potential from pionic atom data and from pion elastic scattering at 50 MeV. The energy dependence of the potential parameters was determined by interpolation. The curves[11] shown in Fig. 2.98 were calculated for our 20-MeV data with the optical-model parameters so derived. As may be seen, the comparison with the data is quite good and lends credibility to both the experimental and theoretical method.

1. Virginia Polytechnic Institute and State University.
2. Los Alamos National Laboratory.
3. University of South Carolina.
4. Instrumentation and Controls Division.
5. University of Tel-Aviv.
6. Massachusetts Institute of Technology.
7. M. Blecher et al., *Phys. Rev. C* **20**, 1884 (1979).
8. B. Preedom et al., *Phys. Rev. C* **23**, 1134 (1981).
9. E. Auerbach, D. Fleming, and M. Sternhein, *Phys. Rev.* **162**, 1683 (1967).
10. K. Stricker, J. Carr, and H. McManus, *Phys. Rev. C* **22**, 2043 (1980).
11. H. McManus, private communication.

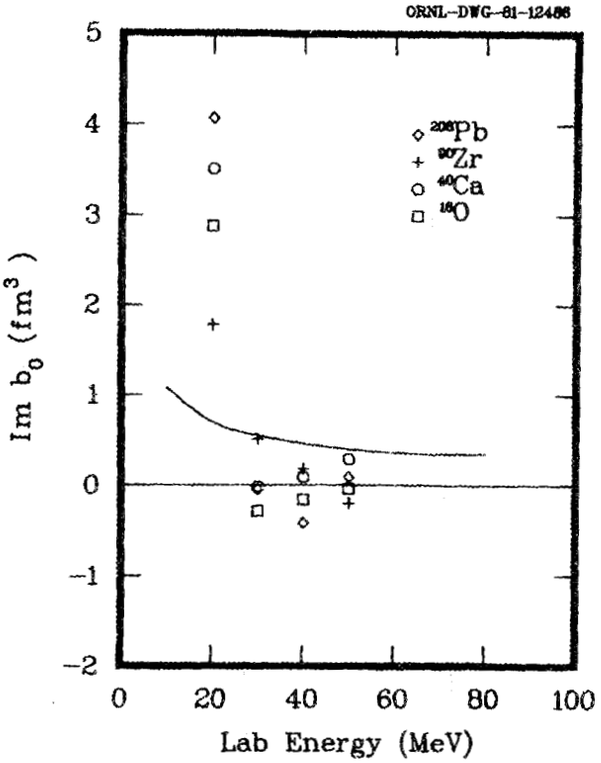


Fig. 2.97. The absorptive *s*-wave strength Im b_0 is shown as a function of energy for ^{16}O, ^{40}Ca, ^{90}Zr, and ^{208}Pb. The curve is a theoretical calculation taken from ref. 9.

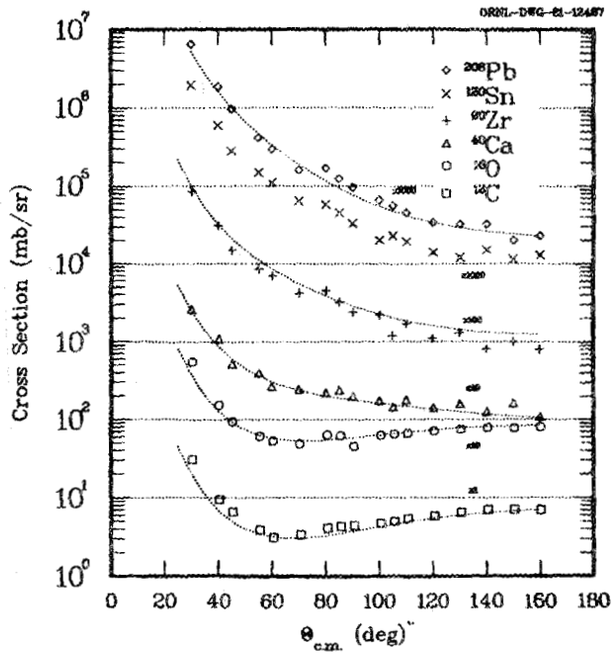


Fig. 2.98. The data shown are the same as in Fig. 2.96. The curves were calculated according to the model of Stricker, Carr, and McManus (refs. 10, 11).

ELASTIC SCATTERING OF π^+ AND π^- FROM ^{40}Ca AT 64.8 MeV

F. E. Bertrand
E. E. Gross
S. H. Dam[1,2]
R. D. Edge[1]
B. M. Preedom[1]
M. Hamm[3]
R. L. Burman[3]
R. Carlini[3]
R. P. Redwine[3,4]
M. A. Yates[3]
M. Blecher[5]
K. Gotow[5]
M. A. Moinester[6]

Elastic pion scattering in the energy region between 50 and 100 MeV is of particular interest since that region provides a transition from a weak to a strongly resonant interaction in the pion-nucleus system. The measurement of both π^+ and π^- distributions is important for several reasons. Cross sections for single charge exchange can be predicted from π^+ and π^- elastic scattering cross sections,[7] and a comparison of these for $N = Z$ targets may lead to information about the off-shell behavior of the πN interaction.[8] Also, data from scattering both charged pions in this energy region should provide a stringent test of pion-nucleus scattering theories, particularly with regard to the correct treatment of the Coulomb part of the interation. This report presents the results for π^+ and π^- scattering from ^{40}Ca at 64.8 MeV. Also presented are attempts to fit these data with a first-order phenomenological optical model.

The data were taken using the Bicentennial Spectrometer at the low-energy pion (LEP) channel[9] of the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF). This spectrometer is a double-focusing, broad-range device. Scattered pions are momentum-analyzed by the spectrometer and are detected by a helical wire chamber[10] placed at the focal plane. A second wire chamber placed above the first provides angle information used to reduce background. The event signature is defined by a coincidence between a small scintillator (SO) placed between the target and the *x-y* collimating slits, a large scintillator (SI) mounted after the second wire chamber, and a *y*-axis (perpendicular to the bend plane of the magnet) signal from either wire chamber. The relative normalization of the incident beam flux was accomplished using a pion-decay monitor.[11] Two scintillators placed at an

angle of 7° from the beam were used to detect muons from decaying beam pions.

The experimental results are shown in Figs. 2.99–2.101. An analysis of these data has been performed using a coordinate-space code developed by Gibbs, Gibson, and Stephenson.[12] This code utilizes

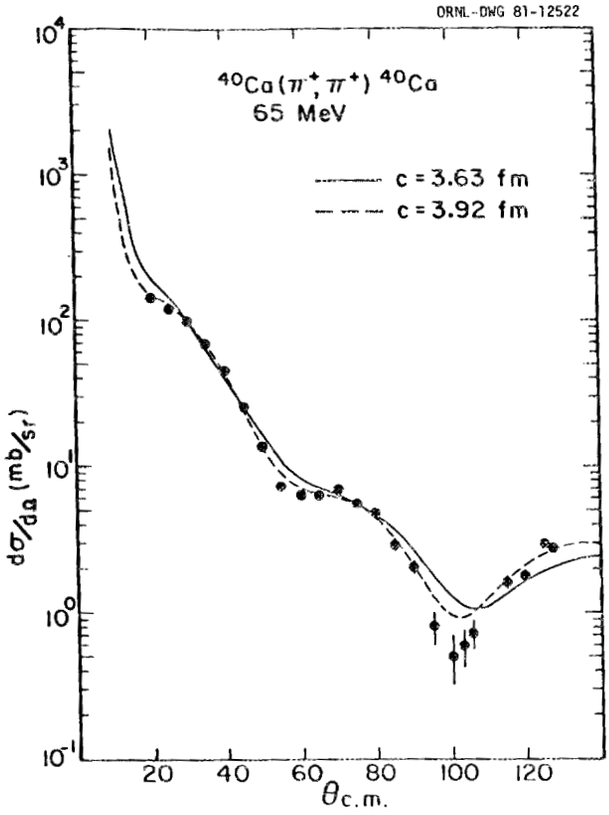


Fig. 2.99. Comparison of optical-model fits to the π^+ data for electron scattering geometry (solid curve) and best-fit geometry (dashed curve) with an off-shell parameter α of 500 MeV/c and fixed diffuseness, a, of 0.51 fm. The corresponding χ^2/N of the fits are 12.8 and 3.7 respectively.

a phenomenological nonlocal Kisslinger t matrix which in momentum-space notation can be written as follows:

$$t(\mathbf{q}, \mathbf{q}', E) \propto \frac{(k^2 + \alpha^2)^2}{(\alpha^2 + q^2)(\alpha^2 + q'^2)} \{b_0 k^2 + b_1(\mathbf{q} \cdot \mathbf{q}')\} . \quad (1)$$

In this expression, α is an off-shell parameter describing a vertex nonlocality in the pion-nucleus interation, k and E are the on-shell pion momentum and energy, $\mathbf{q}$ and $\mathbf{q}'$ are the local pion-nucleon

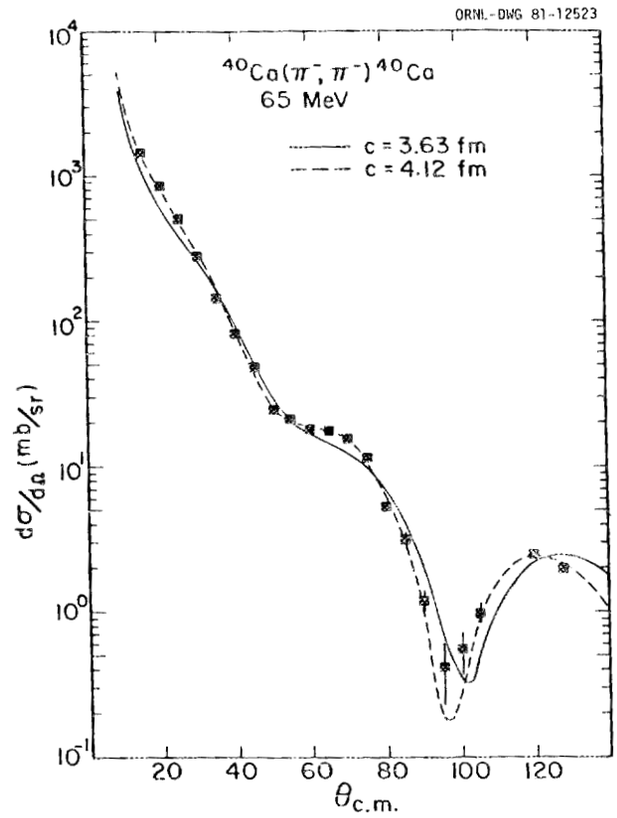


Fig. 2.100. Comparison of optical-model fits to the π^- data for electron scattering geometry (solid curve) and best-fit geometry (dashed curve) with an off-shell parameter α of 500 MeV/c and fixed diffuseness, a, of 0.51 fm. The corresponding χ^2/N of the fits are 17 and 1.5 respectively.

relative momenta before and after the interaction, and b_0 and b_1 are the complex s- and p-wave strength parameters. Since there is considerable evidence indicating that strengths determined from free pion-nucleon phase shifts cannot adequately describe the low-energy pion elastic scattering data, the strengths have been treated as free parameters in the present study.

The nuclear matter density is taken to be a Woods-Saxon distribution

$$\rho(r) = \frac{N(c, a)}{1 + \exp^{(r-c)/a}} , \quad (2)$$

where $N(c, a)$ is the normalization, c is the half-density radius, and a is the diffuseness. The body geometry parameters c and a for ^{40}Ca were initially determined by choosing a set which, when convoluted with a proton charge radius of 0.81 fm,

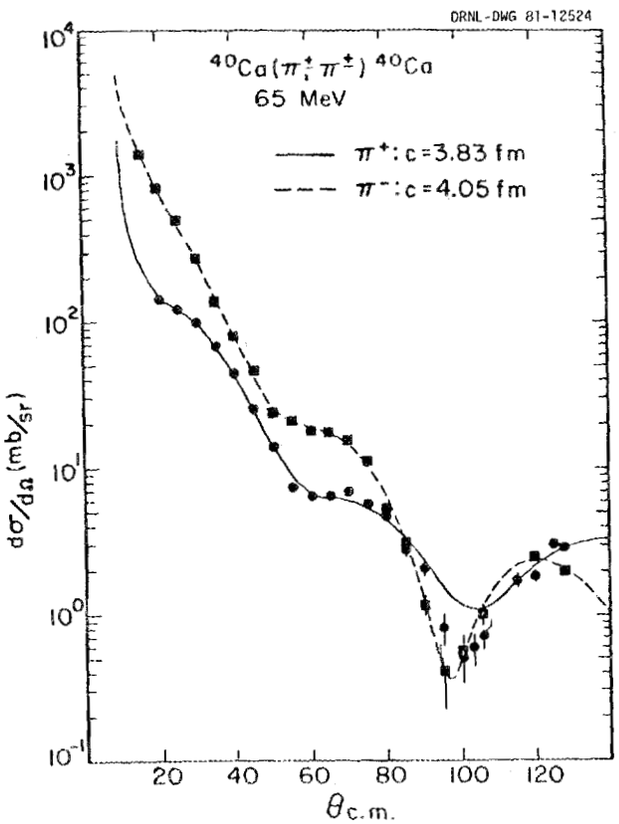


Fig. 2.101. Modified optical-model fits (see text) to the π^+ and π^- data with an off-shell parameter $\alpha = 400$ MeV/c and diffuseness $a = 0.51$ fm, for best-fit radii as indicated. The corresponding χ^2/N are 4.5 for π^+ and 1.5 for π^-.

gave the same rms radius as determined from electron scattering and also reproduced the electron scattering form factor out to several minima. The geometry for the matter distribution thus obtained was $c = 3.63$ fm and $a = 0.51$ fm, which differs slightly from the $c = 3.68$ fm and $a = 0.58$ fm used at lower energies.[13] However, both sets of geometry parameters give equally good fits to the lower-energy data.

The initial attempts to fit the data were performed using the above geometry while searching internally on the strength parameters b_0 and b_1 for various values of the off-shell parameter α. However, it was found that the model was unable to give reasonable fits to either set for any value of α with the geometry derived from electron scattering.

The poor fits obtained with this geometry are presumably indicative of the need to include additional effects in the optical model, some of which can be mocked up by a change in the radius of the Woods-Saxon density distribution.

Representative fits for the best-fit geometries for $\alpha = 500$ MeV/c are plotted in Figs. 2.99 and 2.100. The radii corresponding to these fits are 3.92 fm for π^+ and 4.12 fm for π^-. Note that even the π^+ radius is some 0.3 fm larger than the original 3.63 fm, a strong indication that higher-order effects will play an important role in adequately describing these data. The difference in the π^- and π^+ radii, however, is disturbing and difficult to explain, since the target is an $N = Z$ nucleus and the coordinate-space fitting code explicitly takes into account the Coulomb part of the interaction. Thus there should be no large charge-dependent effects, not even in higher-order terms.

In the solution of the Klein-Gordon equation, the second-order potential terms, V_N^2 and $V_N V_C + V_C V_N$, are normally estimated to be small compared with $V_N + V_C$ and hence are omitted. Since the first term contributes ρ^2 terms from the first-order potential and the second term is charge-dependent, the code was modified to include these terms in order to determine their effect on the best-fit geometry. The radii needed to fit the data are still considerably larger than the value derived from electron scattering, and the radius difference between π^+ and π^- persists. Figure 2.101 shows the fitted angular distributions corresponding to the representative case of $\alpha = 400$ MeV/c for the modified version of the model.

Neither the π^+ nor the π^- data presented here can be fitted with a phenomenological first-order optical model unless the nuclear matter geometry is allowed to vary from the geometry determined from electron scattering. Good fits to the π^- data and reasonable fits to the π^+ data can be obtained for values of c, the Woods-Saxon radius parameter, that are considerably larger than that expected from electron scattering. This is not to be interpreted as a true reflection of the nuclear matter density but rather as an indication of the need to include higher-order terms in the model. The poorer fits for the π^+ data are apparently due to the fact that the π^+ angular distribution exhibits more structure in the s-p interference region, making it more difficult for the model to simultaneously reproduce this region and the diffraction minimum.

---

1. University of South Carolina, Columbia.
2. Present address: Los Alamos National Laboratory, Los Alamos, N. Mex.
3. Los Alamos National Laboratory, Los Alamos, N. Mex.
4. Present address: Massachusetts Institute of Technology, Cambridge.

5. Virginia Polytechnic Institute and State University, Blacksburg.
6. Tel Aviv University, Ramat Aviv, Israel.
7. J. Eisenberg, *J. Phys.* G6, 1265 (1980).
8. W. R. Gibbs, NATO Advanced Study Institutes Series: Series B, *Physics*, vol. 45, eds. B. Castel, B. Goulard, and F. C. Khanna, Plenum, New York, 1979, p. 595.
9. R. L. Burman, R. L. Fulton, and M. Jakobson, *Nucl. Instrum. Methods* **131**, 29 (1975).
10. D. M. Lee, S. E. Sobottka, and M. A. Thiessen, *Nucl. Instrum. Methods* **104**, 179 (1972).
11. E. A. Wadlinger, *Nucl. Instrum. Methods* **134**, 243 (1976).
12. W. R. Gibbs, B. F. Gibson, and G. J. Stephenson, Jr., private communication.
13. B. M. Preedom, S. H. Dam, C. W. Darden III, R. D. Edge, D. J. Malbrough, T. Marks, R. L. Burman, M. Hamm, M. A. Moinester, R. P. Redwine, M. A. Yates, F. E. Bertrand, T. P. Cleary, E. E. Gross, N. W. Hill, C. A. Ludemann, M. Blecher, K. Gotow, D. Jenkins, and F. Milder, in press, *Phys. Rev. C.*

ELASTIC SCATTERING OF $\pi^{\pm}$ AT 80 MeV

F. E. Obenshain — M. Hamm[2]
F. E. Bertrand — N. W. Hill[4]
M. Blecher[1] — M. J. Leitch[1]
R. L. Burman[2] — M. A. Moinester[5]
R. D. Edge[3] — B. M. Preedom[3]
K. Gotow[3] — R. P. Redwine[6]
E. E. Gross — J. R. Wu

Angular distributions for the elastic scattering of positive and negative pion beams from ^{12}C, ^{40}Ca, ^{90}Zr, and ^{208}Pb have been measured[7] with the Bicentennial Spectrometer (BCS) at the low-energy pion channel of the Clinton P. Anderson Meson Physics Facility. The data and analysis presented here are preliminary and represent a continuing program[8-10] to measure the elastic and inelastic cross sections for $\pi^{\pm}$mesons on a series of core nuclei used in many theoretical investigations.

The scattered pions were detected by a vertical drift chamber located near the focal plane of the BCS. Relative beam flux normalization for each angle and target was obtained by detecting decay muons from the pion beam in two scintillator telescopes oriented at an angle with the beam less than the Jacobian peak angle.

The data for the four targets are shown in Fig. 2.102 along with preliminary optical-model fits with a Kisslinger potential. Standard nuclear parameters from electron scattering data were used, and variations of the mass density radius did not significantly improve the quality of the fits. As may be seen from the figure, the angular distributions exhibit considerable structure for the heavier targets but not for ^{12}C.

The structure observed is a result of several different aspects of the pion-nucleus scattering. At smaller angles a contribution from Coulomb-nuclear interference is observed. For the π^- the interference is constructive, and for the π^+ it is destructive. The data for ^{12}C show the *s*- and *p*-wave interference minimum near 70°. For the heavier nuclei this effect becomes less pronounced due to the strong diffraction minima which begin to emerge.

In Fig. 2.103 we show the optical-model complex *s*- and *p*-wave strength parameters obtained from the fitting procedure. The lines in the figure were obtained from predictions of the impulse approximation.

1. Virginia Polytechnic Institute and State University.
2. Los Alamos National Laboratory.
3. University of South Carolina.
4. Instrumentation and Controls Division.
5. University of Tel-Aviv.
6. Massachusetts Institute of Technology.
7. M. Leitch et al., Lawrence Berkeley Laboratory report LBL-11118, p. 716 (1980).
8. B. Preedom et al., *Phys. Rev. C* **23**, 1134 (1981).
9. M. Blecher et al., *Phys. Rev. C* **20**, 1884 (1979).
10. F. E. Bertrand et al., "Elastic Scattering of π^+ and π^- from ^{40}Ca at 64.8 MeV," preceding contribution, this report.

A WINDOWLESS SUPERSONIC GAS-JET TARGET

J. L. C. Ford, Jr. — R. Novotny
D. Shapira — R. L. Parks[1]
S. T. Thornton

The energy resolution obtainable with heavy ions is frequently limited by effects due to the energy loss and straggling within the target. A windowless gas-jet target offers many advantages for heavy-ion measurements, and such a target has been designed for the split-pole spectrometer at the 25-MV tandem.[2] Figure 2.104 presents a schematic of the device. The gas (inlet pressure P_0) enters from the bottom and flows through a convergent-divergent Laval nozzle. Approximately 90% of the gas flow is recaptured by the 2.54-cm-diam first pumping stage, which is pumped by a 70-liter/s mechanical pump. The majority of the remainder of the gas is pumped by the 140-liter/s second-stage

ORNL-DWG-81-12488

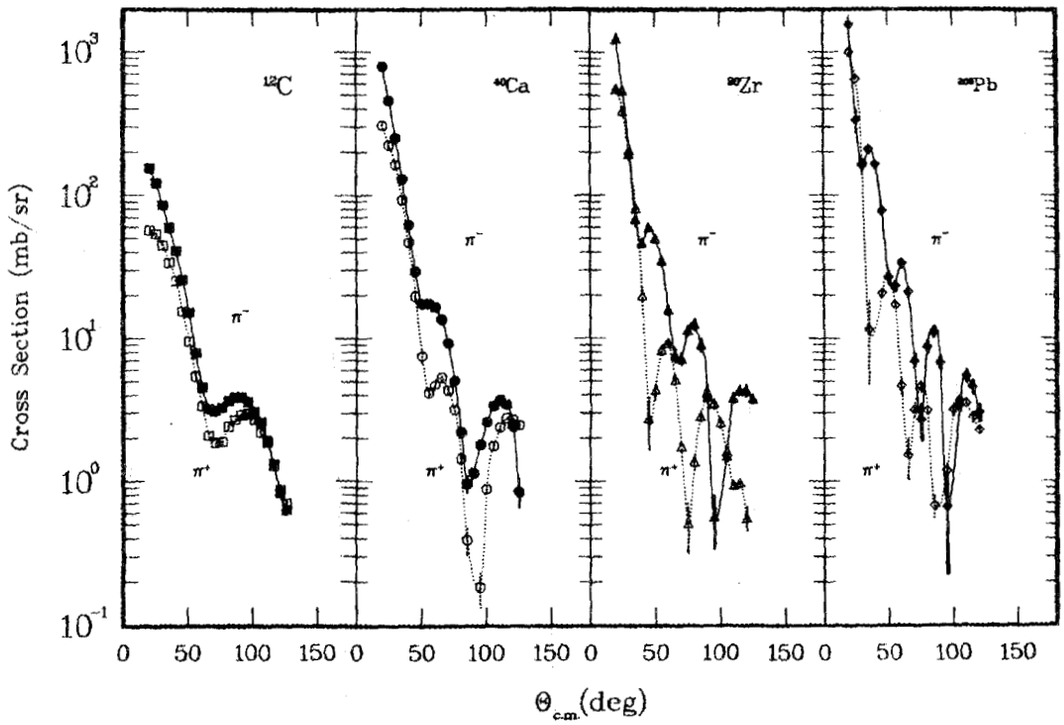


Fig. 2.102. Data from elastic scattering of 80-MeV π^+ and π^- from ^{12}C, ^{40}Ca, ^{90}Zr, and ^{208}Pb. The curves are optical-model fits with a Kisslinger potential.

mechanical pump through tubing 7.62 cm in diameter. The first two pumping stages are connected to a recirculating system so that the captured gas can be reintroduced to the inlet line. The incident beam and reaction products pass through two sets of differential pumping slits (indicated only schematically in Fig. 2.104). These slits are pumped by a third pumping stage—a 2600-liter/s cryopump. The two differential pumping slit systems lead to the scattering chamber vacuum pump (a 1400-liter/s cryopump), which serves as the fourth pumping stage. The exit slit system can be varied between 0 and 60° to permit angular distribution measurements. The beam-defining apertures are located just before the scattering chamber and are small enough so that the beam passes cleanly through the differential pumping slits to eliminate scattering from these slits.

The inlet pressure P_0 is varied to change the target thickness. If this pressure is 760 torr (N_2), then the observed pressures in the four pumping stages are about 6, 0.2, $<10^{-3}$, and $<10^{-5}$ torr respectively. These pressures are determined by the available pumping speeds and the design of the Laval nozzle, which is the heart of the gas-jet system. The above pressures were obtained with a nozzle which produces a target thickness of about 20 $\mu g/cm^2$ for a nitrogen target and a mass flow through the system of approximately 120 torr-liters/s.

A typical Laval nozzle used in the present design is shown in Fig. 2.105. Figure 2.105*a* shows a cross section perpendicular to the long axis of the nozzle. Figure 2.105*b* is the view looking down into the exit opening—a 1.27- by 2.54-mm rectangular aperture which narrows in one dimension to a 0.254-mm-wide throat. Such a nozzle produces a foillike sheet of gas whose smallest dimension is along the beam axis and which has larger extensions perpendicular to the beam. The most significant parameter of a Laval nozzle is the ratio of the area of the exit of the nozzle to the area at the throat. This ratio, together with the characteristics of the gas, determines the values for the Mach number, M, and the ratios P/P_0, ρ/ρ_0, and T/T_0 of the pressures, densities, and temperatures of the gas flow at the exit and in-

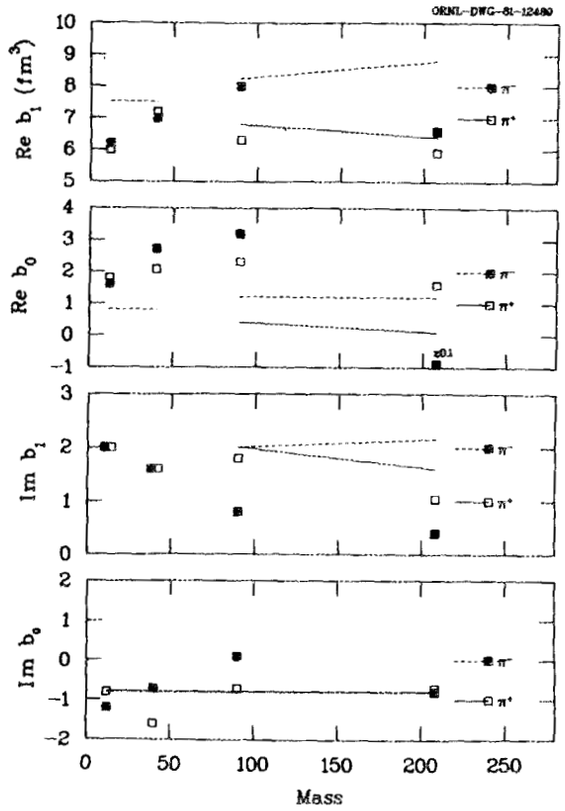


Fig. 2.103. Complex *s*- and *p*-wave strength parameters from the optical-model fits along with predictions of the impulse approximation.

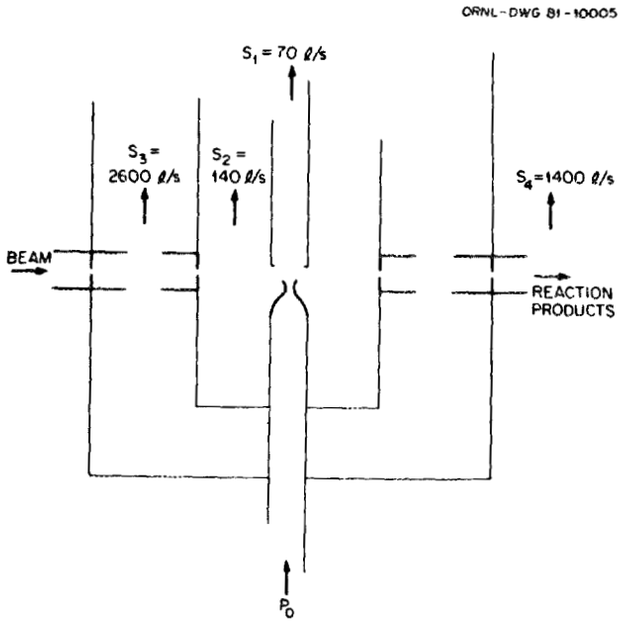


Fig. 2.104. Schematic of the gas-jet apparatus. The pumping speeds of the four-stage pumping system are shown.

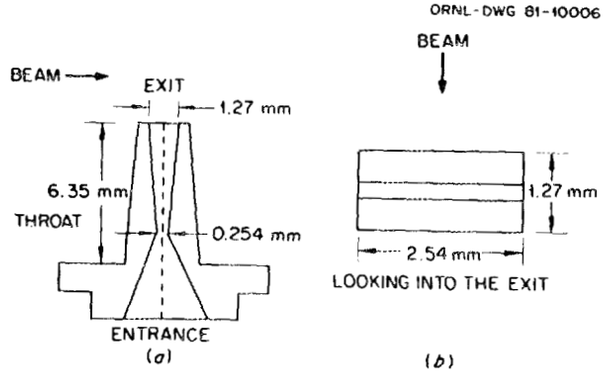


Fig. 2.105. Design of the Laval nozzle.

let of the nozzle. For the nozzle shown in Fig. 2.105 (area ratio 5), a nitrogen jet will be produced at the exit of the nozzle such that $M = 3.2$, $P/P_0 = 0.022$, $\rho/\rho_0 = 0.064$, and $T/T_0 = 0.33$. As the ratio of the nozzle exit to throat increases, the Mach number also increases, while the pressure, density, and temperature ratios all decrease.

The nozzle shown in Fig. 2.105 should produce a homogeneous target approximately 7 mm high, 2.5 mm wide, and 1.25 mm along the beam axis. Although the gas jet is designed to mount on the scattering chamber of the split-pole spectrometer, we have been testing it with a solid-state counter in a scattering chamber at the ORNL EN tandem. Figure 2.106 is a photograph of the test stand. The two cryopumps mounted on the top and bottom of the apparatus are visible, as is the large mechanical pump (at the extreme left of the figure) which pumps the first and second stages of the gas jet. The variation of the target thickness for nitrogen as a function of the inlet pressure is shown in Fig. 2.107. The circles show the calculated pressures, while the triangles result from energy-loss measurements using the solid-state counter. We have obtained a target thickness of 15 $\mu g/cm^2$ with this nozzle (shown in Fig. 2.105) and about 30 $\mu g/cm^2$ with another with a larger throat. The capabilities of the present pumping system will apparently place an upper limit on the usable target thickness of 50 $\mu g/cm^2$.

Further tests on the gas jet are in progress. A more thorough study of the target thickness and homogeneity will of necessity have to wait until the apparatus is mounted at the spectrometer. However, the promise of the gas jet for nuclear physics research is indicated in Fig. 2.108. This spectrum is due to the scattering of a 30-MeV ^{16}O

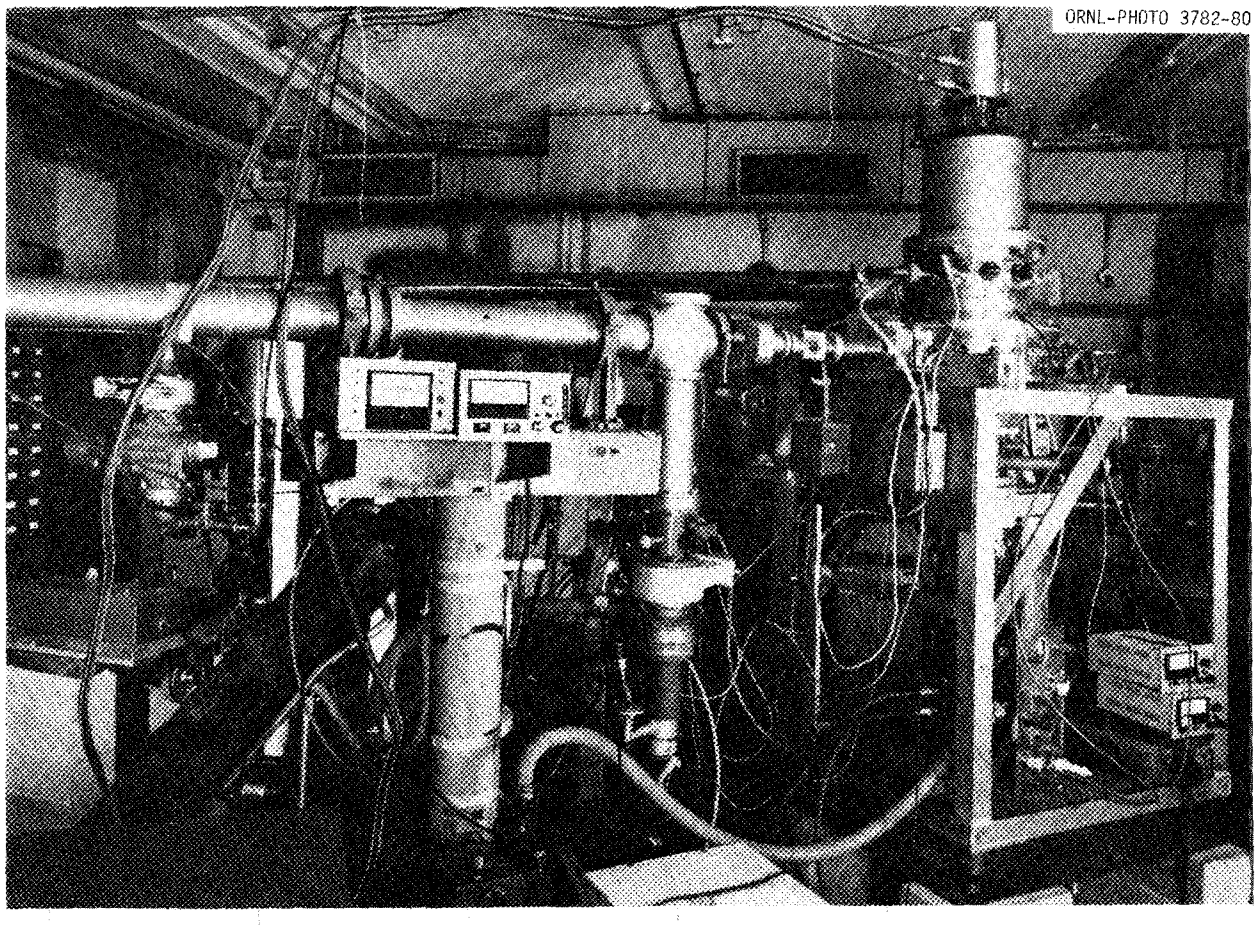


Fig. 2.106. Test stand of the gas-jet apparatus at the ORNL EN tandem.

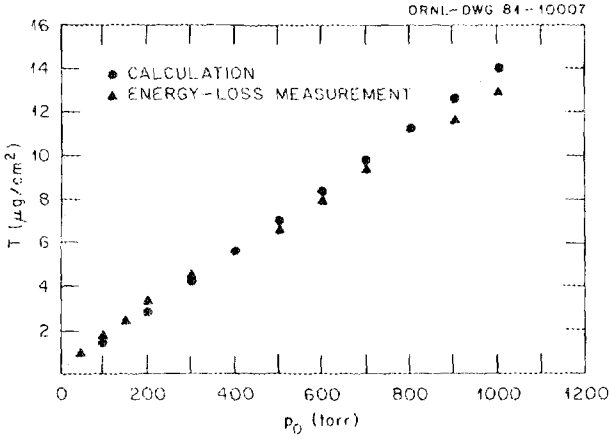


Fig. 2.107. Target thickness for the nozzle design of Fig. 2.105 and N_2 gas as a function of the inlet pressure P_0. The circles and triangles are values which result from calculations and energy-loss measurements respectively.

beam from a target consisting of nitrogen with a 1% Kr admixture. The energy resolution of slightly less than 1% is limited by the resolution of the solid-state counter. The solid angle was kept small so that kinematic broadening would be unimportant. The solid angle to be used with the spectrometer will be at least 1.5 msr. The symmetry of the peaks, the absence of contaminant peaks, and the low general background level indicate the attractiveness of the gas jet as a target.

1. University of Virginia, Charlottesville.

2. J. L. C. Ford, Jr., J. Gomez del Campo, J. W. Johnson, D. Shapira, J. E. Weidley, S. T. Thornton, and R. L. Parks, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498 (June 1979), p. 45.

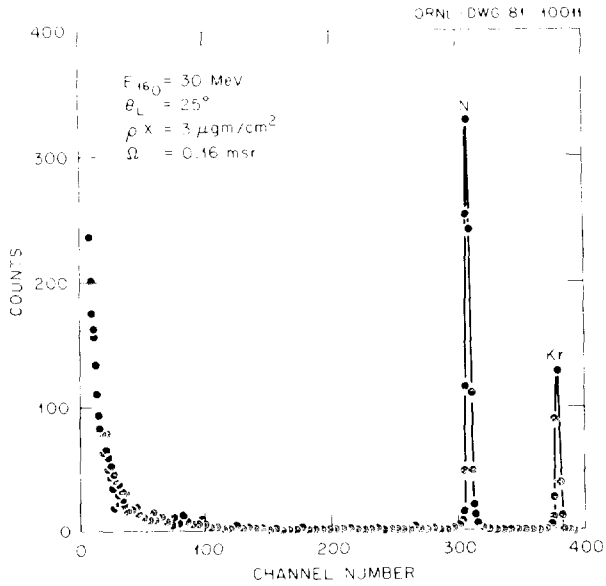


Fig. 2.108. Spectrum resulting from scattering 30-MeV ^{16}O ions from a target consisting of N_2 with a 1% Kr admixture.

DEVELOPMENT OF POLARIZED TARGETS FOR HEAVY-ION REACTION STUDIES

J. R. Beene J. L. C. Ford, Jr.
C. E. Bemis, Jr. K. A. Erb
D. Shapira

Microscopic theoretical treatments of nuclear reactions, including those for heavy ions, invariably describe the reaction effects in terms of matrix elements between states of specified nuclear spin orientation. A complete experimental description of these reactions thus requires a knowledge of the initial spin alignment and the change in spin alignment as a result of the reaction or interaction. In the usual case, especially for heavy-ion reactions, experiments are performed on an ensemble of randomly oriented target nuclei (unpolarized) with unpolarized beams and generally with polarization-independent measurement techniques. The theoretical descriptions must then be summed or averaged over all possible spin directions, in an appropriate fashion, to facilitate comparison with experiment. Potentially important details of the reaction mechanism, which might form crucial points of comparison, are thus lost.

For deformed targets or projectiles (i.e., those which have static equilibrium deformations like the rare-earth deformed nuclei), even macroscopic descriptions of nuclear reactions would predict large differences in results for differing initial spin orientations, since the orientation of the symmetry axis of the nuclear density distribution, K, is often identical ($K = I$). The subtle interplay between the attractive nuclear forces and repulsive Coulomb force, both of which govern the dynamics and results of heavy-ion reactions with deformed reaction partners, are thus a function of the orientation of the nuclear symmetry axis. Examples of these effects have been reported for the sub-Coulomb fusion[1] of ^{16}O with $^{148-154}Sm$ and for the fusion-fission reactions[2] of ^{32}S with $^{144,154}Sm$. Although the effects of target deformation were demonstrated in the above examples, the true effects due to the orientation of the nuclear symmetry axis were masked because the experiments were performed using unpolarized targets.

We are working to develop a polarized rare-earth target assembly for use in the research program at the HHIRF to investigate both static and dynamic target deformation effects in heavy-ion reactions. The assembly is based on the use of the gas-jet target recently developed at ORNL to enable nuclear reaction studies to be performed at high resolution with gaseous target materials.[3,4] The spatially well-defined target (supersonic gas jet) is provided by a Laval convergence-divergence nozzle which exhausts directly into the differentially pumped target chamber. The initial development is based on a "seeded" jet of ^{151}Eu ($I = 5/2$) and/or ^{153}Eu ($I = 5/2$) target atoms entrained in an inert carrier gas of nitrogen. Polarization is accomplished via depopulation optical pumping with polarized resonant laser photons. This polarization technique, called LINUP (laser-induced nuclear polarization), has been previously applied to optical spectroscopic studies of spontaneous-fission isomerism[5] and is being used in studies of short-lived isomers among the francium nuclides.[6] Europium is a particularly favorable case for optical pumping,[7,8] and our development is based on the pumping of the entire upper-state hyperfine-structure multiplet for one of the $^8S_{7/2} \rightarrow y^8P_{5/2\ 9/2}$ resonance transitions with polarized light. These allowed transitions ($\tau \sim 5$ to 6 ns) occur at wavelengths in the region 4594 to 4661 Å and will be excited with a broad-band CW dye laser (output line width about 30 GHz) operated with one of the coumarin dyes and pumped with the uv output from an argon-ion laser. A schematic of the assembly is shown in Fig. 2.109.

We have performed extensive optical pumping calculations for this system by solving the complete

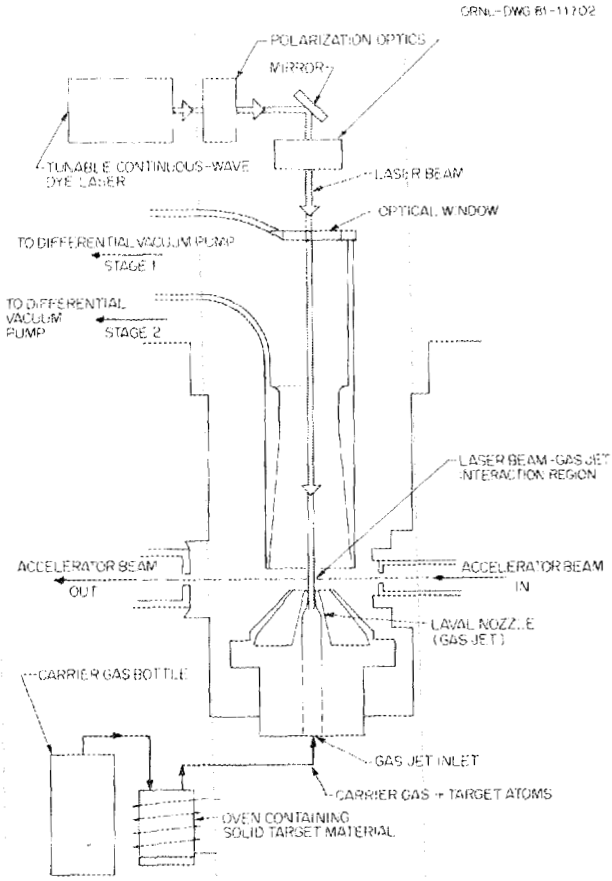


Fig. 2.109. Schematic of the laser-pumped polarized-target assembly based on the ORNL supersonic gas-jet target.

set of coupled differential rate equations to obtain the detailed time evolution of the coupled **I** + **J** density matrix, using the computer program RATES.[9] The nuclear density matrix is projected from the coupled matrix. The rate equations include both ground-state and excited-state relaxation, laser output line width, and Doppler absorption profile effects. In the near-collisionless regime expected for the operating conditions of the gas jet, ground-state relaxation effects are unimportant, and excited-state relaxation does not alter the speed at which the ultimate alignment conditions are reached. We have also considered the effects of "radiation imprisonment"[10] as a limitation to the target thickness/degree of nuclear spin orientation. Under operating conditions, we expect an approximately 90% nuclear spin polarized target with an Eu target thickness in excess of 10^{15} atoms/cm^2. Initial nuclear reaction experiments with the polarized target assembly, when fully developed, will use high-resolution heavy-ion beams from the 25-MV tandem Van de Graaff and include elastic and inelastic Coulomb and nuclear scattering and sub-Coulomb fusion experiments similar to those of refs. 1 and 2 but performed as a function of the orientation of the target nuclear symmetry axis.

We note that the use of lasers in the production of polarized beams and targets, and in nuclear physics in general, is becoming increasingly important.[11,12] We envision the laser-pumped polarized target assembly used for other suitable target species that are as amenable to optical pumping as the Eu case described above.

1. R. G. Stokstad, Y. Eisen, S. Kaplanis, D. Pelte, V. Smilansky, and I. Tserruya, *Phys. Rev. Lett.* **41**, 465 (1978); id., *Phys. Rev. C* **21**, 2427 (1980); R. G. Stokstad, W. Reisdorf, K. D. Hildenbrand, J. V. Kratz, G. Wirth, R. Lucas, and J. Poitou, *Z. Phys.* **A295**, 269 (1980); R. G. Stokstad and E. E. Gross, *Phys. Rev. C* **23**, 281 (1981).
2. B. B. Back, R. R. Betts, W. Heming, K. L. Wolf, A. C. Mignerey, and J. M. Lebowitz, *Phys. Rev. Lett.* **45**, 1230 (1980).
3. J. L. C. Ford, Jr., J. Gomez del Campo, J. W. Johnson, D. Shapira, J. E. Weidley, S. T. Thornton, and R. L. Parks, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498 (June 1979), p. 45.
4. J. L. C. Ford, Jr., R. Novotny, D. Shapira, R. L. Parks, and S. T. Thornton, "A Windowless Supersonic Gas-Jet Target," this report.
5. C. E. Bemis, Jr., J. R. Beene, J. P. Young, and S. D. Kramer, *Phys. Rev. Lett.* **43**, 1854 (1979); id., this report.
6. J. R. Beene, C. E. Bemis, Jr., and J. P. Young, "Optical Pumping in Francium: A Study of the ^{214}Fr Isomers," this report.
7. A. Sahm, J. Kowalski, and G. zu Pulitz, *Z. Phys.* **A281**, 317 (1977).
8. B. Böhmer, "Optical Pumping in ^{151}Eu, ^{153}Eu, and ^{155}Eu and Relaxation Time Measurements in the Stable Isotopes ^{151}Eu and ^{153}Eu," thesis, University of Heidelberg, 1972 (unpublished).
9. J. R. Beene, "RATES: A System of Computer Programs to Perform Optical Pumping Calculations," 1980 (unpublished).
10. T. Holstein, *Phys. Rev.* **72**, 1212 (1947); **83**, 1159 (1951).
11. D. E. Murnick and M. S. Feld, part 2, p. 804 in *Polarization Phenomena in Nuclear Physics—1980*, ed. G. G. Ohlsen et al., American Institute of Physics, New York, 1981.
12. S. S. Hanna, ibid., part 2, p. 1492.

THE SPIN SPECTROMETER

D. G. Sarantites[1] M. L. Halbert
M. Jääskeläinen[1] D. C. Hensley
R. Woodward[1] J. H. Barker[2]
J. T. Hood[1] R. Novotny
F. A. Dilmanian[1] D. Pelte[3]

The spin spectrometer, pictured in Fig. 2.110, is a new type of gamma-ray detector system consisting

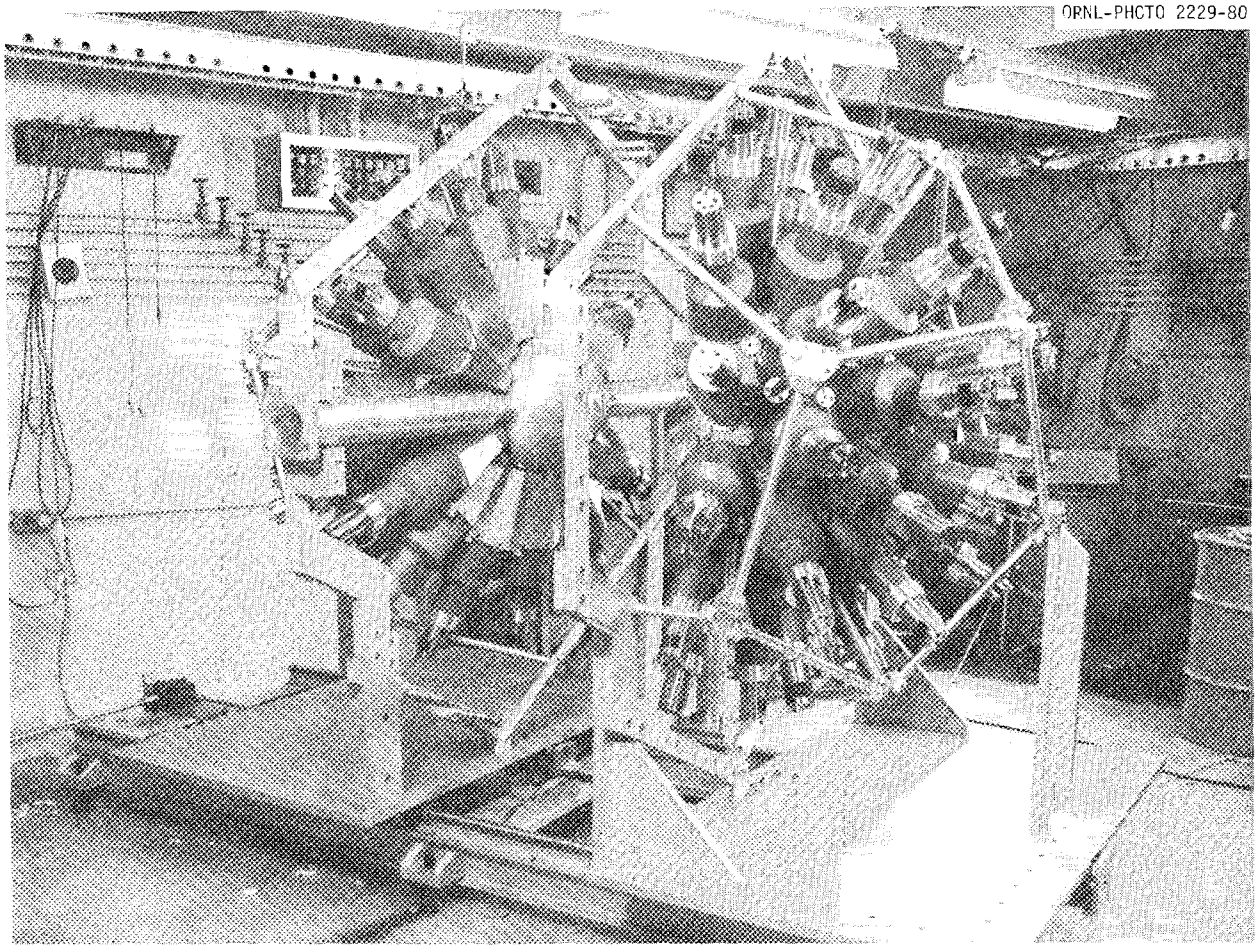


Fig. 2.110. Spin spectrometer after assembly at the Holifield facility. The detector array is shown with one half open to reveal the spherical reaction chamber within the cavity.

of 72 individual NaI detectors arranged in a closely packed spherical shell that surrounds the source of radiation.[4] The instrument was designed and built at Washington University for the Holifield facility. The specialized electronic circuitry for it was designed and built at ORNL.

The spectrometer electronics provide on an event-by-event basis, for each detector that fires, the pulse height, time of firing, pulse width, and an identifying tag. From these data one can obtain the following basic information for each event: (1) the coincidence fold and thus the gamma-ray multiplicity, (2) the pulse-height distribution of the gamma rays in each detector and thus the gamma-ray energy spectra, (3) the total pulse height and thus the total energy carried off by gamma rays, (4) the identification of pulses due to neutrons, (5) the identification of pulses due to detection of a gamma ray and a neutron in the same detector, (6) the time relationships of the gamma rays in a cascade, and (7) the angular correlations of the gamma rays in each cascade. In a typical experiment the spin spectrometer electronics are triggered by one or more auxiliary gamma-ray or particle detectors in order to select the events of interest for that measurement.

Detector Elements

Each detector unit contains a tapered prism of NaI Polyscin[5] material of length 17.6 cm hermetically sealed in an aluminum can with walls of 1-mm thickness. The prism is viewed through a glass window at its large end by an RCA-4522 photomultiplier tube operating at about -1900 V. On the average the pulse-height resolution is 8.6% for 662-keV gamma rays and 6.3% for 1332-keV

gamma rays. It does not change significantly for counting rates up to 50,000 per second. The average time resolution is 2.1 ns FWHM and 4.5 ns FWTM (full width at tenth maximum). This is sufficient to distinguish by time of flight between gamma rays and about 95% of the neutrons in an evaporation spectrum of temperature 3 MeV. The pulse-height response was found to be linear from 60 keV to 2.75 MeV and to deviate from linearity only slightly at 4.43 MeV (Pu plus Be source) and 6.13 MeV (Cm plus ^{13}C source). The stability of the 1332-keV pulse height as a function of counting rate is satisfactory (less than 1% up to 40,000 per second) for most of the units, provided that the focus controls on the tube base are properly adjusted. Different samples of the same tube type exhibit different stability characteristics; a selection from among 15 extra tubes was made to replace the least stable ones.

Electronics and Data Acquisition

The photomultiplier anode signal is first amplified by a fast preamplifier of gain 10. One of the preamplifier outputs is shaped to approximately triangular (FWHM about 100 ns, FWTM about 200 ns), delayed by 240 ns, and then fed into a charge-integrating ADC. The second output is used to trigger a front-edge constant-fraction timing discriminator (CFTD) and a second rear-edge CFTD, which is sensitive to a second pulse arriving in the range from less than 8 ns to 160 ns after the first pulse. The time difference between the two discriminators produces a fixed-amplitude pulse, the width of which is a measure of the time difference between the two pulses arising from the same detector. This pulse is digitized via another charge-integrating ADC. After an adjustable delay (20 to 300 ns), the front-edge CFTD output is used to stop a time-to-digital converter (TDC) and set the corresponding bit in a strobed gated latch. In addition to the 72 bits for the NaI detectors, 16 bits for auxiliary detectors can be set in the gated latch. The two sets of 72 ADCs and one set of 72 TDCs are implemented in a CAMAC system.

The information management and data acquisition occur via the event handler,[6] a programmable CAMAC-based controller which selects events that meet the user's criteria, places them in a suitable format, and transmits them to the on-line computer. The computer program in turn may apply further selection, buffering, and formating before the events are recorded permanently. It may also provide for on-line sampling of the data. Data from the auxiliary detectors may be processed by additional CAMAC modules and interfaced via the same event handler. The time required for digitizing the signals and transmitting them to the computer limits the data acquisition to about 5000 events per second. This has not been a limiting factor in the overall data rate for any of the four experiments carried out thus far.

The phototube high voltages are furnished by computer-controlled power supplies. The high voltages are initially set by reference to a disk file.

All detectors are operated with the same pulse-height dispersion and the same time dispersion in order to minimize the event processing time. The uniform-gain requirement is met by computerized adjustment of the phototube voltage on the basis of spectra from a gamma-ray source. A peak-search routine determines the locations of the selected lines, and the high voltage is adjusted, as required, to give the standard gain. The time dispersion was made uniform for each detector by manual adjustment of each TDC unit. The time dispersion and timing resolution are checked automatically by another program, using data from a source with coincident gamma rays. At present the CFTD threshold adjustments are manual, but provision for computer control has been made.

Beam Transport

The spin spectrometer is located on beam line C-14 and can receive beam from the ORIC alone or with both accelerators coupled. The beam transport is accomplished without collimators in the vicinity of the instrument so as to reduce background radiation. The beam is delivered to the target nondispersively in order to minimize the spot size. The natural width of the ORIC beam (typically $\Delta E/E \sim 1/400$) is acceptable for nearly all of the experiments contemplated with the spin spectrometer. The nondispersive condition is achieved by a focus halfway through each of the two bending magnets. This focus can be monitored easily in BSM1, which has a remotely driven phosphor-collimator assembly, but no such apparatus exists in the other switching magnet, BSM4. Calculations show that the required crossover halfway through this magnet can be obtained by focusing on viewer 4 at the entrance to BSM4 and then reducing the current in the previous quadrupole (Q4) by 8%.

With this procedure a well-defined spot about 4 to 5 mm in diameter has been obtained on target with many different beams from the ORIC. It is im-

portant that the ORIC extraction system be optimized for minimum energy spread of the beam. To reduce the target spot size to about 3 to 4 mm and to clean up the stray wisps of beam sometimes observed, a 4.8-mm-diam collimator is placed at the crossover point in BSM1.

During the summer of 1981 the spectrometer will be moved to the adjacent beam line, C-15, which can receive beam both from the 25-MV tandem directly and from the ORIC. Transport from the ORIC will be more complicated than before, requiring four bending magnets. A 47° bend is required in the last magnet, which is rated for a maximum $K = ME/q^2$ of 121.5 for this radius of curvature. After a lengthy series of calculations, a set of focus conditions was found that seems capable of producing a suitable small spot on the target. Very careful adjustment of quadrupole currents will be required to achieve this focus.

Background Radiation

In view of the extremely high sensitivity to gamma rays and neutrons of such a large mass of NaI, a series of tests was made to evaluate backgrounds. Times of flight with respect to the cyclotron rf were recorded for three of the NaI detectors, one close to the entrance pipe ($\theta \sim 156°$), one close to the exit pipe ($\theta \sim 24°$), and one at 67°. The time spectra clearly showed a strong peak due to beam hitting the target and a much weaker one due to gamma rays from the Faraday cup. For a 150-MeV ^{14}N beam on a 1.5-mg/cm^2 ^{120}Sn target and stopping on a carbon plate in the cup, the Faraday-cup peak was $\lesssim 1\%$ of the intensity of the target peak for the 24° detector and about 5 to 10 times less than this for the 156° detector. A 10-cm-thick lead shield wall between the spectrometer exit and the Faraday cup reduced the intensity of the Faraday-cup peak by an order of magnitude. There was no sign of the 4.43-MeV line of ^{12}C from the carbon plate used as a stopper in the Faraday cup. After this stopper was changed to Ta and some Pb shielding was added around the cup, the Faraday-cup peak was cut approximately in half. With a 124-MeV ^{12}C beam, this peak was about 3 times stronger, and changing the stopper from C to Ta, but with no change in shielding, made no difference.

The continuum on which these time peaks ride, presumably due to neutrons from previous beam bursts bouncing around the room and to target radioactivity, was not affected by the 10-cm Pb shield wall. It could be reduced a factor of 2 to 3 by removing the target or by changing the Ta stop to C.

The beam spot with the BSM1 collimator in place gives no indication on the target phosphor of stray beam or a halo, but the time spectrum in the 156° detector showed an additional peak corresponding to gamma-ray production as the beam burst passed the place where the diameter of the entrance pipe steps down. The intensity of this peak was $\ll 1\%$ of that due to the target peak and appears not to constitute any problem. When the beam was steered to one side, its intensity remained substantially constant except if the beam was moved about 5 cm off axis, thereby hitting the step-down region directly.

The in-beam count rate in the 67° detector was about 5000 per second per electrical nanoampere of ^{14}N on 1.5 mg/cm^2 ^{120}Sn. Similar rates have been observed with Ne beams on various rare-earth targets. This rate drops sharply when the beam is turned off.

No significant amount of neutron activation of the NaI was observed with heavy-ion beams, at least up to 5 nA. Fifteen-hour ^{24}Na activity was seen weakly after about 12 h of a 2-μA ^{7}Li bombardment in the room next door, but its intensity was no more than that of the peaks due to naturally occurring ^{40}K and Th and so does not constitute any problem.

Large pulses due to cosmic rays may be seen occasionally. These are too rare to cause any trouble, particularly since the spectrometer is normally triggered by auxiliary detectors.

In summary, no source of background radiation was found to require any special protective measures. Nevertheless, the shielding erected for the tests remains in place, both the shield wall between the spectrometer and the Faraday cup (now 20 cm of Pb) and the Pb shield around the cup itself (10 to 20 cm).

Neutron Response

Measurements were made of the instrument's response to the evaporation neutrons associated with ^{252}Cf spontaneous fission. It was concluded that for a threshold equivalent to 100 keV the absolute efficiency of a single NaI unit for neutrons up to about 5 MeV is 70 to 80%. A large fraction of the delayed (neutron) pulses are accompanied by a delayed neutron pulse in one or more neighboring detectors; presumably these are (n,n') events. The

neutron mean free path in the NaI deduced from the flight times is about 6.3 cm. Preliminary results from 113-MeV ^{16}O on ^{154}Sm, for which the average neutron and gamma-ray multiplicities are known from our earlier work, are consistent with this efficiency determination and the importance of the (n,n') effects.

Computer Processing

Three computer systems have been used with the spin spectrometer. Setup and checking of the spectrometer may be accomplished at present with either of two computers, the ORIC SEL 840A or a portable LSI 11 minicomputer. The full digital data stream from experiments is directed to one of the new Perkin-Elmer 3220 computers, which records the events on magnetic tape. On-line histograms are built up in the computer memory showing the pulse height, pulse width, and time spectra for each NaI detector and also appropriate quantities for the auxiliary detectors. During data acquisition, any or all of these histograms can be shown on the display unit, with an automatic cycling feature coming into effect if required. Disk files of these spectra can be created for detailed off-line analysis. The data stream being transmitted to the main computer can be sampled by another computer at a lower priority level. Both the 840A and the LSI 11 have been used in this way to offer a choice of several one- or two-parameter on-line displays.

Processing of the event tapes after completion of an experiment has been divided for convenience into two stages, a preliminary scan and then the final scan(s). During the first step each event is carefully analyzed in order to correct for pedestals and nonlinearities in the NaI spectra, match the gains and times in all the NaI elements (if necessary), correct for pulse-height dependence of the timing, derive an accurate time zero for each event by averaging the arrival times of all its gamma rays, discriminate between neutron gamma-ray, and pile-up pulses, and reject events of no interest to the measurement. Then new tapes are written which are generally more compact and which require much less calculation per event, so that the final scans can be done more quickly and with simpler programs.

First Experiments

The first trial run (February 1981), intended primarily as a shakedown to test the complete system, was successful in producing useful reaction data. A sample of the data collected on-line is shown in Fig. 2.111. The reaction was 136-MeV ^{20}Ne on ^{146}Nd; the principal xn and αxn products were ^{160}Yb and ^{157}Er. The spectrometer was triggered by any pulse in a Ge detector which replaced one NaI element at 112° to the beam.

Each dot in Fig. 2.111 represents one event, plotted vertically according to the sum of its NaI pulse heights (related to total gamma-ray energy and hence the excitation energy E^*) and horizontally according to the number of detectors that fired (related to gamma-ray multiplicity and hence the spin J). The density of dots reflects the population of the entry states (the initial states after particle emission, prior to the final gamma-ray cascade). Except for a concentration of points at low E^* and J due to an experimental artifact, the qualitative picture is exactly as expected for decay of a compound nucleus. The population of the entry states forms a narrow band just above the yrast line. Essentially no events occur in the upper left, where particle emission overwhelms gamma decay, or in the lower right, where no levels of the final nuclei exist. Complete analysis of these data is nearing completion, and it is clear that a wealth of information on the characteristics of compound-nucleus reactions will be forthcoming.

Three additional experiments have been carried out, one of them involving 21 charged-particle detectors within the spherical reaction chamber. Although some work remains to be done in measuring the response of the system, improving the circuitry, and writing more software, the spin spectrometer is definitely a working instrument and is fulfilling its promise for new types of measurements.

---

1. Washington University, St. Louis, Mo.
2. St. Louis University, St. Louis, Mo.; present address: South Carolina Electric and Gas Company, Columbia.
3. Guest assignee from the University of Heidelberg, July–October 1980.
4. D. G. Sarantites, M. Jääskeläinen, J. T. Hood, R. Woodward, J. H. Barker, D. C. Hensley, M. L. Halbert, and Y. D. Chan, *J. Phys., Colloq.* **C10**, C10-269 (1980).
5. Trademark of Harshaw Chemical Company, Solon, Ohio, for its polycrystalline NaI(Tℓ)
6. D. C. Hensley, *IEEE Trans. Nucl. Sci.* **NS-26**(4), 4454 (1979).

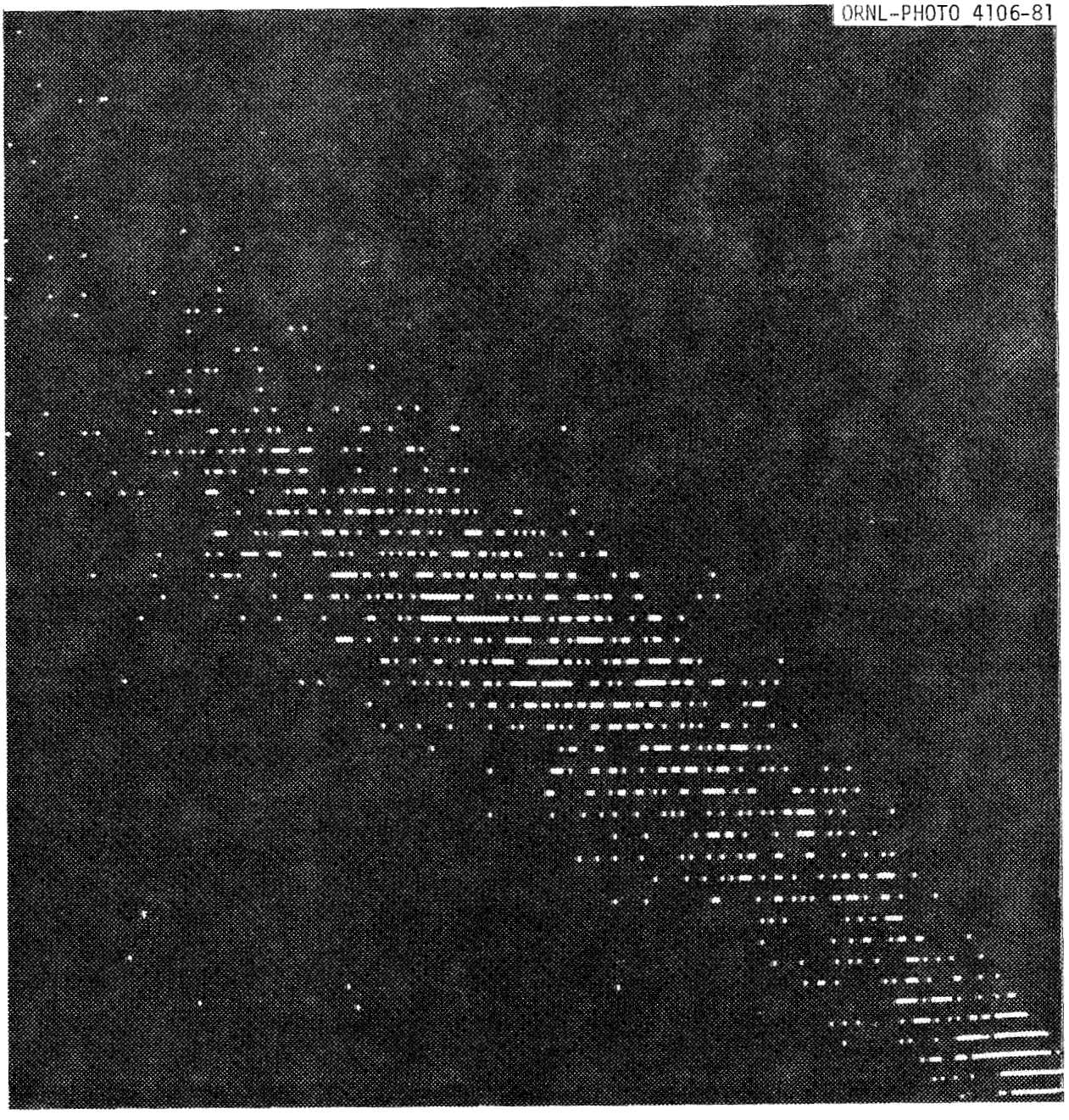


Fig. 2.111. On-line sample of first data from the spin spectrometer, a study of reactions induced by 136-MeV ^{20}Ne on ^{146}Nd. Each dot represents one event, plotted at an ordinate proportional to the sum of the NaI pulse heights and at an abscissa equal to the number of NaI detectors that fired.

HYBRID IONIZATION COUNTERS

D. Shapira J. L. Blankenship[1]
J. L. C. Ford, Jr. R. Novotny
T. P. Sjoreen

A hybrid counter for use at the focal planes of the HHIRF spectrometers has been constructed.[2] This counter is capable of the good-resolution ΔE and E measurements needed for particle identification, in addition to ray tracing in order to exploit the full solid angles of the spectrometers.

Originally this counter was designed for use with ions whose range was equal to or less than the most energetic ^{12}C and ^{16}O accelerated by the new 25-MV tandem (about 200 MeV). However, the prospect of good-resolution beams from the coupled accelerators (tandem plus cyclotron) with high energies ($\leq$400 MeV for ^{16}O) has prompted the desire to extend the capabilities of the hybrid counter. Obtaining a high-resolution energy signal from this focal-plane counter demands that the particle be stopped within the detector volume. It becomes, therefore, necessary to operate at an atmosphere of isobutane rather than the ½ atm which was the maximum pressure intended for the original design. But this increase in pressure then requires that the electric fields between the counter electrodes be significantly increased for proper operation. As a result, the maximum voltage-holding capability had to be increased from 3000 V to 5000 V. To meet the above two requirements, the electrode structure within the counter was substantially modified, and the voltage capabilities of all the electrical feedthroughs and other components were increased. These improvements have not only increased the useful range of the counter but also have improved its performance at the previous lower operating conditions.

The virtues of the hybrid focal-plane counter have led us to build similar counters intended for use directly in scattering chambers. The higher energies and wider choice of projectiles possible with the new heavy-ion facility require the simultaneous detection of reaction products covering a wide range of Z, A, and energy, as, for example, in fusion measurements. The detector system presented in Fig. 2.112 has an extremely large dynamic range in E and ΔE, so that both fused systems (heavy, slow particles) and beamlike particles (lighter, fast ions) can be identified. The detector is similar to the hybrid focal-plane detector, except that a position-sensitive solid-state counter has been added at the rear of the system. For particles stopped within the gas volume of the counter, a position signal is obtained from the position-sensitive proportional counter embedded in the anode structure of the ionization chamber. The ionization chamber also provides ΔE signals (from electrode D1) and an E signal (from capacitively coupling the first grid and cathode) for particle identification. On the other hand, if the incident particle's range in the gas exceeds its path length in the ionization chamber, then it may be stopped in the position-sensitive solid-state counter which provides the position and energy signals. In this case, the energy-loss signal is obtained from the capacitively coupled first grid and cathode of the ionization chamber. In either situation, the counter has the capability of measuring data at a number of angles simultaneously as well as determining the energy and nature of the detected ion.

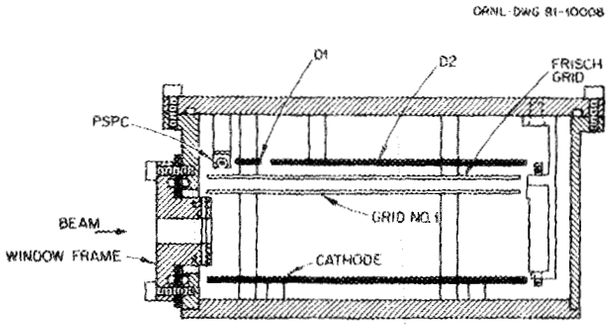


Fig. 2.112. Schematic side view of the hybrid "fusion" counter.

Two such counters have been constructed—the first with an active depth along the beam direction of 12.7 cm and an angular range determined by the 5-cm length of the solid-state counter. A second, improved version has an active depth of 31.12 cm and has an increased angular range, since two position-sensitive solid-state counters comprise the last stage of the detector system. The photograph in Fig. 2.113 displays the electrode structure of this counter.

One of the experiments for which these counters have been utilized is the study of backward-angle cross sections for scattering and reaction products with Z values close to that of the beam. These measurements involve bombarding a ^{12}C target with an ^{20}Ne or ^{28}Si beam and observing the forward-angle recoils. In order to remove the strongly

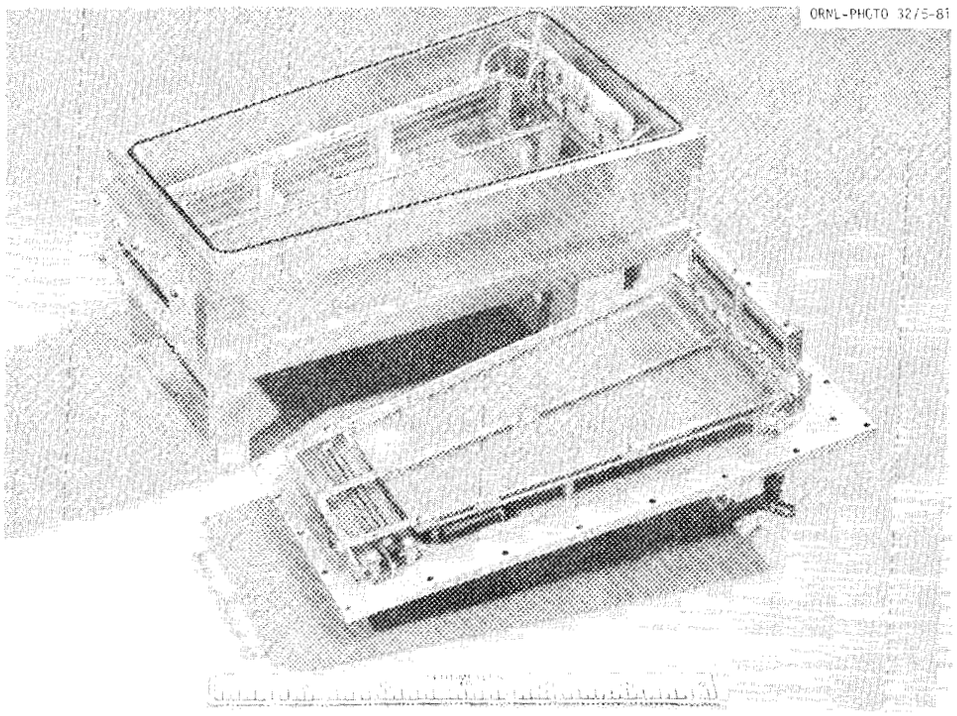


Fig. 2.113. Improved hybrid counter for detecting fusion and backward-angle reaction products.

forward-peaked elastic scattering and fusion products from the spectra, the hybrid counter is preceded be a gas absorber cell. The gas pressure within the cell is adjusted to range out reaction products with Z values equal to or greater than that of the beam. The capability of the entire system is demonstrated in Fig. 2.114. In this experiment, a 120-MeV ^{28}Si beam was incident upon a carbon target. In Fig. 2.114*a*, the 11° $\Delta E \times E$ spectrum measured with no absorber is dominated by the ^{28}Si line and higher Z values due to evaporation residues. The spectrum measured with the absorber (Fig. 2.114*b*) contains a remnant of the silicon line but otherwise only displays Z groups due to reaction products near carbon. Without the absorber, count-rate problems such as pileup and tailing of the strong groups into the low-Z region would make it impossible to obtain adequate data for the backward-angle processes.

1. Instrumentation and Controls Division.

2. D. Shapira, G. L. Bomar, J. L. C. Ford, Jr., J. Gomez del Campo, and L. C. Dennis, *Nucl. Instrum. Methods* **169**, 77 (1980).

LARGE—AREA IONIZATION CHAMBER

R. Novotny

The availability of very heavy ions from the new HHIRF at bombarding energies well above the Coulomb barrier has increased the need for more complex experimental equipment. In order to understand the reaction mechanisms, it will often be necessary to make simultaneous measurements of several significant physical quantities, such as, for example, the kinetic energies and linear momenta of all reaction products. For such measurements, gas detector systems are far superior to solid-state detectors for the following reasons: (1) The large variety of reaction products requires detectors with a wide dynamic range in energy and mass of the detected particles. (2) Only large-area detectors provide sufficient efficiency for coincidence requirements or for the use of time-of-flight methods for mass identification.

A large-area position-sensitive ionization chamber (IC) has been obtained by ORNL from the Physical Institute of the University of Heidelberg, West Germany, and will be attached to the existing time-of-flight facility. A schematic side view of the

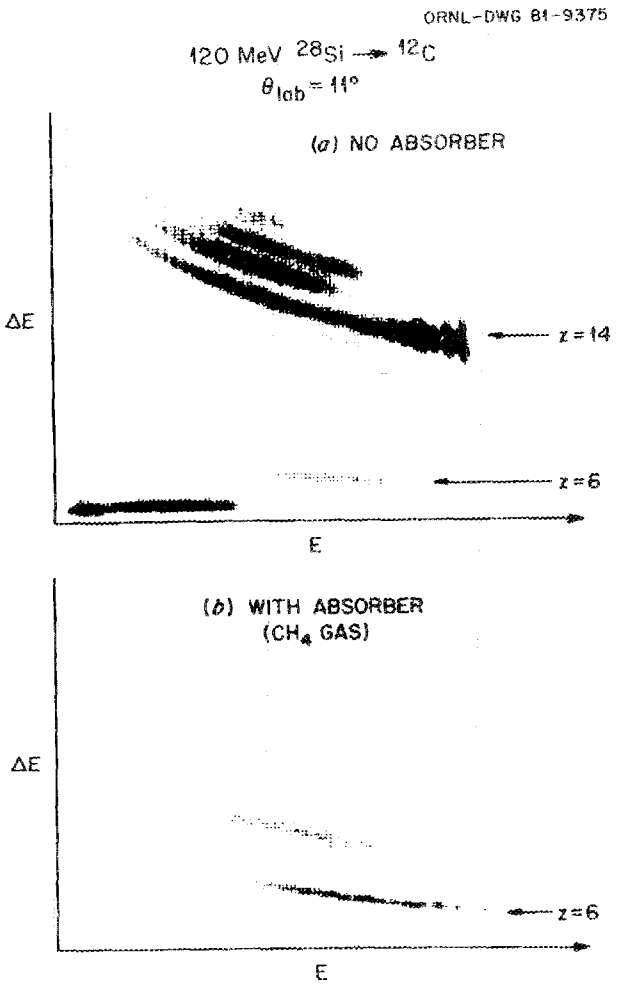


Fig. 2.114. Two-dimensional spectra measured with and without the absorber cell, using the counter of Fig. 2.113.

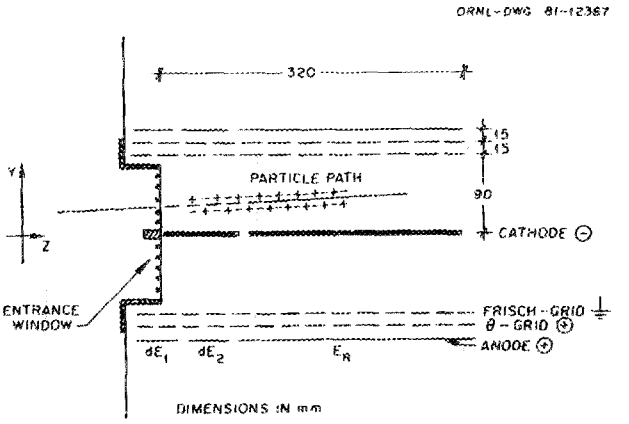


Fig. 2.115. Schematic side view of the position-sensitive ionization chamber.

detector system developed in Heidelberg[1] is shown in Fig. 2.115. The common divided cathode forms the symmetry plane of a double IC and defines, together with the beam axis, the reaction plane. The active volume of the detector is determined by the two grounded Frisch grids. The electrons created in the gas around the path of the incoming particle are separated from the positive ions under the influence of the uniform electric field perpendicular to the particle path. The electrons drift through the Frisch grid toward the anode with a velocity 10^3 times that of the ions. The fast component of the charge signal induced on the cathode depends on the total number of electrons and on the Y position of the entered particle. The cathode pulse signals the detection of a particle and can be used to stop a time-of-flight measurement. It is also used to start a drift-time measurement to determine the Y coordinate of the locus of impact on the entrance window of the IC. The electrons have to cross an additional grid on their way to the anode. This θ grid consists of 200 wires stretched radially toward the target position. They are connected via an LC delay line. The time difference between the delayed θ grid and the anode signal is, therefore, proportional to the scattering angle θ. The signal on the anode stops the drift-time measurement. The time difference is proportional to the shortest distance between the particle track and the Frisch grid and thus determines the coordinate Y. Because of the screening of the positive ions by the Frisch grid, the charge signal at the anode is proportional to the number of electrons, that is, to the kinetic energy of the incoming particle. The anode is divided into two or three parts, to allow element identification via the ΔE-E technique. The entrance window that separates the detector from the high vacuum consists of a thin Mylar foil (about 350 $\mu g/cm^2$) supported by small epoxy bridges and by steel wires. The detector operates with CH_4 in a pressure range of 100 to 800 torr. The active area of the entrance window is 120 $\times$ 400 mm^2, which corresponds to a solid angle $\Delta\Omega$ of 50 msr when the IC is mounted 1 m from the target. Typical resolutions achieved in experiments[2] with ^{32}S projectiles of energies $\leqslant$7 MeV/amu are:

$$\delta E/E \leqslant 1\%,$$
$$\delta\phi,\ \delta\theta \leqslant 0.1,$$
$$\delta t \leqslant 1\ \text{ns},$$
$$\delta Z/Z \leqslant 2\%,$$

Figure 2.116 shows, as an example, a ΔE-E plot of final fragments detected in the $^{32}S + ^{28}Si$ reaction.

The detector will be installed at the HHIRF time-of-flight facility. Fig. 2.117 shows schematically the attachment of the IC to the scattering chamber. The detector and a separate housing for additional transmission detectors (parallel-plate avalanche counters) are easily movable on a rail system. The fixed box mounted close to the scattering chamber supports a cryopump and also contains deflection plates which prevent electrons produced in the target from reaching the IC and from charging up the entrance window. The IC has been tested with alpha and fission-fragment sources at ORNL and is operating satisfactorily. The mechanical setup is under construction.

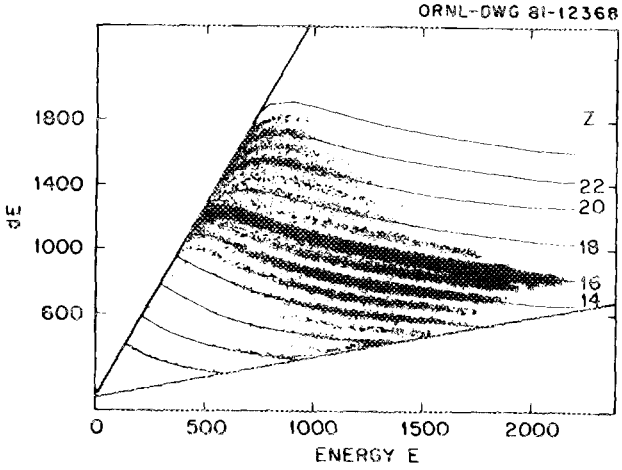


Fig. 2.116. ΔE-E plot of detected end fragments in the reaction 135-MeV $^{32}S + ^{28}Si$.

1. H. Sann et al., *Nucl. Instrum. Methods* **124**, 509 (1975).
2. R. Novotny et al., *Nucl. Phys.* **A341**, 301 (1980).

A VERTICAL-DRIFT FOCAL-PLANE DETECTOR

J. L. C. Ford, Jr. F. E. Bertrand
J. L. Blankenship[1] D. C. Hensley
T. P. Sjoreen M. V. Hynes[2]

Among the important instruments to be used with the HHIRF facility will be the split-pole and modified Elbek spectrometers. However, the dispersion is small (about 2) for both these magnets, and as a result, the higher-energy beams available from the new facility make it essential to develop new focal-plane detectors capable of improved position resolution. The vertical-drift chamber (VDC) developed at the Massachusetts Institute of Technology has detected electrons at the Bates

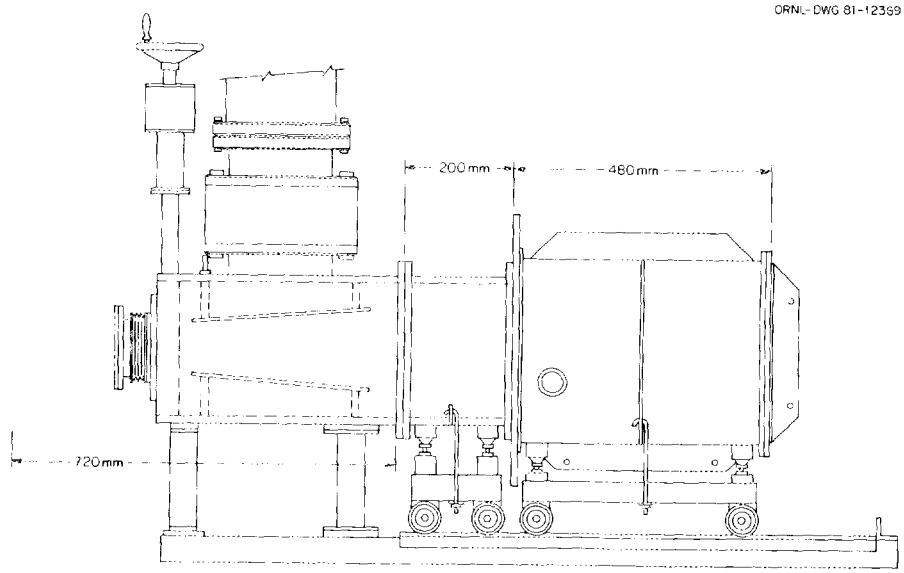


Fig. 2.117. Setup of the detector system on the time-of-flight facility.

Linear Accelerator Facility with a position resolution of a few tenths of a millimeter.[3] Although such a counter has promise to meet our needs, its performance with heavy ions still must be tested.

The principle of the vertical-drift chamber is outlined in Fig. 2.118. The VDC is a multiwire proportional counter with the anode wires placed perpendicularly to the bending plane of the magnet. Between each of the anodes (sense wires) there are two electric field shaping wires (guard wires) which serve to divide the counter volume up into a series of active cells. As the particle trajectory traverses the counter, it intersects at least three of these cells. By timing the drift time of the electron cloud in each cell with respect to an external timing signal, the position and angle at which the trajectory crosses the focal plane can be accurately determined.

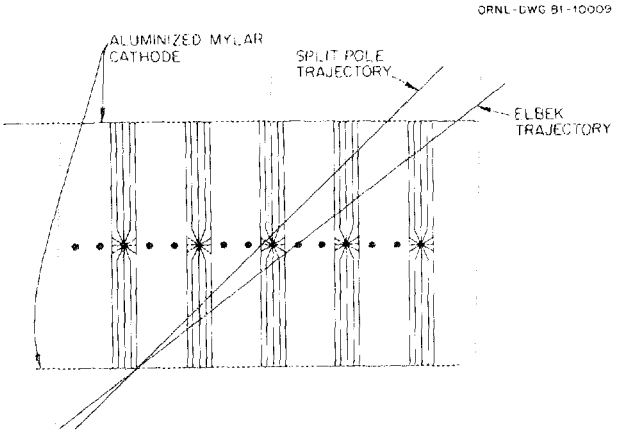


Fig. 2.118. Vertical-drift chamber cross section taken perpendicularly to the signal wires. Note the alternating pattern of sense and guard wires and the field lines for the sense-wire cells. Typical particle trajectories are shown for the split-pole and modified Elbek spectrometers.

Although the VDC is a multiwire detector, the associated electronics are simplified by the fact that timing is used to determine the position information. The electronics are presented schematically in Fig. 2.119. A leading-edge discriminator circuit is connected to each sense wire to provide a proper timing signal.[4] Since at most five cells are expected to fire, the outputs of cells 1, 6, 11, . . . are tapped to delay line 1; cells 2, 7, 12, . . . to delay line 2; cells 3, 8, 13, . . . to delay line 3; cells 4, 9, 14, . . . to delay line 4; and cells 5, 10, 15, . . . to delay line

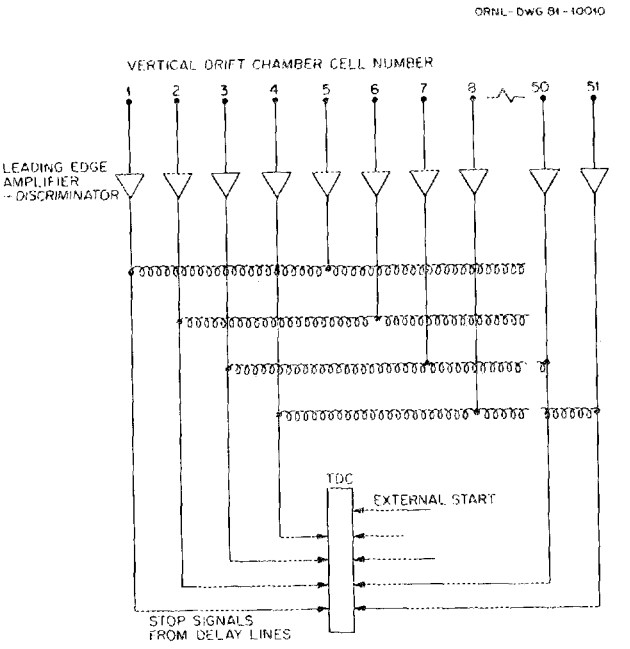


Fig. 2.119. Schematic of the delay-line readout system as anticipated for the split-pole spectrometer, where four delay lines will probably be used.

5. The delay lines consist of 1-ft lengths of RG-174 cable producing 1.7-ns delays between each cell tap. The arrival times of the signals from the two ends of each delay line are measured by a TDC relative to a fiducial signal (obtained from a scintillation counter following the vertical-drift chamber in the initial tests of the chamber).

The present counter as a 5.08-cm-high aperture and an active length spanning 40 cm. The wires are separated by 2.54 mm, so that the active cells are approximately 2.54 mm wide. Figure 2.120 is a drawing of the counter, which consists of a sandwich of planes mounting the pressure-bearing windows, the high-voltage cathode planes, the printed circuit board bearing the multiwire anode structure, and the gas and high-voltage inputs. The different planes are machined from Lucite of G10 epoxy fiberglass to minimize the leakage paths between the planes. A photograph of the assembled counter appears in Fig. 2.121, in which the multitude of lemo connectors attached to the sense and guard wires can be seen. The vertical-drift chamber is designed as a transmission counter so that it can be backed by various counter combinations such as scintillation, avalanche, or large ionization counters providing timing and particle identification signals.

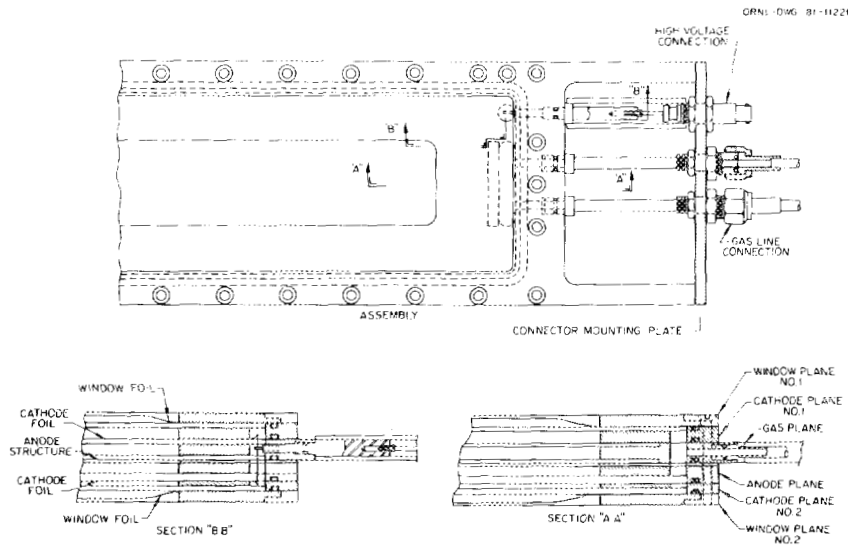


Fig. 2.120. Assembly drawing of the vertical-drift chamber.

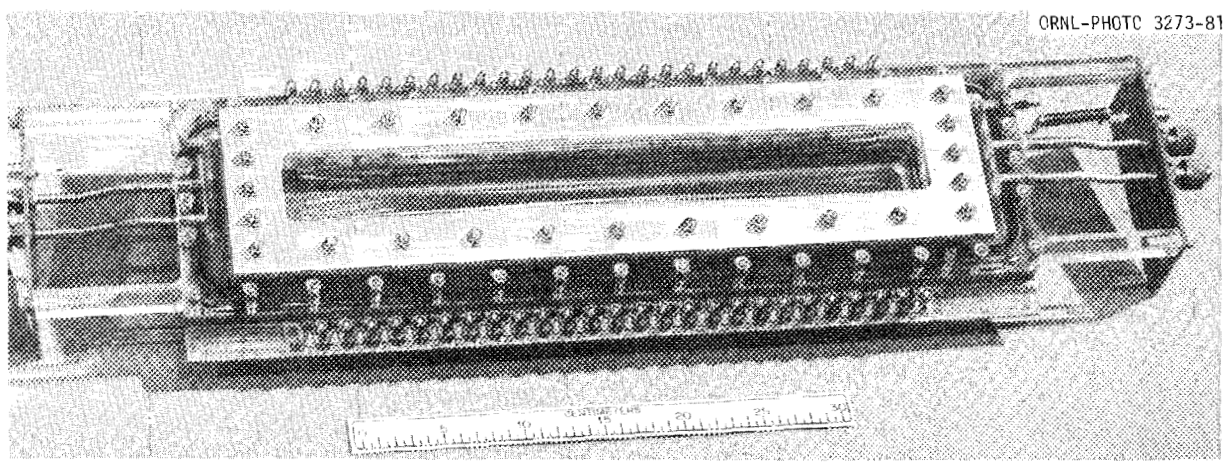


Fig. 2.121. Photograph of the assembled counter.

Initial tests of the counter pressured to 300 torr with pure isobutane with 140-MeV ^{16}O ions from the ORIC cyclotron indicate that the counter response is adequate to provide good performance as a drift chamber. Further testing is required, however, before its capabilities as a heavy-ion counter can be determined.

1. Instrumentation and Controls Division.
2. Los Alamos National Laboratory.
3. W. Bertozzi, M. V. Hynes, C. P. Sargent, C. Creswell, P. C. Dunn, A. Hirsch, M. Leitch, B. Norum, F. N. Rad, and T. Sasanuma, *Nucl. Instrum. Methods* **141**, 457 (1977).
4. Designed by J. L. Blankenship.

A CONSTANT-FRACTION TIMING DISCRIMINATOR FOR THE VERTICAL-DRIFT CHAMBER

J. L. Blankenship[1]

A timing discriminator module which exhibits minimal walk with variations of pulse amplitude and rise time has been developed for the vertical-drift chamber (VDC). The amplitude and rise-time compensation (ARC) of timing walk is achieved by a unique circuit that employs *R-C* components and the differential input and output design properties of ECL logic chips and does not employ delay lines

as does the conventional constant-fraction discriminator design. The timing walk was measured for pulse amplitudes between 1 and 3 mV for a 10-ns-rise-time test pulse and was 0.92 ns. A comparable leading-edge discriminator design exhibited a 4.4-ns walk for the same test conditions. The VDC requires 51 discriminator-preamplifier modules, or one for each active anode wire; therefore, compact design, low cost per module, and ease of servicing were major design objectives. This module was designed around two MC-10216 chips and two A401 transistors. The module generates a 1-ns-rise-time negative-going 0.4-V pulse at one of the tap points along a 50Ω transmission line which provides both position encoding and time-to-drift information.

1. Instrumentation and Controls Division.

LARGE GAS TELESCOPE

J. L. Blankenship[1] C. A. Reed[3]
B. Cheynis[2] A. H. Snell

This is a long (about 1 m) gas-filled ΔE-E telescope designed for heavy-particle isotopic identification when used with the time-of-flight system. It is a quadruple ionization chamber, the first stages being used for ΔE measurements and the whole being used for the E measurement. It is preceded by a parallel-foil avalanche detector to serve as the "stop" detector for the time-of-flight measurement.

Progress has been both mechanical and electrical. On the mechanical side, the chamber has been equipped with a stiff, arched Frisch grid that should be resistant to microphonics; the system has been made vacuum-tight, and techniques have been evolved for stretching and mounting the four thin polypropylene foils required at the entrance of the telescope. Two of these foils are aluminized, to be used as the parallel plates of the avalanche counter; one is the vacuum window foil, and one separates the ionization chamber from the avalanche counter, which will usually operate at different gas pressures. All foils have an effective aperture opening of about 5 × 10 cm, and it is desirable that they be uniform in thickness over this area.

The necessary preliminary electrical measurements have been made on the system, and the required seven preamplifiers (Canberra 2001 A) have been purchased. Voltage-response curves have been obtained for the ionization chamber system, using filling gases of argon–10% methane, isobutane, and methane at various pressures and with various modes of purification. Collimated alpha particles were used for these tests. Pulse rise times have been studied and also drift velocities as functions of E/p; indeed, in isobutane the observed drift velocities are appreciably higher than those published in recent literature. Using Ar–10% methane at 1 atm and the 5.8-MeV alpha particles of ^{244}Cm, a highly satisfactory resolution of 38 keV FWHM has been obtained.

Pulses produced by the avalanche detector have also been studied, using collimated fragments of ^{252}Cf. Figure 2.122 shows a sample.

In summary, we feel that the long telescope is about ready for installation on the time-of-flight system.

1. Instrumentation and Controls Division.
2. Research guest sponsored by the Ministère des Affaires Étrangères, France.
3. Guest assignee from Oak Ridge Associated Universities.

AVALANCHE DETECTOR DEVELOPMENT

I. Y. Lee N. R. Johnson
G. R. Young F. E. Obenshain
R. Novotny

The parallel-plate avalanche counter (PPAC) has many features which make it well suited for the detection of heavy ions. When used together with the latest fast electronics, it can provide good time resolution[1] and position resolution and can be operated at counting rates up to 1 MHz.[2] In addition, it can be built with a large area, it has insignificant deterioration due to radiation damage, and it is insensitive to x-ray, electron, and light background.

We have developed position-sensitive PPACs with an active area of 12 × 12 cm. Each unit consists of four planes. As shown in Fig. 2.123, they are the anode plane, the cathode plane, the sense-wire plane, and the spacer. The anode and the

ORNL-PHOTO 4186-81

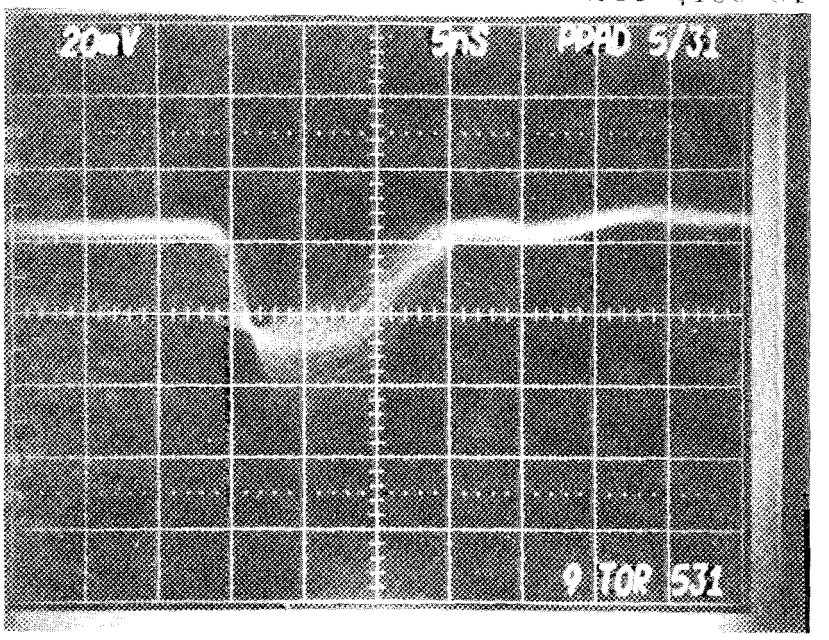


Fig. 2.122. Avalanche detector output pulses into a 50-Ω load. Pressure: 9 torr isobutane; 531 V across the parallel plates.

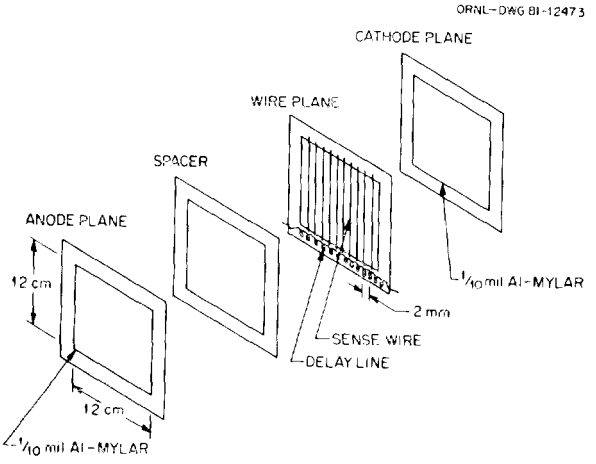


Fig. 2.123. Schematic view of the parallel-plat avalanche counter.

cathode are stretched aluminized 2-μ-thick Mylar foils. The sense-wire plane is a grid of parallel wires stretched 2 mm apart across a PC-board frame. We used 25-μ-diam Au-coated W wires. The ends of the wires are connected to 2-ns taps along a delay line. The sense wires are placed halfway between the anode and the cathode and are biased at half the anode voltage. When the counter fires, an electron avalanche forms, and the resulting anode pulse provides the ΔE and timing signal. The avalanche also induces signals on several of the nearby sense wires. The position of the avalanche is determined from the relative delay between the induced signals at the two ends of the delay line. The size of the induced signal on a given sense wire depends on the distance between the avalanche and the wire, resulting in a distribution in pulse heights centered at the avalanche position. The resulting self-interpolating property makes the position resolution much better than the sense-wire separation. For two-dimensional position determination, two such units with sense wires perpendicular to each other are used in tandem.

Tests using an alpha source and two counters in coincidence mode give a time resolution of 500 ps. To test the position resolution, we placed a mask with 1-mm-diam holes in front of the counter. As shown in Fig. 2.124, position peaks with FWHM of 1 mm were obtained, which indicate that intrinsic resolution of better than 1 mm can be achieved easily. With heavy ions it is expected that better time and position resolution will be obtained due to the much larger signals created. Six such counter units have been built. They will be used in a wide variety of experiments, including use as recoil or

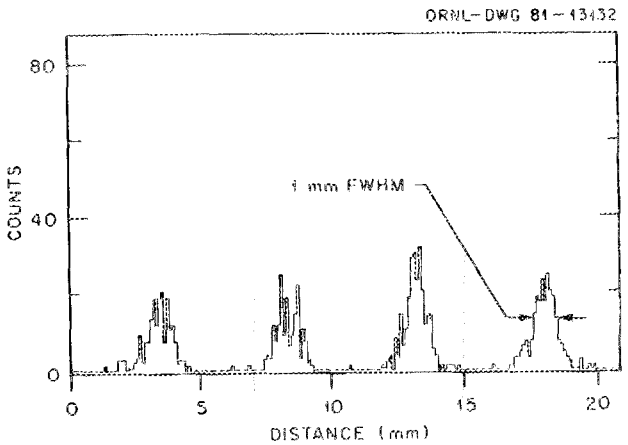


Fig. 2.124. Time spectrum obtained using alpha source and a mask with 1-mm-diam holes in front of the counter.

evaporation-residue detectors with large acceptance angles in time-of-flight or telescope experiments, as scattered-projectile detectors for Coulomb excitation or transfer reactions, and, in pairs, as detectors of both nuclei in binary reactions for a kinematically complete identification of mass and energy. A thin-window version for fission-fragment detection is being developed. Tests are also being planned for using this counter as a focal-plane detector.

1. A. Breskin et al., *Nucl. Instrum. Methods* **148**, 275 (1978).
2. G. Gaukler et al., *Nucl. Instrum. Methods* **141**, 115 (1977).

WIRE STRETCHER APPARATUS

I. Y. Lee G. R. Young J. W. Johnson

Large-area wire grids with uniform spacing and tension are an essential part of many gas counters, such as the parallel-plate avalanche counter, the gridded ionization counter, and the multiwire proportional counter. Due to the accuracy requirement and the tedious nature of this wire stretching task, a machine is needed to perform this work.

A device has been designed and manufactured to produce wire grid sizes up to 60 by 60 cm. It can stretch wire with diameters down to 5 μm, with the spacing between the wires as small as 1 mm. Special care was taken in the design so that fine wires may be stretched without breaking. This included using a high-power motor with a fine speed control to produce a smooth start. The wire spool is mounted on an air bearing to reduce drag, and the tension on the wire is maintained by an air turbine, which allows fine adjustment at low tension.

This apparatus (Fig. 2.125) of a plate with two rods attached to its two opposite edges. Parallel circular grooves with 1-mm spacing were cut on the surface of the rods. The plate is fixed to a shaft which is parallel to the rods and goes through the center of the plate. The shaft is supported by bearings mounted at one edge of a table and is driven by the variable-speed motor. On the other side of the table, a carriage is driven by the same motor through linkages and gears. The wire spool and the tension device are mounted on the carriage, which moves in the same direction as the rotation axis of the plate. The speed of the carriage can be varied to give wire spacing in multiples of 1 mm by using gears of different gear ratios. As the plate turns, the wire is wound on the grooves of the two rods with precise tension and spacing.

The wire plane can be transferred easily to a frame for storage and transfer to the detector. Preliminary tests show satisfactory performance for wires with diameters ranging from 5 to 100 μm.

A DOPPLER-SHIFT RECOIL-DISTANCE DEVICE FOR USE WITH AN NaI SUM SPECTROMETER

N. R. Johnson I. Y. Lee D. R. Haenni[2]
J. W. Johnson J. E. Weidley[1] J. R. Tarrant[3]

A direct measurement of the lifetime of a nuclear state is very important, since it provides, in a model-free manner, the transition matrix element for the state. Such matrix elements are essential for an understanding of the structure of excited states and, hence, for the understanding of such phenomena as back-bending and multiple Coulomb excitation.

In recent years, we have made extensive measurements of lifetimes of states populated in Coulomb excitation. The spectra obtained in these measurements are usually relatively simple to interpret and have provided a rather clear picture for the rotational states in deformed nuclei. However, very little is known about the lifetimes of states in nuclei accessible only through compound-nucleus reactions. The problem here is that the gamma-ray spectra are usually very complex because of the many competing reaction channels in these processes and thus do not lend themsleves to such measurements. Enhancement of a desired reaction channel has

ORNL-PHOTO 4429-81

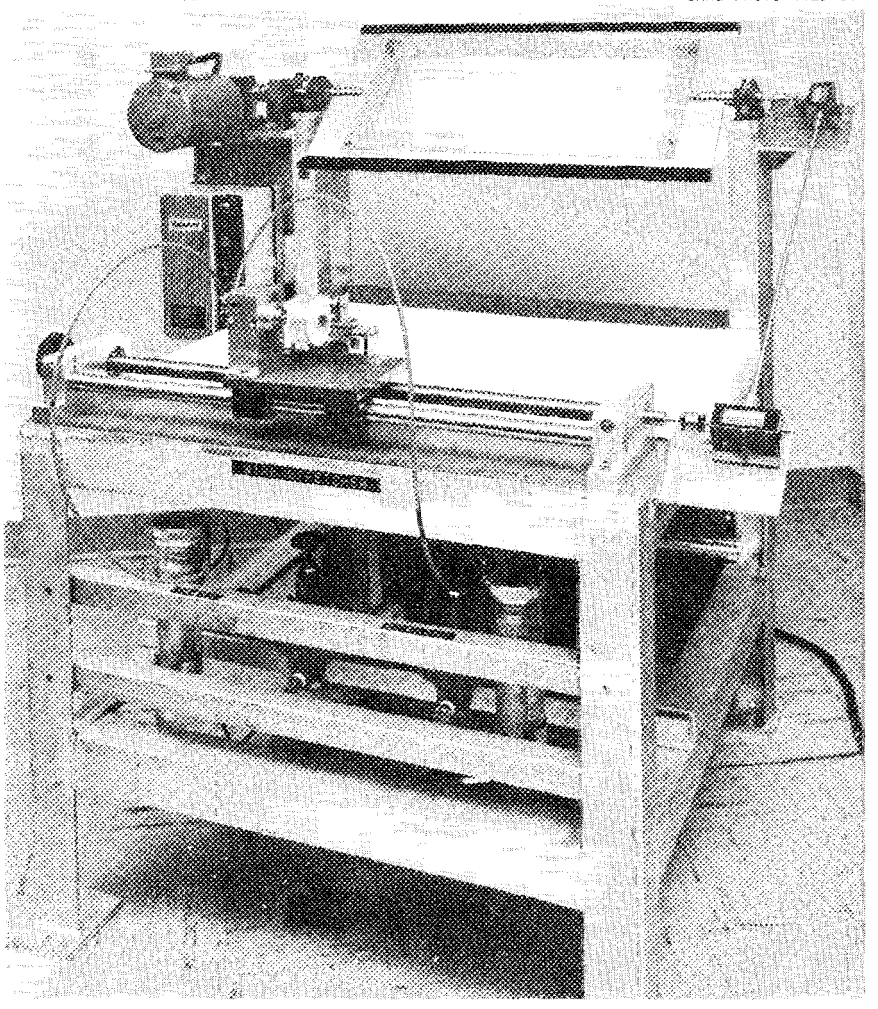


Fig. 2.125. Wire stretcher apparatus.

become possible by utilizing a "total decay energy" filter (e.g., see ref. 4). We[4] have used a 25 × 25 cm NaI detector with an annular opening of 7 cm to sum the total decay energy on which selective gating can be made.

In order to carry out lifetime measurements on the excited states of these nuclei produced in compound-nucleus reactions, we have designed and constructed a Doppler-shift recoil-distance device ("plunger") which fits within the annular opening of a large NaI detector (9), as illustrated in Fig. 2.126. It is designed so that the target foil (3) is located near the center of the NaI crystal. The metallic target foil is mounted on a conical frame and is pressed down over the stretcher cone (5), which defines the final surface position of the foil. The stopper (1) to catch recoiling nuclei consists of a high-quality nickel foil onto which about 40 mg/cm^2 of lead has been evaporated. This stopper foil is stretched over a second stretching cone (2), which is mounted on an assembly whose alignment is controlled by three differential screws.

The tubes supporting the target and stopper and all connecting elements in the positioning mechanism were made from appropriate combinations of Invar, stainless steel, and aluminum. This was done to minimize any change in tartet-stopper separation as a result of thermal expansion. The

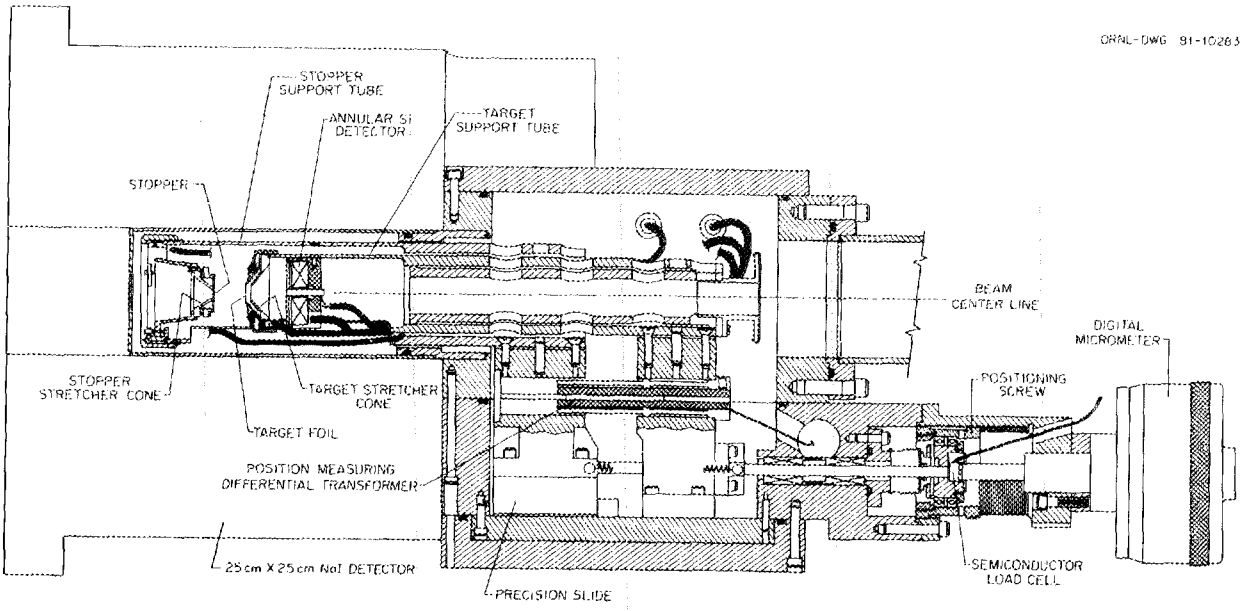


Fig. 2.126. Schematic drawing of the Doppler-shift recoil-distance device.

tube (7) supporting the target foil is fixed, while that (4) supporting the stopper is movable and attaches to an assembly which connects to the core element of a position-measuring differential transformer (8) and the movable stage of a precision slide (10). Movement of the slide, with corresponding change in the target-stopper separation, is accomplished by means of an external positioning drive screw mechanism (12). Once the desired target-stopper separation is achieved (determined by the differential transformer readout), the high-precision digital micrometer (13) is contacted to the semiconductor load cell (&11) until a load of 150 g is attained, and the micrometer reading provides the final value for target-stopper separation. At close distances, the capacitance reading between the target and stopper is utilized for yet higher precision in the spearation value. A photograph of the device with the end housing removed is shown if Fig. 2.127.

In lifetime measurements following heavy-ion-induced compound-nucleus reactions, coincidence information consisting of the gamma-ray energy from the germanium detector, the total-energy signal from the large NaI annulus, and their time relationship from a TAC are stored in list mode on magnetic tape. As illustrated in Fig. 2.126, the plunger can also be fitted with an annular silicon detector (6) for the detection of backscattered projectiles when the device is used for the study of states populated in Coulomb excitation. Our initial tests of the instrument were carried out in this mode of operation by Coulomb-exciting the well-studied[5,6] rotor ^{232}Th with 152-MeV ^{40}Ar projectiles. The tests for the 4^+, 6^+, and 8^+ states of ^{232}Th gave results in good agreement with past measurements.[5,6]

1. Plant and Equipment Devision.
2. Present address: Texas A & M University, College Station.
3. Instrumentation and Controls Division.
4. I. Y. Lee, N. R. Johnson, R. L. Robinson, M. W. Guidry, R. E. Neese, C. R. Bingham, S. W. Yates, and G. R. Young, *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978.*, ORNL-5498, p. 44.
5. N. R. Johnson, R. J. Sturm, E. Eichler, M. W. Guidry, G. D. O'Kelley, R. O. Sayer, D. C. Hensley, N. C. Singhal, and J. H. Hamilton, *Phys. Rev. C* **12**, 1927 (1975).
6. M. W. Guidry, P. A. Butler, P. Colombani, I. Y. Lee, D. Ward, R. M. Diamond, E. Eichler, N. R. Johnson, and R. J. Sturm, *Nucl. Phys.* **A266**, 228 (1976).

THE HELIUM-JET-COUPLED MASS SEPARATOR: ADVANCES AND DIRECTIONS

D. M. Moltz K. S. Toth

The helium-jet technique has been used extensively in the study of nuclei far from beta stability.

ORNL-PHOTO 3740-81

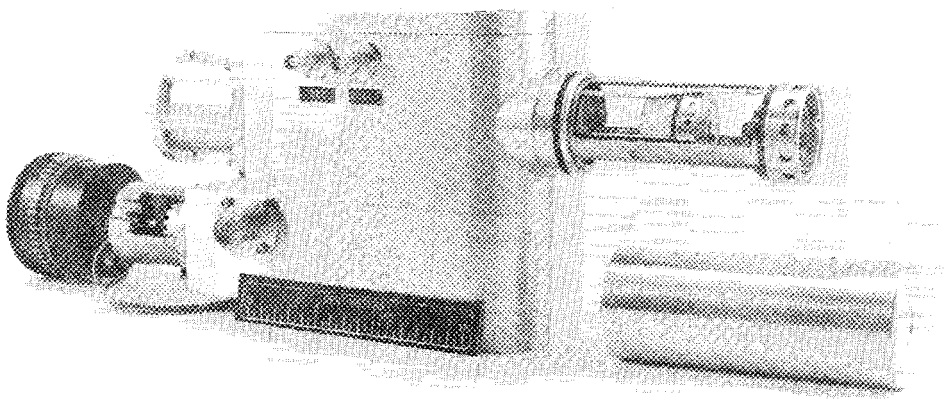


Fig. 2.127. **Photograph of the Doppler-shift apparatus.** The flanged section just above the micrometer attaches to the accelerator beam line.

Such studies have also been aided by isotope separator on-line (ISOL) systems. The coupling of these two techniques as originally proposed by Nitschke[1] was manifested with the successful advent of the RAMA-88 system at the Lawrence Berkeley Laboratory.[2] Other helium-jet systems have been coupled to ISOL systems utilizing reactors[3,4] and off-line sources[5] to study fission products. RAMA, however, represents the only operating accelerator-based system. The Chalk River helium-jet system[6] has been designed to operate with their tandem-based ISOL system but at this time has not been coupled and is operating with an integrated target-ion source.[7,8] The UNISOR system is also an integrated target-ion-source system on-line with the Oak Ridge Isochronous Cyclotron and the Holifiled Heavy-Ion Research Facility. We are now constructing an advanced-design helium-jet system to add this versatile option for performing on-line experiments at Oak Ridge.

The helium-jet technique is endowed with several properties which make it extremely attractive as a method for studying nuclei far from stability. It enables fast transport of radioactivities away from the intense radiation associated with the bombardment region. This transport is reasonably universal for all nongaseous elements produced in many differing target-projectile combinations. Clusters containing the stopped recoil product nuclei exiting from the helium jet possess thermal energies (eV) rather than the large nuclear recoil energies (MeV). All of these properties are desirable, but the general universality in fact stresses the need for mass separation. Coupling of the helium jet to an ISOL system adds several more criteria for stable and reproducible operation. These have been investigated thoroughly[2,8] and have led to the existing RAMA system. All of these considerations have led to the design of a coupled system for the UNISOR.

The most important conceptual change from the RAMA system is the use of a small chamber contained within a larger vacuum chamber, depicted schematically in Fig. 2.128. This design will permit the selective cooling of both the chamber (and thus the internal gas) and the nitrogen-cooled foil windows needed for increased beam intensity. The importance and design of a multiple-target multiple-capillary system have been discussed previously,[8] and such a system has been included along with easy external target-change capabilities. The four-target system shown will be used for light-ion-induced reactions, while another two-target system has been constructed for heavy-ion-induced reactions. The gas mixture of helium plus additives (generally ethylene glycol) will be precooled before introduction into the temperature-controlled chamber. Other major differences from the RAMA system are the operation of the system at the extraction potential (about 55 kV) and the shorter capillary tube (about 1.5 m compared with 6 m). Similar gas flow rates should permit approximately a factor of 4 decrease in transport time. This time decrease is very important, since the relatively slow acceleration[2] to sonic velocity of the clusters formed in the helium[2] creates an absolute transport time constant

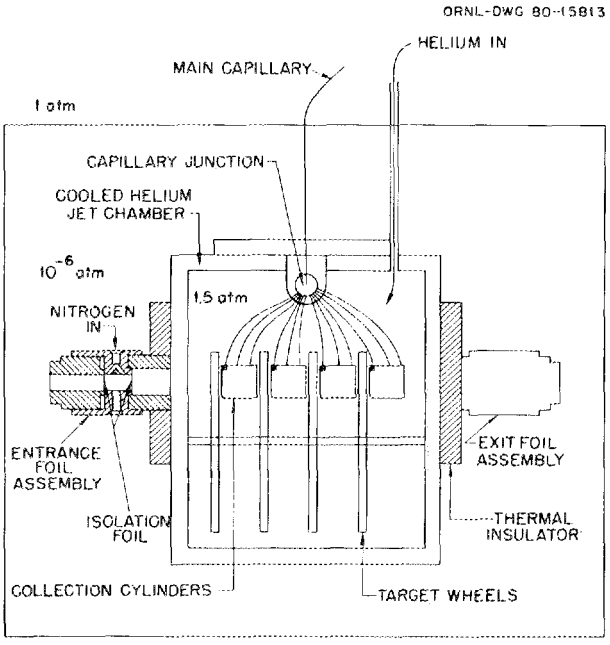


Fig. 2.128. Schematic diagram of the helium-jet box and chamber which will be coupled to the UNISOR system.

that must necessarily reduce the observed reaction yield by an amount which may be calculated by the standard exponential decay formula.

Coupling of the helium jet to an ISOL system has long presented the greatest problem. The need for a fast and chemically universal ion source for this purpose led to hollow-cathode ion sources for the RAMA system.[2,8] The hollow-cathode anode-extraction source has been found to be very reliable and reproducible, and thus a simple version is being constructed. The shorter capillary-plasma distance (about 7 cm) permitted by maintaining the skimmer-capillary potential at 55 kV and the higher plasma density should permit a factor of 5 to 10 increase in yield. Even though this source works well,[8] development of improved sources is clearly of interest. Since the coupling efficiency is hidden away in the ion source efficiency, it is often difficult to decouple it from the efficiency of particles extracted as a percentage of those introduced into the plasma. Efforts are thus needed on both fronts. A newer, higher-temperature hollow-cathode cathode-extraction ion source is being designed, in addition to a very simple thermal source consisting of only a heated tube. Attempts will also be made to increase the plasma density and the ion source output (particularly He^+, which will indicate a higher throughput).

This new helium-jet system should prove to be complementary to the UNISOR integrated target–ion-source system. Although the existing system will be used whenever possible because of its higher total efficiencies, many experiments will require the helium-jet system because of unique target limitations or very short half-lives. Therefore, along with the Chalk River on-line mass separator, the UNISOR will have both operating capabilities, making it a very versatile tool for studying nuclei far from beta stability.

1. J. M. Nitschke, vol. 1, p. 153 in *Proceedings of the International Conference on the Properties of Nuclei Far from the Region of Beta Stability, Leysin, Switzerland, 1970*, CERN, Geneva, 1970.

2. D. M. Moltz, R. A. Gough, M. S. Zisman, D. J. Vieira, H. C. Evans, and J. Cerny, *Nucl. Instrum. Methods* **172**, 507 (1980).

3. J. P. Zirnheld, L. Schutz, and F. K. Wohn, *Nucl. Instrum. Methods* **158**, 409 (1979).

4. A. K. Mazumdar, H. Wagner, W. Walcher, M. Brugger, and N. Troutmann, *Nucl. Instrum. Methods*, to be published.

5. R. A. Anderl, V. J. Novick, and R. C. Greenwood, *Nucl. Instrum. Methods*, to be published.

6. H. Schmeing, V. Koslowsky, M. Wightman, J. C. Hardy, J. A. Macdonald, T. Faestermann, H. R. Andrews, J. S. Geiger, and R. L. Graham, *Nucl. Instrum. Methods* **139**, 335 (1976).

7. H. Schmeing, J. C. Hardy, E. G. Hagberg, W. L. Perry, and J. S. Wills, *Nucl. Instrum. Methods*, to be published.

8. D. M. Moltz, J. M. Wouters, J. Aysto, M. D. Cable, R. F. Parry, R. D. vonDincklage, and J. Cerny, *Nucl. Instrum. Methods* **172**, 519 (1980).

HEAVY-ION APPLICATIONS

S. Raman
C. R. Vane
R. L. Auble
L. D. Hulett, Jr.[1]
S. Kahane[2]
H. J. Kim
G. Lapicki[3]
F. D. McDaniel[4]
W. T. Milner
G. D. O'Kelley[5]
T. Rosseel[1]
O. Shahal[2]
G. G. Slaughter
S. L. Varghese[6]
J. P. Young[1]

The original proposal presented by ORNL in 1972 for the establishment of a national heavy-ion laboratory contained a substantial section on possibilities for applied research with this new facility. Such research is of interest to several divisions at ORNL. Therefore a program has been initiated to identify and pursue the most promising applications.

The first example is the possible use of the HHIRF in obtaining chemical information for com-

plex materials like coal, coal ash, and fly ash through study of x rays emitted under heavy-ion impact. This particular application is of interest to the Chemistry and the Analytical Chemistry Division. It is likely that information concerning the molecular binding of sulfur in coal would be useful in development of suitable practical separation techniques. Heavy-ion-induced x-ray fluorescence analysis with particular emphasis on the satellite lines might be one way of discovering the chemical forms of, for example, sulfur in coal.

In order to better evaluate ion-induced x-ray spectroscopy for chemical analysis, measurements were made at the ORIC during July 1980. A Si(Li) detector was employed to determine the projectile and target *K*, *L*, and *M* x-ray yields for 36- to 103-MeV ^{40}Ar ions on V, Cu, Nb, Ta, and Pt targets. Further detailed study required the use of a moderate resolution (about 7 eV at 2 keV) x-ray dispersing device capable of providing some separation of the chemically sensitive $K\alpha$-satellite line structure. A computer-controlled curved-crystal spectrometer and appropriate targets were employed in a second exploratory run at the ORIC in May of this year. Preliminary results of these measurements for two sulfur-bearing compounds (from a total of 15 different targets) are shown in Fig. 2.129. This particular example compares the sulfur $K\alpha$-satellite lines emitted by Na_2SO_4 and Na_2S targets under 36-MeV ^{40}Ar-ion impact. Although the data analysis is not yet complete, qualitative spectral differences are obvious. The observed variations are entirely due to differences in chemical environment, since no other changes were made from scan to scan. The individual peaks labeled $K\alpha L^n$ arise from sulfur $K\alpha$ x-ray emission in the presence of an additional *n* (in number) *L*-shell electron vacancies created during the violent heavy-ion collision. As examplified here, each chemical compound tested shows a possibly unique complex spectral pattern with wide variations in individual line intensities for various targets. Measurements[7] at Texas A&M and elsewhere have given evidence that these intensity variations with target material may be correlated with the effective charge of the sulfur atoms or the effective valence-electron density. Several serious questions remain, however. For example, the yield of $K\alpha L^0$ x rays from some targets is anomalously high, even after correction for fluorescence by projectile and target x rays.[8]

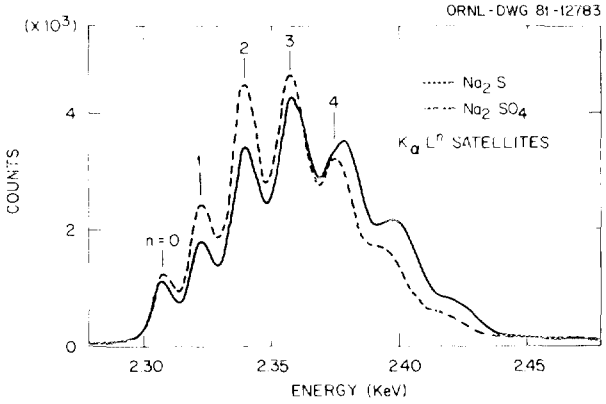


Fig. 2.129. Comparison of $K\alpha$-satellite spectra from Na_2SO_4 and Na_2S targets bombarded by 36-MeV ^{40}Ar ions. Peaks are designated KL^n according to the number of *L*-shell electron vacancies at $K\alpha$ emission.

The peaks shown in Fig. 2.129 are composed of unresolved multiplets of lines, the intensities and spectral positions of which most likely reflect additional chemical information. A spectrometer with better resolution (about 1 to 2 eV at 5 keV) will be needed in the next phase of experimentation in order to fully utilize the chemically specific information derivable from heavy-ion-induced x-ray spectroscopy.

---

1. Analytical Chemistry Division.
2. Nuclear Research Centre-Negev, Beer Sheva, Israel.
3. Northwestern State University of Louisiana.
4. North Texas State University.
5. Chemistry Division.
6. University of South Alabama.
7. R. L. Watson, A. K. Leeper, B. I. Sonobe, T. Chiao, and F. E. Jenson, *Phys. Rev. A* **15**, 914 (1977); M. Uda, H. Endo, K. Maeda, Y. Awaya, M. Kobayashi, Y. Sasha, H. Kumagai, and T. Tonuma, *Phys. Rev. Lett.* **42**, 1257 (1979).
8. R. A. Kenefick, R. L. Watson, and C. C. Bahr, *Progress in Research 1978–79*, Cyclotron Inst., Texas A&M University, p .72.

3. The UNISOR Program

RECENT IMPROVEMENTS IN THE UNISOR FACILITY

R. L. Mlekodaj[1] H. K. Carter[1]
E. H. Spejewski[1] J. D. Cole[2]
E. F. Zganjar[2] F. T. Avignone III[3]
B. G. Ritchie[3] H. Noma[3]

Ion Sources

The recently developed high-temperature ion source[4,5] in its many forms has become the main-line source for on-line mass separation at the UNISOR (University Isotope Separator). On-line efficiencies for this source range up to 18% in the plasma mode and in excess of 30% in the thermal-ionization mode in favorable cases. This source, shown in Fig. 3.1, with its 2000°C operating temperature has allowed the on-line mass separation of many previously unavailable elements including Pb, Bi, Au, Ba, and Tm. Other new elements for the UNISOR that are relatively easily done but separated on-line for the first time include Po, At, Rn, and Fr.

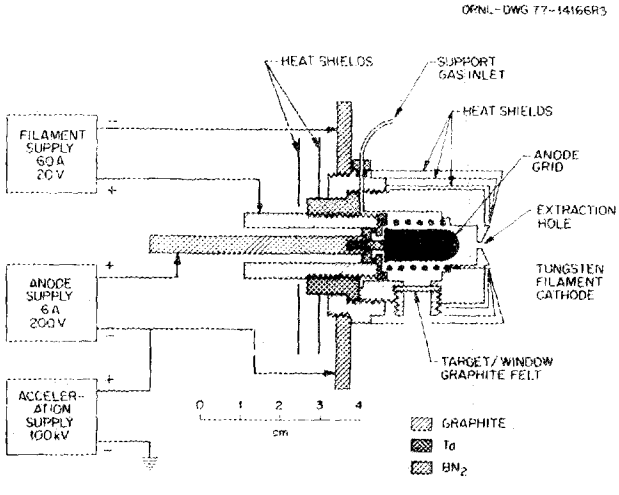


Fig. 3.1. Schematic view of the high-temperature ion source with electrical connections.

The first successful separation of barium isotopes at the UNISOR was accomplished using the high-temperature ion source in the thermal-ionization mode. A new technique[6] involving the addition of fluorine to the ion source was used where the barium is preferentially ionized as the molecular form BaF^+. The extension of this method to rare-earth elements is proceeding where the predominant product is expected to be a difluoride ion for most rare-earth elements.

The original oscillating-election ion source with an operating temperature of 1000°C is still used to discriminate against elements with low vapor pressure. This source is used, for example, to suppress the output of gold produced in the same reaction when the desired product is mercury.

The development of a compact thermal-ionization source capable of operating in the temperature regime around 2500°C has progressed steadily. The successful ionization of all the rare-earth elements is the ultimate goal for this source. Two different approaches for a heat source are being used in this program. One method uses electron bombardment as the heat source, while the other uses direct ohmic heating in a tungsten filament. Both versions of this source have performed well in the off-line mode and at lower temperatures in the on-line mode. But problems with the integrity of the extremely thin (800 $\mu g/cm^2$) tungsten entrance windows and catcher foils under heavy-ion bombardment at the highest temperatures of these sources must still be solved.

Targets

The development of a target mounting system that is external to the ion source and which can be retracted behind a valve has greatly improved the situation for delicate targets. This system allows the incorporation of heat shields that have greatly increased the lifetime of such targets as Ni, Ag, Pr, and Sm. In addition, the time lost for changing broken targets has been significantly reduced.

A new technique for preparing hafnium targets has been developed. This involves the conversion of HfO_2 to HfC directly on the graphite felt catcher, using the graphite as the source of carbon. This technique requires only a few milligrams of material and allows the use of very expensive separated isotopes of hafnium as targets. In addition, the HfC prepared in this way has shown a promising ability to release rare-earth elements when used as a catcher. A development program for producing carbides of the rare-earth elements in a similiar manner is being undertaken.

Separator

A move of the separator operations console and the on-line lens box has been carried out in a reconfiguration of the UNISOR area. These moves were necessary to accomodate the new accelerator beam line and the laser spectroscopy system.

The development of the laser spectroscopy system, described in detail elsewhere in this report, has placed stringent limits on the stability and ripple of the acceleration power supply. This has led to the replacement of the original acceleration power supply with a new one with less than 0.001% rms voltage ripple and less than 0.005% for long-term voltage stability.

A roomy new chamber has been placed in the beam line just prior to the ion source housing. This versatile chamber has been equipped with a wide variety of apparatus including a collimator, a beam stop, and beam energy degraders. An external target holder and changing system as well as several mirrors for alignment and ion source viewing are also included.

A program for changeover of the separator vacuum system from oil diffusion pumps to turbomolecular pumps has begun. At present, all pumps beyond the separation magnet have been converted.

Isotope Collection Systems

A new compact tape transport system[5] has been developed for use at the UNISOR. This transport uses a reel from an eight-track recording cartridge, where the tape is removed and simultaneously rewound on the same reel. The simplicity and compactness of this design has resulted in a much improved vacuum quality especially important for cooled detectors. This high-quality vacuum is obtained by using only the pumping already existing on the separator beam line. In addition, the small size has permitted a much more effective use of the limited floor space in the UNISOR area. The tape reel used gives up to 780 sources before the same area of tape is used again. A graphite coating on one side of the tape provides a convenient surface for monitoring beam current. A maintenance-free and leak-free ferromagnetic fluid feedthrough couples the external stepping motor to the capstan. The mass-separated sources can be moved from the collection point to a detector in about 0.5 s. This move time can be significantly shortened with minor design changes. There are three such systems now in use at the UNISOR. All detection stations on the tape transport systems have been equipped with special air locks to introduce standard calibration sources into the precise position of the mass-separated sources.

With the development of the UNISOR laser program it became apparent that one of the three separated-mass beam lines should be strictly dedicated to laser work. There remained, however, a need for retaining the capability to do simultaneous nuclear decay studies on three different A chains. This problem has been solved by moving one of the compact tape transport systems described above to the side of the collection chamber. From this position the collection tape travels into the collection chamber to the focal plane of the separator and intercepts the desired mass and then exits back to a detector station. The special feature of this system is that the collection tape travels through a pair of butterfly valves located between the tape transport system and the collection chamber. To effect changes or repairs in the tape transport system, the valves are closed upon the tape, and with differential pumping between the valves, the tape transport can be let up to atmospheric pressure with no observable rise in pressure in the collection chamber. Experiments on other beam lines can then continue unaffected.

An ultrasensitive beam current monitor system has been developed and installed on the central separated-mass beam line. This monitor uses a channeltron detector for secondary electrons emitted from the collection tape due to the impinging ions. This detector system has proven to be useful for beam currents as low as 100 ions/s and as high as 10^6 ions/s, at which point standard current reading devices can be employed. This level of sensitivity is quite sufficient to allow detection of the radioactive atoms arriving at the collection point and eliminates the need to deliberately introduce impurities in the ion source to produce mass markers.

Detection Systems

A new spectrometer system for conversion electrons has been developed. The cooled Si(Li) detector is mounted on a bellows arrangement such that when not in use it can be withdrawn behind a valve. This allows the detector to remain cold while the tape transport can be let up to atmospheric pressure for repairs or modifications. In addition, the detector is stored under high vacuum behind the isolation valve by use of its own dedicated ion pump. A miniorange spectrometer has been designed to operate in conjunction with this system. The purpose of the miniorange is to suppress the electromagnetic radiation, primarily x rays, which interfere with low-energy electron lines. The measured resolution and efficiency of the system operating with the miniorange have been measured to be 1.75 keV and 0.5%, respectively, for an electron energy of 60 keV. This system has significantly improved the quality and quantity of conversion electron data at the UNISOR. Two such systems are in operation.

A new spectrometer system for accurate positron measurements has been constructed and is based on an intrinsic germanium detector. Initial experiments have indicated that multiple positron groups can be accurately unfolded. In addition, coincidence measurements with gamma rays can help pin down feeding to excited states. A Monte Carlo program that describes the interactions of the positron in the germanium detector and also incorporates the response to gamma rays is being developed to allow precise determination of end-point energies.

Data Acquisition

The original Tennecomp TP-5000 data acquisition system has been modified to allow up to eight inputs in the coincidence mode and up to six inputs for singles data.

The new Tennecomp TP-5000 system has been upgraded by replacing the original PDP 11/05 CPU with a PDP 11/34 and 128k words of memory. This leaves about 65k channels of data region. In addition, the new operating system will be RSX-11 with new features including FORTRAN and editing capabilities.

The recent acquisition of several new germanium gamma-ray detectors and many NIM electronic modules has also significantly improved the data acquisition capabilities at the UNISOR facility.

---

1. UNISOR, Oak Ridge Associated Universities.
2. Louisiana State University, Baton Rouge.
3. University of South Carolina, Columbia.
4. R. L. Mlekodaj et al., *Nucl. Instrum. Methods* 171, 451 (1980).
5. In press, *Nucl. Instrum. Methods.*
6. P. Hoff et al., *Nucl. Instrum. Methods* 172, 413 (1980).

DEVELOPMENT OF A LASER SPECTROSCOPY FACILITY

H. K. Carter[1] R. L. Mlekodaj[1]
C. R. Bingham[2] E. H. Spejewski[1]
D. J. Pegg[2] J. D. Cole[5]
M. L. Gaillard[3] E. F. Zganjar[5]
P. M. Griffin[4]

During the last two years a laser facility was designed and installed at the UNISOR facility for the purpose of studying the ground-state and isomeric-state properties of nuclei far from stability. This facility will be used to observe small changes in root-mean-square radii of a series of isotopes through observation of the isotope shift. These model-independent measurements are important in testing theories on nuclear shapes and sizes, particularly in regions where deformation may start. Moreover, measurement of the hyperfine structure yields other ground-state or isomer properties: spins, magnetic moments, and spectroscopic quadrupole moments.

The general layout of the facility as it now exists is shown in Fig. 3.2. As indicated, the laser absorption will occur in a fast-ion (atom) beam from the separator, using a collinear laser-ion beam geometry. The Doppler broadening of the absorption line can be reduced by the use of fast beams by a factor of several hundred due primarily to the effect of kinematic compression of the longitudinal velocity distribution upon acceleration of the ions. During normal operation the ring dye laser (Coherent 699-21), pumped by an argon ion laser (Coherent CR-10), produces a single-frequency power of several hundred milliwatts and a line width of less than 1 MHz, which is more than adequate for most optical spectroscopy experiments. The single wavelength from the dye laser can be scanned electronically over an adjustable range $\lesssim$30 GHz.

In order to measure absolute wavelengths from the laser, a wave meter has been built. We have used the coincidence start-stop idea of Salimbeni and Pole[6] as the basis for our wave meter, but do not find

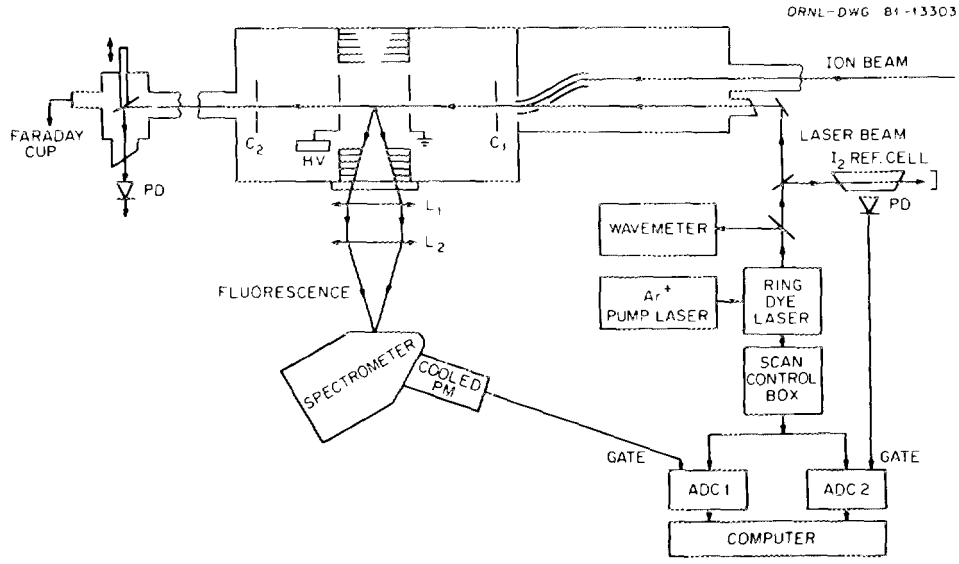


Fig. 3.2. Schematic block diagram of the laser facility on-line to the UNISOR isotope separator.

it necessary to use the expensive and experimentally more cumbersome spherical interferometer used in their system. Our wave meter is a typical two-beam division-of-amplitude type of interferometer except that the interference fringes are counted starting only at a coincidence between the two pulses and, after a preset time, stopped on a coincidence. Without using folded beam paths or further signal processing, this technique enhances the precision of the measurement by a factor of 180 over that expected for an equivalent number of counts. The precision of the wave meter has been tested by making a number of independent measurements of the output wavelength from the frequency-stablized dye laser. With an integration time of only 1 s (5×10^4 counts), a precision of 2×10^{-7} is obtained. The accuracy has been checked by comparing the calculated wavelength with the tabulated wavelength[7] of I_2 and was found to be approximately 5×10^{-7}. We utilize a microprocessor to control the counting and to calculate and display, in real time, the unknown wavelength and to indicate when the result is outside of a preset tolerance (e.g., mode hop).

It has been found convenient to monitor, simultaneously with the laser scanning, the fluorescence from a room-temperature I_2 reference cell. This arrangement allows one to detect discontinuous frequency changes (mode hops) and any frequency drifts that may occur.

The laser beam has already been collinearly merged with several beams of stable isotopes from the isotope separator, using electrostatic deflection plates to vary the path of the ion beam. Electronic excitations in various isotopes of Xe^+, Ba^+, and K^+ have been observed with a resolution of approximately 60 MHz. The excitation of these ions was detected through the observation of the resulting fluorescence, using a cooled photomultiplier. A grating spectrometer was used to limit the bandwidth of light entering the photomultiplier, thus considerably reducing background light signals, for example, from scattered laser light. The spectrum shown in Fig. 3.3 was obtained by scanning the dye laser over the frequency range necessary to excite the $5d^4D_{7/2} \rightarrow 6p^4P_{5/2}$ transition in Xe II when the ions are moving collinearly with the laser beam at an energy of 50 keV. The isotope separator was then used to select several different isotopes of xenon. The resulting frequency shifts of the adjacent peak are a consequence of two effects: a relative Doppler shift of 3500 MHz and an isotope shift of ~80 MHz.

For some elements it will be necessary to measure resonant absorption by neutral atoms, since a convenient transition (one accessible to standard dye laser wavelengths) is not present in the positively charged ion. Thallium is one example of such an element we wish to study. A recirculating sodium charge exchange cell has been designed and built.

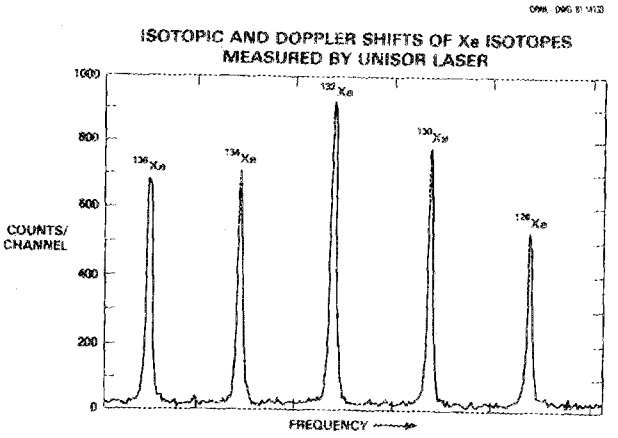


Fig. 3.3 Resonant fluorescence intensity curves obtained using the apparatus described here. The various peaks were obtained by sequentially directing the various xenon isotopes from the separator through the laser interaction region.

Initial tests of the cell indicate that it can serve as an effective sodium target for several days with only a slight loss of sodium.

1. UNISOR, Oak Ridge Associated Universities.
2. University of Tennessee.
3. University of Tennessee. Present address: University of Lyons, France.
4. Oak Ridge National Laboratory.
5. Louisiana State University.
6. R. Salimbeni and R. V. Pole, *Opt. Lett.* **5**, 39 (1980).
7. S. Gerstenkorn and P. Luc, *Atlas du spectre d'absorption de la molecule de l'iode*, editions du C.N.R.S. (1978).

ATOMIC LIFETIMES BY RAPID DOPPLER TUNING

M. L. Gaillard[1] C. R. Bingham[2]
D. J. Pegg[2] H. K. Carter[3]

A new fast ion beam technique for measuring lifetimes of excited states of ions has been developed at the UNISOR laser facility. The range of applicability of the method is limited to ions which have transitions from ground or metastable levels accessible to CW dye lasers and cases where lifetimes of excited levels are greater than a few nanoseconds. It appears that the accuracy of the method should approach 1%.

The principle of this new technique can be understood by referring to Fig. 3.4. The laser and ion beams are made collinear through the interaction region

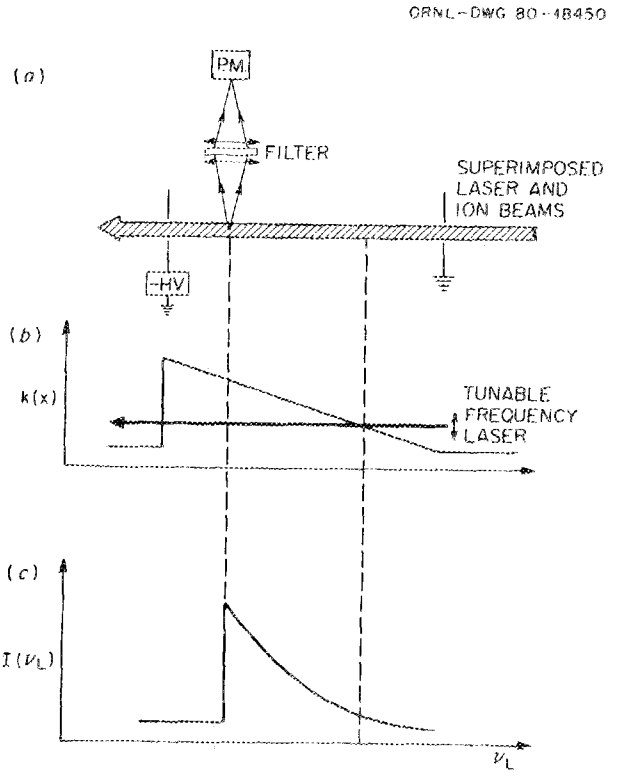


Fig. 3.4. Schematic of the collinear arrangement used at the UNISOR to measure atomic lifetimes. (*a*) Shows the apparatus; (*b*) is a plot of the kinetic energy of the ions as a function of their position between the field plates; (*c*) shows the change in fluorescent intensity resulting from the tuning of the laser frequency.

situated between a pair of parallel electric field plates. The constant electric field across the plates produces a uniform acceleration of the ions, causing them to have different velocities at different positions along the common beam axis between the plates. If the laser frequency is scanned, the ions will come into resonance at different points along the beam axis as a result of the Doppler shift. Since observation of the subsequent fluorescence is restricted to a fixed region downstream of the excitation region, this is equivalent to observing the ions at different times after excitation, thus allowing one to map out the intensity decay curve of the excited atomic states under study. An example of such a curve is shown in Fig. 3.5. Relative changes on the frequency scale are converted to time delays by the following linear relationship, which holds in a first approximation:

$$\Delta t = \frac{M\lambda_0}{qE}\,\Delta\nu_L\,,$$

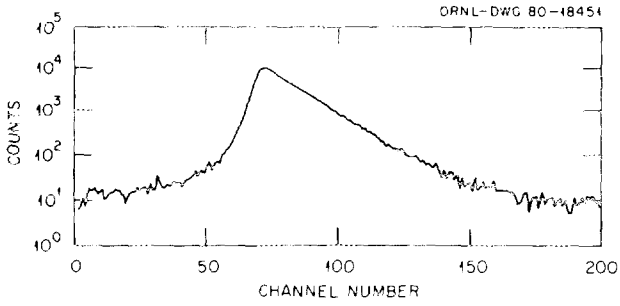


Fig. 3.5. Semilogarithmic fluorescent intensity curve for the decay of the $6p^4P_{5/2}$ level in ^{132}Xe II obtained the technique described here.

where

M = atomic mass of ion,

λ_0 = rest frame wavelength of excitation transition,

q = charge on the ion,

E = electric field at the site of excitation,

ν_L = laser frequency.

The advantages of this technique include: avoidance of the motion of mechanical parts under vacuum, rapid sweeping of frequency in order to average out possible ion and laser beam intensity fluctuations, and selective-state excitation. In addition, the difficult task of accurately measuring the ion beam velocity (common to other time-of-flight methods) is avoided.

We tested the system on the $6p^2P_{3/2}$ level in Ba^+ and obtained a natural lifetime of 6.33 ± 0.1 ns, which is to be compared with 6.312 ± 0.016 ns.[4] We also made preliminary measurements on lifetimes in Xe^+ and K^+. We are continuing to optimize the system by improving and stabilizing the metastable-state production (in most of the work excitation is from metastable states) from the separator in order that we may increase the counting rates and hence our overall precision. We also plan to improve the frequency-scale calibration in order to increase the accuracy of our measurements.

1. University of Tennessee. Present address: University of Lyons, France.
2. University of Tennessee.
3. UNISOR, Oak Ridge Associated Universities.
4. H. J. Andrä, p. 835 in Beam-Foil Spectroscopy, ed. I. A. Sellin and D. J. Pegg, Plenum, New York, 1976.

DYNAMICAL SUPERSYMMETRIES AND THE POSITIVE PARITY STATES IN ^{193}Au

J. L. Wood[1]

Recently, it has been suggested that dynamical supersymmetries may be present in the spectra of complex nuclei.[2] The particularly simple supersymmetric structure of ref. 2 is generated by a single particle with $j = 3/2$ and $L = 0,2$ bosons with 0(6) symmetry. The nuclide ^{193}Au, which has a $J = 3/2$ ground state and lies in a region of even-even nuclei with 0(6) symmetry,[3] has been studied to determine whether its low-lying spectrum can be described by this classification scheme. To this end, the following criteria have been used: (1) the low-lying states must exhibit the level pattern of Fig. 1 in ref. 2; (2) this pattern must be built on a $j = 3/2$ single-particle state; (3) the $E2$ transitions must satisfy the selection rules appropriate to this scheme. Classifying the states with the quantum numbers ($\sigma_1, \sigma_2 = \sigma_3 = 1/2$) and ($\tau_1 = \tau_2 = 1/2$), these $E2$ selection rules are $\Delta\sigma_1 = 0$; $\tau_1 = 0, \pm 1$.

The excited states of ^{193}Au have been studied by radioactive decay of the ^{193}Hg low-spin[4,5] and high-spin[6] isomers and by in-beam gamma-ray spectroscopy.[7,8] The positive-parity states have been discussed using the systematic features[4] of $^{189-195}$Au and have been treated theoretically in terms of the quasiparticle-vibrator model[9] and the particle-asymmetric rotor model.[10] The relevant states of ^{193}Au are shown in Fig. 3.6 and, by comparison with Fig. 1 of ref. 2, indicate that criterion 1 is approximately fulfilled.

A direct discussion of criterion 2 is not possible, since single-proton stripping data are not available. However, because of the close similarity[4,11] of the positive-parity states in ^{193}Au and ^{195}Au, an indirect test is possible by considering single-proton stripping data[12] on ^{195}Au. This indicates that the 38-keV state in ^{193}Au is to a large extent a member of the $\tau_1 = 3/2$ multiplet built on the $d_{3/2}$ configuration and that the state at 780 keV is a member of the $\tau_1 = 5/2$ multiplet.

The test of criterion 3 is rather difficult to perform because of the weakness of the $E2$ components in some of the $E2/M1$ admixed transitions. The relevant data are the relative reduced $E2$ transition intensities shown at the right in Fig. 3.6. The $E2$ transitions forbidden by the selection rules above are marked by an F over the top of the transition arrow. These are indeed weak, supporting the proposition that these states can be described, to a good approximation, by the classification scheme of ref. 2. It

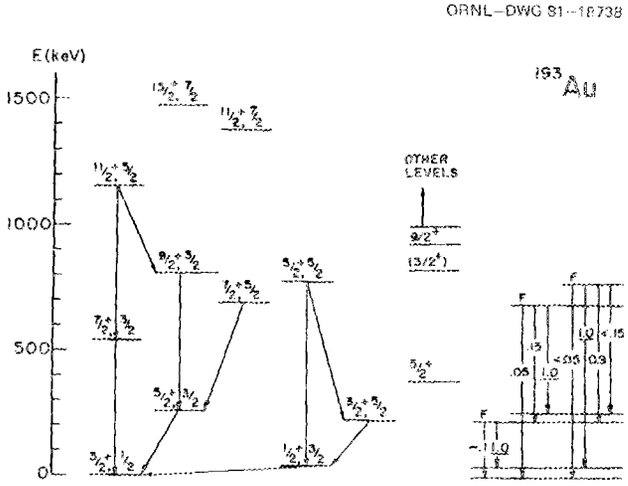


Fig. 3.6. Low-lying positive parity states in ^{193}Au. States are labeled by the quantum numbers J^{π}, τ_1, and all known levels below 1 MeV are shown. At the left side the arrows indicate observed strong $E2$ transitions. Separately at the right are shown those transitions, marked by an F above the arrow, which are τ_1-forbidden by the classification scheme, as well as the other observed transitions depopulating those initial levels. The numbers are the observed relative reduced transition intensities.

should be noted that previous theoretical discussions of these states predict a branching ratio of 1.1 (ref. 9) and 0.7 (ref. 10) from the J^{π}, $\tau_1 = {}^3/_2{}^+, {}^5/_2$ state compared with the experimental value of ~0.1.

In conclusion, the experimental data indicate that ^{193}Au is, to a good approximation, describable by the supersymmetric classification scheme of ref. 2. However, additional information is necessary to understand fully the extent to which the scheme can be applied in this region. Finally, it should be noted that the results presented here can also be related to a microscopic model proposed by Ginocchio.[13]

---

1. School of Physics, Georgia Institute of Technology, Atlanta.

2. F. Iachello, *Phys. Rev. Lett.* **44**, 772 (1980).
3. R. F. Casten and J. A. Cizewski, *Nucl. Phys.* **A309**, 477 (1978).
4. E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, C. R. Bingham, B. D. Kern, J. L. Weil, J. H. Hamilton, A. V. Ramayya, E. H. Spejewski, R. L. Mlekodaj, H. K. Carter, and W.-D. Schmidt-Ott, *Phys. Lett.* **58B**, 159 (1975).
5. J. L. Wood, unpublished data.
6. C. Vieu, thesis, University of Paris, Orsay (1974), CSNSM-T-74-01.
7. P. O. Tjøm, M. R. Maier, D. Benson, F. S. Stephens, and R. M. Diamond, *Nucl. Phys.* **A231**, 397 (1974).
8. H. Strusny, F. Dubbers, L. Funke, P. Kemmitz, E. Will, and G. Winter, Rossendorf Report (1975), ZfK-295, p. 38.
9. V. Paar, C. Vieu, and J. S. Dionisio, *Nucl. Phys.* **A284**, 199 (1977).
10. C. Vieu, S. E. Larsson, G. Leander, I. Ragnarsson, W. deWieclawik, and J. S. Dionisio, *J. Phys.* **C4**, 531 (1978).
11. C. Vieu and J. S. Dionisio, *J. Phys. (Paris) Collog.* **36-C5**, 87 (1975).
12. M. L. Munger and R. J. Peterson, *Nucl. Phys.* **A303**, 199 (1978).
13. J. N. Ginocchio, *Ann. Phys. (N.Y.)* **126**, 234 (1980).

RADIOACTIVE DECAY OF ^{192}Tl AND ^{192}Pb

D. C. Sousa[1,2] K. S. Toth
L. L. Riedinger[2] H. K. Carter[3]
C. R. Bingham[2] R. L. Mlekodaj[3]
F. E. Turner[2] E. H. Spejewski[3]

The decays of ^{192}Tl and ^{192}Pb were investigated by obtaining gamma-ray and conversion-electron multiscaled singles spectra and γ-γ and x-γ coincidence measurements. Half-lives of the 2^- and 7^+ isomers in ^{192}Tl were determined to be 9.4 ± 0.2 and 10.8 ± 0.3 min respectively. The 7^+ isomer decays primarily to a group of negative-parity states (Fig. 3.7), built upon a 5^- state at 1843.9 keV in ^{192}Hg. The 2^- isomer populates the low-lying positive-parity states in addition to a number of states in the region of 1 to 2.5 MeV.

The energy spacings and $E2$ transition probabilities of the 2^+_1, 4^+_1, 2^+_2, and 4^+_2 states are consistent with the vibrational model. However, the 0^+_2 member of the two-phonon triplet has not been observed, the 26% $M1$ admixture in the $2^+_2 \rightarrow 2^+_1$ transition demonstrates the presence of anharmonicities, and the strong transitions to the 2^+_1 state from the other positive-parity levels, particularly the 3^+_1 state, do not fit the simple vibrational picture. Because asymmetric rotor models have been successful in explaining the features of neighboring odd-A nuclei, one might expect that ^{192}Hg might also exhibit a degree of triaxiality in its structure. In the rigid asymmetric rotor model of Davydov and Filippov,[4] the energy of the 3^+_1 level is equal to the sum of the energies of the 2^+_1 and 2^+_2 states, which is precisely true for ^{192}Hg. The energy difference of the 2^+_2 and 4^+_1 states and the ratio $B(E2;2^+_2 \rightarrow {}^+_1)/B(E2;2^+_2 \rightarrow 0^+)$ yield values for the asymmetry parameter γ. Experimentally, these values are 38 and 36°, respectively, and agree very well with those values of γ which reproduce the structure of the $i_{13/2}$ band in ^{193}Hg,[5] the $h_{9/2}$ band in ^{193}Tl,[5,6] and the $h_{11/2}$ band in ^{191}Au.[6,7] Thus the overall general features of the positive-parity states through $I = 6$ in ^{192}Hg are compatible with the degree of triaxiality in the adjacent odd-A nuclei.

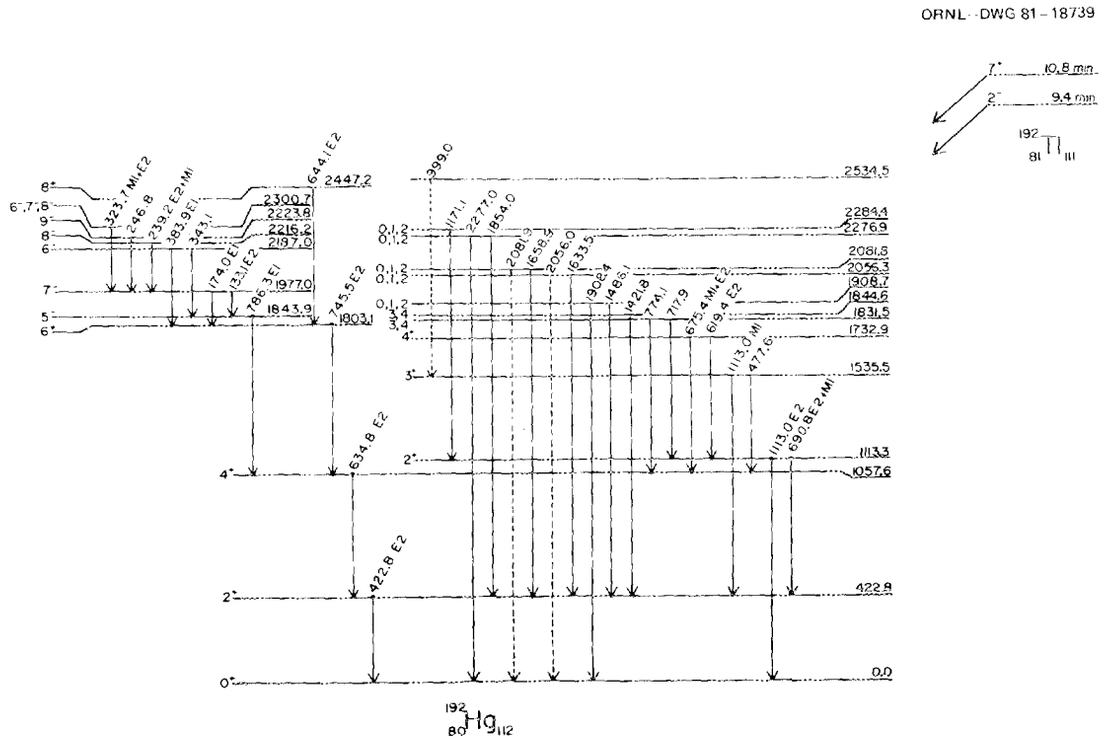


Fig. 3.7. Decay scheme for ^{192}Tl.

Most of the negative-parity states observed are part of a rotational band built upon the 5^- state at 1843.9 keV. This state probably results from the coupling of an $i_{13/2}$ neutron and an $f_{5/2}$ or $p_{3/2}$ neutron.[8,9] An interesting feature of this band is the shift upward in energy of the even-spin members relative to the odd-spin members. This is analogous to the structure of the coriolis-aligned $i_{13/2}$ bands[10] in the adjacent odd-A mercury isotopes. In ^{191,193}Hg the unfavored band members ($^{15}/_2{}^+$, $^{19}/_2{}^+$, $^{23}/_2{}^+$, ...) are shifted up relative to the favored members ($^{13}/_2{}^+$, $^{17}/_2{}^+$, ...). Thus the 5^-, 7^-, 9^-, ... sequence in ^{192}Hg can be explained by the coupling of a $p_{3/2}$ neutron with the favored members of the $i_{13/2}$ band, while the 6^-, 8^-, ... levels represent the coupling to the unfavored members. In a recent calculation of Neergard et al.,[11] two quasiparticles involving the $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, and $i_{13/2}$ neutron orbitals are coupled to an oblate rotor. A comparison of the calculated spectrum with the data shows good agreement, with the exception of the 8^- level, which is predicted to lie higher. Another inconsistency is the absence, experimentally, of evidence for the 3^- and 4^- states predicted.

The decay of ^{192}Pb to ^{192}Tl is found to have a half-life of 3.5 ± 0.1 min. Most of the decay proceeds to levels at 167.5 (1^-) and 1195.4 (1^+) keV (Fig. 3.8). From systematics,[12] the 2^- ground state of ^{192}Tl has been assigned a configuration of $\nu f_{5/2}\ \pi s_{1/2}$. However, the ground-state spin and parity of $^3/_2{}^-$ for ^{191,193}Hg suggest that the 2^- state results from $\nu p_{3/2}\ \pi s_{1/2}$, which could also explain the 1^- level at 167.5 keV. An assignment of $\nu p_{1/2}\ \pi s_{1/2}$ for this state is not reasonable, since no low-lying 0^- state is observed in ^{192}Tl, and the $p_{1/2}$ neutron state in ^{191}Hg is not low-lying. The 1^+ state at 1195.4 keV probably results from a $\nu h_{9/2}\ \pi h_{11/2}$ configuration, since these are the only orbitals available which could give rise to positive parity. The trend of the 1^+ states in the even-A thallium nuclei is to decrease with decreasing mass. Since the $h_{11/2}$ proton orbital remains relatively constant for the odd-A gold and thallium nuclei, one might associate this trend with a decreasing energy for the $h_{9/2}$ neutron orbital. This orbital is, however, unknown in the odd-neutron nuclei in this region.

---

1. Eastern Kentucky University.
2. University of Tennessee, Knoxville.
3. UNISOR, Oak Ridge Associated Universities.
4. A. S. Davydov and F. G. Filippov, *Nucl. Phys.* **8**, 237 (1958).

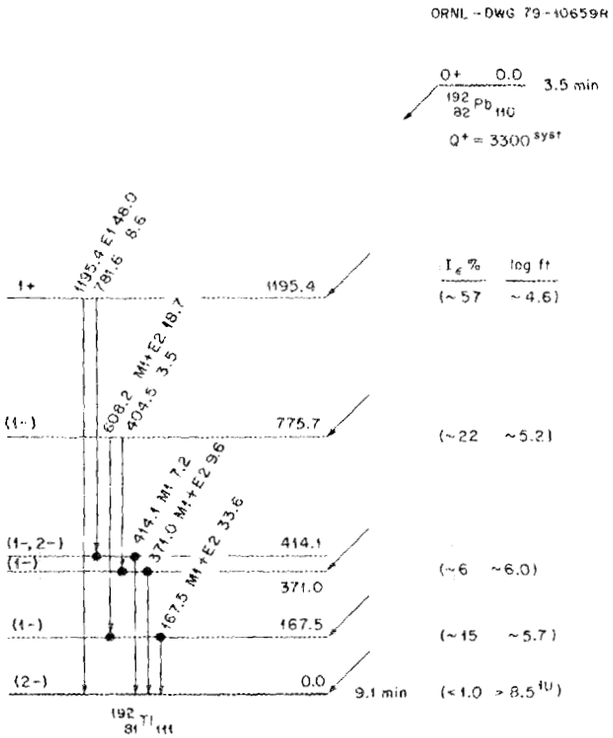


Fig. 3.8. Decay scheme for ^{192}Pb.

5. J. Meyer-ter-Vehn, *Nucl. Phys.* **A249,** 111 (1975).

6. L. L. Riedinger, A. C. Kahler, L. L. Collins, and G. D. O'Kelly, to be published.

7. E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, C. R. Bingham, B. D. Kern, J. L. Weil, J. H. Hamilton, A. V. Ramayya, E. H. Spejewski, R. L. Mlekodaj, H. K. Carter, and W.-D. Schmidt-Ott, *Phys. Lett.* **58B,** 159 (1975).

8. S. W. Yates, J. C. Cunnane, R. Hochel, and P. J. Daly, *Nucl. Phys.* **A222,** 301 (1974).

9. R. M. Lieder, H. Beuscher, W. F. Davidson, A. Neskakis, and C. Mayer-Boricke, *Nucl. Phys.* **A248,** 317 (1975).

10. F. S. Stephens, R. M. Diamond, J. R. Leigh, T. Kammuni, and K. Nakai, *Phys. Rev. Lett.* **29,** 438 (1972).

11. K. Neergard, P. Vogel, and M. Radomski, *Nucl. Phys.* **A238,** 199 (1975).

12. C. R. Bingham, L. L. Riedinger, F. E. Turner, B. D. Kern, J. L. Weil, K. J. Hofstetter, J. Lin, E. F. Zganjar, A. V. Ramayya, J. H. Hamilton, J. L. Wood, G. M. Gowdy, R. W. Fink, E. H. Spejewski, W.-D. Schmidt-Ott, R. L. Mlekodaj, H. K. Carter, and K. S. R. Sastry, *Phys. Rev. C* **14,** 1586 (1976).

STUDIES OF ^{193,195,197}Pb DECAY

L. L. Collins[1] R. W. Fink[5]
L. L. Riedinger[2] E. H. Spejewski[6]
G. D. O'Kelley[3] H. K. Carter[6]
A. C. Kahler[4] R. L. Mlekodaj[6]
C. R. Bingham[2] E. F. Zganjar[7]
J. L. Wood[5] J. H. Hamilton[8]

Extensive studies of the radioactive decay of ^{193,195,197}Pb, using the UNISOR facility, have been completed. The 113- and 125-MeV $^{16}O^{5+}$ beams from the ORIC were used in conjunction with natural tungsten and rhenium targets to produce these lead activities. The 44.6-min $i_{13/2}$ isomer and the 10-min $p_{3/2}$ ground states in ^{197}Pb were observed to populate 53 states in ^{197}Tl, 33 of high spins associated with $h_{9/2}$ or $h_{11/2}$ shell states and 20 of low spin. The 15.8-min ^{195}Pb decay populates 30 states in thallium, 24 of which are "high spin" in nature. The $^{13}/_{2}^{+}$ isomer in ^{193}Pb was measured to have a half-life of 5.6 min, the low-spin ground state 4.0 min; 20 levels in thallium were observed.

Since thallium has 81 protons, the level structure of the isotopes studied here are dominated by shell-model states as shown in Fig. 3.9. The $h_{9/2}$ and $i_{13/2}$ excitations originate above the $Z = 82$ shell gap and intrude into the low-energy region of the thallium schemes. From our studies of the systematic features of these isotopes, three dominant points result:

1. The structure of states built upon the $h_{9/2}$ isomer in thallium is smoothly varying in these three isotopes and can be well described in the triaxial rotor model of Meyer-ter-Vehn. The most γ-sensitive states (γ is the asymmetry parameter) are the second $^{13}/_{2}^{-}$ and first $^{5}/_{2}^{-}$ levels. Their positions and branching ratios yield $\gamma = 40$, 39, and 38° for $A = 193$, 195, and 197 respectively.

2. The level schemes of the thallium isotopes show a consistent separability related to the particle or hole nature of the individual states. In ^{197}Tl, seven high-spin states decay only to the $h_{11/2}$ level (and not to $^{11}/_{2}^{-}$ states built upon the $h_{9/2}$ isomer); in ^{195}Tl, eight states; and in ^{193}Tl, two. Some of these levels can be explained through the weak coupling

ORNL-DWG 75-13743AR2

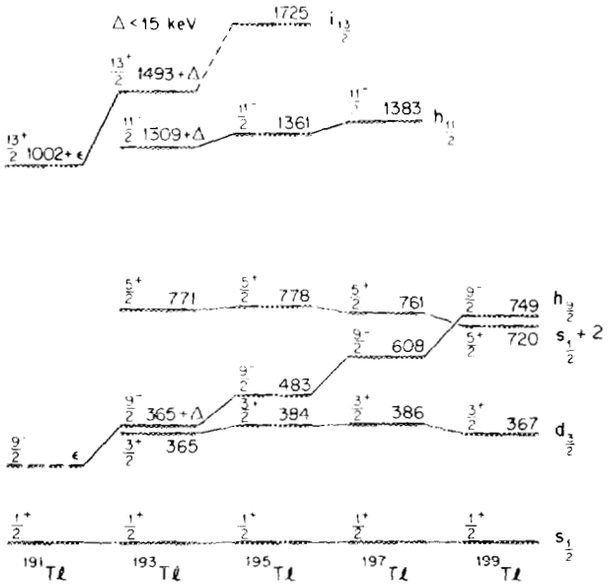


Fig. 3.9. Shell-model states observed in light thallium isotopes. Information on ^{193,195,197}Tl was obtained from our work on the lead decays.

ORNL-DWG 81-18740

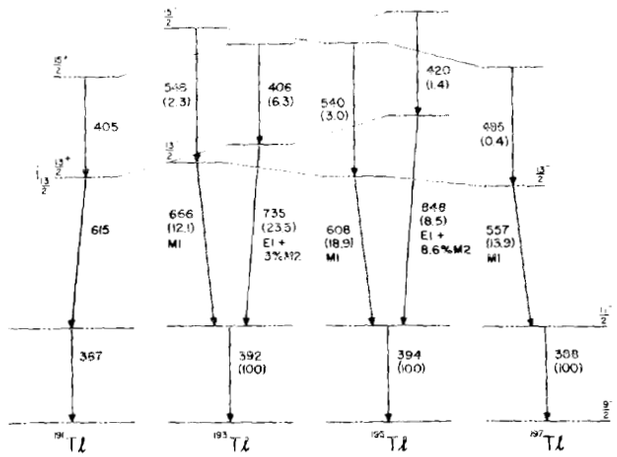


Fig. 3.10. Systematics of the $i_{13/2}$ excitation in the light thallium isotopes. The data on ^{191}Tl come from in-beam spectroscopy (ref. 10).

of the first 2^+ state in even-even lead to the $h_{11/2}$ hole state; decays of these levels to the $h_{9/2}$ particle structure are hindered. In addition, eight levels in ^{197}Tl and one in ^{195}Tl decay to both the $h_{11/2}$ state and to $h_{9/2}$-related states. These can possibly be explained by the coupling of 5^- and 7^- lead core states to the $s_{1/2}$ and $d_{3/2}$ shell states. Couplings to these low-j shell states evidently do not result in such strong particle-hole separability.

3. As illustrated in Fig. 3.9, the $i_{13/2}$ shell state is observed in the lightest thallium isotopes. It is an intruder orbital from above the shell gap (as is $h_{9/2}$), which is related to its decreasing excitation energy for the lighter isotopes. The $^{13}/_2{}^+$ level has been observed through (HI,xn) spectroscopy in ^{191,193}Tl (refs. 9, 10) and is populated in the decay of the high-spin ^{193}Pb isomer. The properties of this level are shown in Fig. 3.10. A candidate for the $i_{13/2}$ state in ^{195}Tl occurs at 1725 keV, as observed in our ^{195}Pb decay measurements. This assignment is not definite, however, since the 848-keV transition from this level to the yrast $^{11}/_2{}^-$ state has a conversion coefficient in agreement with the $E2$ value. To associate the 1725-keV state with the $i_{13/2}$ excitation, one must assume that this transition is actually $E1 + 8.6\%$ $M2$ in character. Only an angular correlation measurement would be able to determine whether this transition is 9 or 100% quadrupole. It is even more difficult to assign a $^{13}/_2{}^+$ state in ^{197}Tl, even though our ^{197}Pb decay data are very good in quality. Perhaps a large $M2$ component is hindering the identification of the state, or perhaps the state has moved very high in energy and thus receives little population. Future angular correlation work at the UNISOR, perhaps with a liquid-helium refrigerator, will be needed to definitely locate this intruding shell state in ^{195,197}Tl.

---

1. University of Tennessee; present address: Babcock and Wilcox, Lynchburg, Va.
2. University of Tennessee, Knoxville.
3. Chemistry Division.
4. University of Tennessee; present address: Westinghouse, Inc., Pittsburgh, Pa.
5. Georgia Institute of Technology.
6. UNISOR, Oak Ridge Associated Universities.
7. Louisiana State University, Baton Rouge.
8. Vanderbilt University.
9. A. C. Kahler et al., to be published.
10. J. O. Newton, F. S. Stephens, and R. M. Diamond, *Nucl. Phys.* **A236**, 225 (1974).

EXCITED STATES IN ^{186,188}Pt

J. D. Cole[1] J. L. Wood[2]
E. F. Zganjar[1] J. H. Hamilton[3]

The ^{186}Au → ^{186}Pt and ^{188}Au → ^{188}Pt decay schemes have been studied previously at the UNISOR by γ-γ-t coincidence spectroscopy.[4] Recently, these investigations have been extended to e-γ-t coincidence spectroscopy. This is of great interest due to the large number of transitions in these decays that take place by the $E0$ internal-conversion process,[5] many of which have never been placed in these decay schemes. The structure of the neutron-deficient even-Pt isotopes is currently of considerable interest (see below), and it is crucial that all transitions at low energy with $E0$ components be located. The e-γ-t data are being analyzed; a preliminary level scheme for ^{188}Pt is shown in Fig. 3.11.

1. Louisiana State University, Baton Rouge.
2. Georgia Institute of Technology.
3. Vanderbilt University.
4. J. D. Cole, thesis, University of Delft (1976).
5. M. Finger, R. Foucher, J. P. Husson, J. Jastrzebski, A. Johnson, G. Astner, B. R. Erdau, A. Kjelberg, P. Patzelt, A. Hoglund, S. G. Malmskog, and R. Henck, *Nucl. Phys.* **A188**, 369 (1972).

A UNIQUE GROUND-STATE STRUCTURE: THE NEUTRON-DEFICIENT EVEN-Pt ISOTOPES AND PARTICLE-CORE COUPLING IN ^{187}Au

M. A. Grimm[1] J. D. Cole[3]
J. L. Wood[2] E. F. Zganjar[3]

The structure of the neutron-deficient even-Pt isotopes has been discussed widely ever since the discovery[4] of very low-lying excited 0^+ states in these nuclei. Recently, Hagberg et al. showed[5] that there is an "odd-even" shape staggering effect analogous to the situation[6] in the neutron-deficient mercury isotopes. This is difficult to understand because, unlike the neutron-deficient even-Hg isotopes, there is apparently no strongly deformed structure at low energy in the neutron-deficient even-Pt isotopes. The answer to this puzzle can be found by considering the yrast band systematics for isotopes in this region.[7] These systematics show that above the 4^+_1 state the neutron-deficient platinum isotopes are strongly deformed, and the apparent absence of deformation at low energy is due to band mixing and distortion of the rotational spacing. Within this picture, the strongly deformed structure in the even-Pt isotopes is predominantly the ground state for $A \leqslant 186$ and an excited state for $A \geqslant 188$, for example, the 799-keV 0^+_2 state in ^{188}Pt (see Fig. 3.11).

Such strong deformation close to the $Z = 82$ shell closure is difficult to understand within the conventional picture of nuclear deformation developing only away from closed shells. A simple and interesting possibility is that of proton intruder orbitals coming across the $Z = 82$ shell to increase the proton valence space and causing these nuclei to deform through the proton-neutron residual force. Such a phenomenon seems to be quite widespread[8] (and is especially pronounced in the $Z = 50$ region). The unique aspect of this proposed[9] structure for the neutron-deficient even-Pt isotopes is that they are the only known case where the intruding orbitals dominate the *ground-state* configuration.

A conceptually simple test of this picture is the blocking effect that would result for an odd proton in an intruder orbital. This is being investigated for $\{^{186}\text{Pt} \otimes \pi h_{9/2}\}^{187}$Au through a study[10] of the ^{187mg}Hg → ^{187}Au decay schemes. The level scheme of ^{187}Au is shown schematically in Fig. 3.12. The $h_{9/2}$ band in ^{187}Au shows two sets of states, some of which are connected by $E0$ transitions.[11] The two sets of states suggest two bands arising from the coupling of the $h_{9/2}$ proton to the 0^+_1 (ground state) and 0^+_2 (471-keV state) configurations and their associated collective band members. The closer spacing of the two bands in ^{187}Au relative to ^{186}Pt supports a picture in which the $h_{9/2}$ proton blocks the 0^+_1 state in ^{186}Pt more than the 0^+_2. This is most readily explained by the proposed dominance of the intruder structure in the ^{186}Pt ground state.

The unique structure proposed here for the ground states of the even-Pt isotopes leads to a number of unusual predictions. The involvement of the intruder configuration in the ground states of just the even-Pt isotopes with $A \leqslant 186$, and not in the neighboring even-mass osmium and mercury isotopes or the even-Pt isotopes with $A \geqslant 188$, implies that an island of discontinuous behavior in ground-state properties exists for these isotopes. For example, ground-state masses should show a discontinuity: a preliminary report of decay energies in the $A = 182$ decay chain[12] is consistent with this. The reduced widths for ground-state-to-ground-state alpha decay between even-mass mercury and platinum isotopes and platinum and osmium isotopes also should be anomalous: although some discrepancies still exist between experimental reduced

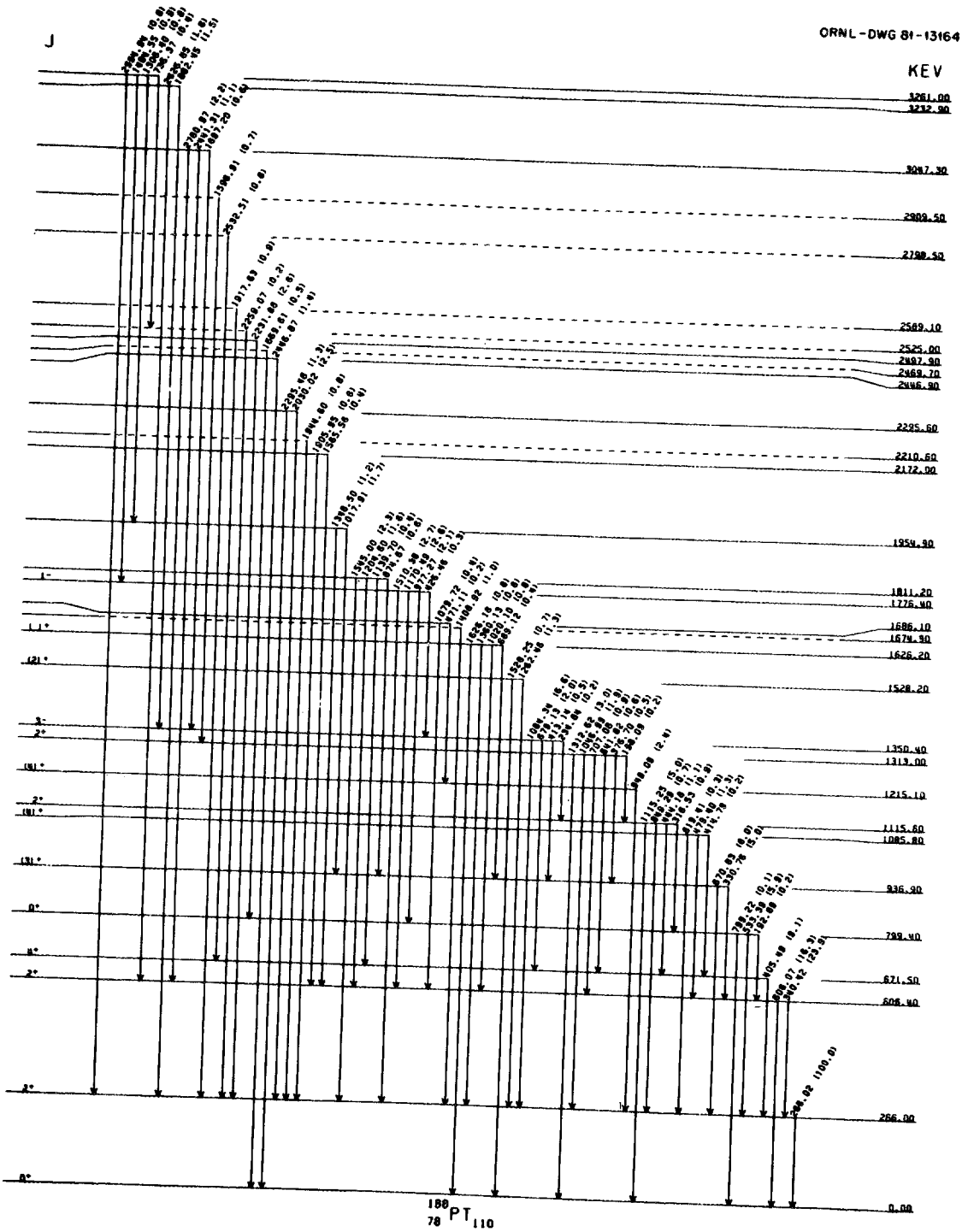


Fig. 3.11. Preliminary level scheme for ^{180}Pt.

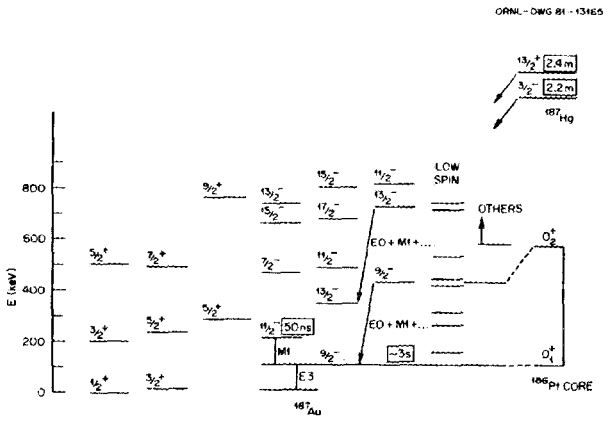


Fig. 3.12. Schematic overview of the bands located in ^{187}Au.

alpha widths in this region, it can be stated safely that anomalous behavior is seen.[13]

Ideally, the structure proposed here is most directly probed by two-proton transfer reactions. This is only possible for ^{186,188}Pt, using targets of low-natural-abundance ^{184,186}Os. The odd-particle blocking effect used in this work is emphasized to be a valuable new tool for probing 0^+ structures in nuclei far from stability, where (near) stable targets are not available for transfer reaction studies. A similar study is in progress in ^{185}Au, and the blocking effect of an odd neutron is under study in the neighboring odd-mass platinum and mercury isotopes (see below). There is also some tentative information on the $\{^{188}\text{Hg} \times \pi h_{9/2}\}^{189}$Tl blocking (see below).

1. Georgia Institute of Technology; present address: University of Louisville.
2. Georgia Institute of Technology.
3. Louisiana State University, Baton Rouge.
4. M. Finger et al., *Nucl. Phys.* **A188**, 369 (1972).
5. E. Hagberg et al., *Phys. Lett.* **78B**, 44 (1978).
6. T. Kuhl et al., *Phys. Rev. Lett.* **39**, 180 (1977).
7. J. L. Wood, in *Frontier Research in Nuclear Physics*, ed. D. H. Feng et al., Plenum, New York (in press).
8. K. Heyde, M. Waroquier, P. vanIsacker, J. L. Wood, and R. A. Meyer, to be published in *Phys. Rep.*
9. J. L. Wood, contribution to the Fourth International Conference on Nuclei Far from Stability, Helsingor, Denmark, June 7–13, 1981.
10. M. A. Grimm, thesis, Georgia Institute of Technology (1978).
11. E. F. Zganjar, J. D. Cole, J. L. Wood, and M. A. Grimm, contribution to the Helsingor Conference (1981).
12. L. Westgaard et al., p. 94 in *Atomic Masses and Fundamental Constants*, ed. J. H. Sanders and A. H. Wapstra, Plenum, New York, 1972.
13. K. S. Toth et al., this report.

STRONGLY DEFORMED STATES NEAR CLOSED SHELLS: EXCITED STATES IN ^{187,189}Hg

J. D. Cole[1] E. F. Zganjar[1]
J. L. Wood[2]

The strong deformation of the ^{185,183}Hg ground states has been known[3] for ten years. More recently, a weakly deformed isomer in ^{185}Hg, analogous to the weakly deformed isomers in ^{187}Hg and the heavier odd-Hg isotopes, has been shown to exist.[4] Strongly deformed states in ^{187}Hg and the heavier odd-Hg isotopes have not been reported until now. The occurrence of strongly deformed 0^+ states in ^{186}Hg and ^{188}Hg at 522 and 825 keV, respectively,[5] suggests that deformed states should occur at low energy, at least in ^{187}Hg.

The deformed states in ^{187,189}Hg are being sought through a study of the ^{187m,g}Tl → ^{187}Hg and ^{189m}Tl → ^{189}Hg decay schemes. We have tentatively identified an ~30-ns isomer in ^{187}Hg as a low-lying strongly deformed configuration.[6] It decays by a 161-keV transition, probably to the weakly deformed $^{13}/_2{}^+$ isomer. This latter state is due to the $_{13/2}$ configuration: its energy of excitation is unknown because it has an approximately 100% beta decay to ^{187}Au. The level schemes of ^{187,189}Hg are extremely complex, and more concrete conclusions must await detailed analysis of the data, which is in progress.

Besides the observation of deformation in these nuclei, a number of other structural features are being studied in ^{187,189}Hg. By establishing the relative energies of the weakly deformed and strongly deformed states, it will be possible to determine the blocking effect of the odd neutron in a manner similar to the odd-proton blocking effect in ^{187}Au (see above). This will provide information on the contribution of neutron pairing correlations to the 0^+_1 and 0^+_2 states in the neutron-deficient mercury isotopes. Further, there is still much to be learned about the systematic features of the odd-Hg isotopes. Some preliminary results were reported[7] at the Nashville Symposium. In this respect, an attractive feature of the decay of ^{187}Tl is that we are able to study two beta-decaying species with spins of $^1/_2$ and $^9/_2$: this provides a very complete picture of excited states in ^{187}Hg with spins up to $^{11}/_2$.

1. Louisiana State University, Baton Rouge.
2. Georgia Institute of Technology.
3. J. Bonn et al., *Phys. Lett.* **38B**, 308 (1972).
4. P. Dabkiewicz et al., *Phys. Lett.* **82B**, 199 (1979).

5. J. D. Cole et al., *Phys. Rev. C* **16**, 2010 (1977); R. Beraud et al., *Nucl. Phys. A* **284**, 221 (1977); C. Bourgeois et al., *J. Phys. (Paris)* **37**, 49 (1976).
6. J. L. Wood, E. F. Zganjar, and J. D. Cole, *Bull. Am. Phys. Soc.* **25**, 739 (1980).
7. J. L. Wood, p. 37 in *Future Directions in studies of Nuclei Far from Stability*, J. H. Hamilton et al., North-Holland, Amsterdam, 1980.

A SHAPE TRANSITION IN THE NEUTRON-DEFICIENT ODD-Pt ISOTOPES

B. E. Gnade[1] R. A. Braga[1]
J. L. Wood[1]

There is now a fairly well established transition from a weakly deformed ground state to a strongly deformed ground state in going from ^{187}Pt to ^{185}Pt. This picture is based on rotational band structures that have been established for ^{185}Pt (ref. 2) and $^{177-181}$Pt (ref. 3) and for the fast β decay of ^{183m}Pt.[4] Although there is no evidence for deformed states in ^{187}Pt from in-beam spectroscopy[2] or from ^{187}Au → ^{187}Pt decay-scheme spectroscopy[5] studies done so far, a situation analogous to the odd-Hg isotopes (see above) should exist.

A scrutiny of the published data[5] on the ^{187}Au → ^{187}Pt decay scheme revealed that it was no better than a very incomplete study previously done at the UNISOR as a by-product of our investigation[6] of the ^{187}Hg → ^{187}Au decay. With the development of a UNISOR ion source that has high efficiency and fast release times for gold activities, we have begun a restudy of this decay scheme. We have taken γ-γ-γ and e-γ-t coincidence data with ten times the statistical quality of our previous study; these data are being analyzed.

In addition, because the systematics of the odd-Pt isotopes are very poorly understood, the ^{189mg}Au → ^{189}Pt decay schemes are being studied (concurrently with the ^{187}Au decay). We previously studied[7] these decays without mass separation, using a helium gas jet. These earlier data contained serious contamination from ^{190}Au. We have taken γ-γ-t coincidence data, and they are being analyzed.

Besides establishing a more detailed picture of the systematic features of the odd-Pt isotopes, these studies will provide information on the blocking effect of the odd neutron coupled to the even-Pt cores, as discussed above for ^{187}Au and ^{187}Hg.

As a by-product of the present study of ^{187}Au decay, we have been able to measure the half-life of the $E3$ isomeric decay in ^{187}Au. A preliminary value is 2.8 ± 0.2 s. This directly illustrates the fast release time for gold activities by this new ion source.

1. Georgia Institute of Technology.
2. M. A. Deleplanque et al., *C. R. Acad. Sci., Ser. B* **280**, 515 (1975).
3. E. Hagberg et al., *Phys. Lett.* **78B**, 44 (1978).
4. A. Visvanathan, E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, and F. E. Turner, *Phys. Rev. C* **19**, 282 (1979).
5. A. Ben Braham et al., *Nucl. Phys.* **A332**, 397 (1979).
6. M. A. Grimm, thesis, Georgia Institute of Technology (1978).
7. B. E. Gnade, J. L. Wood, and R. W. Fink, *Bull. Am. Phys. Soc.* **25**, 740 (1980).

EXCITED STATES IN ^{189}Tl

E. F. Zganjar[1,2] J. L. Wood[3]
J. D. Cole[1] L. L. Riedinger[4]
G. M. Gowdy[2]

The excited states of ^{189}Tl are being investigated through a study of the ^{189m}Pb → ^{189}Tl decay scheme. The primary objective of this work is to determine the blocking effect of the $h_{9/2}$ proton on the 0^+_1 (ground state) and 0^+_2 (825-keV state) configuration in the ^{188}Hg core. This closely parallels the investigation for ^{187}Au (see above).

These investigations are being conducted in collaboration with the on-line isotope separator group at GSI, Darmstadt. The γ-γ-t data were taken at GSI, and the e-γ-t data were takin at the UNISOR; the data are being analyzed. Our preliminary level scheme for ^{188}Tl (Fig. 3.13) suggests that the $h_{9/2}$ proton blocks the ^{188}Hg 0^+_2 configuration more strongly than the 0^+_1 configuration, indicating that the ^{188}Hg 0^+_2 state is the analog of the ^{188}Pt 0^+_1 state[5] (see above).

1. Louisiana State University, Baton Rouge.
2. GSI, Darmstadt.
3. Georgia Institute of Technology.
4. University of Tennessee, Knoxville.
5. J. L. Wood, in *Frontier Research in Nuclear Physics*, ed. D. H. Feng et al., Plenum, New York (in press).

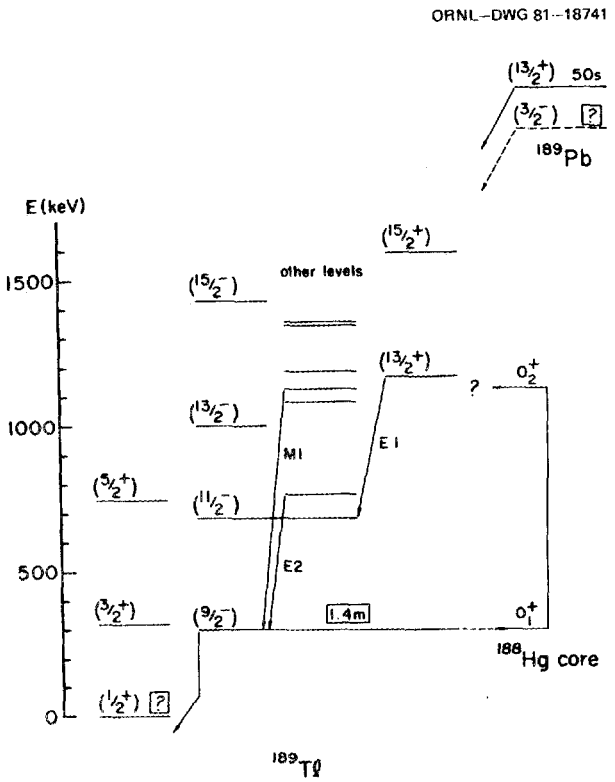


Fig. 3.13. Partial (schematic) level scheme for ^{189}Tl. Besides the $s_{1/2}$ (ground state) band, $h_{9/2}$ isomeric state) band, and $i_{13/2}$ band, a number of other levels are seen below 1.4 MeV. None of them appear to be due to the ^{188}Hg $(0^+_2)\times\pi h_{9/2}$ coupling, suggesting that this configuration is blocked and pushed to a higher energy.

DECAY OF ^{199m,g}Po: ISOMERIC TRANSITIONS IN ^{199}Po and ^{199}Bi

C. R. Bingham[1] R. W. Lide[1]
R. E. Stone[1] H. K. Carter[2]
L. L. Riedinger[1] R. L. Mlekodaj[2]
E. H. Spejewski[2]

The study of the decays of ^{199m,g}Po and ^{201m,g}Po were initiated in order to investigate the possibility of the intrusion of hole states from below the $Z = 82$ shell closure into the region above. Results on the placement of $s_{1/2}$ hole states in ^{199,201}Bi and a severely retarded $M4$ transition in ^{201}Bi have been previously reported.[3] Additional results from the ^{199}Po decays are presented here.

The x-γ and γ-γ coincidence measurements establish the existence of two states below the $^{13}/_2{}^+$ isomer in ^{199}Po. The $M4$ isomeric transition of energy 238 keV was observed with a half-life of 4.17 min. It is in coincidence with an ~72-keV transition populating the ground state. Spin and parity assignments of $^5/_2{}^-$ to the ~72-keV state and $^3/_2{}^-$ to the ground state are consistent with the multipolarities and with the systematic behavior[4] of the levels in the heavier odd-mass polonium isotopes. The placement of the $i_{13/2}$ isomer at ~310 keV in ^{199}Po, combined with previous determinations[5] of the alpha decays of both the ground and isomeric states, allows the placement of the $^{13}/_2{}^+$ isomeric state in ^{195}Pb at ~200 keV (Fig. 3.14).

The previously determined alpha branching ratio and the estimate of isomeric transition/$EC+\beta^+$ from this work are combined to obtain the $M4$ transition rate in ^{199}Po. The decay probability is 8.5×10^{-7} s^{-1}, corresponding to ~2.6 Weisskopf units. This is a retardation factor of 0.38 and is similar to those for $M4$ transitions in other odd-mass nuclei within this region.[3]

A series of transitions observed within ^{199}Bi is similar to those feeding the $^1/_2{}^+$ isomers in the heavier odd-mass bismuth isotopes (Fig. 3.15) and has been so interpreted in this case. The position of this $^1/_2{}^+$ state with respect to the $^9/_2{}^-$ ground state can be estimated from the alpha-decay Q values and mass systematics, yielding a value of ~776 keV. A second estimate can be obtained from the systematic trend of the energy spacing in the heavier odd-mass bismuth

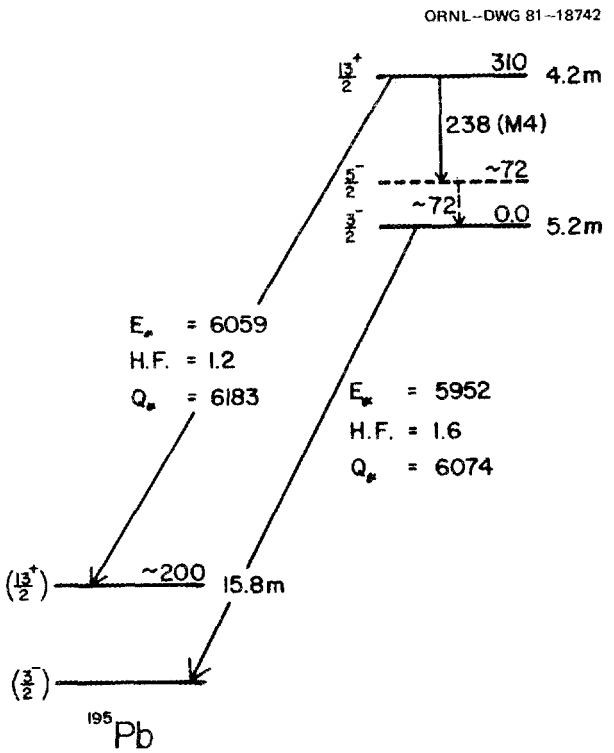


Fig. 3.14. Placement of the 13/2$^+$ state in ^{195}Pb.

ORNL-DWG 81-18743

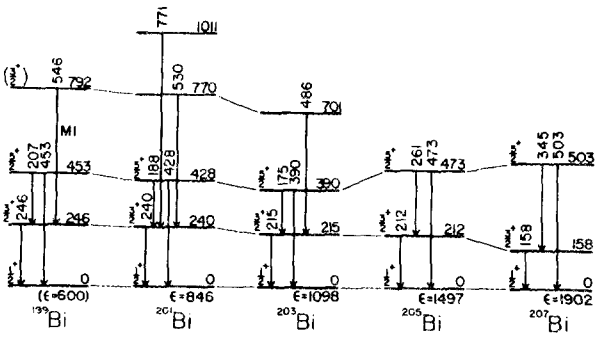


Fig. 3.15. Positions of the 5/2⁺ and 3/2⁺ states with respect to the 1/2⁺ states in odd-A bismuth isotopes. The energies of the 1/2⁺ states relative to the ground states are given below the 1/2⁺ levels.

isotopes, approximately 600 keV. The isomeric transition was not clearly identified in the present experiments because the time scale was inappropriate to the 24.7-min half-life. Nevertheless, the most intense electron line observed and not correlated with an observed gamma transition would correspond to a bismuth transition energy of 667 keV. This is within the estimates above and would correspond, for an $M4$ transition, to a gamma intensity below the detection limits of the measurement. This can then be used to obtain an upper limit on the probability for the $M4$ transition of about $^1/_{390}$ of the Weisskopf estimate, which corresponds to a lower limit on the retardation factor of 390, approximately 1000 times larger than is typical for $M4$ transitions for odd-A nuclei in this region.

The large retardation factor is undoubtedly related to the fact that the $^1/_2{}^+$ state is predominantly an $s_{1/2}$ hole state in a polonium core, whereas the $^9/_2{}^-$ state is predominantly an $h_{9/2}$ proton coupled to a lead core. This explanation is preferable to alternate ones, since in the analogous case of ^{201}Bi, the transition has been shown[3] to be of almost pure $M4$ character with a retardation factor of approximately 2000.

1. University of Tennessee, Knoxville.
2. UNISOR, Oak Ridge Associated Universities.
3. R. A. Braga, W. R. Western, J. L. Wood, R. W. Fink, R. E. Stone, C. R. Bingham, and L. L. Riedinger, *Nucl. Phys.* **A349**, 61 (1980).
4. B. Jonson, M. Alpstein, A. Appelqvist, and G. Astner, *Nucl. Phys.* **A177**, 81 (1971).
5. J. Halperin, *Nucl. Data Sheets* **24**, 57 (1978).

LEVEL SCHEMES OF ^{202,204}Po

R. G. Helmer[1] C. R. Bingham[2]
C. W. Reich[1] L. L. Riedinger[2]
A. J. Caffrey[1] R. W. Lide[2]
M. P. M. Ramos[2] B. G. Ritchie[3]

The level schemes of ^{202,204}Po, as excited in the decays of ^{202,204}At, have been investigated. The sources of ^{204}At ($t_{1/2}$ = 9.2 min) and ^{202}At ($t_{1/2}$ = 3.1 min) were produced by bombarding a natural iridium target with an ^{16}O beam from the ORIC. The recoils from the target were collected in the UNISOR ion source and mass separation followed, making possible the simultaneous accumulation of data from mass 202, 203, and 204 sources. The decays of ^{202,204}At were studied by means of multiscaled gamma-ray and conversion-electron singles spectra and γ-γ-t coincidence measurements, using Ge(Li) and Si(Li) detector systems.

About 50 gamma-ray transitions (compared with approximately 12 previously known) have been assigned to ^{204}At decay, and approximately 35 have been placed in a level scheme for ^{204}Po. The observed lower-lying levels ($I\pi$) are 0(0⁺), 684(2⁺), 1201(4⁺), 1552(4⁺), 1627(6⁺), and ~1639(8³) keV. The energy for the isomeric 8⁺ level ($t_{1/2} \cong 140$ ns) was estimated from several coincidence relationships, but the implied 12-keV transition from it to the 1627-keV, 6⁺ level has not been directly observed. Tentative spin assignments to higher-lying states have been made. The population of the high-spin (>6) states suggests that the ^{204}At ground state has $I_\pi = 7^+$, in contrast to the 5⁺ assignment for ^{206}At. This assignment for ^{204}At allows the weak alpha-decay branch to populate directly the 7⁺ ground state of ^{200}Bi.

Because the ^{202}At was a secondary experiment, the initial data yielded somewhat poorer statistics and no time correlations in the coincidence data. Nevertheless, 20 gamma-ray transitions were observed, 11 of which were not previously reported. The main features of the decay scheme are similar to those observed in the ^{204}At decay, with the lower-lying levels (I_π) at 0(0⁺), 677(2⁺), 1248(4⁺), 1302, 1668(3⁺), and 1697(6⁺) keV. Recently, improved coincidence data, including a time-correlation parameter, and additional multiscaled gamma-ray data were acquired. The analysis of these new data is in progress.

1. Idaho National Engineering Laboratory.
2. University of Tennessee, Knoxville.
3. University of South Carolina, Columbia.

BARIUM ISOTOPE PRODUCTION CROSS SECTIONS IN ^{12}C-INDUCED REACTIONS

E. F. Zganjar[1] H. K. Carter[3]
J. D. Cole[1] R. L. Mlekodaj[3]
R. G. Helmer[2] E. H. Spejewski[3]

In UNISOR experiments, accelerator beam energies are typically chosen on the basis of computer codes which generate the energy dependence of the reaction cross sections. As part of a study of the decay of the barium isotopes, measurements of the energy dependence of the reaction ^{A}Sn(^{12}C,xn)$^{A+12-x}$Ba have been performed. Isotopically separated targets of ^{116,118,120}Sn were used with ^{12}C beam energies of 87 to 137 MeV. As an example, the results for production of ^{124,125}Ba from an ^{118}Sn target are shown in Fig. 3.16. Here, they are compared with the predictions generated by the code ALICE,[4] with the data arbitrarily normalized to the curves. Although the code reproduces the peak positions of the cross sections within a few MeV, it predicts a much longer high-energy tail than is observed. The same general behavior occurs in the case of each reaction studied. A preliminary check with a second computer code, JULIAN,[5] indicates a much better agreement with the data.

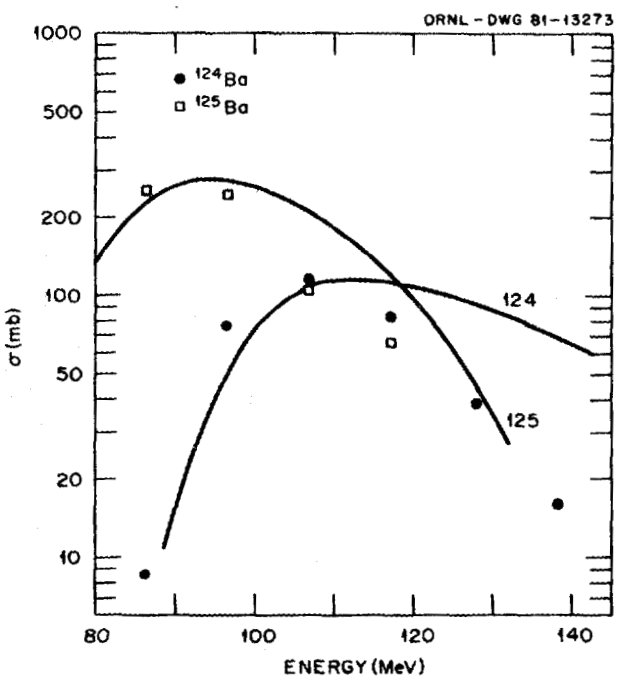


Fig. 3.16. Energy dependence of the ^{118}Sn(^{12}C,xn)^{124,125}Ba reaction. The curves are predictions of the code ALICE, and the data are arbitrarily normalized to them.

1. Louisiana State University, Baton Rouge.
2. Idaho National Engineering Laboratory.
3. UNISOR, Oak Ridge Associated Universities.
4. M. Blann and F. Plasil, private communication.
5. M. Hillman, private communication.

4. Neutron Physics

INTRODUCTION

Neutron total, capture, scattering, and fission cross-section measurements and (n,γ) spectral measurements have continued on many isotopes and elements of interest to basic nuclear physics, to nucleosynthesis, and to the fusion and fission energy programs. Advances have been made on neutron detectors for various experiments and on the buncher for the electron linac.

In basic nuclear physics, high-resolution total, scattering, and capture measurements have been made on several nuclides to obtain detailed information for different partial waves on resonances and on nonresonant contributions to the total cross section. Intermediate structure observed in neutron and gamma-ray strength is evidence for nuclear structure effects at high excitation. An l dependence of the well depths of the spherical optical model for several nuclides is needed to describe the experimental data. The tail of the $E1$ giant resonance has been studied from neutron-capture gamma-ray spectral measurements for several nuclides to test the Axel-Brink hypothesis. The analysis of resonances in ^{86}Kr + n from total and capture measurements adds to the understanding of the decay of the delayed-neutron emitter ^{87}Br. Neutron-induced fission measurements on ^{231}Pa + n give supporting evidence for an asymmetrically deformed third minimum in the ^{232}Pa fission barrier.

Differential fission and capture cross-section measurements and integral analyses of many actinide samples in fast reactors have contributed to the understanding of problems involved in the production and burnup of actinides. The capture cross sections of many high-yield fission products near mass 100 to 110 which are important poisons in a fission reactor have been measured and analyzed. A new technique using Fe window neutrons was developed to measure the inelastic scattering of ^{238}U, which is important for fast reactors. Finally, the total cross sections up to 80 MeV of many elements of interest to the fusion energy program were measured.

MODEL-INDEPENDENT OPTICAL PHASE SHIFTS FROM HIGH-RESOLUTION NEUTRON CROSS SECTIONS

C. H. Johnson R. R. Winters[1]
W. M. MacDonald[2]

Except for light nuclei, the individual properties of the many levels found near the neutron binding energy from total and scattering measurements, such as those at ORELA, are of interest only on the average because individual levels are too complicated to describe by present models. Nevertheless, high-resolution data are essential for isolating the partial waves so that the dependences of the average on spin, parity, and energy can be determined.

Figure 4.1 is a block diagram of a procedure we have developed for extracting the maximum averaged information from high-resolution data. Whether averaging or not, the first step (as indicated by the second block) is a straightforward

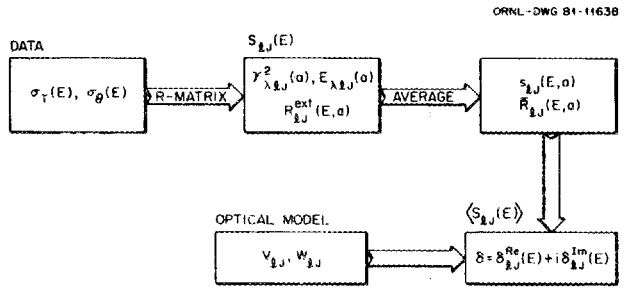


Fig. 4.1. Outline of the method to proceed from high-resolution neutron data to average model-independent optical phases which can be interpreted by an optical-model potential or other possible models.

multilevel R-matrix analysis. For a spin-zero target with negligible inelastic processes the scattering matrix element for each partial wave can be written

$$S_{lJ}(E) = e^{2i\phi_{lJ}} \frac{1 - L^*_{lJ} R_{lJ}(E, a)}{1 - L_{lJ} R_{lJ}(E, a)} , \qquad (1)$$

where ϕ_{lJ} and L_{lJ} are familiar functions at the arbitrary boundary radius a and

$$R_{lJ}(E, a) = R^e_{lJ}(E, a) + \sum_\lambda \frac{\gamma^2_{\lambda lJ}(a)}{E_{\lambda lJ}(a) - E} . \qquad (2)$$

The summation is over the observed resonances, the R^e is the remainder for all resonances external to that region of measurement. The external resonances give rise to a nonresonance contribution with the region. Each term on the right in Eq. (1) depends on the arbitrary boundary conditions, but the overall expression for $S_{lJ}(E)$ does not.

We are concerned with obtaining and interpreting the averages. Past workers have generally deduced limited averages such as the strength function, $\langle\gamma^2/D\rangle$. Recently, two of us[3] included the often-ignored R^e in the averaging and found that a strong l dependence is needed in the spherical optical model for 0 to 1.1-MeV neutrons on ^{32}S. But, for reasons of tradition, the emphasis there was on the individual boundary-dependent terms in Eq. (1). Thus the results were partially boundary-dependent. Subsequently, one of us (WMM) suggested that the entire expression be Lorentzian-averaged by contour integration. Thus, as indicated in the third block of Fig. 4.1, we find the complex R function $R(E, a) + i_m s(E, a)$. The resulting strength function, $s(E, a)$, is more accurate than obtained from the traditional "step" plot.

Using the boundary-dependent complex R function we immediately find the boundary-independent average complex phase shifts, which give a complete model-independent description of the averages. As indicated in the last two blocks of Fig. 4.1, these phases can be compared to those from an optical-model potential.

We have used this method to deduce the average complex phase shifts for ^{32}S from the R-matrix parameters of Johnson and Winters.[3] The results are shown by solid curves in Figs. 4.2 and 4.3. The averaging width for the Lorentzian was 300 keV, or roughly the level spacing; this is large enough to smooth out fluctuations. The resulting experimental curves, unlike those reported previously,[3] can be used directly in the future without again referencing the boundary radius. The description in terms of an optical model is more definitive than before.[3] The dashed curves show visual fits obtained by fixing the potential geometries[3] and varying the well depths. The resulting imaginary well depths are 5.0, 3.0, and 5.3 MeV for $s_{1/2}$, $p_{1/2}$, and $p_{3/2}$ respectively. The real well depth for s waves is 50.8 MeV, and for p waves it is 61.5 MeV with an 11.3-MeV spin-orbit term. Essentially the previous conclusions are

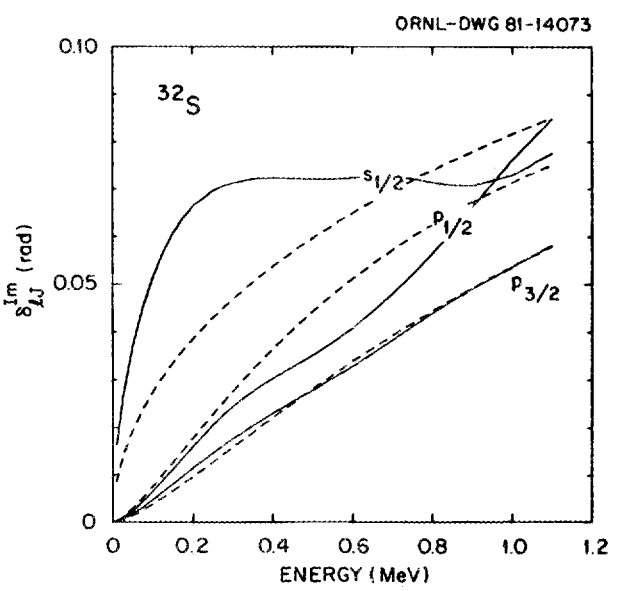


Fig. 4.2. Real parts of the experimental (solid) and model (dashed) optical phases for ^{32}S for s and p waves. The averaging interval for the experimental data was 300 keV.

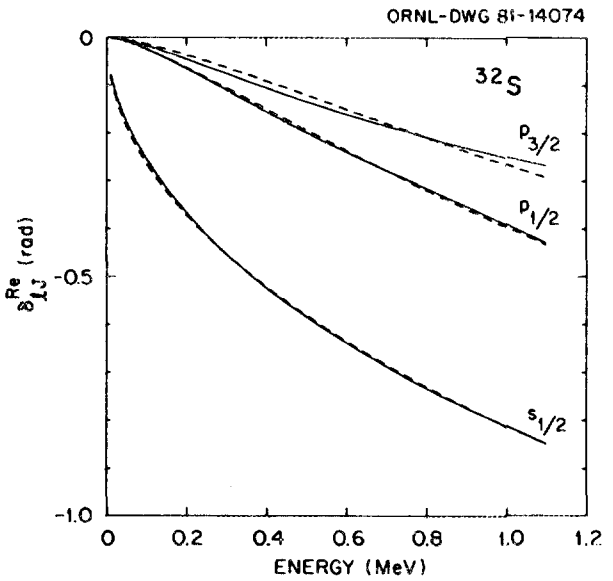


Fig. 4.3. Continuation of Fig. 4.2, showing the imaginary parts of the phase shifts.

reached; mainly the real well has a strong l dependence.

1. Denison University, Granville, Ohio.
2. Department of Physics and Astronomy, University of Maryland, College Park.
3. C. H. Johnson and R. R. Winters, *Phys. Rev. C* **21**, 2190 (1980).

HIGH-RESOLUTION STUDY OF THE ^{204}Pb + n REACTION

D. J. Horen J. A. Harvey
N. W. Hill[1]

We are presently studying the ^{204}Pb + n reaction to test further the hypothesis that intermediate structure in the neutron strength functions can be described in terms of particle-core excitations. Our results[2] for ^{206,207}Pb + n were consistent with such a description. Since the single-particle states are highly fragmented in the bound-state region of ^{205}Pb, it is expected that the corresponding "doorway states" in the ^{204}Pb + n reaction will be broader and thus more difficult to observe.

Since ^{205,207}Pb have almost identical neutron separation energies, comparison of the neutron strength functions for ^{204,206}Pb + n should reveal information pertaining to the dependence of optical-model parameters on neutron excess. Preliminary analysis of the data for $E < 110$ keV already shows that the s-wave strength function (as well as the s-wave level density) in this region for ^{204}Pb + n is about an order of magnitude larger than that for ^{206}Pb + n.

1. Instrumentation and Controls Division.
2. D. J. Horen, J. A. Harvey, and N. W. Hill, *Phys. Rev. C* **18**, 722 (1978); ibid., **20**, 478 (1979); ibid., to be published.

^{206}Pb + n RESONANCES FOR E = 600 TO 900 keV

D. J. Horen J. A. Harvey
N. W. Hill[1]

The analysis of data[2] from high-resolution neutron transmission and differential scattering measurements performed on ^{206}Pb have been extended to the energy region E = 600 to 900 keV. Resonance parameters (i.e., E, l, J, and Γ_n) have been deduced for many of the 161 resonances observed. Strength functions and potential phase shifts for s-, p-, and d-wave neutrons for E_n = 0 to 900 keV are compared with optical-model calculations. It is found that the phase contributed by the external R function (see Fig. 4.4) as well as the integrated neutron strength functions (see Table 4.1) can be reproduced for the s and d waves with a well depth of V_0 = 50.4 MeV for the real potential and W_D = 6.0 MeV for an imaginary surface potential (see Table 4.2 for optical-model parameters used). Somewhat smaller values (V_0 = 48.7 MeV and W_D = 2.0 MeV) are required to reproduce the p-wave data. These values of the real potential are also found to give the experimentally observed binding energies for the $4s_{1/2}$, $3d_{3/2}$, and $3d_{5/2}$ single-particle levels (V_0 = 50.4 MeV) and the $3p_{1/2}$ single-particle level (V_0 = 48.7 MeV). Nuclear level densities for s and d waves are found to be well represented by a constant-temperature model. However, the model underestimates the number of p-wave resonances.

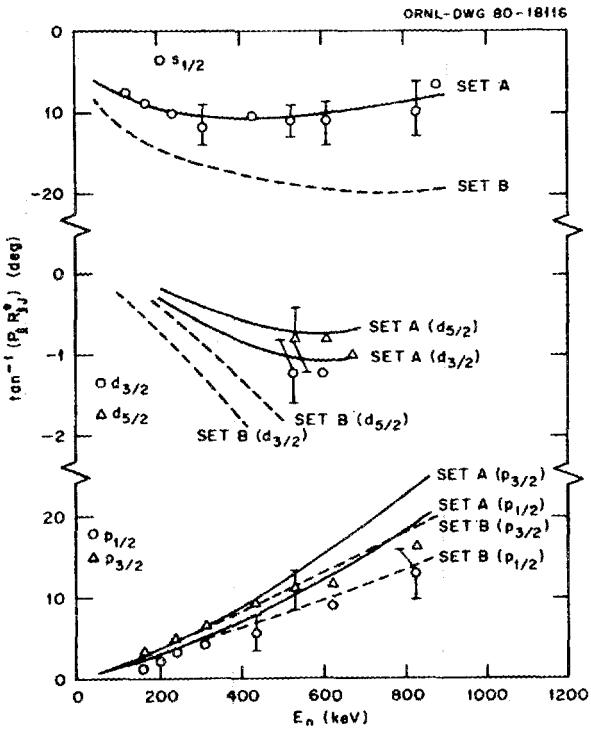


Fig. 4.4. Plots of the contributions to the phase shifts by the external R function (R^ℓ_{LJ}) for s, p, and d waves vs neutron energy. The points represent the phase shifts deduced from analysis of the data, and the solid and dashed curves are values calculated using an optical-model potential.

Table 4.1 Comparison of experimental average strength ($\times 10^4$) at 900 keV with OMP calculations

Partial wave	Experimental	Set A	Set B
$s_{1/2}$	1.06	1.17	0.69
$d_{3/2}$	1.81	1.95	2.3
$d_{5/2}$	1.24	1.12	0.72
p	0.32	1.62	0.37

Table 4.2. Optical-model parameters

Radial parameters (fm)	Potential depths (MeV) Set A	Set B
$r_0 = 1.21$	$V_0 = 50.4$	$V_0 = 48.7$
$a_0 = 0.66$	$W_D = 6.0$	$W_D = 2.0$
$r_W = 1.21$	$V_{SO} = 7.5$	$V_{SO} = 7.5$
$a_W = 0.48$		
$r_{SO} = 1.21$		
$a_{SO} = 0.66$		

This work has been accepted for publication in *Physical Review C.*

1. Instrumentation and Controls Division.
2. D. J. Horen, J. A. Harvey, and N. W. Hill, *Phys. Rev. C* **20**, 478 (1979).

NEUTRON TOTAL CROSS SECTIONS FOR NEUTRON FILTER APPLICATIONS

J. A. Harvey N. W. Hill[1]
J. R. Harvey[2]

Transmission measurements have been made on thick metallic samples of ^{184}W (94.52%) and ^{64}Zn (97.87%) to assess their usefulness as filters to produce neutron beams of 160 eV and 2.1 keV energy, respectively, from a nuclear reactor. Figure 4.5 shows the transmission of ^{184}W ($1/\tilde{N}$ = 2.472 b per atom) measured with an energy resolution of 0.1%. The presence of windows at higher energies limits the usefulness of this material as a neutron filter. The 2-keV window in ^{64}Zn does not offer any advantages over a scandium filter, which is usually used for 2-keV window neutrons.

1. Instrumentation and Controls Division.
2. CEGB Berkeley Nuclear Laboratories, England.

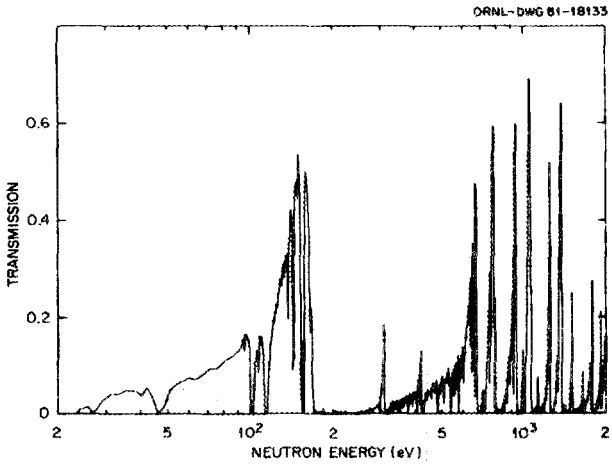


Fig. 4.5. Transmission of ^{184}W ($1/N$ = 2.472 b per atom) vs neutron energy.

MEASUREMENT OF NEUTRON TOTAL CROSS SECTIONS AT ORELA TO 80 MeV

D. C. Larson[1] J. A. Harvey
N. W. Hill[2]

Using the beryllium block target and the 80-m flight path the neutron total cross sections of 14 materials (CH_2, C, O, Al, Si, Ca, Cr, Fe, Ni, Cu, Mo, Sn, Au, and Pb) have been measured to 80 MeV. The intensity of the high-energy neutrons is very sensitive to the electron beam energy (about 140 MeV). The maximum usable neutron energy for these measurements is about 0.6 of the electron energy. The neutron detector was a 7.6-cm-thick, 10.2-cm-diam NE110 scintillator mounted on a selected RCA 8854 phototube. With a 7.5-cm-diam neutron collimator it was necessary to use a 20-cm-thick polyethylene filter in the neutron beam to reduce the intensity of neutrons with energies from 2 to 8 MeV to limit the maximum dead-time correction. Figure 4.6 shows the data (except for H). These data are required for shielding design of the Fusion Material Irradiation Test (FMIT) facility, since neutrons up to about 50 MeV will be produced with this facility. A brief report[3] has described our first measurements and results for a few materials up to 60 MeV.

1. Engineering Physics Division.
2. Instrumentation and Controls Division.
3. D. C. Larson, J. A. Harvey, and N. W. Hill, p. 34 in U.S. National Bureau of Standards Special Publication No. 594, *Proceedings of an International Conference on Neutron Cross Sections for Technology, Knoxville, Tennessee* (1979).

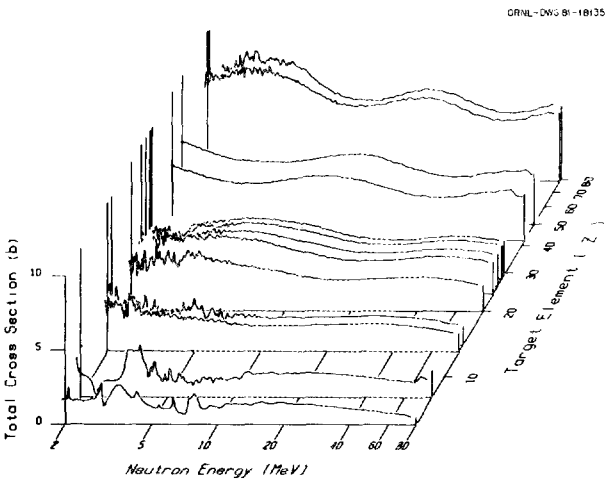


Fig. 4.6. Total cross sections as a function of neutron energy up to 80 MeV for 13 elements.

NEUTRON RESONANCE STUDY OF ^{86}Kr

B. Fogelberg[1] R. L. Macklin
J. A. Harvey S. Raman
P. H. Stelson

The interaction of neutrons with ^{86}Kr is of considerable interest for several reasons. Perhaps the most important one is the fact that ^{87}Kr is a delayed-neutron emitter and that studies of neutron resonances in ^{86}Kr thus offer an independent method for observation of the high-lying neutron-emitting levels in ^{87}Kr. A neutron resonance study, in addition, permits an accurate estimate of the level density in the unbound region, which is of importance for the interpretation of the structure in the delayed-neutron spectrum. The level density and the neutron resonance properties of ^{86}Kr + n are also needed for an accurate understanding of nucleosynthesis in the s process.

The measurements were performed at the ORELA facility, using flight paths of 40 and 80.5 m for the capture and transmission experiments respectively. The targets consisted of 99.5%-enriched ^{86}Kr gas kept at a pressure of 2 – 2.7 MPa in thin-walled containers of stainless steel. The capture data could, for intensity reasons, be analyzed only up to about 90 keV neutron energy. The transmission data were analyzed up to 400 keV. A total of 41 resonances were found in this energy interval. The experimental detection limit, together with the Porter-Thomas distribution, can be used to estimate that about 6 s- and p-wave resonances were not detected. We accept this number and find, by distributing the undetected resonances on spins and parities with the same frequencies as for firmly assigned resonances, that the level density can be well described using the back-shifted Fermi gas formula. With a pairing energy of 1.15 MeV, the value a = 9.7 MeV^{-1} for the level density parameter fits both parities well.

The effective capture cross section curve shown in Fig. 4.7 has been calculated using a Maxwellian energy distribution for the neutrons. For neutron energies up to 90 keV, the measured gamma widths of the resonances have been used. An average value of the gamma width of 0.25 eV was used for all resonances at higher energy. The uncertainty in the curve is estimated to be less than 30%.

1. Visitor from the Studsvik Science Research Laboratory, S-611 82 Nyköping, Sweden.

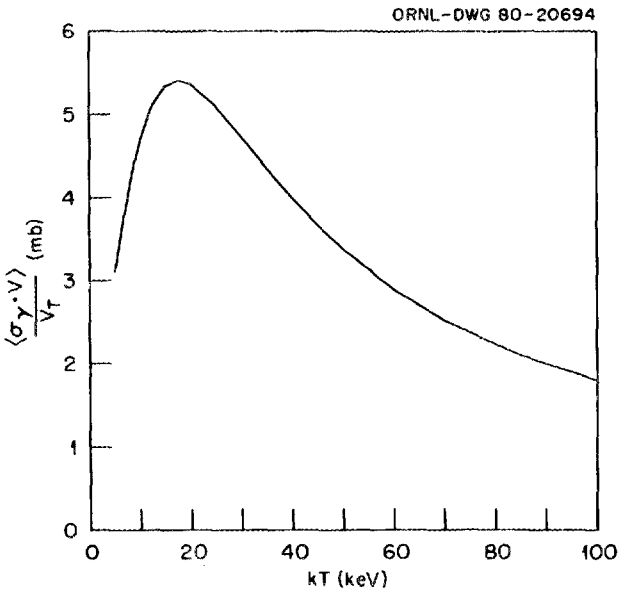


Fig. 4.7. Effective total capture cross section of ^{86}Kr for neutrons with a Maxwellian energy distribution.

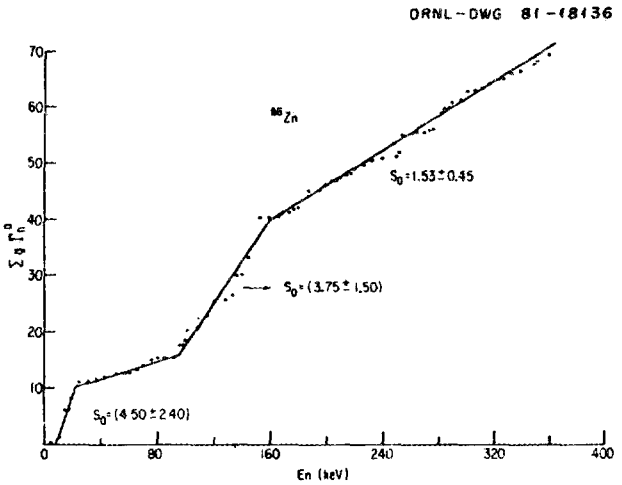


Fig. 4.8. Cumulative plot of the sum of reduced neutron widths for ^{66}Zn + n as a function of neutron energy.

STATISTICAL PROPERTIES OF COMPLEX STATES OF THE ISOTOPES OF ZN

J. B. Garg[1] J. A. Harvey
V. K. Tikku[1] R. L. Macklin
J. Halperin[2]

High-resolution neutron total and capture measurements have been made on the isotopes of zinc up to about 500 keV. The cross-section data are analyzed using multilevel R-matrix codes wherein the resonance parameters are fitted by least squares. From the resonance parameters E_0, $g\Gamma_n$, Γ_γ and l we obtain values for average quantities such as the average radiation widths, average level spacings, and neutron strength functions for both s- and p-wave neutrons. The distributions of neutron widths for both s- and p-wave neutrons are investigated as well as the spacing distribution for s-wave neutrons. Neutron strength functions are examined as a function of neutron energy (see Figure 4.8) to look for neutron doorway states. Correlations between neutron widths and radiation widths are also investigated since significant correlation may be indicative of non-statistical effects. Finally, long-range correlations of level spacings are studied and compared to the theoretical prediction of Dyson and Mehta.[3] Two papers on ^{64}Zn + n have been published,[4] a paper on ^{66}Zn + n has been submitted for publication, the analysis has been completed for ^{68}Zn + n, and analysis is in progress for ^{70}Zn + n.

1. State University of New York at Albany.
2. Chemistry Division.
3. F. J. Dyson, *J. Math. Phys.* **3**, 140, 157, 166, 1199 (1962); F. J. Dyson and M. L. Mehta, ibid. **4**, 701 (1963).
4. J. B. Garg, V. K. Tikku, and J. A. Harvey, *Phys. Rev. C* **23**, 671 (1981); J. B. Garg, V. K. Tikku, J. Halperin, and R. Macklin, *Phys. Rev. C* **23**, 683 (1981).

NEUTRON CAPTURE CROSS SECTIONS EXTENDED TO 2 MeV

R. L. Macklin R. R. Winters[1]

The stable-isotope neutron capture program at ORELA has primarily emphasized the energy range from a few keV to a few hundred keV to exploit the high resolution attainable for determining individual resonance parameters and intermediate structure. Recent work on ^{232}Th + n resonances below 10 keV,[2] for example, shows poor agreement with ENDF/B V parameters. A paper on neutron capture by ^{238}U studied and parametrized the intermediate structure seen in the unresolved resonance range from 5 keV to 100 keV.[3]

In collaboration with Darrell Drake and others from Los Alamos we have extended the neutron capture cross-section measurements up to 2 MeV. This has required several supporting developments to ensure accuracy. To eliminate inelastic scattering interference in the total gamma-ray energy detector technique[4] a fraction of the low-energy pulses must be discarded and their spectrum fraction determined. The neutron flux shape monitor, a thin piece of ^{6}Li glass scintillator, was calibrated[5] against the best standard available, the ^{235}U(n,f) cross section. The absolute efficiency calibration at saturated resonance peaks was also automated for least-squares fitting.[6]

Data on four stable tungsten isotopes are being analyzed, and data on ^{169}Tm(n,γ) are being prepared for publication. The ^{197}Au(n,γ) cross-section measurement[7] shows good agreement with recent "monoenergetic" measurements, while continuous coverage of the energy range with better resolution shows structure with up to about 15% amplitude attributable to inelastic competition, particularly from the 5/2^{+} levels in ^{197}Au.

1. Denison University.
2. R. L. Macklin, "Thorium Resonance Neutron Capture (2.6 to 10 keV)," *Nucl. Sci. Eng.*, in press.
3. R. B Perez, G. deSaussure, R. L. Macklin, and J. Halperin, "Statistical Tests for the Detection of Intermediate Structure: Application to the Structure of the ^{238}U Neutron Capture Cross Section between 5 keV and 0.1 MeV," *Phys. Rev. C* **20**, 528–45 (1979).
4. R. L. Macklin, "Resonance Capture Reactions with a Total Energy Detector" (invited paper), pp. 475–84 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, New York, September 1978), Plenum Press, New York, 1979.
5. R. L. Macklin, R. W. Ingle, and J. Halperin, "^{6}Li(n,α)T Cross Section from 70 to 3000 keV from the ^{235}U(n,f) Calibration of a Thin Glass Scintillator," *Nucl. Sci. Eng.* **71**, 205–8 (1979).
6. R. L. Macklin, J. Halperin, and R. R. Winters, "Absolute Neutron Capture Yield Calibration," *Nucl. Instrum. Methods* **164**, 213–14 (1979).
7. R. L. Macklin, "Gold Neutron Capture Cross Section from 100 to 2000 keV," *Nucl. Sci. Eng., in press.*

FISSION PRODUCT NEUTRON CAPTURE CROSS SECTION

R. L. Macklin R. R. Winters[1]

The combination of high cross section and high fission yield in fast reactors make the odd isotopes near mass 100 to 110 the most important of the long-term reactor poisons. We have measured the capture cross sections for stable ruthenium, rhodium, and palladium isotopes in this mass range[2–4] and have obtain samples of ^{99}Tc, ^{107}Ag, and ^{109}Ag for further measurements. A computer program error, affecting particularly the even palladium data, has been found and corrected.[5] Some additinal data on ^{100}Mo + n capture have also been reported.[6]

1. Dension University.
2. R. L. Macklin, J. Halperin, and R. R. Winters, "^{104,105,106,108,110}Pd(n,γ) Cross Sections above 2.6 keV," *Nucl. Sci. Eng.* **71**, 182–91 (1979).
3. R. L. Macklin and J. Halperin, "^{100,101,102,104}Ru(n,γ) and ^{103}Ruh(n,γ) Cross Sections above 2.6 keV," *Nucl. Sci. Eng.* **73**, 174–85 (1980).
4. R. L. Macklin, R. R. Winters, and J. Halperin, "Recent Capture Cross Section Data from ORELA above 2.6 MeV," p. 103–12 in *Proceedings NEANDC Specialists' Meeting on Neutron Cross Sections of Fission Product Nuclei* (Bologna, Italy, December 1979), CONF-791223, 1979.
5. R. L. Macklin and R. R. Winters, "Stable Isotope Capture Cross Sections from the Oak Ridge Electron Linear Accelerator," *Nucl. Sci. Eng.* **78**, 110 (1980).
6. H. Weigmann, S. Raman, J. A. Harvey, R. L. Macklin, and G. G. Slaughter, "Neutron Resonances in ^{100}Mo and Valence Neutron Capture," *Phys. Rev. C* **20**, 115–27 (1979).

^{238}U INELASTIC NEUTRON SCATTERING

R. R. Winters[1] J. A. Harvey
N. W. Hill[2] D. K. Olsen[3]
R. L. Macklin G. L. Morgan[4]

^{238}U inelastic neutron scattering has mostly been studied[5] above 200 keV, where several inelastic levels compete. In the 45–149 keV energy range, near the peak of a fast reactor's flux spectrum, only the 2^{+} level can be excited. The few measurements and evaluations of the inelastic cross section in this

enegy range showed considerable scatter. The use of the second pronounced cross-section minimum in iron has allowed us to isolate a pulsed 82-keV neutron beam at ORELA and measure the $^{238}U(n,n')$ cross section with it. Inelastically scattered neutrons are separated by time of flight from elastically scattered neutrons using a plastic scintillator coupled to three photomultiplier tubes. The neutron detector was operated in a majority-logic mode[6] to allow discrimination below the single-photoelectron response. Our result for the inelastic cross section is (381 ± 21) mb, in good agreement at 82 keV with calculations.

1. Denison University.
2. Instrumentation and Controls Division.
3. Engineering Physics Division.
4. Los Alamos National Laboratory.
5. R. R. Winters et al., "Uranium-238 Inelastic Neutron Scattering at 82 keV, "*Nucl. Sci. Eng.* **147** (1981).
6. N. W. Hill et al., "Majority-Logic NE-110 Detector for keV Neutrons," this report.

SAMMY: A COMPUTER MODEL FOR MULTILEVEL *R*-MATRIX FITS TO NEUTRON DATA USING BAYES'S EQUATIONS[1]

Nancy M. Larson[2] Francis G. Perey[3]

A computer program has been written for determining the parameters of a model from experimental data based upon the utilization of Bayes's theorem. This method has several advantages over the least-squares method as commonly used; one important advantage is that the assumptions under which the parameter values have been determined are more clearly evident than in many results based upon least squares. Bayes's method has been used to develop a computer code which can be utilized to analyze neutron cross-section data by means of the *R*-matrix theory. A report[4] has been prepared which presents the required formulas from the *R*-matrix theory and describes the computer implementation of both Bayes's equations and *R*-matrix theory. Results of the analysis of ^{60}Ni transmission data from ORELA are compared to the results using an earlier multilevel *R*-matrix code. Finally, details about the computer code and complete input/output information are given in the report.

1. Sponsored by Basic Neutron Physics Research, Physics Division.
2. Computer Sciences Division.
3. Engineering Physics Division.
4. Nancy M. Larson and F. G. Perey, *User's Guide to SAMMY*, ORNL/TM-7485, ENDF-297 (1980).

MAJORITY—LOGIC NE-110 DETECTOR FOR keV NEUTRONS

N. W. Hill[1] D. J. Horen
J. A. Harvey G. L. Morgan[2]
R. R. Winters[3]

A proton-recoil scintillation counter whose efficiency is reproducible and stable has been developed for neutrons in the energy range from 5 keV to 1 MeV. Majority-of-two logic at below the single-photoelectron level is used between two or more phototubes viewing the same scintillator. Pulse-height distributions in two differently shaped detectors have been measured as a function of neutron energy between 5 and 350 keV. One detector was a cylindrical NE-110 scintillator 4.3 cm in diameter and 7.6 cm long with an RCA 8850 photomultiplier on each end. The other was an NE-110 scintillator 1.9 cm thick by 5.7 by 5.7 cm with three photomultipliers. Comparisons of the pulse-height distributions and the absolute efficiencies have been made to Monte Carlo calculations.[4] Figure 4.9 shows the comparison for 24.5-keV neutrons for the three-photomuliplier arrangement. The absolute efficiencies agree to about 5%.

1. Instrumentation and Controls Division.
2. Los Alamos National Laboratory.
3. Denison University.
4. C. Renner, N. W. Hill, G. L. Morgan, K. Rush, and J. A. Harvey, *Nucl. Instrum. Methods* **154**, 525 (1978).

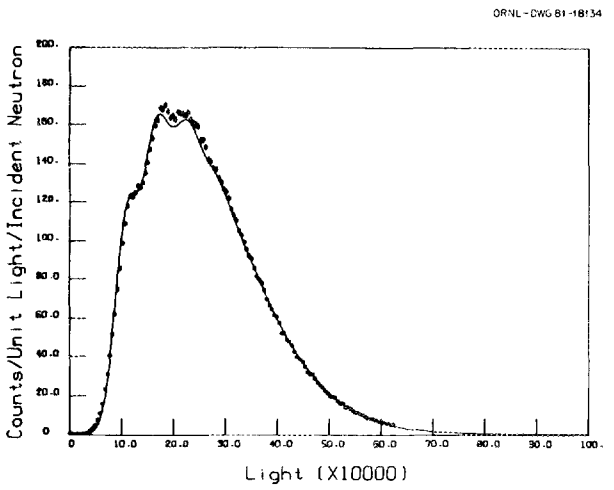


Fig. 4.9. Comparison of the pulse-height distribution for 24.5-keV neutrons compared to Monte Carlo calculations. The structure corresponds to two, three, four, and five photoelectrons.

THERMAL AND RESONANCE NEUTRON CAPTURE GAMMA-RAY MEASUREMENTS

S. Raman
G. G. Slaughter
R. F. Carlton[1]
J. A. Harvey
A. Z. Hussein[2]
E. T. Jurney[3]
S. Kahane[4]
M. J. Kenny[5]
D. A. McClure[6]
W. Ratynski[7]
O. Shahal[4]
R. R. Spencer[8]
J. S. Tang[9]
J. C. Wells, Jr.[10]

The main emphasis of our (n,γ) program is the measurement of gamma rays following neutron capture in individual resonances. To round out this program, we also carry out thermal-neutron capture measurements at Los Alamos and "average-resonance" capture measurements at Brookhaven. A progress report covering these activities is given below. In addition, we have completed studies of the $^{54}Fe(n,\gamma)$ and $^{89}Y(n,\gamma)$ reactions. In ^{54}Fe, it was shown[11] that the 7.76-keV resonance spectrum is in excellent agreement with valence-model predictions. The $E1$ and $M1$ primary gamma rays following resonance neutron capture in ^{89}Y showed[12] some unusual enhancements. The present status of the $M1$ strength in ^{208}Pb and its implications (particularly concerning effective mass) were discussed[13] in a recent review article.

Thermal-Neutron Absorption Cross Section of Sulfur and the ^{252}Cf $\bar{\nu}$ Problem

E. T. Jurney S. Raman
R. R. Spencer

The need for a more accurate value of the thermal-neutron absorption cross section of sulfur has been emphasized by Smith[14] in a recent status report on measurements of the average number of neutrons ($\bar{\nu}_T$) emitted in spontaneous fission of ^{252}Cf. The ^{252}Cf $\bar{\nu}_T$ value is used as the standard in measurements of $\bar{\nu}(E)$ for neutron-induced fission in all the isotopes of thorium, uranium, and plutonium. It is therefore one of the most important parameters used in reactor design and safety analysis calculations, for which its value is requested to an accuracy of 0.25%. The impact of the value of the sulfur absorption cross section on ^{252}Cf $\bar{\nu}_T$ values obtained from $MnSO_4$-bath activation measurements is discussed by Smith,[14] who suggests that an increase in the value used for this cross section may relieve the persistent approximately 0.8% systematic difference between the $\bar{\nu}$ value obtained in manganese-bath measurements and those obtained by the other frequently used precise technique: liquid scintillator. It has been pointed out by him that the currently accepted value of σ_a for natural sulfur of 520 ± 30 mb was derived from measurements which range from about 470 mb to about 620 mb and that an increase in the value used for $MnSO_4$-bath corrections of only 30 mb would increase the value of $\bar{\nu}_T$ obtained by 0.25%. Clearly, an independent measurement of the sulfur thermal capture cross section, which constitutes nearly 99% of the absorption, to an accuracy of better than 5% would be of great benefit in resolving this question.

We have measured $\sigma(n,\gamma)$ for thermal-neutron capture in natural sulfur by summing the intensities in the prompt-gamma spectrum. The spectrum was obtained from a 1-g sample of chemically pure natural sulfur placed in the internal target facility of the Los Alamos Omega West reactor. The detector was a 6.1-cm-diam, 15.2-cm-long NaI scintillator operated in anticoincidence with a NaI annulus. The response function of the detector has been determined over a wide energy range to permit unfolding of the recorded pluse-height spectrum into a superposition of full-energy peaks that correspond to the emitted gamma spectrum (see Fig. 4.10). The

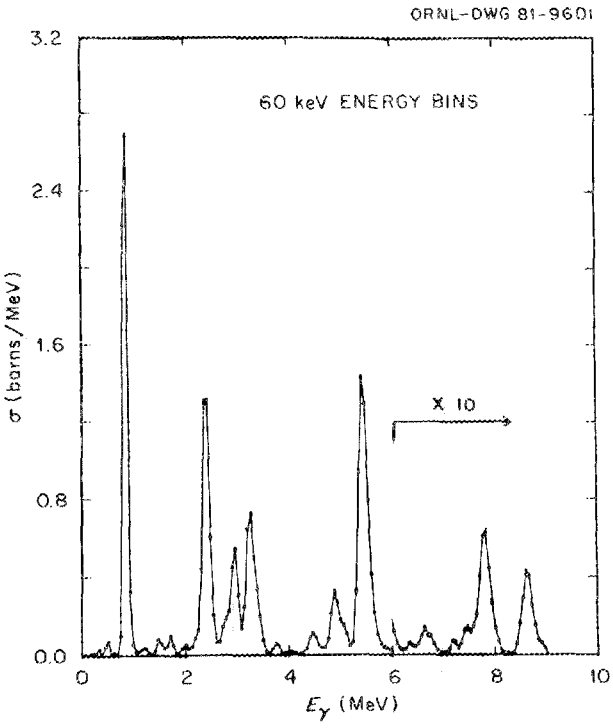


Fig. 4.10. Sodium iodide spectrum from the S(n,γ) reaction.

gamma spectrum thus determined was normalized in terms of partial capture cross section by measuring the intensity of the single gamma from neutron capture by ^{1}H from a 46-mg sample of polyethylene placed at the same target position. The ^{1}H capture cross section was taken[15] as 332 ± 3 mb. Our source of neutrons has a Maxwellian neutron velocity distribution of 350°K. To convert the measured cross sections to thermal (294°K) values, we have assumed that the low-energy capture cross sections of both hydrogen and sulfur vary as $1/v$. Doubts concerning this assumption for sulfur have been largely dispelled by Smith.[14]

The value of the natural sulfur thermal absorption cross section [the (n,α) and (n,p) cross sections were taken from BNL-325] derived from the present measurements, 513 ± 15 mb, is in good agreement with the value 520 ± 30 mb used currently in corrections for $MnSO_4$-bath measurements of ^{252}Cf $\bar{\nu}_T$. This suggests that other areas must be examined to resolve the discrepancy between $MnSO_4$-bath and liquid-scintillator measurements of this important parameter.

Direct Capture in the ^{34}S(n,γ)^{35}S Reaction with Thermal Neutrons

R. F. Carlton S. Raman
E. T. Jurney

We have studied the ^{34}S(n,γ] reaction at the Los Alamos Omega West Reactor thermal-neutron capture facility. These measurements were made with a 1.09-g 78%-enriched ^{34}S target. The 26-cm^3 Ge(Li) detector was located approximately 6 m from the internal target. This detector was operated either in the Compton suppression or pair spectrometer mode. Approximately 60 gamma rays were observed, several with intensities as low as about 2 photons per 10,000 neutron captures. All gamma rays except three weak ones have been incorporated into a level scheme of ^{35}S with 20 excited states. The primary gamma rays and the secondary gamma rays (feeding the ground state) separately accounted for about 100% of the measured total capture cross section of 294 mb. The primary $E1$ gamma rays leading to states at 2348, 3802, 4189, 4903, and 4963 keV accounted for 95% of this cross section.

For several nuclides near A = 40, where thermal cross sections are low and nonresonant, Spits and Akkermans[16] showed that the correlation between thermal (n,γ) intensities and (d,p) spectroscopic strengths is maximized by dividing the primary gamma-ray intensities by the appropriate energy to the first power. A similar result for ^{35}S is shown in Fig. 4.11. This result a priori suggests direct capture, but, as emphasized by Mughabghab and Chrien,[17] it is also necessary to quantitatively compare the measured and calculated partial capture cross sections.

The needed expressions for calculating the direct capture cross sections have been derived by Lane and Lynn[18] and explicitly given by Mughabghab and Chrien.[17] The (d,p) spectroscopic strengths for $1/2^-$ and $3/2^-$ levels in ^{35}S are known.[19] Since the nuclear radius of 4.4 fm is greater than the known scattering length[20] of 3.5 fm, constructive interference betwen hard-sphere and channel capture is expected. The resulting predictions are compared with the measured cross sections in Fig 4.12. The predictions are about 20% lower than the measurements but well within the uncertainties inherent in the compared quantities.

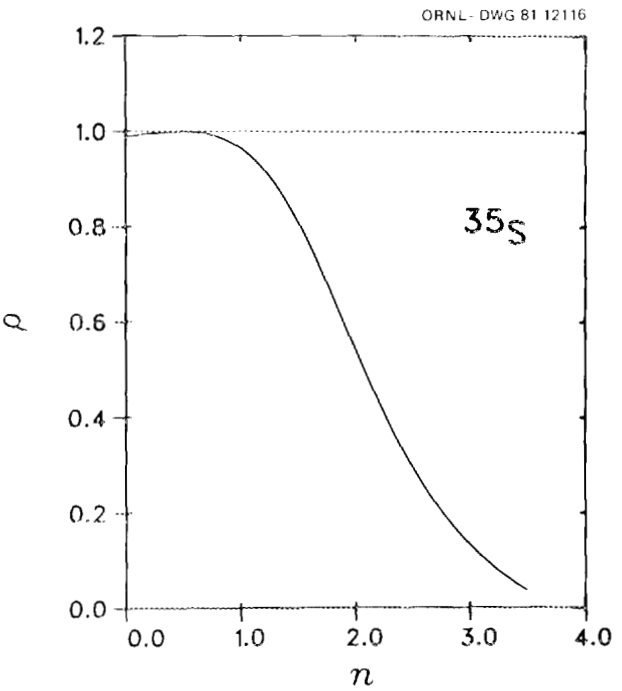


Fig. 4.11. Correlation coefficient ρ between (d,p) strengths and (n,γ) strengths $I_\gamma E_\gamma^{-n}$ plotted as a function of n.

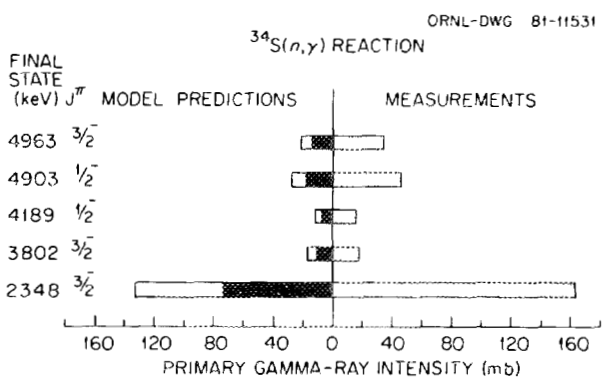


Fig. 4.12. Comparison of measured and predicted partial cross sections. On the left side, the darkly shaded contribution is due to hard-sphere and the remaining due to channel capture.

The $^{36}S(n,\gamma)^{37}S$ Reaction with Thermal Neutrons

S. Raman W. Ratynski
E. T. Jurney

Since ^{36}S has an extremely low natural abundance (0.017%) and a small thermal-neutron capture cross section (about 150mb), the ^{35}S(thermal n,γ] reaction has not been investigated till now. We have studied this reaction utilizing a 100-mg target enriched to 81% in ^{36}S placed in the Los Alamos Omega West Reactor thermal column at a distance of 1.7 m from the reactor core. A 26-cm^3 Ge(Li) detector with a NaI(Tl) annulus was located approximately 6 m from the target and was operated in either a Compton-suppressed or a pair spectrometer mode. Eighteen gamma rays in ^{37}S were identified in the 0.6–3.7 MeV region, several with intensities as low as about 0.5 photon per 100 neutron captures. Ten strong gamma rays have been incorporated into a level scheme as shown in Fig. 4.13. The four primary gamma rays placed in this scheme account for more than 95% of the thermal-neutron capture cross section. The energy levels at 646, 2023, and 3262 keV have been previously excited in the $^{37}Cl(t, {}^3He)^{37}S$ reaction.[21] The levels at 2312 and 2958 keV are ambiguous because reverse ordering of gamma rays would lead to levels at 2638 and 1991 keV respectively. A planned $^{36}S(d,p)^{37}S$ study should remove these ambiguities. The neutron separation energy was deduced as 4304 ± 2 keV.

We had earlier measured the thermal-neutron capture cross section of ^{32}S to be 518 ± 14 mb. This value was subsequently employed to determine the thermal-neutron capture cross section of ^{34}S as 294 ± 15 mb. Since the present enriched ^{36}S target material contained 18.8% ^{34}S, the use of the above cross section for ^{34}S resulted in a value of 230 ± 20 mb for the thermal-neutron capture cross section of ^{36}S.

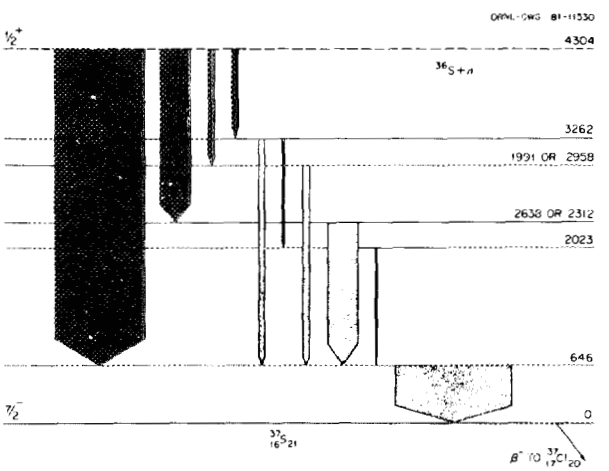


Fig. 4.13. Main decay modes in the $^{36}S(n,\gamma)^{37}S$ reaction.

Parity of the 398-eV Resonance in ^{35}Cl

A. Z. Hussein S. Raman
J. A. Harvey

A comparison[22] of neutron capture gamma-ray spectra in neighboring *s*- and *p*-wave capture states in a ^{35}Cl target shows that the spectra are highly correlated. In this case, the *s* wave refers to thermal-neutron capture and *p* wave to capture by the 398-eV resonance. The *p*-wave (or $l = 1$) assignment for this resonance is ascribed to work of Singh et al.,[23] who made l assignments for several resonances in Cl below 200 keV on the basis of the observation ($l = 0$) or nonobservation ($l = 1$) of shape asymmetry in total cross-section measurements. Understandably enough, Singh et al.[23] made no special effort to single out the 398-eV resonance for either a discussion or a figure concerning its *p*-wave assignment. Since this resonance has assumed importance and since this resonance has a neutron width so small ($g\Gamma_n \approx 40$ meV) that a visual inspection of the total cross-section data is inadequate to readily yield its l value, we undertook a more elaborate measurement.

Transmission data were acquired at the 78.2-m flight path station of ORELA. The liquid CCl_4 sample was contained in a cylindrical brass container of 2.71 cm diameter. The sample weight was 76.42 g, which corresponded to 0.1572 atom per barn. Neutrons were detected by an 11-cm-diam, 1.27-cm-thick ^{6}Li glass scintillator. The electron burst width was 35 ns, with a repetition rate of 800 s^{-1}. Compensator samples of brass and carbon were also employed concurrently.

The transmission data, shown in Fig. 4.14, were analyzed with the *R*-matrix computer codes MULTI[24] and SAMMY.[25] The measured data points are fitted well by a *p*-wave resonance at 398 eV ($g\Gamma_n \approx 38$ meV, $\Gamma_\gamma \approx 420$ meV), together with a bound level at approximately -100 eV ($g\Gamma_n \approx 4.4$ eV, $\Gamma_\gamma \approx 500$ meV). The data points do not exhibit the expected interference between resonance and potential scattering if this resonance is assumed to be *s* wave.

ORNL-DWG 81-9603R

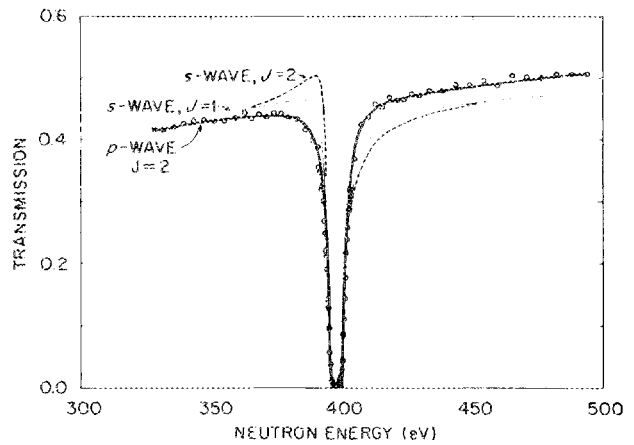


Fig. 4.14. *R*-matrix analyses of neutron transmission data of ^{35}Cl.

Test of Axel-Brink Predictions in ^{174}Yb and ^{168}Er

S. Raman S. Kahane
O. Shahal G. G. Slaughter

In recent years, the limitations imposed by Porter-Thomas fluctuations in the study of primary gamma rays following neutron capture have been partly overcome by "resonance-averaging" techniques. The incident neutron beam is chosen with an energy distribution sufficiently broad that many compound-nucleus resonances contribute to the capture process. The two techniques most commonly employed in average-resonance-capture measurements involve the use of "reactor neutrons" and "filtered beams." A third method of obtaining individual gamma-ray spectra from a large number of resonances and summing them after appropriate normalizations was accomplished recently by Raman, Shahal, and Slaughter[26] in the case of the ^{173}Yb(n,γ) reaction. The resulting average radiation widths (and hence the gamma-ray strength function) were found to be in good agreement with the Axel-Brink predictions. The predictions are based on two key ideas: (1) The giant dipole resonance (GDR) governs the width of the transition from the capturing state to the ground state (Axel[27]) and (2) if it were possible to perform a photoabsorption experiment on an excited state, the cross section would still have the same Lorentzian energy dependence as the GDR (Brink[28]).

The ^{174}Yb results for the gamma-ray strength function are shown in Fig. 4.15. In the original paper,[26] we relied on the known giant dipole resonance (GDR) parameters for ^{175}Lu because experimental parameters for ^{174}Yb were unavailable at that time. Recent photoabsorption measurements[29] have remedied that situation.

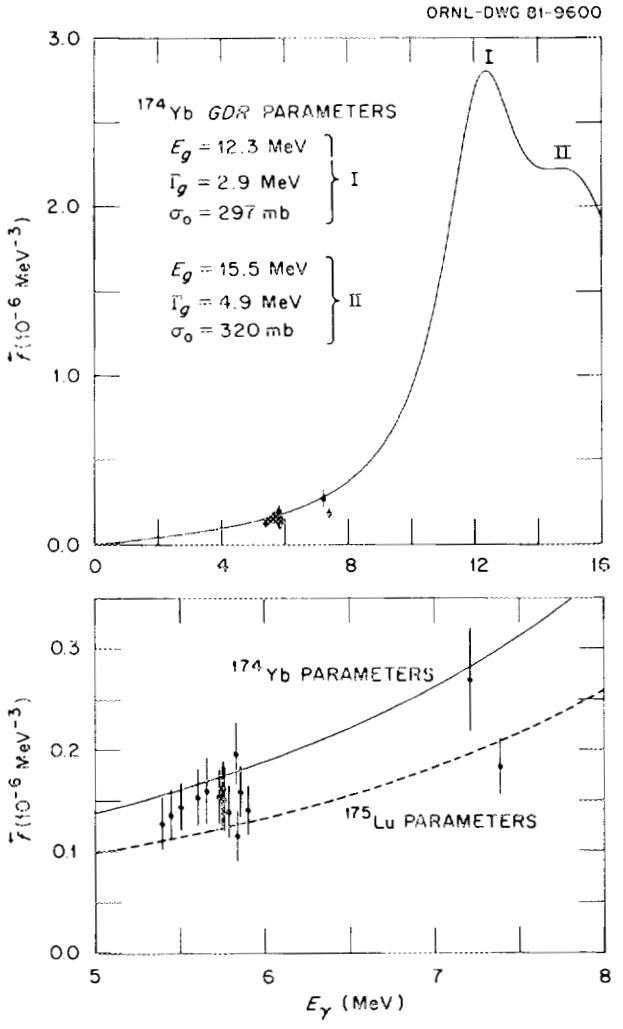


Fig. 4.15. Comparison of the measured strength function for ^{174}Yb with the predictions of the Axel-Brink giant dipole resonance model.

In a subsequent study, we have obtained 110 4096-channel spectra (87 on resonance and 23 off resonance) from the ^{167}Er(n,γ) reaction. The spectra were normalized through the use of the 816-keV $3_1^+ \rightarrow 2_1^+$ transition, which has a measured absolute intensity of 30 photons per 100 thermal-neutron captures. The measured[30] average intensity values deduced from the summed spectrum (see Fig. 4.16) were in good agreement with the "2-keV" results of Davison et al.[30]

The measured gamma-ray strength function ($\bar{f} = \Gamma_\gamma / D_l E_\gamma^3$) is compared to the Axel-Brink predictions in Fig. 4.17. The giant resonance parameters are from recent photoabsorption measurements.[29] The

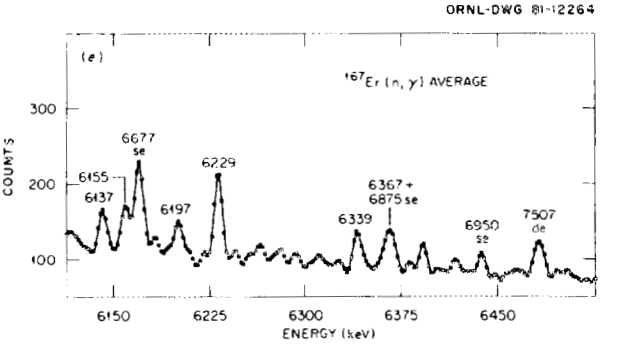


Fig. 4.16. Selected portions of the summed spectrum from 87 resonances in ^{167}Er below 590 eV.

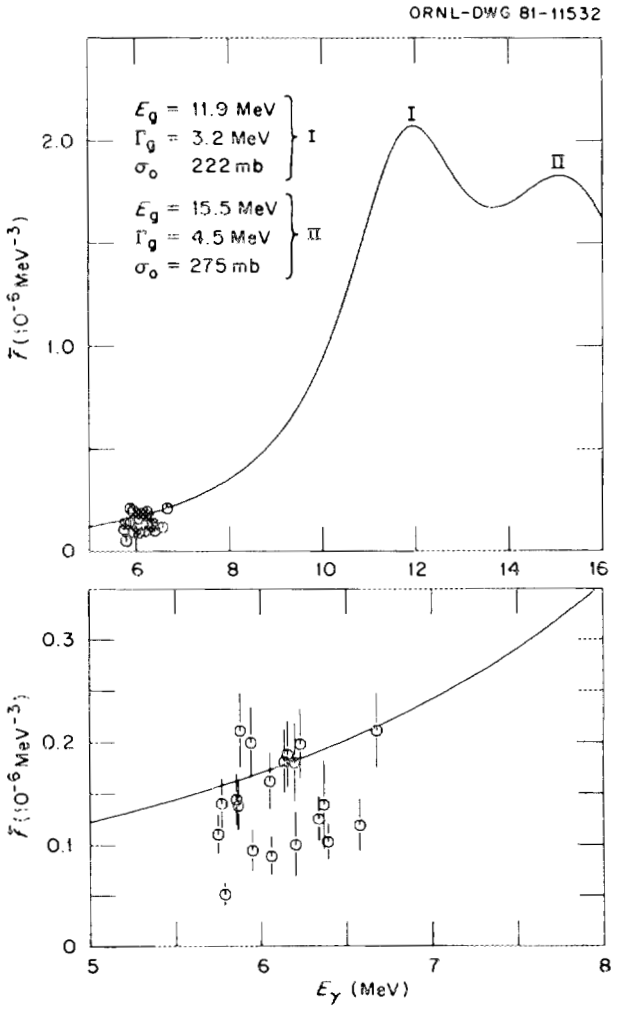


Fig. 4.17. Comparison of the measured strength function for ^{168}Er with the predictions of the Axel-Brink giant dipole resonance model.

predictions are, on the average, about 20% higher than the measurements, but the overall agreement is quite reasonable. As the next step, we plan to test whether the strength function is independent of the spin of the capturing state, as generally supposed.

The Use of Oxide Targets in 2-keV Average Neutron Capture Measurements

J. S. Tang S. Raman

Large samples (about 10–100 g are usually required for "2-keV" filtered-beam measurements, and such samples invariably come in the oxide form. In order to fully evaluate the implications of employing an oxide instead of a metal, we have performed Monte Carlo calculations of a neutron energy spectrum in a neodymium oxide sample. The continuous energy Monte Carlo code PXMORSE[31] was used in the calculations. A monodirectional neutron beam uniformly impinging on one side of the sample is shown in Fig. 4.18. The neutron beam has a rather narrow energy spectrum, which ranges from 0.5 to 3 keV and peaks at about 2.0 keV. Neodymium in the sample is assumed to be 100% ^{145}Nd. Neutron cross-section data used in the calculations were obtained from the ENDF-IV library. The sample weighs 643 g and therefore constitutes an "extreme case."

In the Monte Carlo calculations, source-energy biasing was applied to sample the source energy spectrum. This biasing increased the number of source neutrons on both sides of the energy spectrum and thereby improved the statistics by reducing the uncertainties of results in these energy ranges. The neutron spectrum in the sample was estimated using both the track-length estimator and the collision estimator. The track-length estimator scored on neutron trajectories (tracks) in the sample while the collision estimator scored on neutron collisions in the sample. Excellent agreement between results of the two estimators was achieved. A boundary-crossing estimator, which scored on neutrons crossing a surface outside the sample, was used to obtain the source spectrum.

Figure 4.19 shows the normalized neutron spectrum of the source and the spectra in the oxide sample with and without a 0.005-mm-thick polyethylene enclosure. As expected, the neutron spectrum is softened in the sample. The polyethylene bag has negligible effect on the spectrum except below 0.7 keV. Scattering interactions are elastic because the energies are below inelastic thresholds of the scattering isotopes. More than

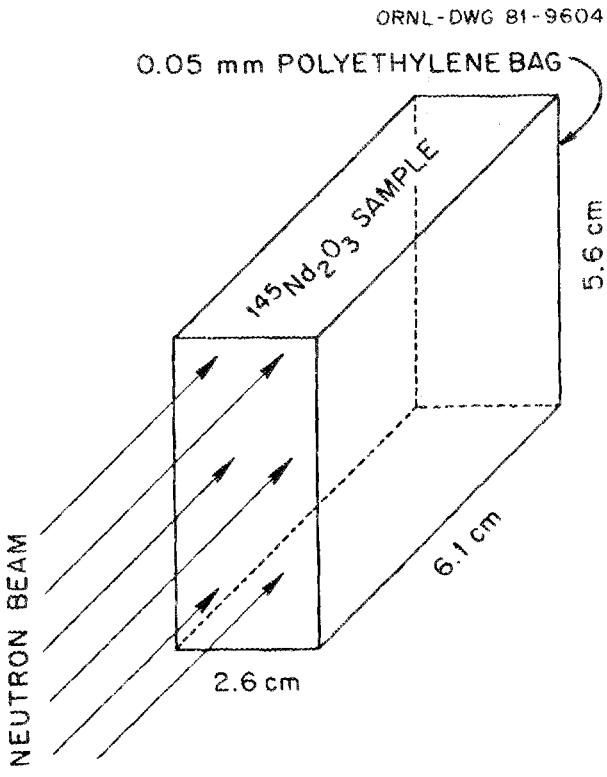


Fig. 4.18. Problem geometry.

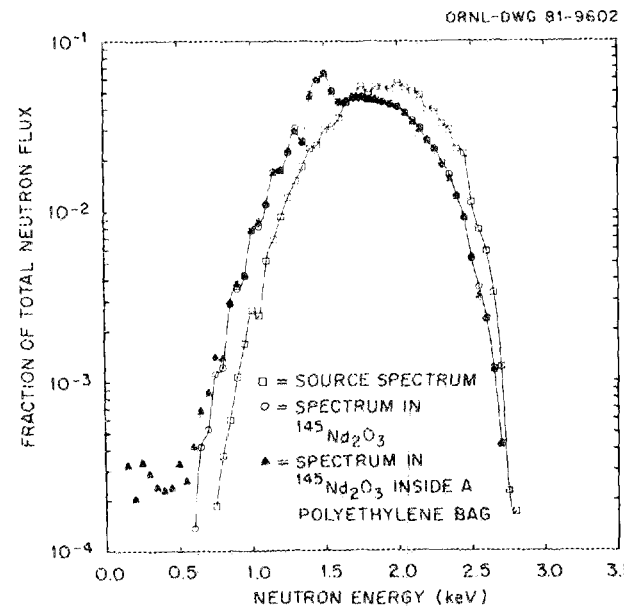


Fig. 4.19. Results of Monte Carlo calculations.

90% of scattering was by neodymium and the rest mainly by oxygen (neutron interaction with polyethylene was less than 1%.

From elastic slowing-down theory[32] the minimum neutron energy (in the laboratory system) after an elastic collision is $E(\min) = \alpha E_0$, where the elastic slowing-down parameter α is $(A - 1)^2/(A + 1)^2$, with A being the mass number and E_0 the initial neutron energy in the lab system. Let us define the elastic slowing-down power of an isotope in a mixture as the product of the maximum fraction of energy loss and the fraction of the total elastic scattering. That is, for the ith isotope in a mixture, $P_i = (1 - \alpha_i)f_i$. The α values for ^{16}O and ^{145}Nd are 0.779 and 0.973 respectively. At an elastic scattering ratio of 9:1 between Nd and O in the sample, the elastic slowing-down powers are 0.243 for Nd and 0.221 for O. Therefore these two elements contribute about equally to the neutron slowing-down effect.

The centroids of the neutron source spectrum and the oxide spectrum are at 1.90 and 1.73 keV respectively. The oxide spectrum is also about 10% wider. It may be concluded that the averaging process in "2-keV" filtered neutron beam experiments is not adversely affected by the use of oxide targets.

Anomalous Transitions in ^{144}Nd and ^{146}Nd in "2-keV" (n,γ) Measurements

S. Raman D. A. McClure
O. Shahal M. J. Kenny

We have carried out average resonance neutron capture measurements on ^{143}Nd and ^{145}Nd at the Brookhaven High Flux Beam Reactor. The measurements utilized about 100 g each of 91.7% ^{143}Nd and 89.7% ^{145}Nd in oxide form. A Sc-filtered neutron beam characterized by a flux of about 7×10^6 neutrons per square centimeter per second, a full width at half maximum of about 0.9 keV, and a centroid of about 2 keV was employed. The resulting gamma-ray spectra represented an average over about 28 resonances in ^{143}Nd. The ground states of both target nuclei are $7/2^-$. Since capture at 2 keV proceeds mainly via s wave, the capturing states are 3^- and 4^- in the ratio about 7:9. The gamma-ray spectra were obtained with a pair spectrometer having a central 55-cm^3 Ge(Li) detector and two 25 × 18 cm NaI(Tl) detectors. The $E1$ transitions to the 3^+ and 4^+ levels in ^{144}Nd and ^{146}Nd are expected to be about 2.3 times more intense than $E1$ transitions to 2^+ levels.

The results are shown in Fig. 4.20. The most striking feature is the enhancement in the intensities of transitions leading to the 1560-keV level in ^{144}Nd and the 1778-keV level in ^{146}Nd. The 1560-keV level is known[33] to be a definite 2^+ level. The 1778-keV level is most probably also a 2^+ level. If one relied only on average capture measurements, one would have erroneously concluded that these were 3^+ or 4^+ levels. The intensity enhancements are especially interesting because they are also present in average resonance capture measurements[35] with "reactor neutrons," where averaging takes place over approximately similar numbers of resonances.

In the case of ^{144}Nd, there are strong reasons, based on systematics and shell-model calculations, to suppose that the 1560-keV level is predominantly a "two-proton" 2^+ excitation. Even so, it is surprising that the gamma-ray intensity, averaged over so many resonances, shows sensitivity to such nuclear structure details. In the same vein, an anticorrelation has been reported[36] between the strengths of transitions from 3^- resonances to "one-and two-phonon final states" in ^{144}Nd. Additional resonance capture measurements on ^{143}Nd are planned at ORELA.

1. Middle Tennessee State University, Murfreesboro.
2. Nuclear Research Center, Cairo, Egypt.
3. Los Alamos National Laboratory, Los Alamos, N. Mex.
4. Nuclear Research Centre-Negev, Beer-Sheva, Israel.
5. Australian Atomic Energy Commission, Lucas Heights.
6. Applied Physical Technology, Inc., Smyrna, Ga.
7. Institute for Nuclear Research, Swierk, Otwock, Poland.
8. Engineering Physics Division.
9. Computer Sciences Division.
10. Tennessee Technological University, Cookeville.

11. S. Raman, G. G. Slaughter, J. C. Wells, Jr., and B. J. Allen, *Phys. Rev. C* **22**, 328 (1980).
12. S. Raman, O. Shahal, A. Z. Hussein, G. G. Slaughter, and J. A. Harvey, *Phys. Rev. C* **23**, 1979 (1981).
13. G. E. Brown and S. Raman, *Comments Nucl. Part. Phys.* **9**, 79 (1980).
14. J. R. Smith, *Status of the Quest for ^{252}Cf ν*, EPRI NP-1258 (1979).
15. S. F. Mughabghab and D. I. Garber, *Neutron Cross Sections*, BNL-325 (1973).
16. A. M. J. Spits and J. A. Akkermans, *Nucl. Phys.* **A215**, 260 (1973).
17. S. F. Mughabghab and R. E. Chrien, pp. 265–83 in *Neutron Capture Gamma-Ray Spectroscopy*, ed. R. E. Chrien and W. R. Kane, Plenum, New York, 1969.
18. A. M. Lane and J. E. Lynn, *Nucl. Phys.* **17**, 563, 586 (1960).
19. R. Abegg and S. K. Datta, *Nucl. Phys.* **A287**, 94 (1977).
20. L. Koester, K. Knopf, and W. Waschkowski, *Z. Phys.* **A289**, 399 (1979).

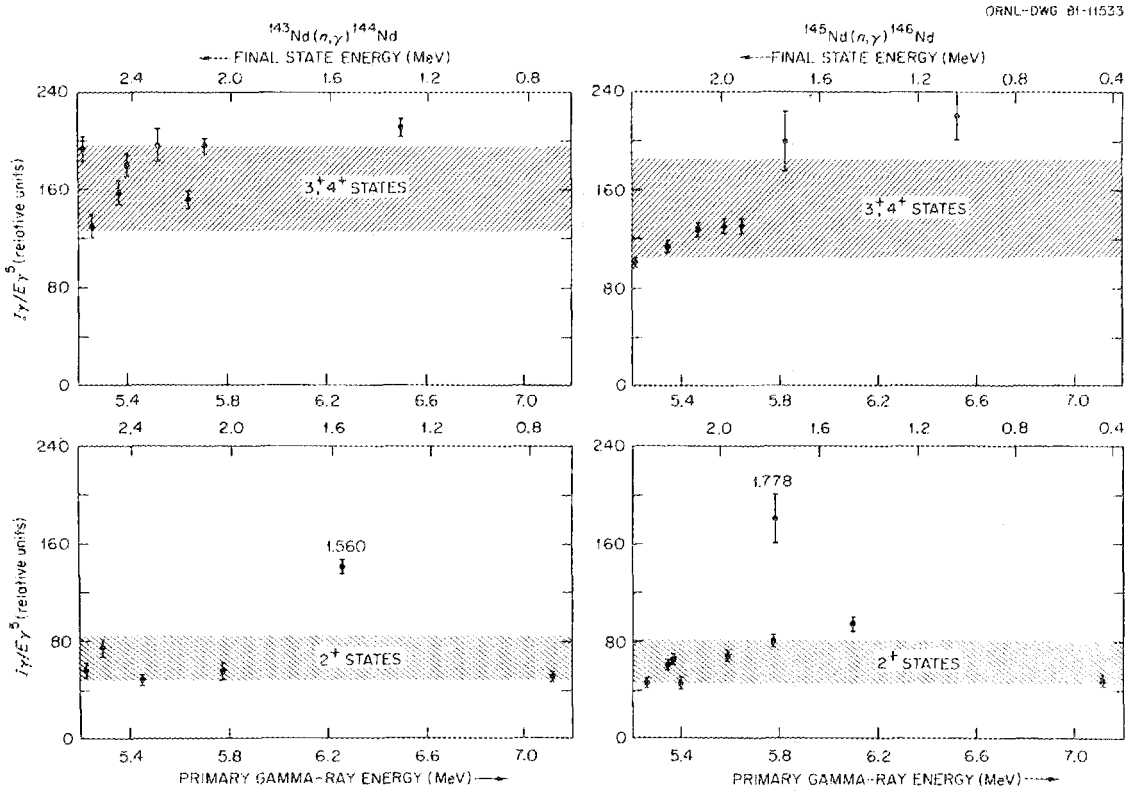


Fig. 4.20. Summary of 2-keV average capture results.

21. F. Ajzenberg-Selove and G. Igo, *Nucl. Phys.* **A142**, 641 (1970).

22. R. E. Chrien and J. Kopecky, *Phys. Rev. Lett.* **39**, 911 (1977).

23. U. N. Singh et al., *Phys. Rev. C* **10**, 2138 (1974).

24. G. F. Auchampaugh, LA-5473-MS (1974).

25. N. M. Larson and F. G. Perey, ORNL/TM-7485 (1980).

26. S. Raman, O. Shahal, and G. G. Slaughter, *Phys. Rev. C* **23**, 2794 (1981).

27. P. Axel, *Phys. Rev.* **126**, 671 (1962).

28. D. M. Brink, Ph.D. thesis, Oxford University, 1955.

29. G. M. Gurevich et al., *Nucl. Phys.* **A351**, 238 (1981).

30. W. F. Davidson et al., *J. Phys. G* **7**, 455 (1981).

31. M. M. Waddell, Jr., "A Continuous Energy Monte-Carlo Code," M. S. thesis, University of Tennessee, 1980.

32. J. R. Lamarsh, *Introduction to Nuclear Reactor Theory*, Addison-Wesley, Reading, MA, 1966, chap. 6.

33. M. Behar, Z. W. Grabowski, and S. Raman, *Nucl. Phys.* **A219**, 516 (1974).

34. Z. Berant, J. Tenenbaum, and R. Moreh, *Nucl. Phys.* **A276**, 221 (1977).

35. D. L. Bushnell, G. R. Tassotto, and R. K. Smither, *Phys. Rev. C* **14**, 75 (1976) and private communication.

36. H. Weigmann, G. Rohr, and M. Heske, *Nucl. Phys.* **A185**, 229 (1972).

MEASUREMENT OF THE FISSION CROSS SECTION OF ^{241}Am

J. W. T. Dabbs C. E. Bemis, Jr.
C. H. Johnson K. Rush[1]

Although the main body of measurement runs at ORELA had been completed at the time of the last report,[2] several important difficulties appeared in subsequent months and required considerable effort to overcome. First, a hidden oscillation at 25 MHz was found to have occurred in the early-time data from one of the preamplifier systems during the entire measurement sequence. This required reestablishing the experimental setup, finding the difficulty (a poor ground connection at the fission chamber wall), repairing same, and making new runs to establish reference (^{235}U) data in the high-energy region. These runs were completed in March 1979. Second, during the data-taking period it became clear (from measurements of the alpha-

particle-induced ionization current in those portions of the fission chamber containing ^{241}Am) that the quantities of this isotope which were present did not correspond to the quantities quoted by the suppliers of the vacuum-evaporated plates. Questions also existed with respect to the rather old (fabricated in 1970) ^{235}U stnadard plates used in the fission chamber. Accordingly, in early 1980 the chamber was disassembled and the plates subjected to careful photon-counting analysis, utilizing the 59-keV photons from ^{241}Am (in comparison with a known standard) and the 185.7-keV gamma ray from ^{235}U. The results were quite encouraging in that the newly determined amounts of material agreed quite well with the previously observed ionization currents mentioned above.

The measurements of ^{241}Am fission cross section were made in a new type of chamber, called a "honeycomb" chamber, in which approximately 1-cm hexagonal cells were formed between the plates using a commercially available aircraft structural material.[3] This material was a glass-fiber-loaded phenolic plastic with a cell wall thickness of 0.1 mm. This type of chamber was used because the limited transverse alpha-particle range permitted by the structure gives a strong suppression of the very large alpha background. Such a structure necessarily introduces some undesirable neutron scattering into the experiment.

In the particular case of ^{231}Am the fission cross section at intermediate energies (10–100 keV) is so low that background subtraction corrections become exceedingly important if accurate values are to be obtained. (This problem was the basis of an error of more than a factor of 40 which occurred in this cross section by the earlier experiments made using an underground nuclear explosion.) For this reason a careful examination of the backgrounds introduced in scattering of neutrons from all the various materials of the chamber and its filling gas was made. This effort led to a new approach in these calculations which can be characterized by an effective (in-scattered) cross section which can be subtracted from the normally calculated cross section in order to obtain the actual cross section of the sample.

Figure 4.21 shows a graph of the fission cross section of ^{241}Am as determined in our experiment; the lower curve in this figure represents the in-scattered cross section. Peaks in the lower curve reflect resonances in the scattering material or in the target fission cross section. The relative importance

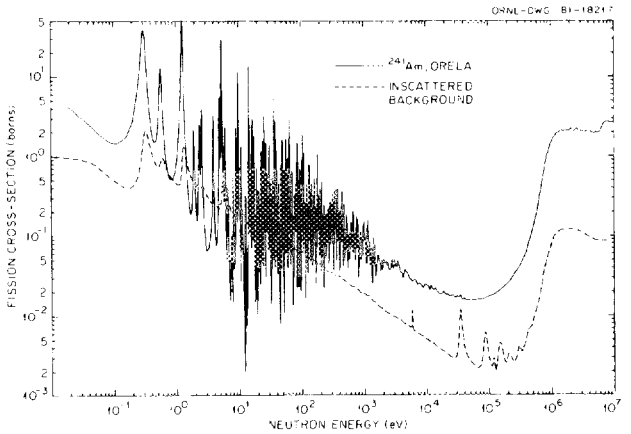


Fig. 4.21. Fission cross section for ^{241}Am.

of the in-scattering correction can easily be determined by inspection of these curves. A resonance analysis of the low-energy data will be performed.

1. Now at Hewlett-Packard Corp., Loveland, Colo.
2. J. W. T. Dabbs et al., *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498, p. 94.
3. Manufactured by Hexcel Corp.
4. J. W. T. Dabbs, H. W. Sang, K. Rush, and H. Weigmann, *Bull. Am. Phys. Soc.* 23, 594 (1978).

MEASUREMENT OF THE NEUTRON-INDUCED FISSION CROSS SECTION OF ^{242m}Am

J. W. T. Dabbs R. J. Dougan[1]
C. E. Bemis, Jr. R. W. Hoff[1]
S. Raman

The alpha decay ($T_{1/2}$ = 152 years) of ^{242m}Am leads to a growth of spontaneously fissionable ^{242}Cm in a sample with a half-life of 162 days.[2] This circumstance requires that any measurement on this isotope be done very promptly after the chemical removal of previously formed Cm from the sample. In the present measurement, such a separation was made at LLL only 75 h prior to the commencement of the runs at ORELA. At the end of one month measuring time (in June 1979) the spontaneous fission rate from the ^{242}Am sample had grown from 500 counts per hour to some 4000 counts per hour, and the experiment was terminated. This cross-section measurement used time-of-flight techniques

at ORELA and covered the range from thermal energies to 20 MeV. The fission chamber comprised a number of hemispherical plates and was mounted at 9 m in flight path 2 of ORELA. ^{235}U fission and ^{6}Li(n,α) served as standards for the measurement. The ^{242m}Am sample weighed 512 μg, was 99.25% pure, and contained 0.75% of ^{241}Am, which has a much smaller fission cross section. A sample of 168 μg of ^{235}U was mounted in the same chamber along with a small ^{252}Cf sample for chamber testing. Three hundred sixty hours of data were obtained, primarily with 40-ns bursts.

During the rather extended process of reducing the measured data to fission cross section, it was found that the choice of material for the hemispherical plates was somewhat unfortunate in that the in-scattered correction (mentioned elsewhere) was noticeably larger than had been expected and required very careful attention. The basic difficulty arose because of small ^{55}Mn impurities in the stainless steel used. These led to a number of regions where backgrounds exceeded 10%. Accordingly the analysis was extended to include iterative techniques to remove the effects of in-scattered neutrons from the resulting cross sections.

The determination of the quantity of ^{242m}Am led to an auxiliary measurement (reported elsewhere in this report) from which a determination of $\bar{\nu}$ for ^{242}Cm resulted. Figure 4.22 shows the fission cross section of ^{242m}Am as determined in these experiments and as compared with the ENDF/B-V standard values for this cross section which have been used until recently. A comparison with recent measurements of Browne et al.[2] indicates that our cross-section values were some 13% higher at low energies and some 25% higher at high energies. A possible renormalization of our results is being considered.

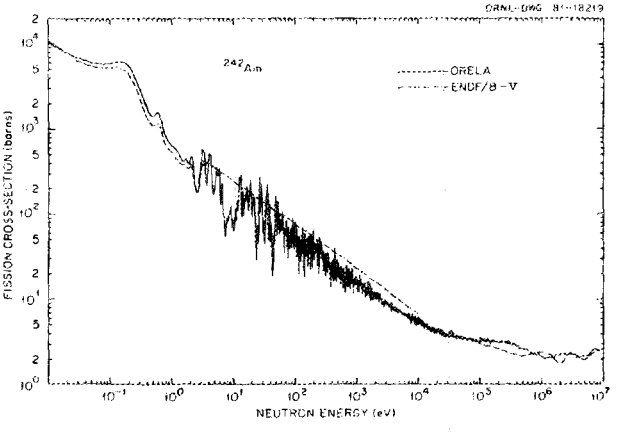


Fig. 4.22. Fission cross section for ^{242m}Am.

1. Lawrence Livermore Laboratory.
2. J. C. Browne et al., LLL report UCRL-8099 (September 1978).

MEASUREMENT OF THE FISSION CROSS SECTION OF ^{249}Cf AT ORELA

J. W. T. Dabbs C. E. Bemis, Jr.

In 1972 a measurement of the fission cross section of below ^{249}Cf 18.5 eV was made at ORELA using silicon solid-state detectors.[1] This measurement suffered from the difficulty that the intense alpha activity of the sample ($T_{1/2}$ = 352 years) caused essentially complete deterioration of the detectors in times of the order of 15 h. It was, in fact, this problem which led to the development of the hemeispherical fission chamber somewhat later.[2] The measurement of the fission cross section of ^{249}Cf has now been repeated, using time-of-flight techniques at ORELA, a flight path of 9 m, and pulse widths generally of 40 ns. With the use of a gaseous ionization (hemispherical) chamber, the measurements show almost no deterioration with time. As in the ^{242m}Am measurement, ^{235}U fission and the ^{6}Li(n,α) reaction served as standards at high and low energies respectively. A total of 360 h of data were obtained using a sample of 131 μg of ultrapure material. The cross section obtained in these measurements is substantially higher than that derived in the 1972 experiments. However, the agreement with the measurements of Silbert[3] are quite satisfactory in the resonance region from 18.5 eV to 58 eV. Several resonances found by Silbert[3] in his relatively impure sample do not exist in the present results. The very large resonance at 0.7 eV, originally found in the 1972 measurements, was verified except that the peak cross section is now found to be 8300 b instead of the 5800 b previously reported. There exists in this experiment the possibility that a renormalization will be required because of the possibility of loss of a portion of the ^{235}U standard prior to the experiment. An important cross check appears to be possible utilizing the results on the total cross section of ^{249}Cf which were recently obtained at ORELA.[4] Figure 4.23 shows

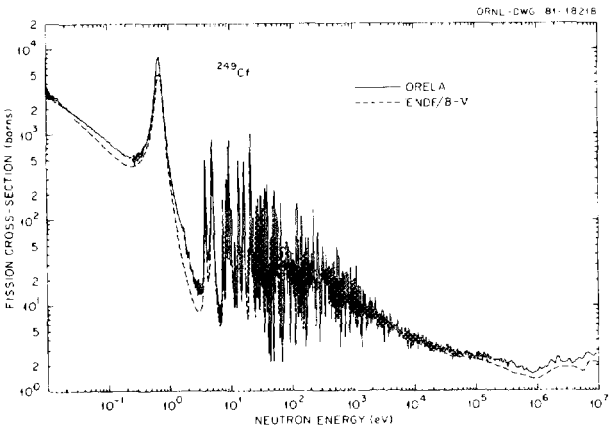


Fig. 4.23. Fission cross section for ^{249}Cf.

the results of the present experiment together with a curve showing the ENDF/B-V, which is based on the 1972 ORNL results below 18.5 eV.

1. J. W. T. Dabbs et al., ORNL-4937, p. 181 (1974).
2. J. W. T. Dabbs, N. W. Hill, C. E. Bemis, and S. Raman, p. 81 in *Proc. Conf. Nuclear Cross Sections and Technology*, ed. R. A. Schrack and C. D. Bowman, Natl. Bur. Stand. (U.S.) Spec. Publ. 425, 1975.
3. M. G. Silber, *Nucl. Sci. Eng.* **51**, 376 (1973).
4. R. F. Carlton et al., "Parameters of Neutron Resonances of ^{249}Cf," this report.

FISSION AND TOTAL CROSS SECTIONS OF ^{231}Pa

S. Plattard[1] G. deSaussure[4]
G. F. Auchampaugh[2] J. A. Harvey
N. W. Hill[3] R. B. Perez[5]

This study of ^{231}Pa + n is part of a general program on the investigation of the fission barriers of light actinides such as ^{234}U (ref. 6) and ^{232}Th (ref. 7). High-resolution fission cross section and angular distribution measurements on high-purity samples (less than 0.1 ppm fissile materials) of ^{231}Pa were made from 1 eV to 10 MeV using a gas scintillator (98% He–2% N_2). The fission cross section in the threshold region (0.1 to 0.4 MeV) has been resolved into separate members of various rotational bands. Two narrow peaks at 156.7 and 173.3 keV are assigned K^π of 3^+ and 3^-, respectively, using the fission-fragment angular distribution data of Sicre.[8] The occurrence of two such resonances is very likely the signature of a vibrational level ($K = 3$) trapped in the asymmetrical deformed third well of the ^{232}Pa potential energy surface.[9] Calculations of Möller and Nix[10] for the fission barrier of light actinides predict an asymmetrically deformed third minimum that can account for close-lying K bands of opposite parity.

Total cross-section measurements have been made on two samples of ^{231}Pa at liquid nitrogen temperature with an energy resolution of about 0.08%. The data have been analyzed with the R-matrix coed MULTI[11] to obtain neutron widths for 137 resonances up to 120 eV.[12] The average value of the radiation width was determined to be 40 ± 2 meV. The neutron widths of ^{231}Pa are needed to combine with the subthreshold fission data below 100 eV to obtain fission widths of the resonances. The fission strength appears to be randomly distributed over resonances and not concentrated in particular energy regions. This feature, together with the average fission width of 8 μeV, indicates that the first minimum of the ^{232}Pa fission barrier is of the order of, or lower than, the neutron separation enegy and the third minimum is rather shallow (0.5 to 1 MeV).

1. Centre d'Etudes de Bruyeres-le-Chatel.
2. Los Alamos National Labortatory.
3. Instrumentation and Controls Division.
4. Engineering Physics Division.
5. University of Tennessee.
6. G. D. James et al., *Phys. Rev. C* **15**, 2083 (1977).
7. G. F. Auchampaugh, S. Plattard, N. W. Hill, G. deSaussure, R. B. Perez, and J. A. Harvey, IAEA Symposium on Physics and Chemistry of Fission, Julich (RFA), May 14–18, 1979, and submitted to *Phys. Rev.*
8. A. Sicre, Ph.D. thesis, University of Bordeaux, 1976 (unpublished), report No. CENGB 7603; A. Sicre et al., vol. I, p. 187 in *Physics and Chemistry of Fission — 1979*, IAEA, Vienna, 1980.
9. S. Plattard, G. F. Auchampaugh, N. W. Hill, G. deSaussure, R. B. Perez, and J. A. Harvey, *Phys. Rev. Lett.* **46**, 633 (1981); also U.S. National Bureau of Standards Special publication No. 594, 1980 (unpublished), *Proceedings of the Conference on Nuclear Cross Sections for Technology, Knoxville, Tennessee, 1979*, p. 491.
10. P. Möller and J. R. Nix, vol. I, p. 103 in *Physics and Chemistry of Fission — 1973*, IAEA, Vienna, 1974.
11. G. F. Auchampaugh, Los Alamos Scientific Laboratory report LA-4633 (1974).
12. Abdel-Razik Z. Hussein, J. A. Harvey, N. W. Hill, and J. R. Patterson, *Nucl. Sci. Eng.*, in press.

NEUTRON CAPTURE CROSS SECTION MEASUREMENTS ON ACTINIDE NUCLEI

L. W. Weston[1] J. H. Todd[2]

The measurement of the neutron capture cross section of ^{237}Np, mentioned in the last report of this series,[3] has now been extended to high energies, completed, analyzed, and submitted for publication in *Nuclear Science and Engineering*. The neutron capture cross section of ^{237}Np was measured from 0.01 eV to 200 keV. The cross section was normalized at thermal-neutron energy to a value of 180 ± 6 b derived from previous total cross-section measurements from 1 to 100 eV and from the shape of the present data from thermal to the resonance region. Resonance parameters of some 120 levels were derived for the neutron energy region from 0.01 to 100 eV. Agreement with ENDF/B-V is poor in the thermal region (6.4%), excellent in the resonance region (about 2%) except for the 0.491-eV resonance, and good (about 5%) in the keV neutron energy region. An uncertainty analysis including a correlation matrix for group average cross sections was developed. Figure 4.24 shows the results of the cross-section measurements in the higher energy region. The resonance at 0.491 eV showed a major discrepancy but was fitted well with the new resonance parameters. The uncertainty analysis mentioned above represents a new departure and a new approach in actinide capture measurements and required a very considerable effort to carry out.

Preparations have now been completed for an important measurement on the capture cross section of ^{243}Am. Measurements are expected to begin, using very much improved electronic equipment, in the early part of the next reporting period.

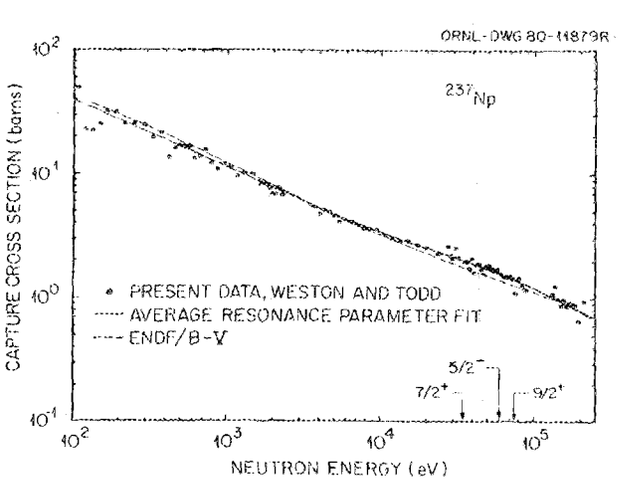


Fig. 4.24. Neutron capture cross section for ^{237}Np.

1. Engineering Physics Division.
2. Instrumentation and Controls Division.
3. J. W. T. Dabbs et al., *Phys. Div. Annu. Prog. Rep.* Dec. 31, 1978, ORNL-5498, p. 94.

PARAMETERS OF NEUTRON RESONANCES OF ^{249}Cf

R. F. Carlton[1] N. W. Hill[2]
J. A. Harvey M. S. Pandey[3]
R. W. Benjamin[4]

The *R*-matrix analysis of the total cross section of ^{249}Cf using the code MULTI[5] has been completed. The neutron and fission widths of 55 resonances were obtained based on an average radiation width of 30 meV. After correcting for missed resonances up to 62 eV, we obtain a value for the *s*-wave average level spacing of 1.22 ± 0.12 eV. The *s*-wave neutron strength function determined from the neutron widths of resonances up to 90 eV is $(1.06 \pm 0.22) \times 10^{-4}$. The distribution of reduced neutron widths agrees with a Porter-Thomas distribution, but the fission width distribution requires a χ^2 distribution with 3.2 ± 0.5 degrees of freedom. Resonance parameters reported earlier by M. G. Silbert[6] and J. W. T. Dabbs[7] from fission cross section measurements are in fair agreement with our results[8] from the analysis of the total cross section. Thermal-neutron cross-section measurements have also been made to determine the parameters for a bound level.

1. Middle Tennessee State University.
2. Instrumentation and Controls Division.
3. Virginia Polytechnic Institute.
4. Savannah River laboratory.
5. G. F. Auchampaugh, Los Alamos Scientific Laboratory report LA-4633.
6. M. G. Silbert, *Nucl. Sci. Eng.* **51**, 376 (1973).
7. J. W. T. Dabbs, N. W. Hill, C. E. Bemis, Jr., M. S. Moore, G. D. James, and A. N. Ellis, USAEC report ORNL-4937, p. 181 (1974).
8. R. F. Carlton et al., p. 707 in *Proceedings of the Conference on Nuclear Cross Sections for Technology, Knoxville, Tennessee, 1979*, U.S. National Bureau of Standards Special Publication No. 594, 1980 (unpublished).

PROMPT $\bar{\nu}_p$ OF ^{242}Cm

J. Halperin[1] B. H. Ketelle[1]
C. E. Bemis, Jr. R. W. Stoughton[1]
J. W. T. Dabbs R. W. Hoff[2]
R. J. Dougan[3]

The prompt-neutron multiplicity distribution for the spontaneous fission of ^{242}Cm and its average, $\bar{\nu}_p$ have been measured. The measurement was carried out with a neutron multiplicity counter using hydrogen moderation and neutron detection with ^{3}He proportional gas counters. The fission chamber was fabricated to be just under 10 cm in diameter in order to fit in the source cavity of the multiplicity counter. A value of 2.532 ± 0.013 was found for $\bar{\nu}_p(^{242}\text{Cm})$ and is based on an assumed value $\bar{\nu}_p(^{252}\text{Cf}) = 3.760$. A related measurement permitted the determination of the absolute efficiency of the fission chamber. A paper on this measurement has been published.[3]

1. Chemistry Division.
2. Lawrence Livermore Laboratory.
3. J. Halperin et al., *Nucl. Scie. Eng.* **75**, 56 (1980).

MEASUREMENT OF FISSION CROSS SECTION OF SPONTANEOUSLY FISSIONING ACTINIDES

H. T. Maguire[1] R. E. Slovacek[2]
C. Stopa[1] R. W. Hoff[3]
D. R. Harris[1] R. Lougheed[3]
R. C. Block[1] J. W. T. Dabbs

Using restricted transverse range (hemispherical plate) fission chambers and fast amplifiers developed at ORNL,[4] a program of measurements on spontaneously fissioning even isotopes of Cm has commenced at R.P.I. Neutron-induced fission events can "overwhelm" spontaneous events because of the large neutron flux available inside the 75-ton cube of Pb which comprises the RINS (Rensselaer Intense Neutron Spectrometer).[5] The energy resolution obtained is quite poor (≥30%), and averaged fission cross sections are obtained by comparison with a known standard (usually ^{235}U). Runs on ^{248}Cm and ^{246}Cm have been made; a measurement on ^{244}Cm will be made during FY81.

1. Rensselaer Polytechnic Institute, Troy, N.Y.
2. Knolls Atomic Power Laboratory, Schenectady, N.Y.
3. Lawrence Livermore Laboratory.
4. J. W. T. Dabbs et al., NBS Special Publication 425, 1975, vol. 1, p. 81; K. Rush, ORNL/TM-6239 (1978).
5. R. C. Block et al., NBS Special Publication 425, 1975, vol. 1, p. 93.

ACTINIDE CALCULATIONS; IMPACT OF ACTINIDE CROSS-SECTION MEASUREMENTS

C. R. Weisbin[1] D. Gilai[1]
M. L. Williams[1]

In addition to support for the analysis of actinide samples irradiated in EBR-II, which is described elsewhere in this report,[2] a substantial calculational effort has been placed on the impact of ORELA measurements on reducing data uncertainties. In particular, the impacts of ORELA measurements in recent years on the ENDF/B-V evaluated neutron data files have been examined; the impact in the actinide region has been particularly large and shows that measurements made at ORELA have had an extremely important impact on the reduction of data uncertainties in this area.

The technique of sensitivity analysis, which has been extensively developed in the Engineering Physics Division of ORNL,[3] has been applied in this work. A review of the changes in cross sections which occurred between the publication of ENDF/B-IV (1975) and ENDF/B-V (1979) has been made. In one case these cross sections were reduced to one-group effective cross sections for a typical LMFBR reactor neutron spectrum. Table 4.3 shows the results of the comparison between ENDF/B-IV and ENDF/B-V and the change in this one-group effective cross section. Table 4.4 shows a related effect on actinide waste production and neutron strength in spent fuel based on these calculations. The importance of the changes shown in these tables seems quite evident.

Table 4.3. Comparison of ENDF/B-IV and -V cross sections (One-group effective cross section for an LMFBR)

Data	ENDF/B-IV	ENDF/B-V	% change
^{241}Am capture	1.40	1.91	+36
^{241}Am fission	0.42	0.29	−31
^{243}Am	0.88	1.22	+39
^{243}Am fission	0.18	0.23	+28
^{244}Cm capture	0.53	0.93	+75
^{244}Cm fission	0.52	0.42	−19

Table 4.4 Effects of cross section changes (IV → V) on actinide production during an LMFBR refueling cycle

Nuclide	Change in actinide waste production per cycle (%)
^{241}Am	− 7
^{242m}Am	+30
^{243}Am	+ 6.3
^{242}Cm	+29
^{244}Cm	+29

Change in neutron source strength in spent fuel, +23%.

A summary report describing the results of all these comparisons and calculations is in preparation and is expected to be completed during FY81. This report will emphasize the matters described above and will make an assessment of current cross-section accuracies and will also include recommendations for future experiments based on the needs of reactor designers.

1. Engineering Physics Division.
2. S. Raman et al., "Experimental and Calculational Analyses of Actinide Samples Irradiated in EBR-II," this report.
3. C. R. Weisbin et al., *Nucl. Sci. Eng.* **66**, 307 (1978).

ACTINIDE NEWSLETTER

S. Raman

The Actinide Newsletter has been continued on approximately an annual basis since the first issue, which appeared in October 1977. Table 4.5 gives a listing of the number of contributions, the number of laboratories represented, and the number of countries from which contributions were received. Response from recipients of the report has been favorable. It appears that the newsletter is serving a useful purpose in providing cross communication among workers in the field throughout the world.

Table 4.5. Actinide newsletter

Issue No.	Date	Contributions	Laboratories	Countries
1	October 1977	36	23	15
2	February 1979	70	27	13
3	March 1980	60	25	11
4	March 1981	72	24	11

Regrettably, no contributions were received from the Soviet Union in time for inclusion in issue No. 4.

OAK RIDGE ELECTRON LINEAR ACCELERATOR

H. A. Todd[1] J. A. Harvey
T. A. Lewis[1] R. W. Peelle[2]

During the 27 months of this report period, the Oak Ridge Electron Linear Accelerator (ORELA) has continued to be operated an average of 400 h per month for neutron measurements. Trouble has been encountered due to after-pulses, and much work has been done to correct that condition. At this time it appears that the problem has been solved by the addition of a resistive network to absorb the reflected wave created when the high-voltage pulse hits the ferrite line. This after-pulsing has limited the power in the short-pulse modes.

The accelerator improvement project has been formally completed and has demonstrated a factor of 2 decrease in the width of a 17-ns (FWHM) bunch with an average beam power of 12 kW at 800 pulses per second. Vacuum difficulties have persisted, however, and gaps of a new mechanical design are now being fabricated. A technical report[3] has been written describing techniques for preparing cathodes and fabrication of high-current electron guns for ORELA.

1. Instrumentation and Controls Division.
2. Engineering Physics Division.
3. O. W. Christian and T. A. Lewis, *ORELA Electron Guns*, ORNL/TM-7886, to be published.

EXPERIMENTAL AND CALCULATIONAL ANALYSES OF ACTINIDE SAMPLES IRRADIATED IN EBR-II

S. Raman D. Gilai[2]
P. H. Stelson W. R. Laing[1]
J. H. Cooper[1] R. L. Walker[1]
M. L. Williams[2]

During 1967–70, several actinides between ^{232}Th and ^{241}Pu were irradiated in either position 1 or position 2 (see Fig. 4.25) inside the Idaho EBR-II

ORNL-DWG 81-9951

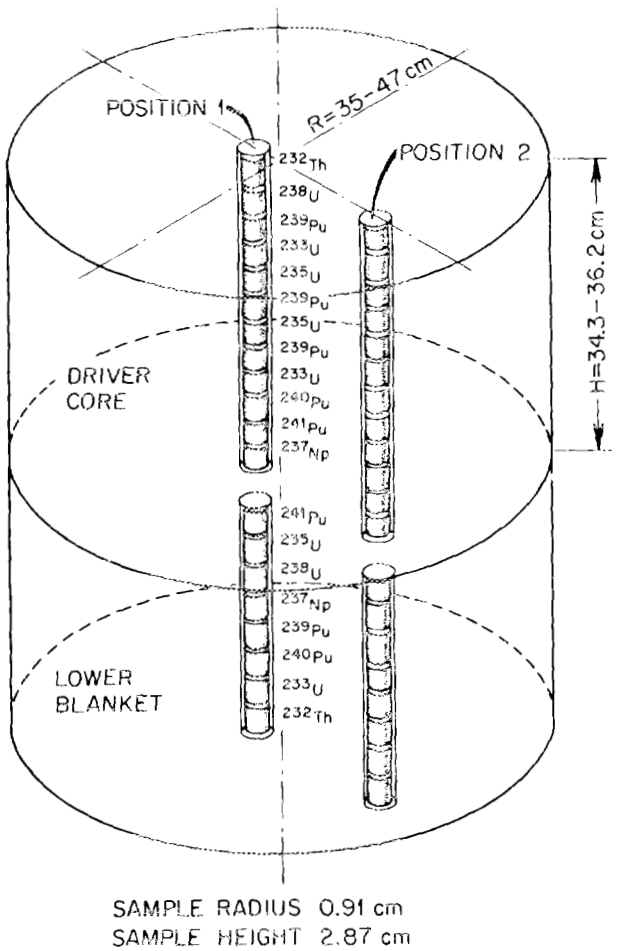


Fig. 4.25. Actinide irradiations in EBR-II.

reactor by ANL personnel. The EBR-II reactor configuration during this experiment consisted of a driver core of highly enriched (approximately 50%) ^{235}U, surrounded by a blanket of depleted ^{238}U or stainless steel. For a variety of reasons, the irradiated samples remained unanalyzed at ANL for several years. The samples were transferred to ORNL in 1977, and work began in earnest to determine their isotopic composition through mass spectroscopy and alpha counting. Because of the variety of samples that were irradiated and the numerous results that were obtained (in each sample, at least 5–6 nuclides were measurable), this experiment qualifies as a "depletion benchmark experiment." Such a study is useful for checking current methods and data used in the prediction of fast-reactor fuel-cycle parameters, such as breeding gain, reactivity swing, waste actinide production, and spent fuel characteristics (e.g., decay heat and neutron source strength). A calculational program was therefore initiated to answer the following questions: (1) How well can the burnup process be calculated? (2) How well do the calculations based on ENDF/B-IV compare with ENDF/B-V? (3) Can the experimental results be used to reduce the uncertainties in the cross-section files? Answers to these and other questions will be documented in an ORNL/TM report that is presently undergoing review.

1. Analytical Chemistry Division.
2. Engineering Physics Division.

U.S./U.K. HIGHER ACTINIDE IRRADIATIONS IN THE DOUNREAY PFR

S. Raman
H. L. Adair[1]
J. L. Botts[2]
J. H. Cooper[2]
E. H. Kobisk[1]
R. Pope[3]
T. C. Quinby[1]
R. L. Walker[2]

The objective of the joint U.S/U.K. program is to investigate the neutronic and irradiation behavior of higher actinides in fast breeder reactors. This is a joint program involving ORNL, HEDL, and the U.K. The higher-actinides test pin designed for insertion in the Dounreay PFR contains three sections of actinide oxides (fuel pellets) in a fuel configuration and 21 actinide oxides (physics samples) encapsulated in vanadium. ORNL has specific responsibilities for selecting and providing the isotopes, for fabricating the fuel pellets, for fabricating the dosimeters and the physics samples, and for loading and seal-welding the segments (with HEDL assistance). HEDL is responsible for test pin design, pin fabrication, final assembly of pin sections, quality assurance, and shipping to the U.K. ORNL responsibilities pertaining to test-pin preparation were successfully met (on schedule) by the middle of June 1981.

A major effort was required by several ORNL divisions to successfully prepare and characterize both physics specimen and fuel pellet materials. A significant accomplishment was the loading of 12 fuel pins, 4 each with $^{244}Cm_2O_3$, $^{241}Am_2O_3$, and a

mixture of $^{244}Cm_2O_3$, $^{241}Am_2O_3$, and several lanthanide oxides, which were essentially contamination-free after the loading process. This was accomplished by preparing high-density hot-pressed actinide pellets from fine powder produced in a urea precipitation process. The high-integrity pellets (3.8 mm in diameter and 3.8 mm long) were prepared in an ATJ graphite die (Fig. 4.26) by hot-pressing seven pellets at a time at 1300–1400 °C. Seven $^{244}Cm_2O_3$ pellets fabricated in a single pressing are shown in Fig. 4.27.

1. Solid State Division.
2. Analytical Chemistry Division.
3. Quality Assurance, Director's Division.

ORNL PHOTO 3768-81

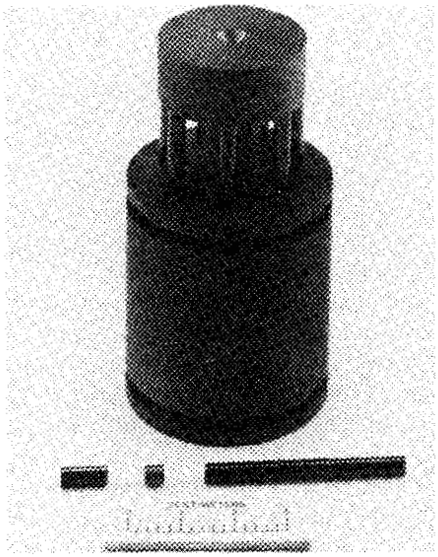


Fig. 4.26. A seven-position hot-press die employed in the preparation of fuel pellets.

ORNL PHOTO 3543-81

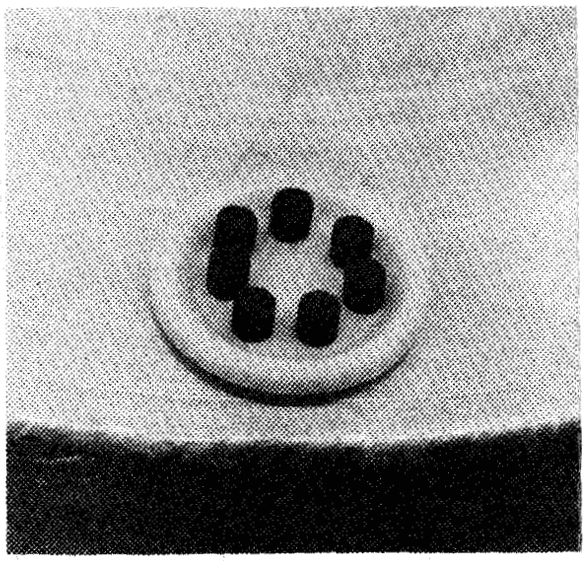


Fig. 4.27. Fuel pellets of ^{244}Cm on a thoria planchet.

5. Theoretical Physics

INTRODUCTION

J. B. McGrory

The theoretical physics program at ORNL is focused primarily on the nuclear physics of low- and intermediate-energy heavy-ion-induced reactions, that is, the physics which will be studied at the Holifield Heavy-Ion Research Facility. Major components of the program deal with the theory of ion-ion potentials in folding-model approximations, time-dependent Hartree-Fock descriptions of heavy-ion reactions, classical and semiclassical descriptions of heavy-ion reactions as derived from quantum-mechanical formulations of such reactions, and nuclear structure studies in the shell-model approximations. In the area of nuclear physics, two new programs have been instituted since the last report. One involves coupled-channels calculations of low-energy heavy-ion collisions. A second program has developed around a new nuclear theory position established as an integral part of the UNISOR program at ORNL and funded through the Oak Ridge Associated Universities. The program focuses on studies of nuclear structure in medium- and heavy-mass nuclei in which collective and single-particle degrees of freedom interact strongly. Both the theoretical and experimental nuclear physics programs at ORNL have benefited significantly in the past two years through an enlarged nuclear theory visitors program which has involved extended visits (one to three months) by theorists from other nuclear physics centers—Copenhagen, Frankfurt, Oxford, Liége, Giessen, etc.

A significant effort in theoretical atomic physics continues with particular interest on charge-exchange reactions which are of relevance to an orderly development of the magnetic fusion energy program.

We present here brief highlight statements of many large programs. Further detailed material is found in the references or can be obtained from the authors.

NUCLEAR STRUCTURE THEORY

G. Leander[1] J. B. McGrory

Shell-Model Calculations of $B(M1)$ Strengths in the Calcium Isotopes and the Quenching of the Spin Operator

J. B. McGrory B. H. Wildenthal[2]

As discussed in the experimental section, there is now available valuable new information on the positions and strength of the spin operator, σ, as deduced from analyses of (p,n) reactions. In certain cases, where only valence neutrons are "important," measurements of $M1$ strengths to excited states can yield complementary information on the nuclear σ operator. Recently, $M1$ strengths to 1^+ states in ^{42,44,48}Ca have been extracted from (e,e') cross sections to these states at Darmstadt.[3] "Giant" $M1$ states are observed in ^{42,48}Ca, and if the measured $M1$ strengths are compared to predictions of a simple $f_{7/2}^{n} \rightarrow f_{7/2}^{n-1}, f_{5/2}$ model for these transitions, the implication is drawn that the observed strength is about one-third of the predicted strength, implying a large renormalization of σ for these transitions. A shell-model calculation of these $M1$ strengths in a complete $(f,p)^{A-40}$ shell model of the Ca isotopes has

been carried out.[4] A modified Kuo-Brown shell-model residual interaction has been used. The observed magnetic moment of the ground state of ^{41}Ca is $-1.59\mu_N$ as compared to the value of $-1.91\mu_N$ which is calculated from the free magnetic operator. For the single-neutron nucleus ^{41}Ca, the $M1$ operator involves only σ. We assume a state- and energy-independent effective operator which reproduces this ground-state moment, namely, $\sigma_{eff} = 1.59/1.91\ \sigma$. With these effective operators, the total observed $M1$ strength is accurately reproduced in terms of total strength and centroid energy in both ^{42}Ca and ^{48}Ca. Ground-state configuration mixing effects reduce the total available $M1$ strength by 40% in ^{42}Ca and 25% in ^{48}Ca, suggesting such correlations cannot be neglected in considering the quenching effects of the operator σ. The results suggest that the quenchings of the σ operator extracted from excitation of 1^+ states are the same as that observed for many ground-state magnetic moments.

1. UNISOR.
2. Michigan State University.
3. W. Steffen et al., *Phys. Lett.* **95B**, 23 (1980); A. Richter, private communication.
4. J. B. McGrory and B. H. Wildenthal, to be published in *Physics Letters*.

Isotope Shifts in the Pb Isotopes

J. B. McGrory

Recent extremely precise measurements[1] of $K\alpha_1$ x-ray lines in Pb isotopes have been analyzed to produce "experimental" determinations of the change in the root-mean-square radius between the isotopes of ^{208,207,206,204}Pb, $\langle r^2\rangle_{A'\to A}$. Speth et al.[2] have calculated single-particle matrix elements of the operator r^2 for ^{207}Pb in an R.P.A. approximation based on the Migdal "Fermi liquid model." $\langle r^2\rangle_{208\text{-}206}$ and $\langle r^2\rangle_{208\text{-}204}$ have been calculated in a "complete" shell model of ^{206,204}Pb. The one-body matrix elements of $\langle r^2\rangle$ were taken from Speth et al.[2] The lowest six neutron-hole orbits in ^{208}Pb were included in the model space, and a modified Kuo-Herling interaction is used. The results are summarized here.

	$\langle r^2\rangle_{A'-A}$ (fm^2)	
$A'-A$	Calculated	"Observed"
208–207	0.061	0.080
208–206	0.116	0.121
208–204	0.226	0.220

The numbers extracted from experiment include effects due to $\langle r^4\rangle$ and $\langle r^6\rangle$ contributions, but these are estimated to be approximately 7% effects. Thus there is good agreement for the shifts in ^{204,206}Pb between theory and experiment.

1. G. L. Borchert et al., to be published
2. J. Speth, L. Zamick, and P. Ring *Nucl. Phys.* **A232**, 1 (1974).

NUCLEAR DIRECT REACTIONS

G. R. Satchler

Folded Potentials

G. R. Satchler W. G. Love[1]

Following the successful use of the folding model with semirealistic interactions to generate the real part of the optical potential for many heavy-ion systems (about 156 sets of data for 67 pairs of nuclei),[2] the model has been applied to the heavier systems ^{24}Mg, ^{28}Si + ^{208}Pb,[3] and ^{40}Ar + ^{160}Gd.[4] A nonspherical density was used for Gd so that the resulting nonspherical potential could describe inelastic excitation of the rotational states. Good agreement with the potential contours deduced semiclassically from the data was obtained (Fig. 5.1).

The folding model was found to overpredict (by a factor of about2) the strength of the real potential for the weakly bound ions ^{6}Li and ^{9}Be.[2] This anomaly was confirmed for ^{6}Li scattering data at higher energies of 74 MeV (MSU) and 88 MeV (ORNL)[5] and for ^{9}Be at 45 and 60 MeV.[6] It was also shown that analysis of inelastic data did not throw new light on the anomaly for these projectiles because the coupling potential is dominated by its imaginary part.

Extension of the model to describe the fusion barriers for fusion cross sections (which tend to be sensitive to the potential at slightly smaller radii) was found to be a little more successful than the use of global potentials such as the proximity potential.[7]

1. Consultant from University of Georgia, Athens.
2. G. R. Satchler and W. G. Love, *Phys. Rep.* **55**, 183 (1979); G. R. Satchler, *Nucl. Phys.* **A329**, 233 (1979).
3. J. S. Eck, T. R. Ophel, P. D. Clark, D. C. Weisser, and G. R. Satchler, *Phys. Rev.* **C 23**, 228 (1981).
4. R. E. Neese, M. W. Guidry, and G. R. Satchler, to be published.

5. G. R. Satchler, *Phys. Rev.* **C 22**, 919 (1980); C. B. Fulmer, G. R. Satchler, E. E. Gross, F. E. Bertrand, C. D. Goodman, D. C. Hensley, J. R. Wu, N. M. Clarke, and M. F. Steeden, *Nucl. Phys.* **A356**, 235 (1981).

6. J. S. Eck, T. R. Ophel, P. D. Clark, D. C. Weisser, and G. R. Satchler, *Nucl. Phys.* **A341**, 178 (1980).

7. L. C. Vaz, J. M. Alexander, and G. R. Satchler, *Phys. Rep.* **69C**, 373 (1981).

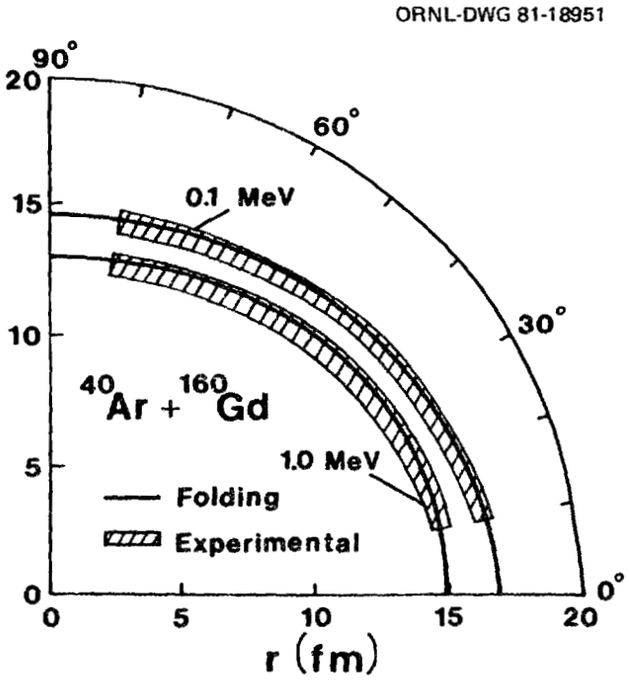


Fig. 5.1. Optical potential contours for ^{40}Ar + ^{160}Gd referred to the body-fixed axes for ^{160}Gd.

Heavy-Ion Scattering

S. Mukhopadhyay[1] G. R. Satchler
M. J. Rhoades-Brown

New elastic and inelastic data from ORNL for ^{10,11}B scattering ($E_{10} = 87$, $E_{11} = 80$ MeV) have been analyzed using both Woods-Saxon and folding-model potentials. (For data and fits, see experimental section.) The folding model gives good fits to the data without significant renormalization of the potentials; ^{10,11}B appear to be "normal," not "anomalous" like ^{6}Li, etc. As has been observed at lower energies, the large quadrupole moment of ^{10}B appears to give rise to significant quadrupole elastic scattering, which smooths out the angular distribution. This is illustrated in Fig. 5.2, where the quadrupole component was calculated in DWBA. The effects for

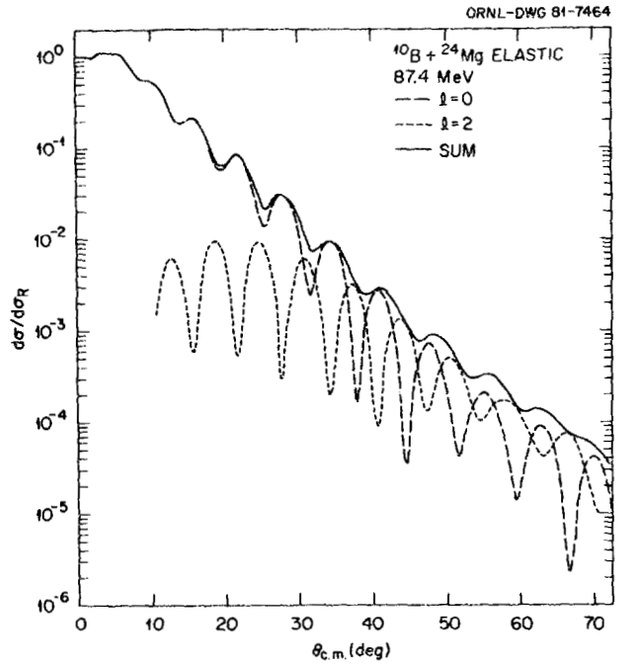


Fig. 5.2. Contributions to the elastic scattering of ^{10}B from its quadrupole moment ($l = 2$), calculated in distorted-waves Born approximation, compared to the usual monopole ($l = 0$) optical potential scattering.

^{11}B are smaller ($Q_{11} \approx 1/2\ Q_{10}$). The importance of these effects implies that the use of a simple spherical optical-model potential is questionable and that a coupled-equations analysis should be undertaken. This is now being considered.

A program of studies of the elastic scattering of certain interesting systems is under way. Part of the motivation has been to extend the folding model to systems like ^{16}O + ^{16}O and ^{16}O + ^{28}Si which exhibit large-angle scattering behavior that is characteristic of incomplete absorption (at least in the surface) and which is sensitive to the potential at smaller radii than is usually the case. This might reveal what kinds of corrections to folding are required. One tool has been the use of "model-independent" potentials that are defined by their values at a small set of radial points with spline interpolation between them. The results obtained so far are inconclusive. The presently available ^{16}O + ^{16}O data do not appear to be complete enough and suffer from fluctuations. The parameter search routine at present in use may not be efficient enough for this work, and the new fitter MINUIT is being incorporated in the optical-model code.

1. Guest assignee from Khalsa College, Bombay, India.

Dynamic Polarization Potential for $^{12}C + ^{12}C$

R. Wolf[1] U. Mosel[1]
O. Tanimura[1] G. R. Satchler

The contributions to the folded optical potential due to the individual and mutual excitations of the ^{12}C ions to their lowest 2^+ states have been calculated explicitly. The resulting complex nonlocal angular momentum and energy-dependent "polarization" potentials were examined and the "trivially equivalent" local potentials constructed. It was shown that these channels account for a substantial part of the absorptive potential besides making a significant attractive contribution to the real part.

1. Justus-Liebig-Universität, Giessen, West Germany.

Giant Resonances

G. R. Satchler

A collective-model analysis was made of data for (n,p) charge-exchange reactions on ^{14}N and ^{16}O, including excitation of the analoges of the giant dipole resonance, in collaboration with the University of California, Davis, group.[1]

A folding-model analysis of the excitation of giant resonances by (α,α') (ORNL data) was completed successfully except for some underestimate of the giant monopole state cross section. A similar study of results for these excitations by 200-MeV protons (ORNL data) has been initiated (with W. G. Love). Realistic interactions are available for this energy region, and density dependence is known to be of importance, for example, resulting in optical potentials of nonstandard shapes. The effects of these new features upon the inelastic scattering will be examined.

1. G. A. Needham, F. P. Brady, D. H. Fitzgerald, J. L. Romero, J. L. Ullmann, J. W. Watson, C. Zanelli, N. S. P. King, and G. R. Satchler, *Nucl. Phys.*, to be published.

Heavy-Ion Direct Reactions

M. J. Rhoades-Brown

The broad ambitious goal of heavy-ion direct-reaction physics is to understand in detail the nature of nuclear reactions explicitly involving a few degrees of freedom and the competition between these processes and other more complicated reaction mechanisms as a function of energy. This competition is associated with the imaginary component of the effective interaction between the two ions.

Heavy-ion collisions leading to multiple excitation of projectile or target require the use of a coupled-channels approach. The recent introduction of new mathematical techniques, which enable large-scale quantum-mechanical coupled-channels calculations to be carried out, have meant it is now possible to address many of the key physical questions in the field. Since October 1980, this work has concentrated in two main areas: (1) a detailed investigation of the role played by classical dynamics in the collision of two heavy ions and (2) the sensitivity of inelastic scattering to the radial form factors and structure models employed, especially for the mutual excitation channel.

Quantum-Mechanical and Classical-Limit Coupled-Channels Calculations for Very Heavy Systems

M. J. Rhoades-Brown M. W. Guidry[2]
R. J. Donangelo[1] R. E. Neese[2]

Inelastic excitation of heavy ions to high-spin states ($I \sim 20$) is expected to be a continued source of information on nuclear moments and localization in nuclear collisions. Most theoretical analysis of high-spin excitation data has been via the DeBoer–Winther classical trajectory prescription or the classical-limit S-matrix technique (CLSM) developed at Berkeley. In the latter approach, both the trajectory and internal degrees of freedom are treated with classical equations of motion.

To test and understand the validity of semiclassical methods, we performed a theory-theory comparison of quantal and CLSM calculations for the inelastic scattering reaction $^{40}Ar + ^{160}Gd$ at $E_{lab} = 120$ MeV to 185 MeV, exciting the ground-state rotational band of ^{160}Gd up to the 12^+ state by multiple quadrupole excitation.[3] This energy range includes regions of Coulomb excitation, Coulomb-nuclear interference, and strong absorptive damping. These quantal calculations were probably the largest ever carried out for both Coulomb and nuclear excitation.

In Fig. 5.3 we compare the CLSM calculations with two quantum-mechanical calculations for 180° scattering. The 8^+ state is the highest classically allowed excited state for this energy range. To reach states of higher spin using classical dynamics, it is necessary to analytically continue the dynamical motion into the classically forbidden region. The results confirm the accuracy of the CLSM technique

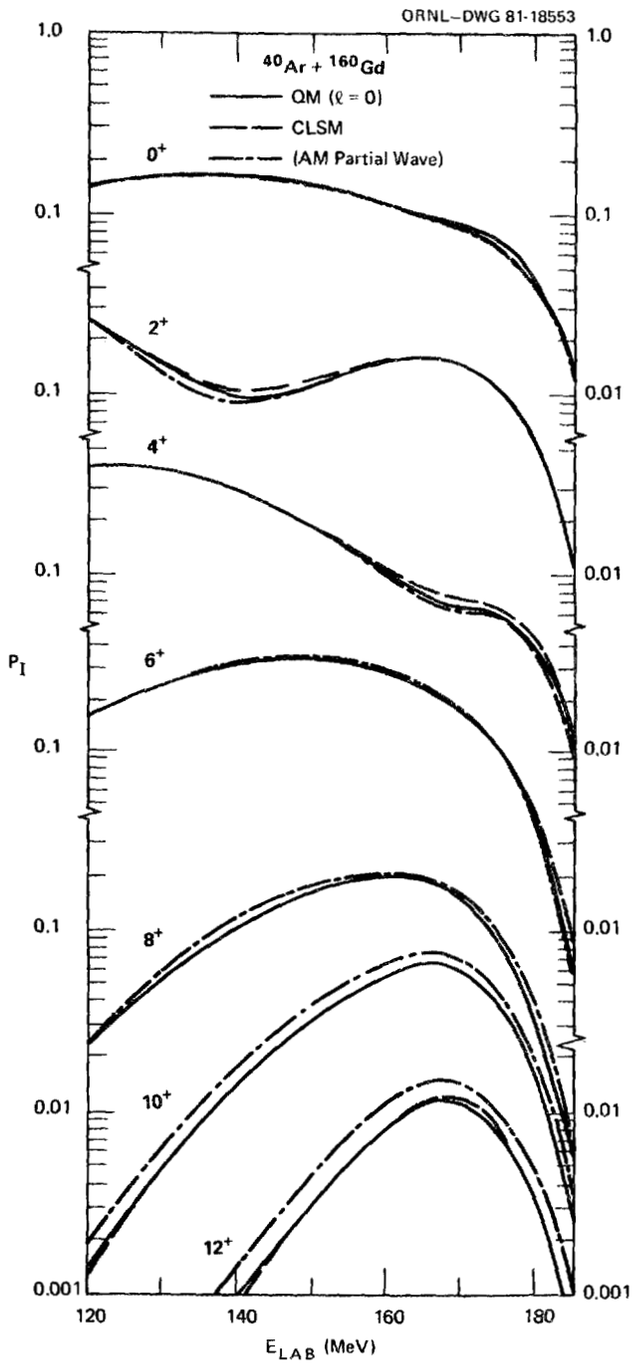


Fig. 5.3. Excitation probabilities calculated with the potential parameters described in the text. The solid line represents the quantal excitation probabilities calculated with $J = 0$ only. The dashed line is the $J = 0$ CLSM results. The dot-dashed line is the result of the full quantal calculation summed over many partial waves. The parameters used are given in the caption to Fig. 5.4.

for total angular momentum $J = 0$ S-matrix elements and suggest a classical and monotonic nature for the deflection function for spins $\leqslant 8^+$. The difference between the $J = 0$ quantal calculations and the full quantal calculations for ρ_{10+} (180°) and ρ_{12+} (180°) suggest that quantal interference effects are becoming important when we pass into the classically forbidden domain. This boundary represents a reliable measure of when simple single-trajectory semiclassical approaches will begin to lose their accuracy.

Calculations are in progress for other systems, including vibrators, exploring a range of asymptotic wavelengths.

---

1. Guest assignee from Universidade Federal do Rio de Janeiro, Brazil.
2. Part-time employee from University of Tennessee, Knoxville.
3. M. J. Rhoades-Brown, R. J. Donangelo, M. W. Guidry, and R. E. Neese, submitted to *Phys. Rev. Lett.*

Angular Localization and Approximations to the Deformed Nuclear Potential in Heavy-Ion Reactions

R. J. Donangelo[1] R. E. Neese[2]
M. W. Guidry[2] M. J. Rhoades-Brown

Studies of the ^{40}Ar + ^{160}Gd reaction have indicated that inelastic scattering reactions involving very heavy ions exhibit a large degree of classical behavior. In addition to radial localization, characterized by a small De Broglie wavelength, a large amount of angular momentum transfer and large moment of inertia $\mathscr{I}$ can lead to localization in the angle θ, defined by the symmetry axis of the deformed nucleus and the line joining the two centers of projectile and target.

These localization effects manifest themselves in a strong way by calculating CLSM excitation probabilities for different deformed nuclear potential shapes.[3] Figure 5.4 shows the effect of CLSM calculations using an exact deformed Woods-Saxon potential and a first-order expansion of this potential in the deformation parameter β. The strong state-dependent effects can be understood by plotting equipotentials for both potential prescriptions, as in Fig. 5.5. This figure also shows the near orientation associated with excitation of a given angular momentum state. These orientations are readily

ORNL-DWG 81-18952

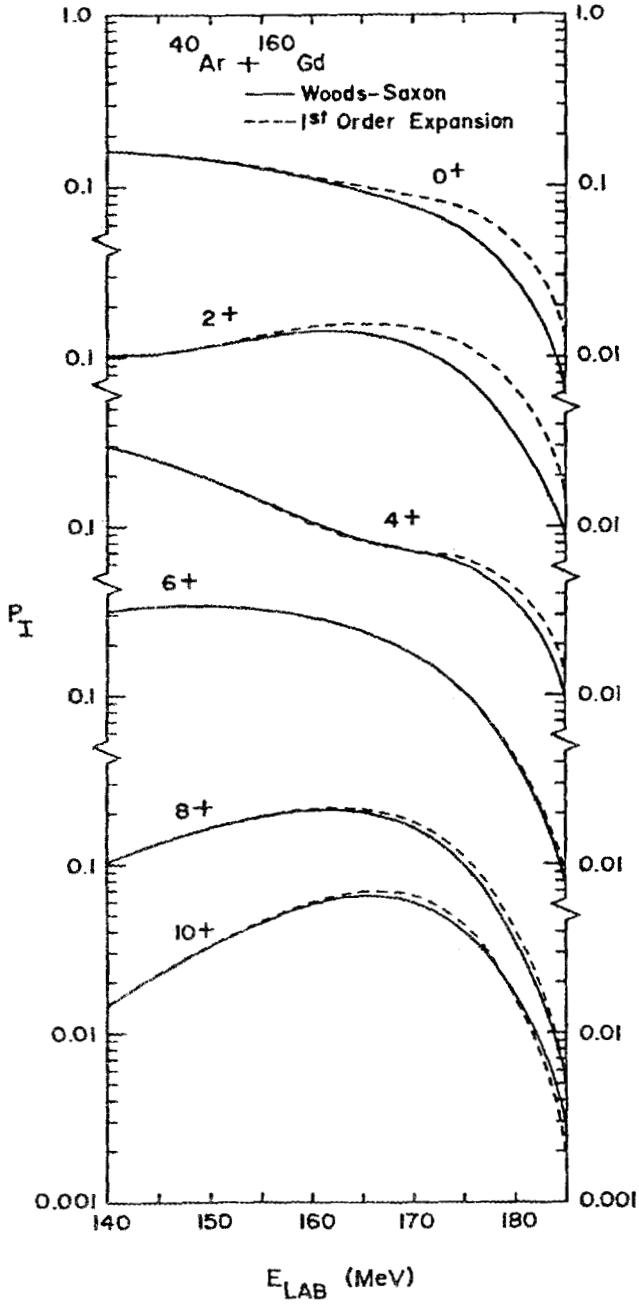


Fig. 5.4. Excitation probabilities for $J=0$ and 180° scattering using the CLSM technique and potentials given in the text. We used the following realistic parameters: quadrupole moment = 6.168 eb, real nuclear potential strength = 15 MeV, imaginary nuclear potential strength = 10 MeV, $R_0\beta_2$ = 1.3 fm. The radius parameter R_0 and diffuseness a in the equal geometry complex Woods-Saxon potentials were taken to be $R_0 = 1.2(40^{1/3} + 160^{1/3})$ fm and $a = 0.5$ fm. The moment of inertia $\mathcal{J}$ was taken from the first excited 2^+ state of the rotor, and higher excitation energies were assumed to be given by the deduced value of $\mathcal{J}$ and a static rotor model.

ORNL-DWG 81-18953

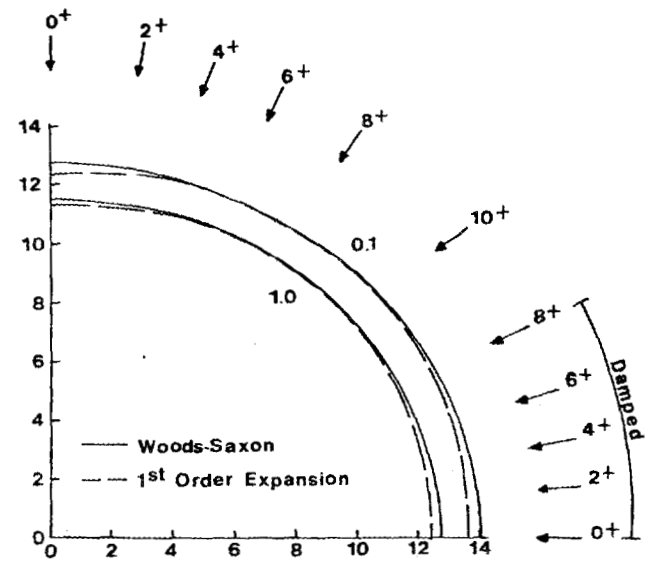


Fig. 5.5. Polar plot of the nuclear potential shape considered in the calculations presented in Fig. 5.3. The rotational symmetry axis coincides with the horizontal coordinate axis. The horizontal and vertical axes are in units of fermtometers. The regions of the ion-ion potential relevant for excitation of particular rotational states are indicated by arrows.

deduced by solving Hamilton's classical equations for the system, as required in the CLSM technique. These results, together with the reasonable agreement of CLSM and quantum-mechanical coupled-channels calculations, provide further evidence for angular localization in heavy-ion inelastic scattering reactions.

1. Guest assignee from Universidade Federal do Rio de Janeiro, Brazil.
2. Part-time employee from University of Tennessee, Knoxville.
3. R. J. Donangelo, M. W. Guidry, R. E. Neese, and M. J. Rhoades-Brown, submitted to *Phys. Lett. B.*

Classical Limits for Complex Optical Potentials

M. J. Rhoades-Brown R. Y. Cusson[1]
P. G. Reinhardt[2]

The reasonable agreement between $J = 0$ CLSM calculations and full quantum-mechanical treatments of very heavy-ion inelastic scattering reactions has prompted an investigation of the role played by complex optical potentials within possible Newtonian descriptions of heavy-ion reactions.

With these ideas in mind, the Vlasov equation for the case of a complex optical potential has been obtained from the Wigner representation for the density matrix and its classical limit derived. Solving the Vlasov equation within this limit shows that the corresponding classical equations of motion are the ones for a real potential augmented by a new equation for the time-dependent probability that the classical particle remain in its ground state. Classical elastic and absorption cross sections have also been worked out.

Higher-order terms in $\hbar$ (Wigner-Moyal limit) provide a logical basis on which to study wave-mechanical properties, such as tunneling and reflection, and their influence on classical trajectories. Calculations are in progress for simple one-dimensional problems and for more realistic problems where it will be possible to obtain comparison with full quantum-mechanical treatments.

1. Consultant from Duke University, Durham, N.C.
2. Guest assignee from University of Mainz, West Germany.

Multichannel Analysis Including Mutual Excitation

M. J. Rhoades-Brown

Experimental data[1] on the single and mutual excitation of $J_1^+ = 2_1^+$ states in the reaction ^{60}Ni(^{28}Si, ^{28}Si)^{60}Ni at E_{lab} = 140 MeV have been analyzed in a quantum-mechanical coupled-channels model. In the coupled-channels analysis it was assumed that the low-lying 2^+ level in ^{28}Si is a symmetric rotor and the 2^+ state in ^{60}Ni a one-phonon vibrational level. A simple four-parameter Woods-Saxon form was used for the optical model, and the transition form factor was constructed from the usual deformation prescription, expanding up to second order in the quadrupole nuclear and Coulomb deformation parameters.

Calculations within this model space show that Coulomb-nuclear interference is more dramatic for the mutual channel than for either of the single 2^+ excitation channels. For the single excitation channels, Coulomb excitation dominates the reaction mechanism at forward angles and nuclear excitation at more backward angles. For the mutual excitation channel, Coulomb and nuclear components were found to be approximately equal in magnitude across the whole angular range of interest. Calculations confirming the increased sensitivity of mutual excitation over single excitation were performed by perturbing the optical-model parameters by small amounts.

The calculations also showed that simultaneous Coulomb and nuclear excitation of projectile and target is an important contribution to the mutual excitation cross section. This direct second-order process interferes constructively with the two-step sequential excitation mechanism.

1. P. D. Bond et al., to be published.

STUDIES OF HEAVY-ION COLLISIONS IN THE TIME-DEPENDENT HARTREE-FOCK APPROXIMATION

K. T. R. Davies

TDHF Studies of Kr-Induced Reactions

K. T. R. Davies, K. R. Sandhya Devi[1], S. E. Koonin[2], M. R. Strayer[3]

Time-dependent Hartree-Fock (TDHF) calculations have been performed for head-on collisions of ^{86}Kr + ^{139}La and ^{84}Kr + ^{209}Bi over a wide range of bombarding energies.[4] Also, at particular energies, these calculations have been done for a number of incident total angular momentum (L) values.[5-7] Studies have been made of both fusion and deep-inelastic (DI) scattering. The computer code used is based on the approximation that the system is *axially symmetric* about the line joining the centers of mass of the colliding ions.[7,8]

Results of a typical calculation illustrating DI behavior are shown in Fig. 5.6 for ^{84}Kr + ^{209}Bi at E_{lab} = 600 MeV and L = 140ħ, which is a moderately central collision. The two ions come together, coalesce, and rotate, with an interchange of nucleons and energy. After a fairly long time, scission occurs from a rather compact shape, and then the two ions scatter through an angle of about 40° with an energy loss of about 170 MeV. Throughout the collision, the two ions distinctly retain their identities, while the surface diffuseness and the interior density are roughly constant, with some fluctuations due to single-particle motion. In Fig. 5.7 we compare the calculated final fragment kinetic energies and scattering angles with the experimental Wilczyński plot for ^{84}Kr + ^{209}Bi at E_{lab} = 714 MeV. The line connecting the TDHF points qualitatively follows the ridges of the contours of the experimental double-differential cross section. Many partial waves are concentrated in the DI region. For L = 250ħ, one observes a pronounced single-particle fluctuation, a

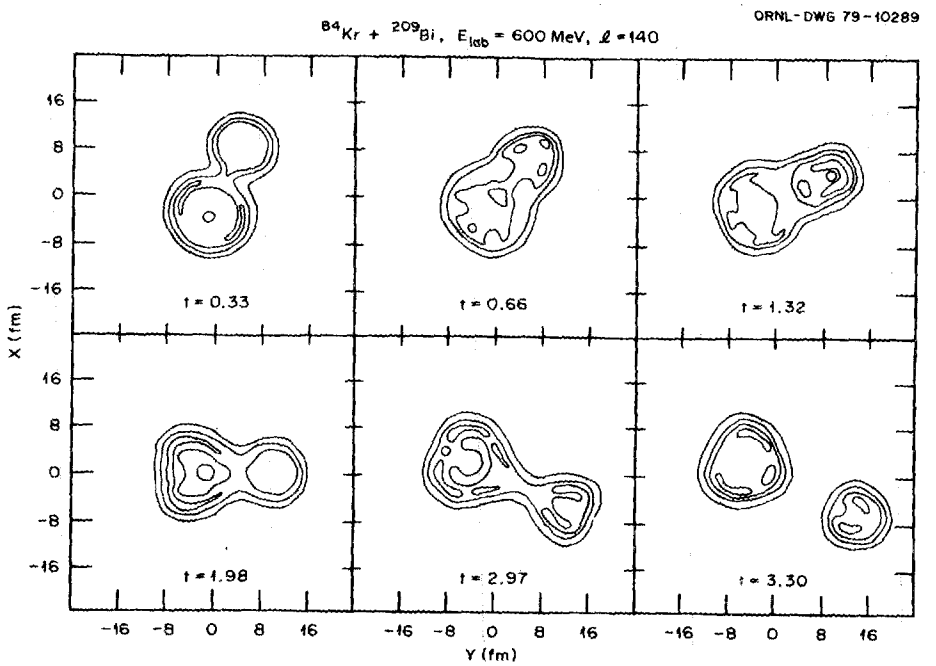


Fig. 5.6. Equidensity contours in the reaction plane at various times for the collision $^{84}Kr + ^{209}Bi$ at $E_{lab} = 600$ MeV and $L = 140\hbar$. The times are in units of 10^{-21} s.

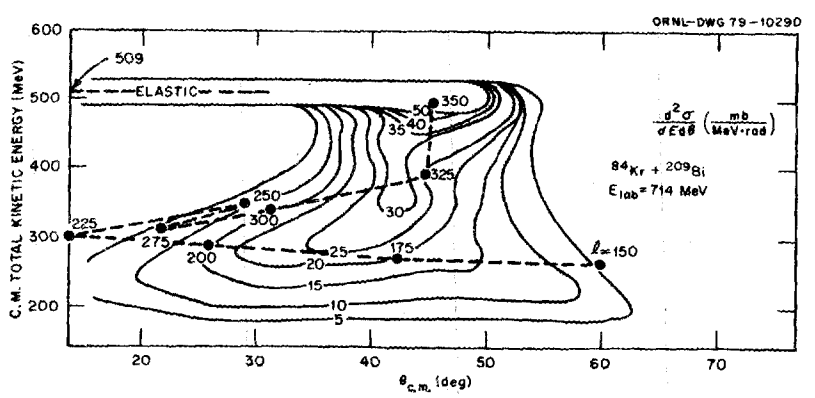


Fig. 5.7. Comparison of calculated points, labeled by the total angular momentum and joined by a dashed line, with the experimental Wilczyński plot from ref. 6 for $^{84}Kr + ^{209}Bi$ at $E_{lab} = 714$ MeV.

feature also found in calculations at $E_{lab} = 600$ MeV and $L = 180\hbar$. The calculated points are a bit too far forward relative to the data. The most serious discrepancy with experiment occurs for the small L, or large-angle, events, which are about 50 MeV above the experimental ridge; this is a weakness which persists in all of the TDHF Kr-induced reactions.[6,7]

Other scattering features which have been observed include the following. The calculated *mean* mass and charge of the scattered projectile-like ion are very close to those of the initial projectile, which agrees with the experimental behavior. However, the TDHF mass and charge distribution widths are always in very poor agreement with the experimental values. For some cases there is evidence of "fractionation along the mass asymmetry degree of freedom."[10] In all of the studies at small angular momentum, the final center-of-mass (c.m.) kinetic energy of the separated fragments is well below the entrance-channel Coulomb barrier and is roughly constant

over a wide range of bombarding energies; this effect is due to deformation effects in the exit channel.[4,7]

Figure 5.8 summarizes the fusion behavior for head-on collisions of $^{86}Kr + ^{139}La$. (Similar results are obtained for $^{84}Kr + ^{209}Bi$.[4]) First, we see that there is a relatively narrow low-energy region (near but above the Coulomb barrier) where one finds very long-lived coalesced configurations which eventually separate into two fragments. The fluctuations in τ_{int} in this regime suggest some type of underlying resonance structure. Then real fusion occurs for a broad band of higher energies. For all energies below the shaded region, the Kr-like ion appears to be "reflected from the target," whereas above the shaded region the Kr-like ion appears to "pass through the target." Above the fusion region we have verified the existence of a fusion angular momentum window. In Fig. 5.8 we also note the presence of a fusion energy threshold, that is, an energy above the Coulomb barrier below which fusion does not occur. Such thresholds have also been observed in macroscopic fluid dynamical calculations[11] and can be qualitatively explained as follows. The energy above the Coulomb barrier must be sufficiently high so that the two ions strongly interpenetrate one another, and if enough energy is dissipated the system *may* fuse. However, the energy of this threshold is extremely sensitive to the two-body effective interaction used in the TDHF calculation. In Fig. 5.9 we display the rms radius as a function of time for TDHF calculations of $^{86}Kr + ^{139}La$ at $E_{lab} = 505$ MeV and $L = 0$ with two different choices of the finite-range Skyrme interaction.[7,8] For Skyrme II the radius reaches a minimum value and then increases indefinitely as the system separates into two ions. For Skyrme III the rms radius undergoes several large oscillations and then is considerably damped, as fusion occurs. Thus TDHF calculations with the Skyrme III interaction give fusion at much lower energies than for Skyrme II.

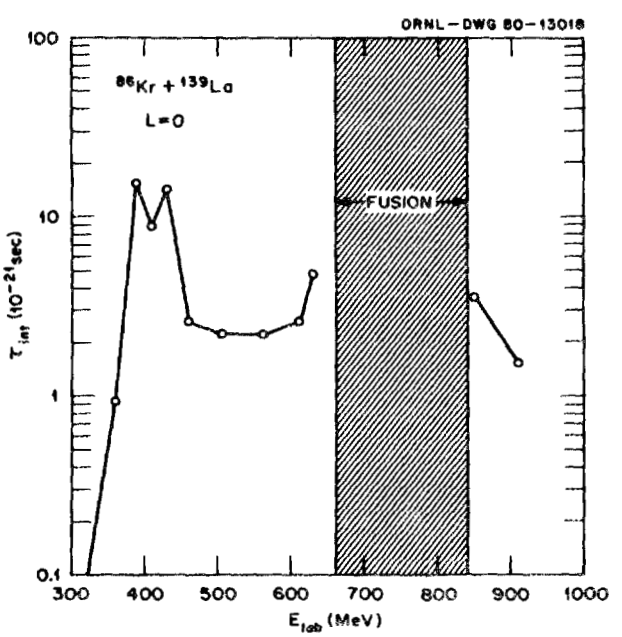


Fig. 5.8. The interaction time, τ_{int}, vs the laboratory bombarding energy for head-on collisions of $^{86}Kr + ^{139}La$. The interaction time is defined as the time interval during which the minimum density in the overlap region (between the two ions) exceeds half nuclear matter density. The open circles are the results of the TDHF calculations. The shaded area is the higher-energy fusion region.

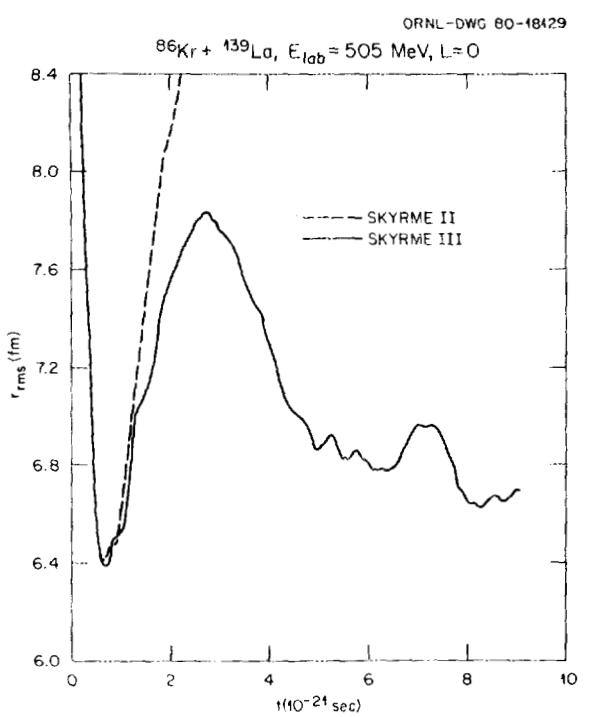


Fig. 5.9. The rms radius of the total system as a function of time for a head-on collision of $^{86}Kr + ^{139}La$ at $E_{lab} = 505$. The interactions used are the finite-range Skyrme potentials.[7,8]

1. California Institute of Technology, Pasadena.
2. Consultant from California Institute of Technology.
3. Consultant from Yale University.
4. K. T. R. Davies, K. R. Sandhya Devi, and M. R. Strayer, *Phys. Rev. Lett.* **44**, 23 (1980), and to be published in *Phys. Rev.*
5. K. T. R. Davies, V. Maruhn-Rezwani, S. E. Koonin, and J. W. Negele, *Phys. Rev. Lett.* **41**, 632 (1978).

6. K. T. R. Davies, K. R. Sandya Devi, and M. R. Strayer, *Phys. Rev. C* **20**, 1372 (1979).

7. K. T. R. Davies and S. E. Koonin, *Phys. Rev. C* **23**, 2042 (1981).

8. S. E. Koonin, K. T. R. Davies, V. Maruhn-Rezwani, H. Feldmeier, S. J. Krieger, and J. W. Negele, *Phys. Rev. C* **15**, 1359 (1977).

9. K. L. Wolf and C. T. Roche, vol. I, p. 295 in *Proceedings of the Symposium on Macroscopic Features of Heavy-Ion Collisions*, Argonne, Illinois, 1976, ed. D. G. Kovar, ANL report No. ANL/PHY-76-2 (unpublished).

10. R. Regimbart, A. N. Behkami, G. L. Wozniak, R. P. Schmitt, J. S. Sventek, and L. G. Moretto, *Phys. Rev. Lett.* **41**, 1355 (1978).

11. J. R. Nix and A. J. Sierk, *Phys. Rev. C* **15**, 2072 (1977).

TDHF Calculations of ^{136}Xe + ^{209}Bi

A. K. Dhar[1] K. T. R. Davies
B. S. Nilsson[2] S. E. Koonin[3]

TDHF calculations, using the axially symmetric two-dimensional model, have been completed for the heavy system ^{136}Xe + ^{209}Bi at E_{lab} = 940 and 1130 MeV.[4] The DI results are very similar to the Kr-induced reactions. In Fig. 5.10 we display the TDHF results on the experimental[5] Wilczyński plot for E_{lab} = 1130 MeV. In general, the agreement with experiment is excellent for this system since the calculations very well reproduce the grazing energies and angles, as well as the experimentally observed strong focusing into a narrow angular range in the DI region.

In Fig. 5.11 we demonstrate the pronounced three-body behavior which exists for E_{lab} = 1130 MeV and for L values between 0 and about 150ħ. Before scission occurs, a small alpha-like fragment of matter forms in the neck region. In most cases the dynamics causes the small fragment to eventually coalesce with one of the larger ions, as we see in Fig. 5.11*a* for L = 0. However, for L values in the neighborhood of L = 100ħ, the small fragment is able to completely separate from the two larger ions, thus exhibiting alpha-like emission (Fig. 5.11*b*). Similar behavior was found in TDHF calculations of ^{86}Kr + ^{139}La at E_{lab} = 710 MeV.[6]

Studying head-on collision of this system for a wide range of incident energies, we also searched for a fusion region analogous to that for the Kr-induced reactions. No fusion was found for any of the energies considered. For $E_{lab} \leqslant 1500$ MeV, the Xe-like ion was observed to "bounce off" the Bi-like ion, whereas for $E_{lab} \geqslant 1520$ MeV, the Xe-like ion was seen to "pass

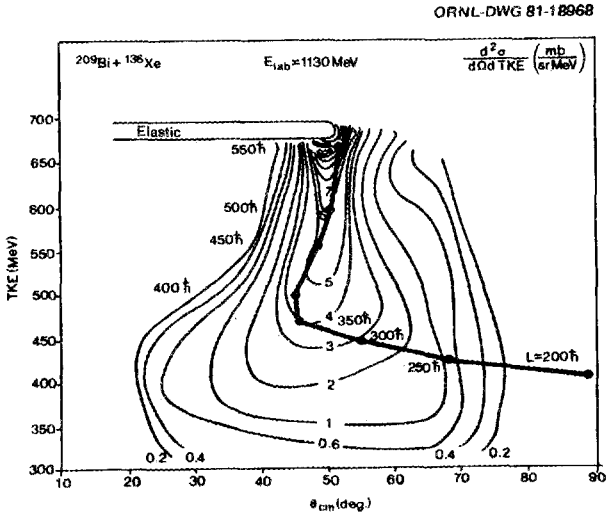


Fig. 5.10. Energy-angle correlation for TDHF calculations of ^{136}Xe + ^{209}Bi at E_{lab} = 1130 MeV, plotted on the corresponding experimental[5] Wilczyński plot. TKE is the final c.m. kinetic energy of the separated fragments. The TDHF results for various total angular momenta are joined by straight lines.

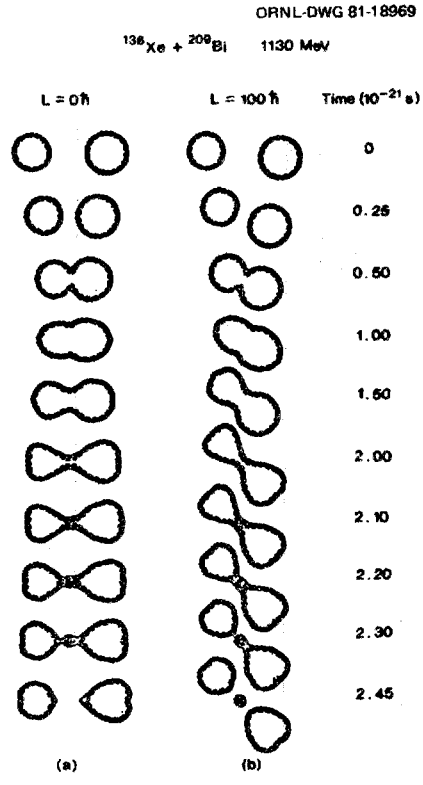


Fig. 5.11. Density contour plots in the reaction plane for ^{136}Xe + ^{209}Bi at E_{lab} = 1130 MeV, with L = 0 and 100ħ.

through the target." Therefore, if fusion exists, it must occur in a very narrow energy band ($\lesssim$20 MeV) near $E_{lab} \approx 1500$ MeV where a dramatic change from reflection to transparency occurs in the scattering behavior for head-on collisions.

1. Daresbury Laboratory, Daresbury, Warrington, England.
2. Niels Bohr Institute, Copenhagen, Denmark.
3. Consultant from California Institute of Technology, Pasadena.
4. A. K. Dhar, B. S. Nilsson, K. T. R. Davies, and S. E. Koonin, to be published in *Nucl. Phys. A*.
5. W. U. Schröder and J. R. Huizenga, *Annu. Rev. Nucl. Sci.* **27**, 465 (1977).
6. K. T. R. Davies, K. R. Sandhya Devi, and M. R. Strayer, *Phys. Rev.* C **20**, 1372 (1979).

Results of TDHF Calculations of $^{16}O + ^{93}Nb$ at E_{lab} = 204 MeV, Including Preequilibrium Emission of Nucleons

K. R. Sandhya Devi[1] S. E. Koonin[3]
M. R. Strayer[2] A. K. Dhar[4]
K. T. R. Davies J. M. Irvine[4]

TDHF calculations have been performed for $^{16}O + ^{93}Nb$ at $E_{lab} = 204$ MeV.[5] The model used for these studies is the frozen approximation,[6] in which each single-particle wave function ψ_i is assumed to separate into a time-dependent function ϕ_i and a time-independent function χ_i:

$$\psi_i(r, t) = \chi_i(z)\, \phi_i(x, y, t),\ i = 1, 2, \ldots, A,$$

where x and y are the coordinates of the scattering plane and $\chi_i(z)$ is chosen to be a one-dimensional harmonic oscillator wave function. In this model, nonaxial configurations are allowed.

Figure 5.12 shows a comparison between the TDHF results and the experimental[7] cross-section contours on a Wilczyński plot in the lab frame. All TDHF final lab energies below $E_{lab} \approx 175$ MeV correspond to negative-angle scattering and have been reflected to positive angles for the comparison with experiment. Fusion is found for initial angular momenta between $L = 31\hbar$ and $L = 75\hbar$, with strongly damped inelastic scattering observed both above and below the fusion region. We find that the total reaction cross section is composed of roughly equal amounts of fusion and DI scattering. However, a recent calculation[8] of this system using the axially symmetric model gives a fused final state for $L = 0$. Thus this discrepancy between the two models makes the identification of the lower inelastic branch somewhat uncertain.

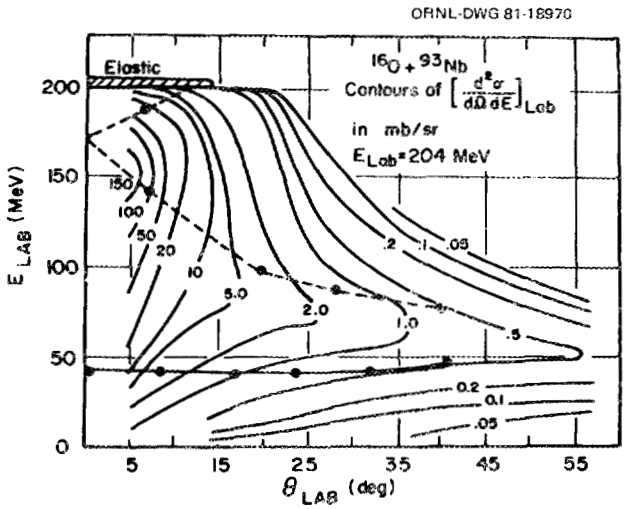


Fig. 5.12. Comparison of the TDHF results with the experimental (ref. 7) contours of the double-differential cross section in the lab frame. The solid circles are the TDHF points; those above the fusion region are connected by a dashed curve, while those below the fusion region are connected by a full curve.

This reaction also exhibits the emission of a small jet of nucleons very early in the calculation.[9] This behavior is found for both the frozen and axially symmetric approximations. The nucleon emission occurs roughly 0.2×10^{-21} s after the rms radius reaches its minimum value, when the system attains its most compact shape. Figure 5.13 shows density contour plots in the reaction plane for $L = 0$ and $L = 33\hbar$ at two times (just before and after the nucleon jet is emitted). Note that the emission is mostly along the x axis, which is the incident beam direction. An analysis of the jet reveals that it consists of roughly equal parts of neutrons and protons, predominantly from orbitals initially localized in the projectile. For the frozen approximation, the calculated fast-neutron *multiplicity* in coincidence with DI scattering is

$$M(\text{TDHF}) \approx 0.19,$$

which is consistent with the experimental value[10] of

$$M(\text{exp}) = 0.15 \pm 0.05.$$

As the total angular momentum L increases, we find that the number of particles decreases; above a critical angular momentum of $L_c \approx 70\hbar$, no jetting is observed. We have also roughly calculated the laboratory velocity V_{lab} of the jet. Comparisons are being made with predictions of various Fermi-gas models.

1. California Institute of Technology, Pasadena.
2. Consultant from Yale University, New Haven, Conn.
3. Consultant from California Institute of Technology, Pasadena.
4. Daresbury Laboratory, Daresbury, Warrington, England.
5. K. R. Sandhya Devi, M. R. Strayer, J. M. Irvine, and K. T. R. Davies, *Phys. Rev. C* **23**, 1064 (1981).
6. S. E. Koonin, B. Flanders, H. Flocard, and M. S. Weiss, *Phys. Lett.* **B77**, 13 (1978); K. R. Sandhya Devi and M. R. Strayer, *J. Phys. G* **4**, L97 (1978); *Phys. Lett.* **B77**, 135 (1978).
7. F. Obenshain, R. L. Ferguson, F. Plasil, A. H. Snell, and G. R. Young, unpublished.
8. K. T. R. Davies, unpublished.
9. K. R. Sandhya Devi, M. R. Strayer, K. T. R. Davies, S. E. Koonin, and A. K. Dhar, to be published.
10. A. Gavron, R. L. Ferguson, F. E. Obeshain, F. Plasil, G. R. Young, G. A. Petitt, K. G. Young, D. G. Sarantites, and C. F. Maguire, *Phys. Rev. Lett.* **46**, 8 (1981).

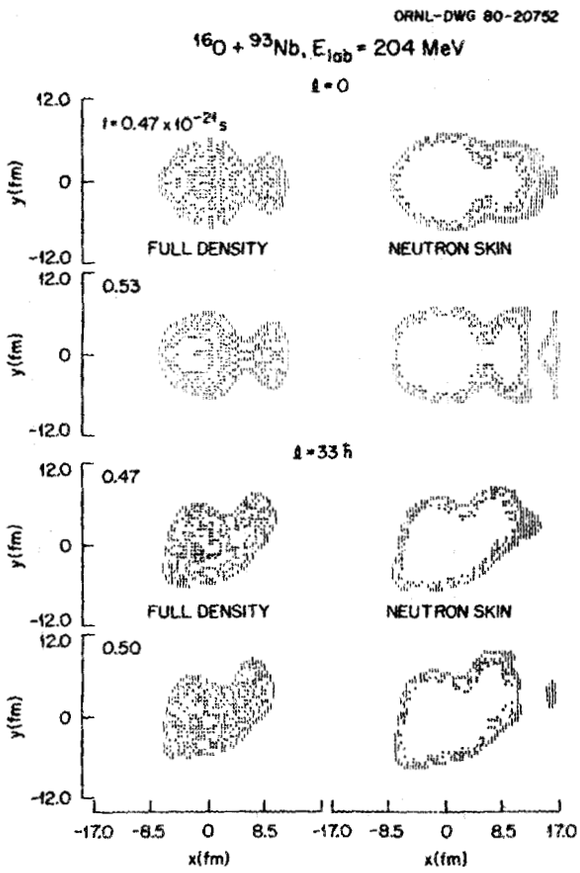


Fig. 5.13. Nucleon emission for $^{16}O + ^{93}Nb$ at E_{lab} = 204 MeV and for L = 0 and 33ħ. The left-hand pictures are density contours in the reaction plane (for $\rho > 1/10\ \rho_0$), while the right-hand pictures show the "skin" of the reaction-plane neutron distribution (for $1/100\ \rho_0 < \rho_n < 1/10\ \rho_0$), with $\rho_0 \approx 0.15\ \mathrm{fm}^{-3}$. The "skin" of the proton distribution is almost identical to that of the neutrons.

Transformations between Harmonic Oscillator Wave Functions in Different Coordinate Bases

K. T. R. Davies S. J. Krieger[1]

In a static Hartree-Fock (HF) calculation of a nucleus, one performs a series of iterations in order to achieve self-consistency of the nonlinear equations.[2] How fast the iterative process converges depends, in part, upon the choice of the initial set of basis states, which are usually chosen to be harmonic oscillator wave functions. For rapid convergence, it is especially desirable that these wave functions have symmetries which correspond as closely as possible to the geometric symmetries of the actual nucleus being calculated. Unfortunately, the basis states used do not always correspond to the natural geometric shape of the nucleus. For example, suppose one is performing the HF iterations in a cylindrical oscillator basis (or in cylindrical coordinates for a calculation in the coordinate representation) of a spherical closed-shell nucleus. Then it becomes useful to construct the initial harmonic oscillator wave functions from

$$|nlm\rangle = \sum_{n_\rho n_z} \delta_{2n+l,2n_\rho+n_z+m} \times \langle n_\rho n_z m | nlm\rangle | n_\rho n_z m\rangle ,$$

where n, l, m are the usual quantum numbers for a spherical representation and n_ρ, n_z, m are those for a cylindrical representation. Analogous expressions can obviously be written down for other cases in which the basis (or the coordinate system) is not appropriate for the shape of the nucleus being studied.

Using the creation operator formalism of Moshinsky,[3] we have derived general closed-form expressions for the three transformation brackets.

$$\langle nlm | n_\rho n_z m\rangle ,$$

$$\langle nlm | n_x n_y n_z\rangle ,$$

$$\langle n_x n_y n_z | n_\rho n_z m\rangle ,$$

where n_x, n_y, n_z are oscillator quanta for Cartesian coordinates. The expressions obtained contain rather simple sums of products of factorials. Formulas for all of these quantities have been derived by other authors.[4] However, we feel that our approach has the advantage of giving a single *unified* derivation of all three brackets. Also, our expressions appear in some cases to be simpler to evaluate on a computer than

those previously derived. These formulas have been recently used in constructing static HF wave functions by the imaginary time-step method.[5]

1. Lawrence Livermore Laboratory.
2. K. T. R. Davies, S. J. Krieger, and M. Baranger, *Nucl. Phys.* **84**, 545 (1966); S. J. Krieger, *Phys. Rev. C* **1**, 76 (1970).
3. M. Moshinsky, *The Harmonic Oscillator in Modern Physics: From Atoms to Quarks*, Gordon and Breach, Inc., 1968, pp. 4–41.
4. J. D. Talmon, *Nucl. Phys.* **A141**, 273 (1970); E. Chacon and M. deLlando, *Rev. Mex. Fis.* **XII**, 57 (1963); R. R. Chasman and S. Wahlborn, *Nucl. Phys.* **A90**, 401 (1967).
5. K. T. R. Davies, H. Flocard, S. J. Krieger, and M. S. Weiss, *Nucl. Phys.* **A342**, 111 (1980).

Effect of Dissipation on the Eigensolution near the Fission Saddle Point

K. T. R. Davies J. R. Nix[1] A. J. Sierk[1]

For any physical system it is important to understand the behavior of small oscillations about its equilibrium positions. For a nucleus undergoing fission, the normal modes about its saddle point have been calculated several years ago on the basis of the nonviscous liquid-drop model.[2] However, since that time, it has been recognized that large-amplitude nuclear motion such as that which occurs in fission and heavy-ion reactions involves some dissipation of collective energy into internal single-particle excitation energy.[3] It is, therefore, important to be able to calculate the small oscillations when the equations of motion include viscosity.

Two equivalent methods have been developed for determining the eigenvalues and eigenvectors for small oscillations near an equilibrium point when dissipation is present. One method relies on the Lagrangian formulation of the equations of motion, and the other relies on the Hamiltonian formulation. The eigenvalues are, in general, complex, but for unstable or overdamped motion they are purely real. The Hamiltonian can be expressed as a sum of single harmonic oscillations, but these cannot be interpreted as normal modes of motion. Calculations of various nuclei are currently in progress.

1. Los Alamos National Laboratory.
2. J. R. Nix, *Ann. Phys. (N. Y.)* **41**, 52 (1967); *J. R. Nix, Nucl. Phys.* **A130**, 241 (1969).
3. K. T. R. Davies, A. J. Sierk, and J. R. Nix, *Phys. Rev. C* **13**, 2385 (1976); K. T. R. Davies, R. A. Managan, J. R. Nix, and A. J. Sierk, *Phys. Rev. C* **16**, 1890 (1977); A. J. Sierk, S. E. Koonin, and J. R. Nix, *Phys. Rev. C* **17**, 646 (1978); F. Beck, M. Dworzecka, and H. Feldmeier, *Z. Phys.* **A289**, 113 (1978).

NUCLEAR DYNAMICS FROM A MICROSCOPIC AND A MACROSCOPIC VIEWPOINT

C. Y. Wong

The comprehensive program to study nuclear dynamics from a microscopic and a macroscopic viewpoint has been continued. We list below the recent advances.

Elastic Nuclear Vibrations

C. Y. Wong N. Azziz[1]

Previously, we showed that starting with the time-dependent Hartree-Fock approximation, the equation of motion for some collective motion of the nuclear fluid can be approximated by the Lamé equation appropriate for the propagation of elastic waves,[2] the properties of elasticity being a peculiar manifestation of the quantum stress tensor.[3] We have now considered the nuclear giant resonances as elastic vibrations of a nucleus.[4] Eigenenergies and widths for the isoscalar electric multipole states (0^+, 1^-, 2^+, 3^-, 4^+, ...) and the isoscalar magnetic multipole states (1^+, 2^-, 3^+, 4^-, ...) are obtained. The energies and the widths of the 0^+, 2^+, and 3^- states agree well with those of the observed giant resonances. Nuclear viscosity coefficients and the incompressibility of nuclear matter are extracted. As the surface tension and Coulomb charges are also taken into account, both the high-lying electric multipole "giant resonance" state and the low-lying "liquid-drop" states emerge as eigenstates of the same characteristic equation. Similarities and differences between these two types of states can therefore be assessed.

Calculations of the elastic mode of giant multipole resonances has been extended to other types of collective vibrations involving spin and isospin waves. We have determined the relevant electric and magnetic multipole states for the isovector, the spin vector, and the spin-isovector modes. We find that for a given electric or magnetic state with multipolarity l different from zero, the lowest eigenenergies for the different modes of giant resonances (isoscalar, isovector, spin-vector, spin-isovector) are approximately degenerate.[5] On the other hand, the positions of the $l^\pi = 0^+$ states depend on the nuclear incompressibility and the symmetry energy coefficients. Their eigenenergies can be quite different. The theoretical eigenenergies for the giant isovector electric multipole states compare well with experimental data.

Extended TDHF Calculations

C. Y. Wong K. T. R. Davies

Previously, we formulated an extended time-dependent Hartree-Fock approximation (ETDHF) to include particle collisions due to residual interactions.[6] We have studied numerically a concrete case in the collision of ^{16}O and ^{40}Ca in the extended time-dependent Hartree-Fock approximation.[7] We find that particle collisions are inhibited by the presence of a large single-particle shell gap. The fusion window persists even in the ETDHF approximation.

Mean Field Effects in Intermediate-Energy (about 200 MeV/A) $^{16}O + {}^{40}Ca$ Collisions

C. Y. Wong K. T. R. Davies

To compare with the results of heavy-ion collisions obtained with the assumption of nuclear hydrodynamics,[8] we have examined the effects of the mean field in intermediate-energy heavy-ion collisions with the TDHF approximation.[9] It is found that there is a prominent volcano effect in which the high-density region resulting in the collision produces a repulsive potential to drive the nucleons away from this region. By such an effect, the ^{16}O nucleus is completely disintegrated in the collision of ^{16}O and ^{40}Ca at about 100 MeV per nucleon, while the ^{40}Ca nucleus becomes only moderately excited after the collision.

Studies of Transverse Momentum Widths in Intermediate-Energy Heavy-Ion Collisions

K. van Bibber[10] C. Y. Wong

Previously, in our investigation of the intermediate-energy heavy-ion peripheral reaction, we observed an interesting orbital dispersion effect due to the motion of the projectile before breakup. We have now examined the systematic decrease of the transverse momentum width as a function of the isotopic charge of the fragment.[11] It is found that this isotopic effect may be due to the final-state Coulomb interaction between the fragment and the exploding protons on the same side of the other nucleus.

Fragmentation and Hard-Scattering Processes in Relativistic Heavy-Ion Collisions

C. Y. Wong R. Blankenbecler[12]

We have examined the direct fragmentation process and the hard-scattering processes in relativistic heavy-ion collisions.[13] In terms of these two processes, the proton-inclusive data of Anderson et al. for the reaction $\alpha + {}^{12}C \rightarrow p + X$ at different bombarding energies have been successfully analyzed. It is found that direct fragmentation dominates the cross section at 0° and 180°. On the other hand, the hard-scattering process dominates the quasi-elastic peak when the transverse momentum far exceeds 0.1 GeV/c.

The examination of the direct fragmentation and hard-scattering processes leads to the proper scaling variables for the two different processes.[14] They give the Feynmann scaling variable at the ultrahigh-energy limit and can be considered the generalization of the Feynmann scaling variable in the case when the rest masses are not negligible. These variables have been successfully applied to the proton and the pion production in relativistic heavy-ion reactions. In terms of these variables, the counting rules of Schmidt and Blankenbecler[15] are found to be approximately valid.

A Basic Distribution Model for Intermediate-Energy Heavy-Ion Collisions

C. Y. Wong

To examine intermediate-energy heavy-ion collisions, we introduce a basic distribution model[16] which includes the peripheral fragmentation model of Feshbach[17] and Goldhaber[18] as a special case. The model is applicable to both peripheral and central collisions and is not limited to isotropic basic momentum distributions. In terms of such a model, the experimental data for ^{40}Ar at 800 MeV per nucleon for the production of proton and composite particles in the central region can be successfully analyzed.

---

1. University of Pureto Rico, Mayaguez, Puerto Rico.
2. C. Y. Wong and J. A. McDonald, *Phys. Rev. C* **16**, 1196 (1977).
3. C. Y. Wong, *J. Math. Phys.* **19**, 1008 (1975).
4. C. Y. Wong and N. Azziz, to be published.
5. C. Y. Wong, to be published.
6. C. Y. Wong and H. H. K. Tang, *Phys. Rev. Lett.* **40**, 1070 (1978); *Phys. Rev C* **20**, 1419 (1979).
7. C. Y. Wong and K. T. R. Davies, *Phys. Lett.* **96B**, 258 (1980).
8. H. H. K. Tang and C. Y. Wong, *Phys. Rev. C* **21**, 1846 (1980).
9. C. Y. Wong and K. T. R. Davies, to be published.
10. Stanford University, Stanford, Calif.
11. K. van Bibber and C. Y. Wong, to be published.
12. Stanford Linear Accelerator Center, Stanford, Calif.
13. C. Y. Wong and R. Blankenbecler, *Phys. Rev C* **22**, 2433 (1980).

14. C. Y. Wong and R. Blankenbecler, SLAC report 2488 (1980); C. Y. Wong and R. Blankenbecler, *Proceedings of the Workshop on Nuclear Dynamics, March 17–21, 1980, Granibakken, California*, LBL-10688.

15. I. Schmidt and R. Blankenbecler, *Phys. Rev. D* **15**, 332 (1977).

16. C. Y. Wong, *Proceedings of the 5th High Energy Heavy Ion Summer Study, Berkeley, California, May 1981.*

17. H. Feshbach, *International School of Nuclear Physics Heavy Ion Interactions at High Energies*, ed. D. Wilkinson, Pergamon Press, Oxford, England.

18. A. S. Goldhaber, *Phys. Lett.* **53B**, 306 (1974).

THE UNISOR NUCLEAR STRUCTURE THEORY PROGRAM

G. A. Leander[1]

A theory program which connects UNISOR—the university isotope separator facility located at ORNL—with the theory division was started in April 1981. The line of research it includes now is concerned with the theoretical understanding and spectroscopic signatures of nuclei whose single-particle and collective features may interact strongly. This area has a large interface with the experimental activity at UNISOR and more generally at the heavy-ion center. Listed here are some of the in-progress projects in this program.

Transitional Nuclei

In order to compare systematically several distinct elements of the interacting boson-plus-fermion model with earlier core quasi-particle coupling models and results, a scheme of calculation is being developed in collaboration with F. Dönau and S. Frauendorf (University of Tennessee and Dresden). Subsequent calculations will be applied to a spectroscopic analysis of odd-A nuclei in the neutron-deficient $Z = 52$ to 60 region. This region is poorly understood and relevant for experimental reasons.

Deformed Nuclei

Recent calculations[2] have charted a region of light actinide nuclei where the potential energy according to the folded Yukawa model is minimized for parity-breaking shapes. Currently, generalizations of standard models for low-energy states are being made and applied to check the overall plausibility of the theory. A crucial experiment, suggested in some detail together with A. Winther, would be to measure directly the octupole moment of ^{227}Ac.

Nuclei at Very High Spins

Recent work based on the cranking model has predicted a variety of band characteristics in rare-earth nuclei. Improved techniques and investigations relevant to the cerium region, now being studied at ORNL, are planned with S. Frauendorf (University of Tennessee and Dresden). In order to obtain quasi-continuum gamma-ray spectra from microscopic theories, a probability spectrum method is being developed in collaboration with Y. S. Chen (University of Tennessee and Institute of Atomic Energy, Academia Sinica, Peking). Current topics include cranking and particle-rotor calculations to evaluate the $M1$ contributions, Monte Carlo cascade calculations to study the applicability of a temperature concept, and a random matrix model to investigate band structure at high level density.

1. UNISOR.
2. Collaboration with P. Möller, R. S. Sheline, A. Sierk, et al.

THEORETICAL ATOMIC PHYSICS

R. L. Becker C. Bottcher

Our research has concentrated on processes involving inner-shell electrons or highly excited outer-shell electrons, for which the independent Fermi particle (IFP) description is most nearly valid. Coupled-channel quantum-mechanical theory is used for the inner-shell reactions and classical trajectory Monte Carlo theory for the Rydberg collisions. A major task for the future is the development of methods for electrons in intermediate shells where dynamical correlations with other electrons, during a collision with an ion, are expected to be important. Below we review the main projects of the past year.

Contributions of multielectron processes to inner-shell charge transfer and vacancy production (R. L. Becker, A. L. Ford,[1] and J. F. Reading[1]) We denote by $\sigma_{C,\nu K}$ the inclusive cross section for producing all final states containing at least one charge transfer to the projectile and at least one vacancy in the target K shell. In the IFP model, multielectron processes, such as transfer from the L shell together with ionization or excitation from the K shell, contribute to $\sigma_{C,\nu K}$. Different pathways (reaction mechanisms) leading to the same final state have interfering amplitudes. Our previous coupled-channels calculations of inner-shell charge transfer and vacancy production for p + Ar collisions have been extended[2] to the bare projectiles

α and C^{6+} with 1 to 9 MeV amu^{-1}. The contributions of multielectron processes to our calculated $\sigma_{C,VK}^{IFP}$ increase strongly with Z_p. For $Z_p = 6$, $\sigma_{C,VK}^{IFP}$ differs by up to a factor of 3 from the single-electron value, $\sigma_{C,VK}^{SP}$. The first experimental data for the projectile-charge dependence of the cross section $\sigma_{C,VK}$ have recently been obtained by Rodbro et al. at Aarhus with H^+, He^{2+}, and Li^{3+} on neon. We have performed calculations[3] for these cases. Figure 5.14 shows that for He^{2+} the inclusion of multielectron processes improves the agreement with the data but that for Li^{3+} the data do not extend to low enough impact energy to confirm the predicted enhancement by multielectron processes. (Another predicted manifestation of IFP many-electron effects in ion-atom collisions is the intensity distribution of x-ray satellites, which is discussed separately below.) Both the experiments and our calculations exhibit a dependence of $\sigma_{C,VK}$ on Z_p less strong than the factor Z_p^5 contained in the OBK approximation.

A new version of atomic-orbital coupled-channels theory, the "one-and-a-half-center expansion"[4] (J. F. Reading,[1] A. L. Ford,[1] and R. L. Becker) In the near-symmetric situation where the charges of the target and projectile nuclei are nearly the same, a single-centered expansion in target orbitals becomes inaccurate because it fails to allow for the depletion of probability density near the target, caused by the charge transfer. A novel approach to this problem retains the computational advantage of the single-centered expansion yet maintains unitarity. It is based on the observation that when a large number of target-centered states are employed, a projectile-centered state can be well described by the target-centered basis when the projectile is near the target and only becomes independent of that basis when the projectile moves out of the region of interaction. In the full two-center coupling method the matrix of time-dependent coefficients of the single-electron states becomes ill-conditioned when the projectile is close to the target, because of the redundancy (strong overlap) of states. The time dependence of these coefficients loses physical meaning so long as the redundancy persists. In our new method the time dependence of each charge-transfer coefficient is prechosen to within a constant factor. These constants, the charge-transfer amplitudes, are determined self-consistently. A simple, physically reasonable choice of the time dependence leads to a solution which can be expressed in terms of that of the single-centered expansion. The accuracy of the method has been demonstrated in a calculation, shown in Fig. 5.15, of the proton-hydrogen collisions in the 15–100 keV energy range. Extensive use of the method is planned.

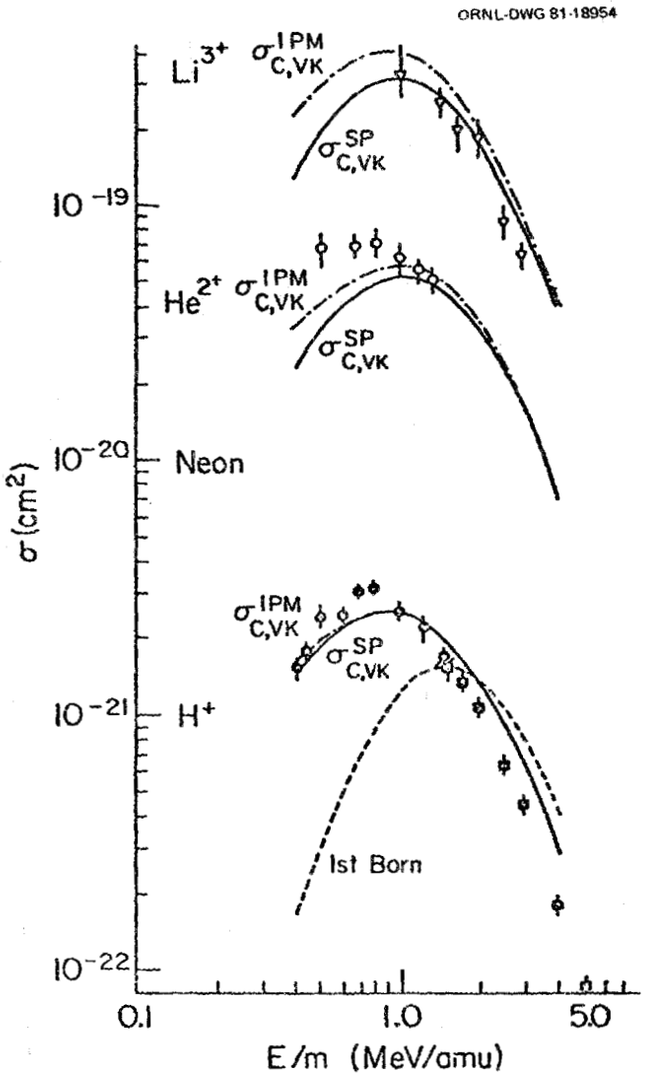


Fig. 5.14. Cross sections σ_{C+VK} for producing the charge-transfer state in coincidence with a *K*-shell hole in the target. Cross sections for a neon target and H^+, He^{2+}, and Li^{3+} projectiles are given as a function of projectile energy *E* divided by the projectile mass *m*. The solid squares that comprise the high-energy half of the H^+ data are from C. L. Cocke et al., *Phys. Rev. A* **16**, 2248 (1977); the other experimental points are from M. Rødbro et al., *Phys. Rev. A* **19**, 1936 (1979).

Nonstatistical theory of multiple vacancy production in atomic collisions[5] (R. L. Becker, J. F. Reading,[1] and A. L. Ford[1]) Till now, interpretation of x-ray satellite data has been limited to the use of models in which the emissions of electrons are treated as statistically independent. This assumption leads to a

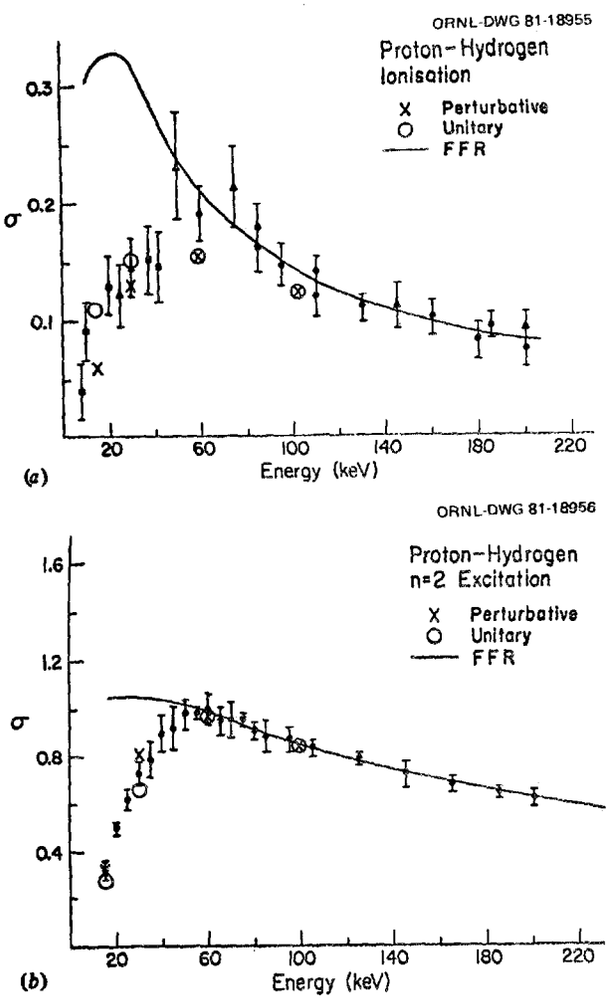


Fig. 5.15. Cross sections for proton-hydrogen collisions. (*a*) Cross section in units of 10^{-16} cm^2 for $n = 2$ excitation in proton-hydrogen collisions. The experimental points (with error bars) are from J. T. Park et al., *Phys. Rev. Lett.* **34**, 1253 (1975) and *Phys. Rev. A* **,14**, 608 (1976). The full curve labeled FFR is the Theoretical single-centered expansion result of Fitchard et al., hys. Rev. A **16**, 1325 (1977). The crosses and open circles are from the perturbative and unitary versions, respectively, of our new "one-and-a-half-center expansion" method. (*b*) Cross section in units of 10^{-16} cm^2 for ionization in proton-hydrogen collisions. The full curve, crosses, and open circles are as in *a*. The experimental points (with error bars) are from the following sources: triangles, Park et al., hys. Rev. A **15**, 508 (1977); squares, Fite et al., *Phys. Rev.* **119**, 663 (1960); circles, Gilbody and Ireland, *Proc. Roy. Soc. London* **277**, 137 (1963).

product of binomial distributions, one for each shell. However, we found that even in the IFP model of the target atom, quantum theory predicts that the holes are correlated. At a given impact parameter the IFP probability for producing several holes in a given shell can be written as a term containing only probabilities for the individual vacancies, which reduces for "average holes" to the binomial distribution, plus a correlation term which involves interference among amplitudes for the single-electron transitions. Expressions for the general case have been derived and will be used.

Initial-*l* dependence of ion–Rydberg-atom cross sections[6] (R. L. Becker and A. D. MacKellar[7]) In the first experiment on ionic collisions with (n, l)-selected highly excited Rydberg states (produced by laser excitation), MacAdam et al.[8] recently succeeded in obtaining a value for the largest expected cross section, that for the "*l*-changing" transitions, in which n is unchanged. To explain these data and to provide predictions of others to come, we worked out for the first time a classical ensemble corresponding to the manifold of hydrogenic quantum states of specified n and l and performed classical trajectory Monte Carlo calculations for all the cross sections (excitations, ionization, and transfer) in (He^+ or Ar^+) + Na($n \gg 1$, $l = 2$ or $n - 1$) collisions. Substantial initial-*l* dependence was found, as shown in Fig. 5.16 for the ionization and electron transfer. The *l*-changing cross section was close to the experimental datum.

1. Texas A&M University, College Station.
2. R. L. Becker et al., *J. Phys. B* **13**, 4059 (1980).
3. A. L. Ford et al., *Phys. Rev. A* **23**, 510 (1981).
4. J. F. Reading et al., *J. Phys. B*, in press.
5. R. L. Becker et al., *Proceedings, Sixth Conference on Applications of Small Accelerators*, Denton, Texas, November 1980 [*IEEE Trans. Nucl. Sci.* **NS-28**(2), Part 2, 1092 (April 1981)].
6. R. L. Becker and A. D. MacKellar, *Bull. Am. Phys. Soc.* **24**, 1204 (1979), and paper in preparation.
7. University of Kentucky, Lexington.
8. K. MacAdam et al., *Phys. Rev. Lett.* **44**, 980 (1980).

Numerical Solution of the Schrödinger Equation

C. Bottcher

We have developed methods of solving the time-dependent Schrödinger equation in two or three dimensions in the presence of Coulomb interactions. Propagation of the wave function in time is achieved by the Peaceman-Rachford algorithm, while the wave function is discretized in space by expanding in finite elements. As an application of the methods, we have chosen the ionization of a hydrogen atom by electron impact in the vicinity of the ionization threshold,

$$e + \mathrm{H}(1s) \rightarrow e + e + \mathrm{H}^+ . \qquad (1)$$

The problem is converted into a time-dependent one by considering the evolution of a wave packet.

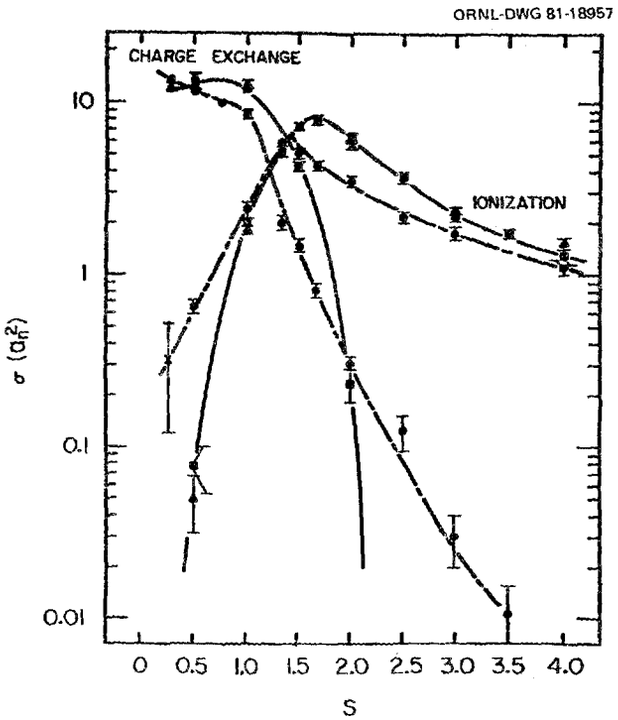


Fig. 5.16. Classical trajectory Monte Carlo ionization and charge-transfer cross sections, with statistical standard deviations, for specific initial l reduced impact speed $s = v/v_n$, with $v_n = e^2/n\hbar$. The circles are for $2/15 \leqslant l_c/n_c \leqslant 3/15$ and the squares for $14/15 \leqslant l_c/n_c \leqslant 1$, where l_c is the classical angular momentum divided by and n_c is the classical principal quantum number, $(\text{Rydberg}/E)^{1/2}$.

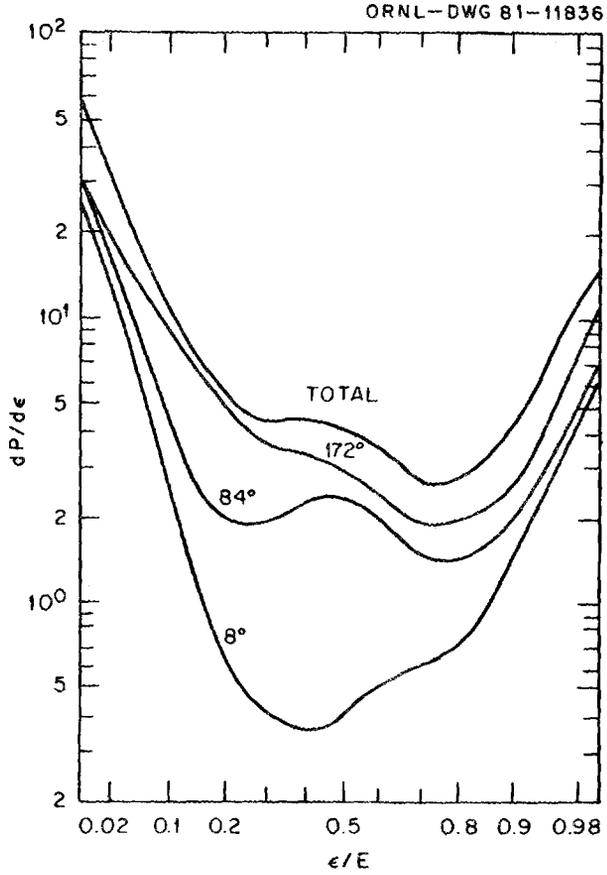


Fig. 5.17. The differential probability of electron ejection is plotted vs the fraction of available energy for three values of the angle between the outgoing electrons, $\theta = 8°$, 84°, and 172°. The probability integrated over all θ is also shown, labeled "total." The process considered is a 16-eV electron initially incident on a ground-state hydrogen atom.

Studies of a two-dimensional model, which neglects the angle between the two electrons, have already been published.

We now have fully three-dimensional solutions of (1), and typical results are shown in Fig. 5.17. The differential probability of ejecting an electron of energy ϵ is plotted vs ϵ for several values of the angle θ between the outgoing electrons. The results confirm the long-established speculation that near threshold there is a significant probability that electrons will be ejected with the same energy and $\theta \sim 180°$.

These calculations represent the first accurate solution of any collision problem with two unbound charged particles. Since full use was made of the vector processing capacity of a Cray-1 computer, they are also at the limit of computer technology. A wide range of other applications, for example, to heavy-particle collisions, is planned in the near future.

Autoionizing Contributions to Electron Impact Ionization of Positive Ions

C. Bottcher D. C. Griffin[1] M. S. Pindzola[2]

In close association with the Fusion Atomic Collisions Experimental Group, we have been searching for positive ions for which the excitation of autoionizing states makes a significant contribution to the total electron impact ionization cross section. Cases have been found where autoionization is 10–20 times the direct mechanism; the position and magnitude of the excitation structures are predicted theoretically in reasonable accord with experiment.

Figure 5.18 compares theory and experiment for electron impact on Ti^{3+} for which the excitation step has the form

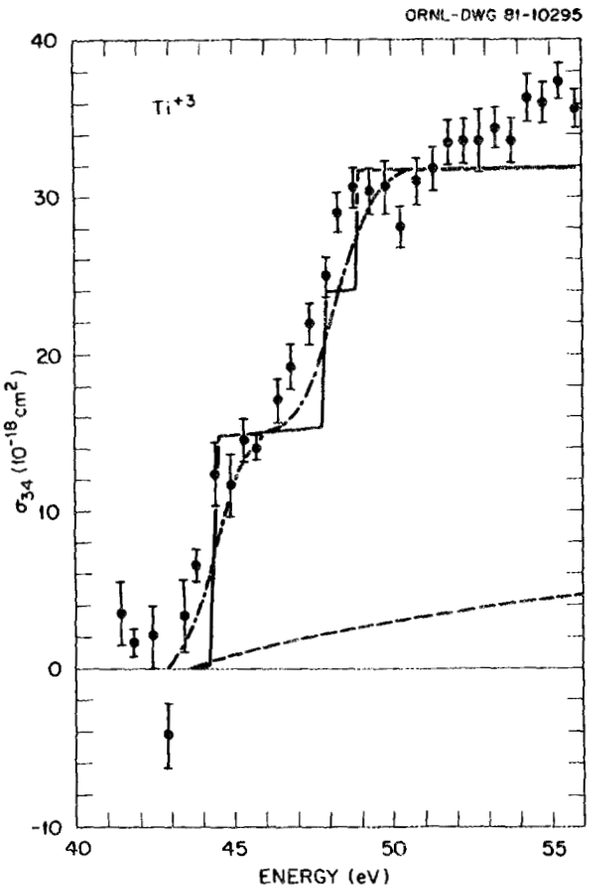


Fig. 5.18. The ionization cross section for electrons incident on Ti^{3+} is plotted vs the initial electron energy. The points with error bars are the measurements of Falk et al. described elsewhere in this report. The dashed curve is the Lotz semiempirical formula, which provides an upper estimate of direct ionization. The full curve is the distorted-wave theory of Griffin et al. (divided by 2.5), which allows for excitation-autoionization. The dot-dashed curve is the same theory convoluted into the experimental energy profile.

$$e + [(np)^6\, nd] \rightarrow e + [(np)^5\, (nd)^2] \qquad (2)$$

with n = 3, 4, and 5 respectively. The theoretical cross section was calculated in a rather simplified version of the distorted-wave method, then convoluted into the experimental energy resolution profile, and in all cases reduced by the same factor (divided by 2.5). It is clear that positions of the autoionizing thresholds are well predicted, and we are hopeful that more elaborate calculations will reduce the discrepancy in absolute magnitude. Though the scattering theory used is rather crude, the initial- and final-state wave functions were calculated using state-of-the-art atomic structure codes developed at LASL.

More precise calculations have indeed been carried out for Al^{3+}, Si^{4+}, and Mg^{+}, where the effects are smaller, but nonetheless interesting, and experimental data are also available. In general, the agreement is good, though certain features cannot be correctly described in the distorted-wave framework.

1. Guest assignee from Rollins College, Winter Park, Fla.
2. Consultant from Auburn University.

Charge Transfer to Highly Stripped Ions at Low Energies

C. Bottcher T. G. Heil[1]

Processes such as

$$C^{q+},\ O^{q+} + H \rightarrow C^{(q-1)},\ O^{(q-1)+} + H^{+} \qquad (3)$$

at energies below 200 eV are currently of the highest interest in the design of magnetic fusion devices. At these low energies, it is necessary to use the fully quantal formulation initiated by Dalgarno and Heil. From the viewpoint of applications, it is desirable to know the cross sections for all stages of ionization of a given species. We have completed a survey of all the stages of C^{q+} from $q = 2$ to 6. We have been able to compare our predictions with the recent measurements of Phaneuf on C^{q+} for $q = 3$ to 6; in all cases, agreement is reasonable; for example, the comparison for $q = 3, 4$ is shown in Fig. 5.19.

The cross sections for $q = 4$ and 5 were obtained using a new method developed for highly charged projectiles with some remaining electrons. Such methods are required if the large number of cases required in applications are ever to be surveyed in detail. The method provides new insight into the physics of the problem; for example, it is possible to explain why the capture cross sections to C^{4+} and Be^{4+} differ by several orders of magnitude at low energies.

1. ORAU consultant from University of Georgia, Athens.

Response of Molecules to Coherent Radiation

C. Bottcher C. Feuillade[1]

For some time, we have been engaged in a program of setting up realistic descriptions of the response of few-level atomic and molecular systems to coherent radiation. By "realistic," we mean that rotational degeneracies are fully incorporated and that allowance is made for collisional relaxation. Recent advances include the following: (1) A study

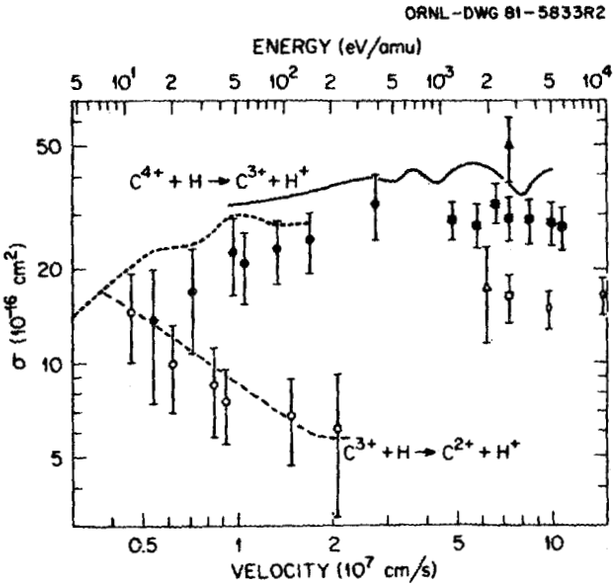


Fig. 5.19. Cross sections for charge capture from hydrogen atoms by very slow multicharged carbon ions are plotted vs the H-atom velocity (or the ion-energy/amu). The dotted lines are the quantal calculations of Bottcher and Heil. The open and filled circles are the measurements of Phaneuf on G^{3+} and C^{4+}, respectively, as described elsewhere in this report. The full curve is the semiclassical calculation of Olson et al. on C^{4+}. Other experiments at higher energies are also shown (filled points, C^{4+}; open points, C^{3+}).

has been completed of the time-dependent solutions of the two-level system. (2) The two-level equations have been extended to three levels. (3) Collisional relaxation rates have been worked out for symmetric top molecules. Some progress has also been made on *l*-degenerate Rydberg states.

We have now assembled all the elements required to model the multiphoton excitation processes involved in laser isotope separation.

---

1. Consultant from Manchester University, Manchester, England.

6. Nuclear Data Project

S. J. Ball[1]
Y. A. Ellis-Akovali
W. B. Ewbank[2]
B. Harmatz
F. W. Hurley[1,3]
M. J. Martin[4]
M. R. McGinnis[1]
J. T. Miller[5]
S. Ramavataram[6]
M. R. Schmorak

During the past year the scope of the Nuclear Data Project (NDP) has been gradually decreased as responsibility for the publication of the *Nuclear Data Sheets* and for certain other aspects of the Project's original functions has been transferred to the National Nuclear Data Center at BNL (BNL/NNDC). In October 1980 the literature scanning operation was transferred to BNL/NNDC, and in January 1981 responsibility for maintenance of the Evaluated Nuclear Structure Data File (ENSDF) and Nuclear Structure References (NSR) file was also transferred. By June 1981, responsibility for publication of the *Nuclear Data Sheets* will have been transferred to BNL/NNDC.

The Project is now basically an evaluation center. As part of the U.S. Nuclear Data Network, the Project will be responsible for the evaluation of nuclear structure information in the mass region $A \geqslant 195$. The Project will also maintain a complete computer-indexed library of published works in experimental nuclear physics and, in addition, will maintain copies of the ENSDF and NSR files. These files will be provided on tape by BNL/NNDC several times each year and will be maintained for the use of members of the Physics Division, as well as for NDP evaluators.

The Project will continue to house the position of editor of the *Nuclear Data Sheets*. All mass chains from each center in the international nuclear data network will be edited here. The editor will have the ultimate responsibility for the quality of what is entered into the ENSDF and, thus, for what is published in the *Nuclear Data Sheets*.

ACTIVITIES

Nuclear Structure References (responsibility now of BNL/NNDC)

During 1980, over 5000 new entries were indexed and added to the NSR file. Monthly lists of new NSR entries for approximately 50 mass chains were sent to the appropriate evaluator. Two four-month cumulations of indexed additions to the NSR were published in "Recent References" issues of *Nuclear Data Sheets*. As a "library of last resort," the NDP provided copies of about 100 reports and abstracts to other centers in support of their data evaluation activities.

Data Evaluation

In 1980, 1015 new or revised data sets were merged onto the ENDSF. These represented complete updates for 24 mass chains and significant changes for approximately 100 other nuclear decay schemes. The ENSDF now includes:

1965 sets of adopted level properties ($A = 1$ to 263)
2139 sets of decay scheme data
3688 sets of reaction data

Complete copies of ENSDF contents were distributed twice through BNL/NNDC as the International File of Evaluated Nuclear Structure

and Decay Data (responsibility now of BNL/NNDC).

As part of the international network for nuclear structure data evaluation, the NDP has continuing responsibility for 70 mass chains in the region $A \geqslant 195$. Revised *Nuclear Data Sheets* for 11 mass chains were prepared by the NDP in 1980; also provided was a thorough review for 11 mass chains prepared by new evaluators.

Publication Activities

Twelve issues of the journal *Nuclear Data Sheets* (over 2100 pages) were prepared and published in 1980. These included complete manuscripts (drawings, tables, reference lists) for 23 revised mass chains and two issues of "Recent References."

Individually and in collaboration with other researchers in the Physics Division, NDP staff members published or prepared for publication the following papers:

1. Ellis, Y. A., and K. S. Toth, "Determination of Q Values for Electron-Capture Decay of ^{172}Hf and ^{199}Pt from X-Ray Intensities," pp. 459–64 in *Atomic Masses and Fundamental Constants 6* (Proceedings, Sixth International Conference on Atomic Masses, East Lansing, Michigan, September 1979)0, Plenum, New York, 1980.
2. Ellis-Akovali, Y. A., K. S. Toth, C. R. Bingham, H. K. Carter, and D. C. Sousa, "Electron-Capture and Alpha-Particle Decay of ^{190}Pb," *Phys. Rev. C* **23**, 480–86 (1981).
3. Ewbank, W. B. (invited paper), "Status of Transactinium Nuclear Data in the Evaluated Nuclear Structure Data File," pp. 109–41 in *Proceedings, IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data* (Cadarache, France, May 1979), Report IAEA-TECDOC-232 (1980).
4. Martin, M. J. (invited paper), "ENSDF—Its Structure, Contents, and Use in Applied Research," pp. 2–16 in *Proceedings, 1979 Seminar on Nuclear Data, Japanese Nuclear Data Committee (Tokai-mura, Ibaraki-ken, Japan, December 1979)*, Japanese Atomic Energy Research Institute Report JAERI-M8769 (1980).
5. Schmorak, M. R., "Systematics of Nuclear Level Properties in the Lead Region," *Nucl. Data Sheets* **31**, 283–380 (1980).

Special Activities

A complete collection of radiations from 1553 radioactive nuclides based on data in the ENSDF was assembled and printed on microfiche. It will be distributed in 1981.

Level and decay information from new evaluations for $A = 18$ to 44 has been extracted from the journal *Nuclear Physics* (Endt and van der Leun) and entered into the ENSDF.

A training session, sponsored and financed by the Japanese Nuclear Data Committee and conducted by an NDP evaluator, was held in Tokai, Japan, in December 1979. Ten Japanese evaluators attended this session, and a review of two of their mass chains was performed.

Radioactivity and decay data based on the ENSDF are being prepared for an article to appear in the *Encyclopedia of Chemical Technology*.

In 1980, NDP evaluators responded to over 60 requests by researchers outside the evaluation centers for specific information by means of NSR searches, ENSDF printouts, and personal consultations.

---

1. Technical support staff.
2. Former director; now with Information Division (March 1981).
3. Retired December 1980.
4. Present director.
5. Technical support staff on loan from Information Division.
6. Now with NNDC at BNL (October 1980).

7. Atomic and Plasma Physics Group

OVERVIEW

The activities of this section are divided between atomic collisions research and plasma diagnostics development. Most of these activities are supported through the ORNL fusion program but are executed within the Physics Division.

The plasma diagnostics activities are primarily the development of far-infrared (FIR) lasers and the arrangement of these lasers into configurations which can probe high-temperature plasmas like ISX-B and EBT-P. Laser systems for measurement of ion temperature, electron density, and internal magnetic field distribution in such plasmas are under development. Principal progress during this reporting period has been development of Faraday rotation (rotation of laser-light polarization by a magnetic field) as a probe which will follow the electron current density in plasma by sampling the local magnetic field. A laser system which serves both to develop this technique and to provide current plasma parameter data is in place on the ISX-B. This and the other systems in progress all require further development but are expected to be significant new tools for studying plasma dynamics.

The atomic physics activities are not dependent on any particular fusion energy device but are basic physics studies directed primarily at processes and collision reactants of fusion interest. Important progress has been achieved in our understanding of electron impact ionization of ions and of both electron capture and ionization in collisions of multicharged ions with atomic hydrogen through the experimental activities described here. In addition, there has been strong interaction in these areas with atomic theory activities here at ORNL (see Chap. 5 of this report) which has helped guide the experimental activities and has provided the theoretical work with specific new challenges. The atomic physics group also operates the Controlled Fusion Atomic Data Center, which categorizes all publications on atomic collisions and attempts to compile and evaluate atomic data for fusion.

CONTROLLED FUSION ATOMIC DATA CENTER

D. H. Crandall C. F. Barnett
B. J. Farmer D. C. Gregory
P. M. Hafford F. W. Meyer
R. A. Phaneuf

The data center categorizes all publications on atomic collisions and compiles and evaluates atomic data for fusion. In keeping with the center's responsibilities, three editions of the indexed bibliography of atomic and molecular processes for the period 1978–80 have been completed during the present reporting period. The data center categorizes all bibliography on atomic collisions and on some areas of particle-surface collision studies. This bibliography is used in compilation and evaluation of numerical atomic data for fusion needs.

The most time-consuming part of the work has been the bibliographical categorization in which about 3000 entries per year are selected from the total literature and divided into one or more of 114 process categories within 10 areas of collision studies.

Author, title, reactants, energy, and category are specified in computer file entries which can be sorted according to any of the input data. In addition to our use, these bibliographies are used by the IAEA and Japanese data centers, as well as by individual scientists. Copies of the bibliography are published and disseminated throughout the United States and abroad (available through the NTIS). We are searching 1981 publications for the bibliography, which will receive similar distribution.

In October 1980 a workshop between U.S. and Japanese data centers which are compiling and evaluating atomic collision data for fusion interests was held at the Joint Institute of Laboratory Astrophysics in Boulder, Colorado. The principal purposes were to review procedures used in evaluation or selection of recommended cross sections and to identify both technical criteria and specific collaborative efforts which could improve this data selection process. The report *U.S.-Japan Workshop on Atomic Collision Data for Fusion* (ORNL/TM-7675) contains the abstracts of the discussions and presentations and an overall review of the meeting.

In a cooperative effort with the Atomic Transition Probabilities Data Center of the National Bureau of Standards, we have continued publication of the bimonthly newsletter *Atomic Data for Fusion*. The IAEA is also publishing a similar bulletin which covers bibliographical citations of atomic data. In order to avoid duplication we are helping to supply bibliographic information to the IAEA, and at the same time the ORNL-NBS newsletter is shifting emphasis toward publication of actual numerical data of current interest for fusion. An author and subject index has been published for 1979 (vol. 5) and 1980 (vol. 6) as a supplement to these newsletters.

We are planning a third volume of cross sections and rates for fusion impurity ions. To this end we have completed a compilation of electron impact excitation cross sections for iron ions where data have been selected from the many calculations as the best available values but cannot be evaluated in the usual critical sense because no experimental data are available. Cross sections at one to seven specific collision energies for about 800 transitions in iron ions have been compiled. A compilation of atomic data for oxygen ions covering electron impact excitation and electron capture from hydrogen is in progress as a joint endeavor with the Japanese data center at IPP-Nagoya.

DISSOCIATION OF TRIATOMIC HYDROGEN MOLECULAR IONS IN H_2

C. F. Barnett

Dissociative cross sections to form positive and negative fragments have been measured for isotopic, triatomic, hydrogen ions in H_2 gas in the energy range 10 to 60 keV. This investigation was motivated by the theoretical prediction that the formation cross section of H^+ from HD_2^+ would be different from that of H_3^+ producing H^+ due to the nonsymmetric vibrational configuration of HD_2^+. Also, previous measurements indicated that dissociation of HD_2^+ in H_2 produced a measurable D^- formation cross section, but the H^- produced was less than background. These processes are of general interest and have specific application in interpreting ion source operation.

Measurements were done in the conventional manner. Ions were produced in an rf ion source, accelerated to the desired energy, mass analyzed, passed through a static gas cell, energy analyzed by a parallel-plate electrostatic analyzer, and detected by Faraday cups. Cross sections were determined by measuring the rate of increase of the ion fragment current as a function of the gas cell pressure.

During the course of the measurements, several problems were encountered which prevented accurate cross-section determinations: (1) Differential scattering cross-section measurements of the positive ion fractions indicated scattering greater than $\pm 7°$ of H^+ from HD_2^+ dissociation. This places a requirement of unusually large diameters for gas cell exit aperture and detector entrance aperture. (2) The dissociation cross section is dependent on the ion source pressure, with the cross section decreasing by as much as a factor of 2 when the ion source pressure increases. This pressure dependence suggests that the cross sections are sensitive to the vibrational level populations of the triatomic ions. (3) The fraction of negative ions formed in the dissociative process has a background contribution dependent on the gas cell pressure. With the present apparatus no satisfactory method has been devised to subtract out this contribution.

The following tentative conclusions can be stated: (1) Within the statistical fluctuations of the measurements in this energy range, no differences in H^+ or D^+ formation cross sections were measured. Also, no differences were found in the dissociative collisions to

produce H_2^+, HD^+, or D_2^+. (2) Cross sections are dependent on the vibrational level of the triatomic ion. (3) Cross sections for the formation of positive ions are of the order 10^{-17} to 10^{-16} cm^2 and for negative ions 10^{-18} cm^2.

Atomic collision theory predicts that if diatomic or triatomic hydrogen negative ions exist, the molecular ion must be in an excited electronic state. Preliminary measurements of the formation of D_2^-, D_3^-, and HD_2^- by double-electron collisions of the parent positive ion in H_2 indicated a cross section of 10^{-18} to 10^{-19} cm^2 in the 10- to 50-keV energy range. Subsequent measurements proved that these cross sections were obtained from the positive molecular ion being dissociated in the H_2 gas cell with the D^+ of one-half or one-third E being deflected into one of the plates of the energy analyzer. The D^+ was reflected from the surface as D^- at the analyzer voltage required to deflect the full energy component into the Faraday cup. As the gas cell pressure was increased, the amount of D^+ increased along with the reflected D^-, giving rise to an apparent cross section for the formation of negative molecular ions. By making changes in the analyzer and detector geometry this spurious signal was eliminated, and D_2^- and D_3^- ions were not observed. For 30 keV, D_2^+ and D_3^+ in H_2 upper limits can be placed on the double-electron capture of 5×10^{-21} cm^2 and 2×10^{-20} cm^2 respectively.

BEAM SPECIE ANALYZER FOR INTENSE NEUTRAL BEAMS

C. F. Barnett J. A. Ray R. R. Feezell

Uncertainty has existed in the past as to the relative energy specie concentration of intense neutral beams used in heating tokamak plasmas. In an attempt to provide a quantitative instrument to measure the one-half, one-third, and full-energy component of the beams, a three-channel, neutral particle, energy analyzer has been fabricated and calibrated for H° particles. H° with energies 3.5 to 55 keV was passed through an N_2 gas cell maintained at charge equilibrium pressures. H^+ ions formed by stripping collisions were energy analyzed by a 45°, parabolic, electrostatic analyzer and detected by three Faraday cups spaced to intercept the three energy components. The conversion efficiency of the analyzer system increased from 0.11 at 3.5 keV to 0.54 at 55 keV. Statistical analysis of the calibration data yielded an accuracy of ±3%.

Preliminary data on a neutral beam line with a PDX- or ISX-B–type source indicated the following components in the neutral beam: full energy, 0.42; one-half energy, 0.34; and one-third energy, 0.24. These results may be compared directly with results obtained by Langley using a beryllium-crystal technique, which gave a full-energy component of 0.36, a one-half energy of 0.26, a one-third energy of 0.32, and a component of one-seventeenth energy of 0.06. Both sets of measurements indicate much larger fractions for the low-energy than was previously supposed.

ELECTRON LOSS FROM ATOMIC HYDROGEN IN COLLISIONS WITH MULTICHARGED IONS

F. W. Meyer H. J. Kim

An ion-atom crossed-beams approach[1] is being used in an ongoing study of electron loss from hydrogen atoms during collisions with multicharged-ion projectiles. We have investigated the excited-state dependence, ion-charge scaling, and velocity dependence of electron loss from excited hydrogen atoms ($10 \leqslant n \leqslant 24$, where n is the principal quantum number) in collisions with multicharged ions having charge ($1 \leqslant q \leqslant 4$) at collision velocities spanning the range $2.2–3.3 \times 10^8$ cm/s.

The fast atomic hydrogen beam used in the experiment was obtained by passing energy-analyzed protons through a neutralizer cell. In addition to producing principally ground-state hydrogen atoms, the electron-capture neutralization also yields a small population of excited hydrogen-atom states whose abundance as a function of principal quantum number, n, was measured to have the form a/n^3 in the range $9 \leqslant n \leqslant 24$. The experimental yield of protons due to collisional electron loss from this atomic hydrogen beam is given by

$$Y(N) = \sum_{n=1}^{N} P_n \sigma_n ,$$

where the P_n is the population of the excited states, σ_n is the total electron loss cross section for each of the n levels and N is the maximum value of n in the beam. The value of N, ranging from 9 to 24, was varied by changing the strength of a static, transverse, electric field situated upstream of the collision region, in which the excited hydrogen atoms with $n > N$ are field ionized and attenuated from the neutral beam.

By taking differences between proton yields obtained for two different field ionizer settings, the collisional behavior of a selected band on n levels could be isolated and studied.

The trend of the present data as functions of projectile charge q and collision velocity v is consistent with the $(q/v)^2$ dependence of electron loss predicted by Born approximation calculations and by classical theory, both expected to be valid in the present velocity regime ($v > v_e$). Figure 7.1 shows the dependence of collisional electron loss from the band of Rydberg levels ($17 \leqslant n \leqslant 24$) of atomic hydrogen on projectile charge q. Electron loss from the band of Rydberg levels ($10 \leqslant n \leqslant 14$) of atomic hydrogen exhibits a similar dependence on projectile charge and collision velocity.

The n dependence of electron loss from H(n) colliding with N^{3+} (Fig. 7.2)[2] can also be understood in terms of the above theories. However, one must consider[3] in addition to collisional ionization of the initial Rydberg state, excitation from the initial state to higher n levels (in the present case, $n > 27$) that can be field ionized by the transverse electric field in which the collisions occur.

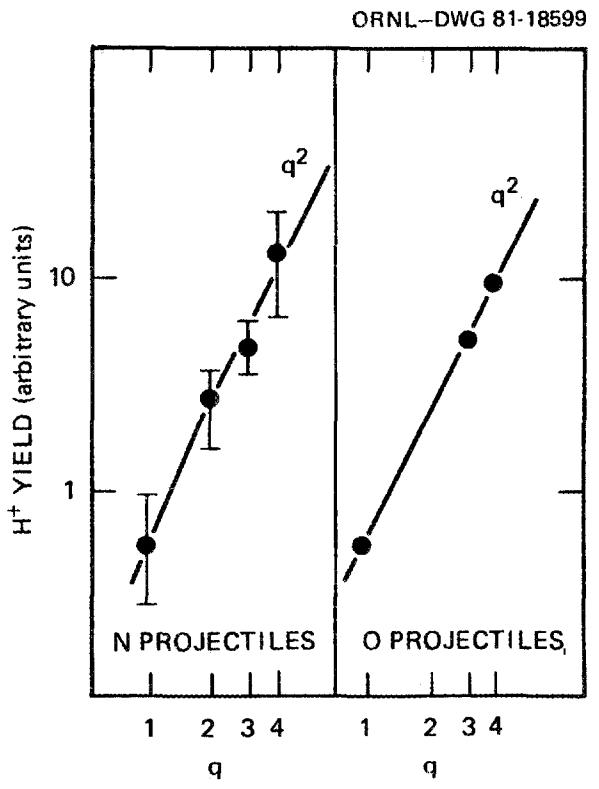


Fig. 7.1. Dependence of the H^+ yield from H($17 \leqslant n \leqslant 24$) on the charge q of the collision partner; $v = 2.8 \times 10^8$ cm/s.

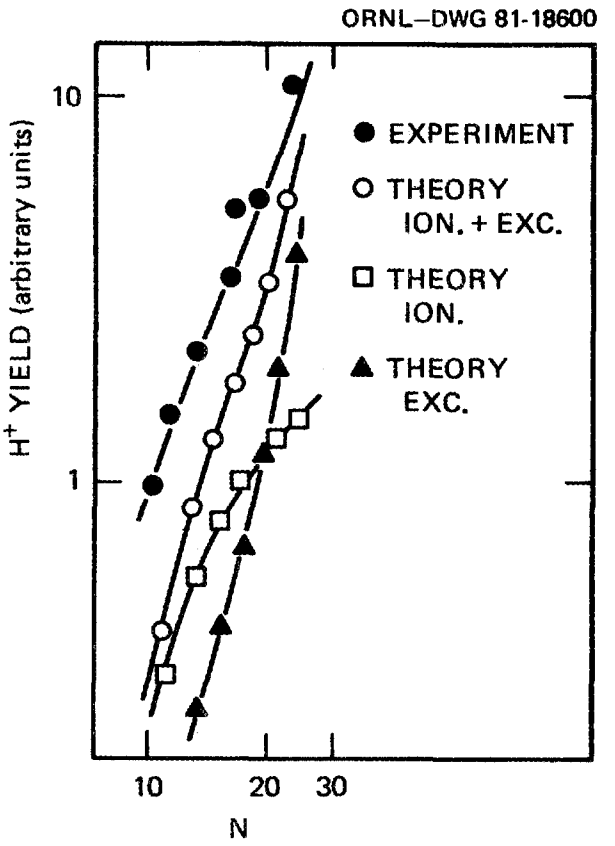


Fig. 7.2. Dependence of the H^+ yield $\sum_{n=9}^{N} P_n\sigma_n$ from H(n) in fast collisions with N^{3+} on the cutoff principal quantum number N; $v = 2.8 \times 10^8$ cm/s. Solid squares and triangles, calculated using the prescription of ref. 2.

In addition to charge-transfer neutralization of a proton beam, the fast atomic hydrogen beam used in the experiment could be prepared by gas stripping an H^- beam. It was found[4] that while both ways of preparation resulted in a Rydberg state population consistent with the form a/n^3, the value of the population coefficient a was a factor of 2 lower for neutral beams produced by stripping H^- than for the beams produced by neutralizing H^+.

Figure 7.3 shows the n dependence of electron loss Y_1 from H(n) produced from H^+, and electron loss Y_2 from H(n) produced from H^-, during collisions with N^{3+} at $v = 2.3 \times 10^8$ cm/s. Using these two sets of data points and the above form for $Y(N)$,

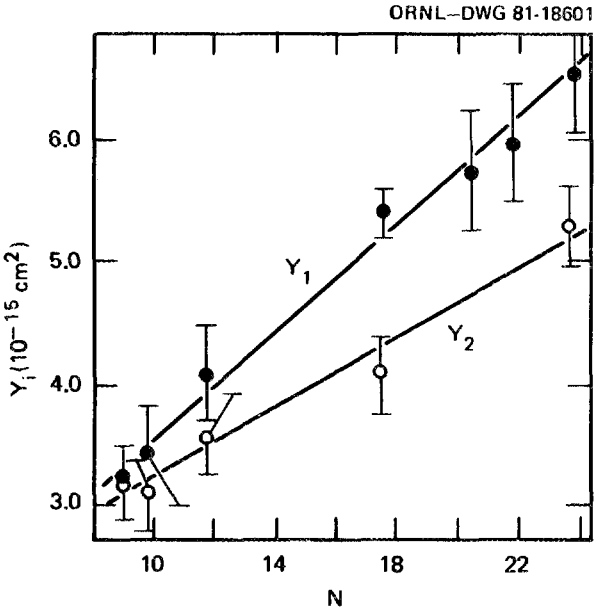


Fig. 7.3. Total electron loss from H(n) colliding with N^{3+} at v = 2.3×10^8 cm/s as a function of N, the maximum value of n in the neutral beam. Open circles, neutral beam formed from H^-; closed circles, neutral beam formed from H^+.

the ground-state electron-loss cross section can be estimated using the relation

$$\sigma_1 = \frac{Y_1(N) - (a_1/a_2)\,Y_2(N)}{1 - a_1/a_2}$$

The value of σ_1 obtained using the above expression is $(3.0 \pm 1.4) \times 10^{-15}$ cm^2. This value is consistent with the sum of measured cross sections for electron capture[5] and ionization,[6] the two dominant processes contributing to electron loss.

1. H. J. Kim and F. W. Meyer, *Phys. Rev. Lett.* **44**, 1047 (1980).
2. L. C. Johnson, Astrophys. J. **174**, 227 (1972).
3. R. E. Olson, private communication (1980).
4. F. W. Meyer and H. J. Kim, "Electron Loss from Atomic Hydrogen in Collisions with N^{3+}," contributed paper for XII ICPEAC, Gatlinburg, Tenn. (July 1981).
5. R. A. Phaneuf, F. W. Meyer, and R. H. McKnight, *Phys. Rev. A* **17**, 534 (1978).
6. M. B. Shah and H. B. Gilbody, The Queen's University of Belfast, Research Report (1981).

ELECTRON-ION CROSSED-BEAMS EXPERIMENT

D. H. Crandall
R. A. Phaneuf
R. A. Falk[1]
D. C. Gregory
J. W. Hale
G. H. Dunn[1]

A variety of experiments have been performed since the last reporting period. Both electron impact ionization and electron impact excitation have been studied, but principal results have been for ionization and for the role of excitation-autoionization in total ionization cross sections. Previously[2,3] we found that for the simple lithium-like ions of C^{3+}, N^{4+}, and O^{5+} the excitation of an inner-shell electron followed by autoionization resulted in an abrupt rise in the total ionization cross section at the inner-shell excitation threshold energy and that the relative importance of this process increased with ionic charge along the isoelectronic sequence. This excitation-autoionization mechanism is likely to be important for many ions of high electronic charge and is a subject of some interest in basic collision studies, fusion energy plasma investigations, and astrophysics.[4]

During the present reporting period we have measured cross sections for electron impact ionization of C^{2+}, O^{2+}, Al^{2+}, Si^{3+}, Ti^{3+}, Zr^{3+}, Hf^{3+}, Ne^{3+}, Ar^{3+}, Kr^{3+}, Xe^{3+}, and Ta^{3+} (where 2^+ and 3^+ ions could be studied with the particular apparatus arrangements employed). We are attempting to identify trends in ionization, particularly in the excitation-autoionization components. For instance, Al^{2+}, Ti^{3+}, Zr^{3+}, and Hf^{3+} all have alkali-like electronic structures, and the singly charged alkali-like ions of Mg^+, Ca^+, Sr^+, and Ba^+, are the primary cases for which excitation-autoionization had been studied[5] before our work. The most dramatic excitation-autoionization effects observed to date are apparent in our Ti^{3+}, Zr^{3+}, and Hf^{3+} data (shown in Fig. 7.4) for energies near the ionization threshold. The Lotz formula predictions[4] are generally used as the simplest and best estimate for direct ionization by electron impact. For the cases shown in Fig. 7.4 the ionization cross sections are enhanced by more than a factor of 10 due to $\Delta n = 0$ excitations of the form $np^6\,nd \rightarrow np^5\,nd^2$ which then autoionize (n is the principal quantum number of the outermost electron orbitals; for example, $n = 4$ for Zr^{3+}).

Simultaneously with our experimental studies, theoretical activities here at ORNL (see Atomic Theory Sect. of Chap. 5.) and elsewhere (e.g., see ref. 6) have provided improved predictions of both the

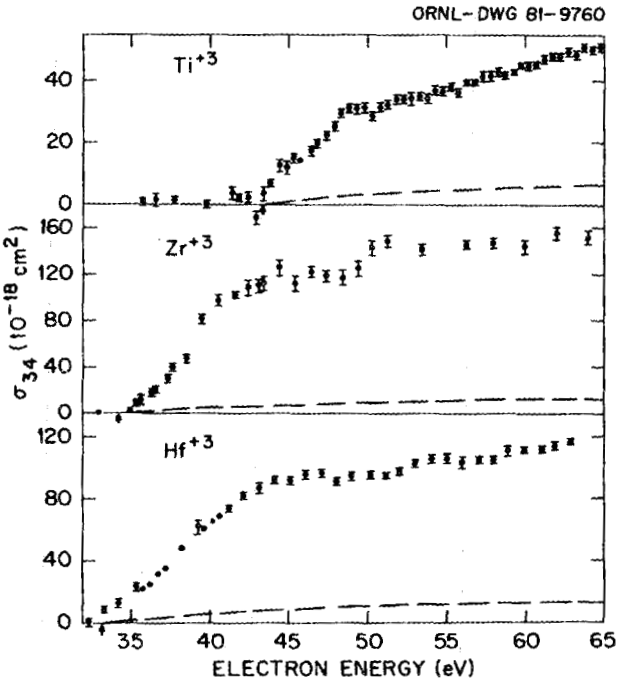


Fig. 7.4. Electron impact ionization cross sections of Ti^{3+}, Zr^{3+}, and Hf^{3+} as a function of electron energy near ionization threshold. The dashed curves are the direct ionization predicted by the Lotz formula. The arrows indicate threshold for ionization of ground-state ions. Error bars are 1 std. dev. statistical variations taken as representative of relative uncertainty, points without bars having statistical uncertainty smaller than the point. Total absolute uncertainty is better than ±10% at high confidence.

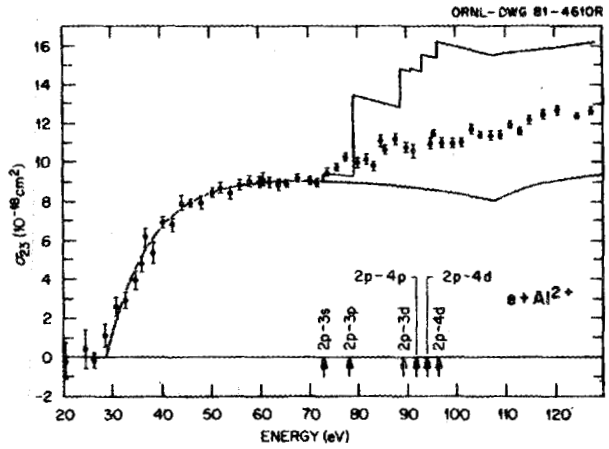


Fig. 7.5. Electron impact ionization of Al^{2+} near ionization threshold. The solid curve is the distorted-wave calculation of Younger (ref. 6) normalized to experiment at 70 eV by multiplying by 0.65 and with the excitation-autoionization results of Griffin et al. (Chap. 5 of this report) added to the results of Younger. The arrows indicate energies for excitation of $2p^63s \rightarrow 2p^53snl$ from Griffin et al.

direct ionization and the excitation-autoionization contribution to ionization. These theoretical activities allow detailed comparisons between predictions and observations which are providing improved physical understanding. A comparison of theory and experiment for details of the Ti^{3+} case are shown in Fig. 5.18 in Chap. 5.

Perhaps the best systematic approach to studying electron-ion collisions is to progress along isoelectronic sequences so that the number and arrangement of electrons on the ion is constant, but the ionic charge increases. The current studies are aimed at doing this for the sodium-like sequence for which we have studied Mg^+, Al^{2+} and Si^{3+}. Detailed results for Al^{2+} are shown in Fig. 7.5. The effects of excitation of the form $2p^63s \rightarrow 2p^53snl$ followed by autoionization are apparent in both the experiment and the theory. However, the excitation $2p^63s \rightarrow 2p^53s3p$ (indicated as $2p$-$3p$ on Fig. 7.5), which is largest in the theoretical prediction, is missing or quite small in the experiment. This same result is found for Mg^+ and Si^{3+} and is not unique to a particular theoretical variation. We do not yet understand this discrepancy, but the detailed comparisons are providing specific information for development of improved theoretical approaches.

Another general insight derived from these studies is that the importance of indirect processes, like excitation-autoionization, increases with the number of electrons on the ion. We have studied a total of 13 ions of charge $^{3+}$ ranging from B^{3+} to Ta^{3+}. In order of the increasing number of electrons, there is a steadily increasing relative importance of indirect to direct ionization (with some particularly strong effects for specific electronic structures such as the alkali-like cases).

A number of publications, invited and contributed papers at conferences, and review papers are in progress based on these studies. (References 7–9 are examples.) We will extend these studies to cases of higher initial ionic charges of particular interest to fusion and astrophysics and where our understanding of electron impact ionization is not well established. The experiments become progressively more difficult for higher charge states and will require improvements in both experimental techniques and ion sources.

1. Research participants from the Joint Institute for Laboratory Astrophysics, Boulder, Colo.

2. D. H. Crandall, R. A. Phaneuf, B. E. Hasselquist, and D. C. Gregory, *J. Phys. B* **12**, L249 (1979).

3. D. H. Crandall, R. A. Phaneuf, and D. C. Gregory, ORNL/TM-7020 (September 1979).

4. D. H. Crandall, *Phys. Scr.* **23**, 153 (1981).

5. K. T. Dolder and B. Peart, *Rep. Prog. Phys.* **39**, 693 (1976).

6. S. M. Younger, "Cross Sections and Rates for Direct Electron Impact Ionization of Na-like Ions," submitted to *Phys. Rev. A* [see also S. M. Younger, *Phys. Rev. A 23, 1138 (1981)*].

7. *R. A. Falk, G. H. Dunn, D. C. Griffin, C. Bottcher, D. C. Gregory, and D. H. Crandall, "Excitation-Autoionization Contributions to Electron Impact Ionization, Phys. Rev. Lett.* **47**, 494 (1981).

8. D. C. Gregory, P. F. Dittner, and D. H. Crandall, "Electron Impact Ionization of Xe^{3+}," contributed paper for XII ICPEAC, Gatlinburg, Tenn. (July 1981).

9. D. H. Crandall, "Experiments on Collisions of Electrons and Multicharged Ions," invited paper for XII ICPEAC, Gatlinburg, Tenn. (July 1981).

LOW-ENERGY ELECTRON CAPTURE MEASUREMENTS

R. A. Phaneuf R. H. Hughes[1]

In addition to their fundamental significance, electron capture collisions of highly ionized atoms at very low velocities are important in many astrophysical and laboratory situations. During such collisions, the electrons in the system have sufficient time to adjust to the slowly varying interatomic field, and a quasi-molecular theoretical description of the collision becomes necessary. In order to evaluate developing theoretical methods, experimental data are needed on simple few- or one-electron systems involving highly charged ions. To address this problem, a pulsed-laser-produced plasma has been used as a source of highly ionized atoms, and a time-of-flight apparatus has been developed to study electron capture by nearly and fully stripped carbon ions colliding with hydrogen atoms at unprecedented low energies (10 to 400 eV/amu).[2,3]

The apparatus is shown schematically in Fig. 7.6. The thermal dissociation atomic hydrogen gas-target cell was calibrated in an auxiliary experiment, using a probe beam of 20-keV protons. In Fig. 7.7 the experimental cross sections for C^{6+} + H and C^{5+} + H collisions[3] are compared with theoretical calculations,[4-9] and in the C^{5+} case with higher-velocity measurements.[10] The C^{5+} data substantiate the

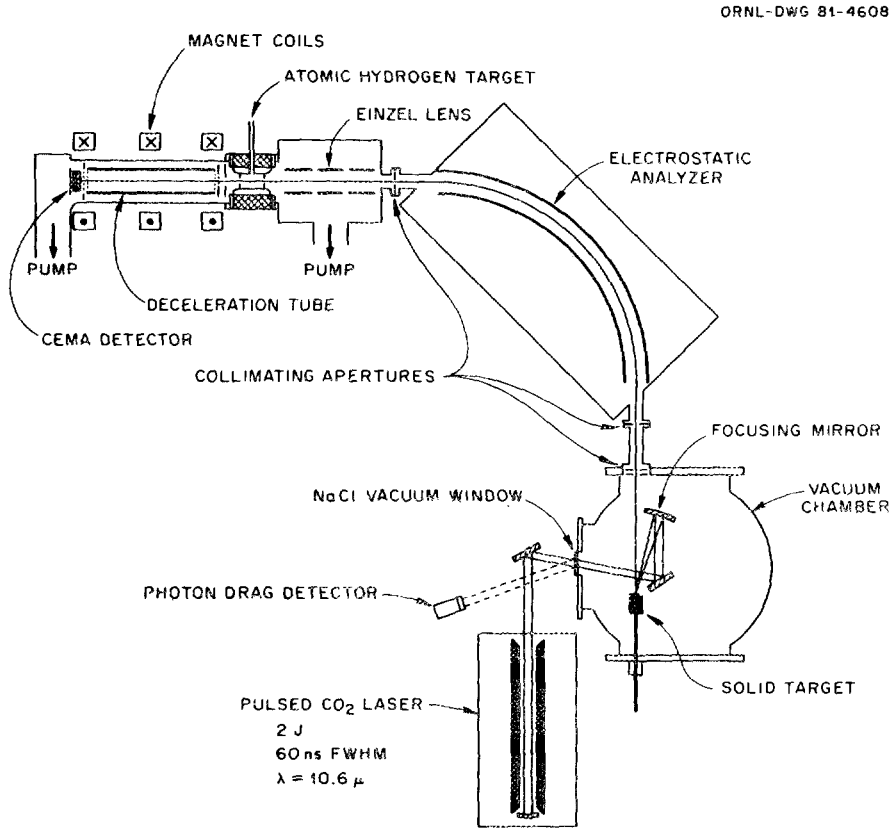


Fig. 7.6. Pulsed-laser ion source and time-of-flight electron capture collision apparatus.

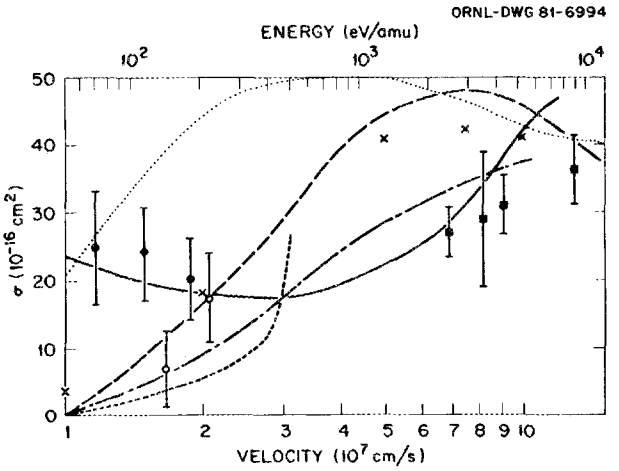


Fig. 7.7. Electron capture cross sections for C^{5+} + H (solid points and solid curve) and C^{6+} + H (open points, crosses, and broken curves). Circles are present experimental results, and squares are data of Crandall et al. (ref. 10). Solid curve is 5-PSS calculation of Shipsey et al. (ref. 4), long-dashed curve is 6 PSS of Salop and Olson (ref. 5), dash-dot curve is 11 PSS of Vaaben and Briggs (ref. 6), short-dashed curve is 3 PSS of Bottcher and Heil (ref. 8), dotted curve is distorted-wave calculation of Ryufuku and Watanabe (ref. 9), and crosses are 8 PSS and 10 PSS of Green et al. (ref. 7).

magnitude and weak velocity dependence predicted by the five-perturbed-stationary-state (PSS) calculation of Shipsey et al.[4] In contrast, the C^{6+} + H measurements show the strong falloff with decreasing velocity predicted by the PSS calculations,[5-8] but are significantly below the distorted-wave theory of Ryufuku and Watanabe.[9] Present experimental data for C^{4+} + H and C^{3+} + H are compared with theory in another section of this report.[8] Measurements on O^{q+} and Fe^{q+} ions are in progress.

1. Participant on sabbatical from the University of Arkansas, June–November 1979.

2. R. A. Phaneuf, *IEEE Trans. Nucl. Sci.* **NS-28** 1182 (1981).
3. R. A. Phaneuf, *Phys. Rev. A* **24**, 1138 (1981).
4. E. J. Shipsey, J. C. Browne, and R. E. Olson, *J. Phys. B* **14**, 869 (1981).
5. A. Salop and R. E. Olson, *Phys. Rev. A* **16**, 1811 (1977).
6. J. Vaaben and J. S. Briggs, *J. Phys. B* **10**, L521 (1977).
7. T. A. Green, E. J. Shipsey, and J. C. Browne, *Phys. Rev. A* **23**, 546 (1981).
8. C. Bottche and T. Heil (unpublished 1981). See Chap. 5 of this report.
9. H. Ryufuku and T. Watanabe, *Phys. Rev. A* **19**, 1538 (1979).
10. D. H. Crandall, R. A. Phaneuf, and F. W. Meyer, *Phys. Rev. A* **19**, 504 (1979) and unpublished data 1979.

MEASUREMENTS OF TOKAMAK POLOIDAL FIELDS BY FARADAY ROTATION

D. P. Hutchinson
P. A. Staats
K. L. Vander Sluis
C. H. Ma

We have been developing FIR lasers near the 0.4-mm wavelength for measurement of several plasma parameters. A principal objective during this reporting period has been development of a system for measuring the rotation of the laser polarization vector by the magnetic field of a tokamak plasma. Only the component of magnetic field which is parallel to the light propagation direction interacts with the polarization, producing the rotation. The magnitude of this Faraday rotation for a given chord through the plasma is proportional only to the poloidal component of magnetic field that changes in time during a plasma shot because of changes in the plasma current density, which is an important, time-dependent plasma parameter. In order to make a useful measurement, the electron density $\langle n_e \rangle$ along the same chord must be simultaneously measured. The $\langle n_e \rangle$ determination is also useful data but has been available previously with the FIR lasers in an interferometer arrangement.[1] The new development has concentrated on measuring the Faraday rotation with the same interferometer laser beam and on extending the technique to a working, multichannel, diagnostic system.

The electron density–Faraday rotation diagnostic system tested on the RENTOR tokamak at Rensselaer Polytechnic Institute has been installed on the ISX-B tokamak. During this installation the single-channel system used on RENTOR was expanded to four channels. Operation of the system has been limited to two channels per discharge due to a lack of detectors. Figure 7.8 shows electron density results of a typical ISX-B discharge. The center channel is located on the geometric center of the ISX-B vacuum chamber, and the outer channel is located 15 cm out. The plasma radius is 27 cm. Figure 7.9 displays the first multichannel measurements of both line-averaged electron density and Faraday rotation on a tokamak plasma in the ISX-B. For these experiments all of the laser power was concentrated in one channel to improve the S/N ratio, and different chords were observed during a sequence of nearly identical discharges. Channel 1 is located at the vacuum chamber center, channel 2 at a radius of 7.62 cm, channel 3 at 15.2 cm, and channel 4 at 22.8 cm. Figure 7.10 is a display of the same results plotted as a function of plasma radius with time during the

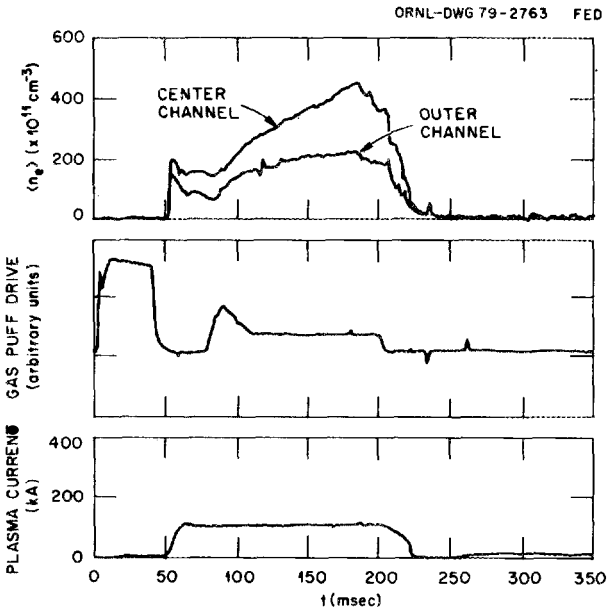


Fig. 7.8. Variation of line-averaged electron density vs time compared with the gas feed rate and plasma current.

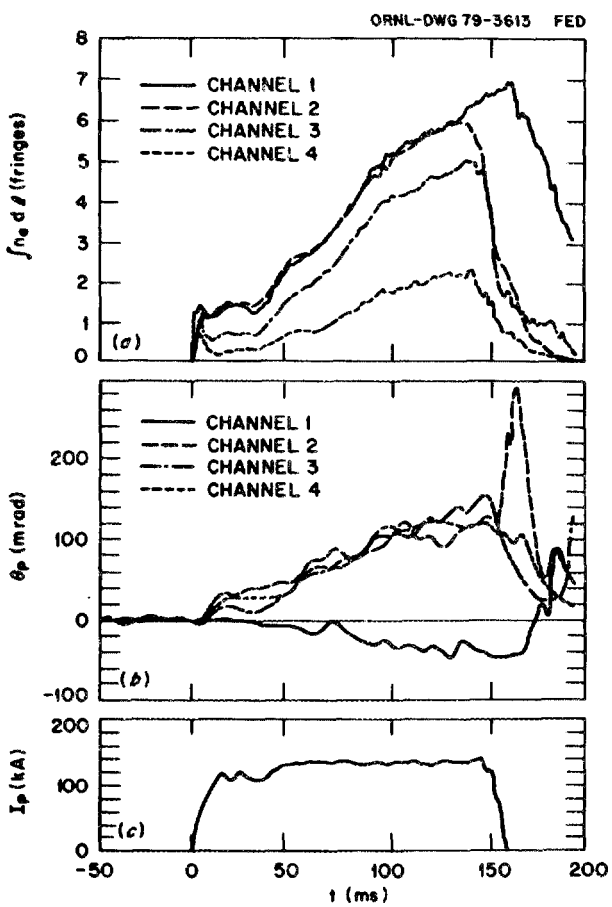


Fig. 7.9. Line-averaged electron density (*a*), the plasma-induced Faraday rotation (*b*), and the total plasma current (*c*).

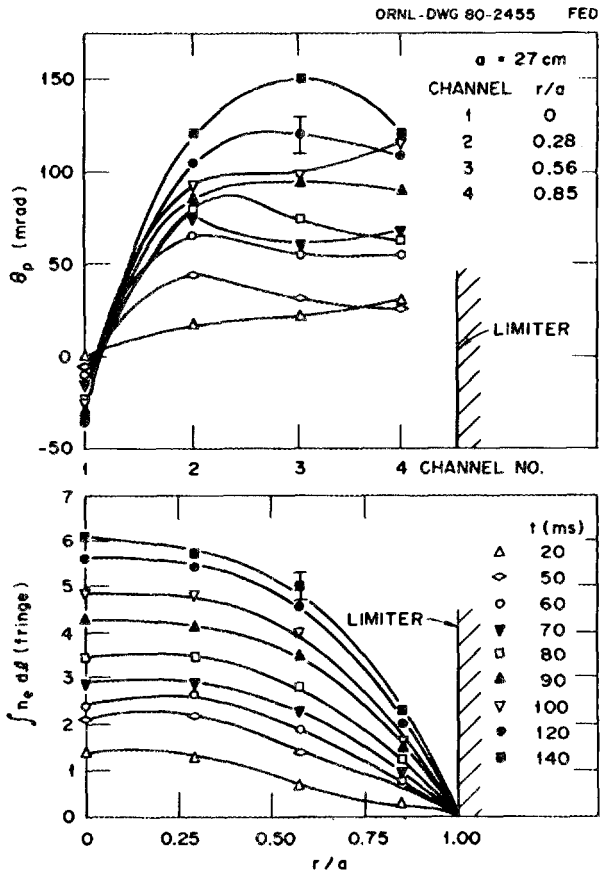


Fig. 7.10. Faraday rotation signal (*a*) shows strong response to the injected neutral beam at $t = 100$ msec, while the electronic density shows no noticeable change (*b*).

discharge as a parameter. From this figure, increases in poloidal flux produced by a current ramp at $t = 40$ ms and neutral beam injection at $t = 100$ ms may be observed.

During the past year the submillimeter-wave, phase-modulated polarimeter on the ISX-B has been modified to provide better electron density and Faraday rotation measurements along four chords of the plasma column. This modification is the result of two major improvements to the laser and detection systems: (1) use of a hollow dielectric waveguide for beam transport to and from the tokamak and (2) modification of the electronics to allow heterodyne detection of the Faraday rotation signals. The previous optics system utilized open-air transmission of the 0.393-mm-wavelength laser beams by a set of relay lenses. Loss of light intensity with this approach was $\sim 10^4$ to 10^6 due to water vapor absorption during humid summer days and lens losses due to Fresnel reflection and material absorption. The waveguide

system uses hollow dielectric waveguides consisting of 2.54-cm-ID Plexiglas tubing. Water vapor absorption is eliminated by slightly pressurizing the waveguide with dry nitrogen. Upon entering the waveguide, the submillimeter laser beams assume an EH_{11} high-order waveguide mode and are transmitted without the need for relay lenses to maintain a uniform beam size. Thin transparent pellicles of Mylar are used to seal the ends of the waveguide against the atmosphere. The transmission of this waveguide system is more than an order of magnitude better than with the previous lens system, even under dry atmospheric conditions.

The heterodyne detection system makes use of the reference interferometer laser beam as a local oscillator for a superheterodyne receiver system. The electron density variation is measured by comparing the phase of the carrier signal at the difference frequency between the source and reference laser; the system is illustrated in Fig. 7.11. The Faraday rotation signal appears as sidebands on this same carrier signal and, when demodulated with a square-law detection circuit, yields a signal whose amplitude is proportional to the polarization rotation of the laser beam by the plasma. The results of an initial single-channel measurement using the heterodyne technique is shown in Fig. 7.12.

Also by utilizing the heterodyne scheme, we have eliminated the need for the lossy polarizer grid in each channel of the interferometer-polarimeter system. These improvements have made possible routine measurements of electron density and Faraday rotation over any two chords of the plasma column. As before, operation is limited to two chords at a time due to a lack of detectors. Sufficient reserve laser power is now available to extend this system to five simultaneous channels when more detectors are obtained.

During this past year, work has continued on a new polarization modulator for the Faraday rotation experiment. The present magneto-optic modulator, consisting of a ferrite disk in the center of a high-current coil, is limited to relatively low modulation frequencies (4 to 10 kHz) due to the high current required to drive the coil. Also, the ferrite is lossy (~30% transmission) at the polarimeter wavelength of 0.393 mm. The new modulator operates as an electro-optic device and uses an aligned $LiTaO_3$ crystal. Rather than linearly oscillating the polarization proportional to the applied coil current, as with the ferrite modulator, the electro-optic modulator produces a phase difference between two orthogonal axes of the crystal proportional to an applied voltage. If the input-laser beam is properly aligned with the

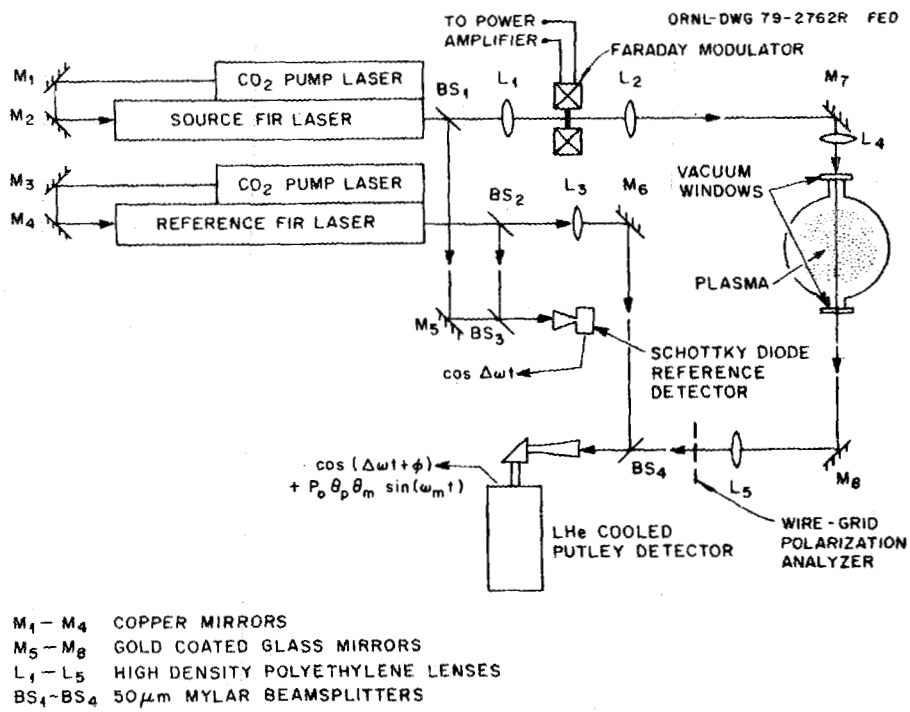


Fig. 7.11. Schematic diagram of a single channel of the multichannel ISX-B interferometer-polarimeter system.

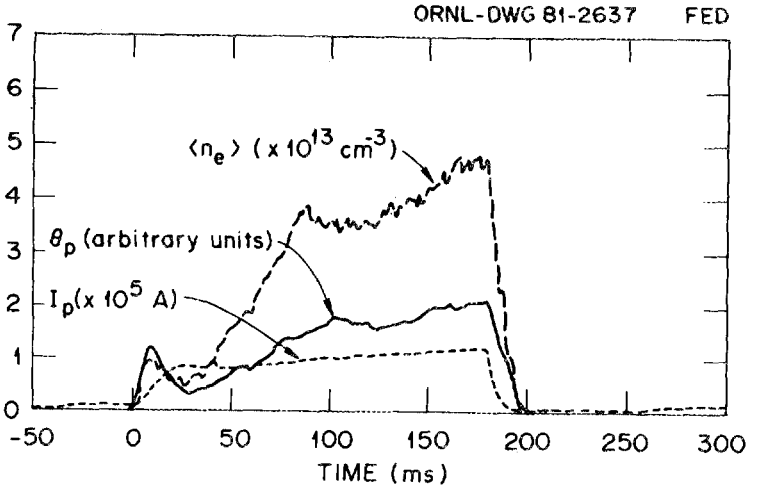


Fig. 7.12. Results of a single-channel Asterodyne measurement of the Faraday rotation signal shown with the electron density variation and plasma current.

crystal, the polarization of the beam is oscillated about the initial polarization direction, not linearly as with the ferrite, but in a periodic and predictable fashion. The functional dependence of the Faraday rotation signal produced by the plasma, using the $LiTaO_3$ modulator, is identical with that produced by the ferrite modulator, which simplifies the data analysis and makes the two modulators interchangeable. Also, the crystal presents only a small shunt capacitance (~25 pF) to a driving circuit, and very high modulation frequencies appear possible. When fully developed, this new modulator should be sufficiently fast to allow studies of magnetic fluctuations in tokamaks associated with MHD activity.

1. D. P. Hutchinson, P. A. Staats, K. L. Vander Sluis, and J. B. Wilgen, ORNL/TM-7015 (September 1979).

PLASMA ION TEMPERATURE MEASUREMENT BY THOMSON SCATTERING

D. P. Hutchinson C. H. Ma
P. H. Staats K. L. Vander Sluis

The use of Thomson scattering of a submillimeter laser beam as a diagnostic technique for the determination of plasma ion temperatures has been proposed. To provide a proper submillimeter laser source an unstable resonator was designed in conjunction with a large-volume beam expansion amplifier. Basic to this design is a high-power, tunable, pulsed, CO_2 laser needed to optically pump the D_2O molecules, which are the active media for the submillimeter resonator and amplifier.

Subsequent evaluation of the output of this submillimeter source has provided the following conclusions, based on data derived from a Fabry-Perot interferometer and time studies of the wave forms recorded with a 0.5-ns resolution transient digitizer.

The tunable, pulsed, CO_2 laser will provide 60 J of narrow-frequency (FWHM < 20 MHz) pump energy in a 150-ns pulse. Furthermore, the operation of the laser is uncomplicated and reliable.

Several general conclusions may also be drawn on the basis of our evaluations and analyses of the unstable resonator and beam-expanding amplifier high-power laser system. First, the oscillator was found to be very efficient and to have the proper frequency characteristics; however, the amplifier did not meet the requirements because the amplification of a Raman transition is power dependent, making the expansion of the beam and consequent reduction of power density counterproductive. Also, the far-field beam profile of an unstable resonator depends upon a diffractive recombination of the annular near-field beam. An optic (e.g., an amplifier) placed in the near field of the oscillator must meet surface and angle tolerances characteristic of an interferometer in order to permit proper recombination of diffracted

amplitudes and phases. This results in an unusually sensitive alignment requirement for the amplifier.

A further deficiency of the tested diagnostic was due to the fact that the combined oscillator-amplifier system, consisting of the unstable resonator and 5 m of 6-in.-diam amplifier, has inherent flaws in the frequency characteristic that make it unsuitable as a Thomson-scattering laser source. Although this system does produce the required power level, it suffers from superradiance because of the amplifier length.

It appears that the length of a high-power laser system needs to be made a secondary consideration. Since an oscillator is an excellent amplifier, a linear oscillator of sufficient length (3 to 5 m) would be a proper choice to produce a laser source of 1-MW power with an FWHM of 30 MHz. The spurious multiple longitudinal modes anticipated with the use of a linear oscillator can be controlled by dispersive or absorptive methods. Further, our experience indicates that, with appropriate modifications, an injection-tuned, CO_2, pump laser may be used to achieve the 200-ns pulses.

Based on information gained from the first series of experiments, additional design and development work are proceeding on the coherent light source as well as on other aspects of the Thomson-scattering diagnostic system.

8. Accelerator-Based Atomic Physics

INTRODUCTION

P. D. Miller

The period covered by this progress report has witnessed a number of significant developments within the Accelerator-Based Atomic Physics Group. In the sections which follow, the details of some of these experiments may be found, but the highlights will be summarized here. The merged heavy-ion–electron beam experiment has been designed, constructed, and installed. Progress toward measuring a dielectronic recombination cross section will be described. An experiment has been done in collaboration with Bell Labs, Brookhaven, and the University of Aarhus to quantify the deviation from a projectile Z^2 dependence of bare-ion stopping powers in a crystalline channel. The very puzzling result is that for the range of projectile Z and the projectile velocity chosen, the stopping power divided by Z^2 is a constant. In another channeled-ion experiment the influence of ionic charge and mass on the transverse oscillation frequency in planar channels as a function of oscillation amplitude was investigated. The results showed a surprising sensitivity to the details of ion-atom potentials assumed. The studies of resonant coherent excitation of channeled ions was continued, and new results utilizing planar channeling of one- and two-electron ions will be presented. Multiple electron-loss cross-section studies for Fe^{4+} ions incident on a wide variety of gases were completed. In large molecules, evidence of shadowing for the loss of one electron was shown, and effects of multiple excitation in the case of many-electron loss were demonstrated.

Collaboration with universities and other divisions within ORNL has continued. The University of Tennessee continued its studies of convoy electrons by showing the possible influence of the second Born approximation in leading to asymmetries in the forward-ejection spectrum of electrons by bare ions incident on gas targets. This experiment and others involving electron cusps will be described in the following sections. A new activity of the UT group in collaboration with Texas A&M University is concerned with the trapping and storage of recoil heavy ions formed by the collision of MeV heavy ions with a gas. These trapped recoil ions may then be used for very-low-energy (eV) charge exchange studies. This activity was started using a grant from the ORNL Seed Money Committee.

The group consisting of a collaboration between ORNL and North Texas State University has continued its studies of vacancy production mechanisms by investigating direct ionization of the M shell of heavy-atom targets and by investigating M electron transfer from heavy-atom targets to projectile K-shell vacancies.

Since the period of the last annual report, the Enge split-pole magnetic spectrograph has been moved from the EN tandem to the Holifield Heavy-Ion Research Facility (HHIRF). To replace its capability, an Elbek spectrograph has been obtained from Los Alamos. Funding has been granted for the installation, pumping, camera modifications, power supply, and scattering chamber for this instrument. The

conceptual design studies for this project will be completed during 1981, and installation will take place during 1981 and 1982.

The first three atomic physics experiments have been approved by the Program Advisory Committee for the HHIRF. One of these is a collaborative experiment between Kansas State University and ORNL to investigate double K electron transfer from a titanium target to a high-energy bare projectile by means of detecting K hypersatellite lines from the target. The second approved experiment is an investigation, by the University of Tennessee group, of electron cusps at high velocities, and the third experiment is an investigation of beam foil bare-ion capture and excitation of hydrogenic ions of chlorine to the $2p$ and higher n,p states by carbon foils. This last proposed experiment is a collaboration between Murray State University; Harwell, UK; and ORNL.

MERGE ELECTRON-HEAVY-ION BEAMS

P. F. Dittner C. D. Moak
W. B. Dress P. H. Stelson
P. D. Miller S. Datz

An apparatus to merge an ion beam from the ORNL EN tandem with a high-density beam of electrons has been constructed. The first goal of this project is to study dielectronic recombination (DER) in a number of lighter ion species, for example, oxygen, chlorine, and silicon. A major goal is to obtain DER cross sections of heavier ions at charges and relative energies which would be of interest to those studying plasma energy-loss mechanisms.

At present, the apparatus has been constructed and installed in the ORNL EN tandem on a dedicated ultrahigh-vacuum beam line. Figure 8.1 shows a schematic of the system. Our double-gridded, Pierce-type electron gun produces a space-charge-limited electron beam having a perveance ($P = I/V^{3/2}$) of

ORNL-DWG 79-19166

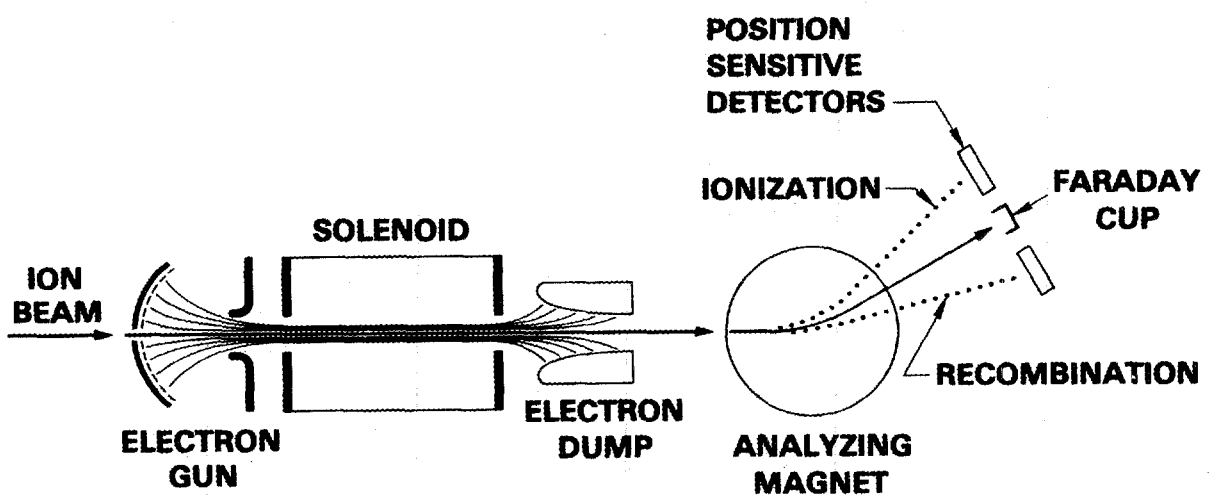


Fig. 8.1. Schematic diagram of the merged-beam apparatus.

10^{-6} A/(V)$^{3/2}$. The waist of the focused electron beam ($D \approx 3$ mm) occurs about 6 mm downstream from the exit aperture of the gun anode. The electron beam is injected axially into a region having a constant axial magnetic field (B_z) produced by a solenoid. The value of B_z is adjusted such that Brillouin flow results; that is, the beam has a spatial distribution such that $\rho =$ a constant ($r \leqslant r_{max}$) and $\rho = 0$ ($r > r_{max}$) and has a uniform axial velocity and rotates as a solid cylinder about the axis with the Larmor frequency. The region over which the electron beam is so confined by B_z is ~1 m long. After leaving the solenoid the beam expands radially due to space charge repulsion and is collected on a water-cooled beam dump. The ion beam enters the electron beam region through an ~$^1/_2$-mm-diam hole in the cathode of the electron gun and travels along the electron beam axis. The relative velocity, v_r, between the ions having velocity v_i and the electrons having velocity v_e can be varied by varying either v_i or v_e and with greater than or less than $v_i v_e$. The ion beam emerging from the interaction region is then charge-state-analyzed by a deflecting magnet. The initial beam (charge $= q$) impinges on a Faraday cup, and those ions that have captured an electron (charge $= q - 1$) strike a solid-state detector and are subsequently counted.

Several experiments have been performed with ion beams of 32-MeV O^{5+}, 45-MeV Cl^{7+}, and 28-MeV Si^{4+} and electrons of the appropriate energy to provide a resonant relative energy for DER. For these ion beams (initial charge $q+$) the fraction of $(q-1)+$ ions, which mask the "real" signal, has been larger than could be explained by charge capture from the background gas density (as determined from various gage readings and a residual gas analyzer). However, a DER signal should have been observable for reasonable theoretical estimates of the cross sections.

As an example of the operating parameters of the experiment, consider the case of 45-MeV Cl^{7+}, a neon-like ion. The series limit for the transition $Cl^{7+}(2p^6) + e \rightarrow Cl^{6+}(2p^5 3dnl)$ occurs for an electron energy (E_r) relative to the Cl^{7+} of 247 eV. Thus, for 45-MeV Cl^{7+} ions, the two resonant laboratory electron energies are 1787 and 118 eV. For the 1787-eV case, giving a higher electron density, the electron current is 80 mA. The electron density would be 3.5×10^9 electrons/cm^3 under a Brillouin flow condition. For an estimated cross section of 1.3×10^{-18} cm^2 (calculated assuming that the FWHM of $E_r \approx 1$ eV), the probability of an incident Cl^{7+} changing to Cl^{6+}, in a low enough n state to survive passage through the charge-state analyzing magnet without being Stark stripped, is $\sim 2 \times 10^{-7}$.

The background capture event rates per incident Cl^{7+} are 6×10^{-7} with the electron gun off and 18×10^{-7} with the electron gun on. In this experiment the electron beam energy was swept over a 100-V range centered about the resonance corresponding to a 40-V range in relative energies. Under the assumed conditions of the experiment, a recombination probability of 0.1×10^{-7} would have been observable (i.e., ~0.1 of the value estimated from the calculated cross section). However, no signal was seen within this limit. Similarly, no resonance was observed for beams of O^{5+} and Si^{4+}. The possible reasons for the lack of observation of resonant DER include:

1. An anomalously low electron density in the region of space occupied by the ion beam.
2. A very much larger velocity spread of the electron beam than would be expected under Brillouin flow conditions.
3. The cross section is significantly less than expected theoretically.

At present we are conducting theoretical and experimental studies related to possible sources of additional velocity spread of the electron beam.

CHARGE-STATE DEPENDENCE OF CHANNELED-ION ENERGY LOSS

J. A. Golovchenko[1] C. E. Thorn[2]
A. N. Goland[2] H. E. Wegner[2]
J. S. Rosner[2] H. Knudsen[3]
C. D. Moak

The charge-state dependence of channeled-ion energy loss has been determined for a series of ions ranging from fluorine to chlorine along the ⟨110⟩ direction in a silicon crystal. Energy losses for both bare ions and ions partially clothed with bound electrons at $E/A \cong 3$ MeV/amu have been measured. The energy loss rate for bare ions follows a strict Z_1^2 scaling. The clothed-ion energy losses appear to demonstrate screening effects that agree qualitatively with simple estimates.

Theoretical analysis by Ashley, Ritchie, and Brandt[4] indicated that stopping powers would be expected to show departure from a strict Z^2 scaling, an effect first observed by Barkas, Dyer, and

Heckman.[5] Lindhard has pointed out that higher-order correlations for stopping power must include not only the Z_1^3 term but also a Z_1^4 term of comparable size (known as the Bloch term[6]).[7] Recent reports for protons, alpha particles, and lithium ions indicate the presence of both Z_1^3 and Z_1^4 terms in the stopping power.[8]

We have measured the stopping powers of bare ions in the range $9 \leqslant Z_1 \leqslant 17$ in crystal channels of silicon. It was expected that the Z_1^3 and Z_1^4 terms would be large. The results are shown in Fig. 8.2, and it appears that no higher-order effects occur.

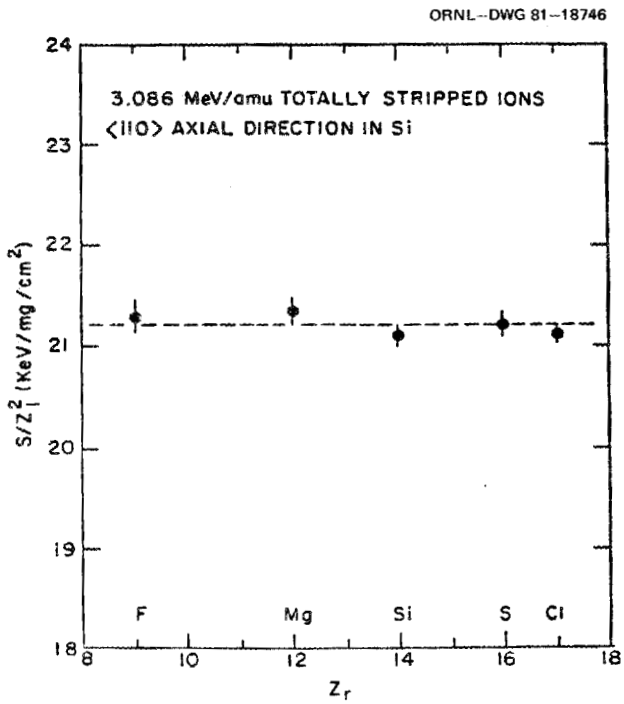


Fig. 8.2. S/Z_1^2 vs Z_1 for bare F, Mg, Si, S, and Cl ions.

A theoretical extension of the Bloch term to our range of nuclear charge shows that (see Fig. 8.3) the term exhibits a Z_1^4 behavior at low Z_1, but the term becomes almost exactly a Z_1^3 term in the range $9 \leqslant Z_1 \leqslant 17$. Calculations of both Z_1^3 and Z_1^4 terms for our cases for extreme limits of assumed crystal electron density are compared with the data in Fig. 8.4. The possibility exists that, for channeled particles in this range of Z_1, a cancellation occurs between the Z_1^3 and Z_1^4 terms.

Experiments with clothed ions indicate that discontinuities in stopping power occur when changing

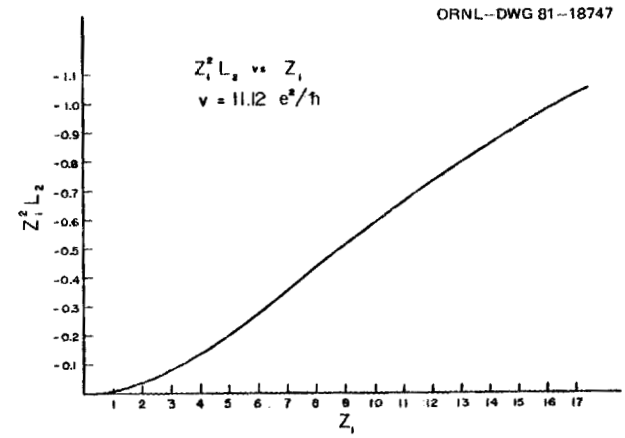


Fig. 8.3. Bloch correction Z_1 dependence for $v = 11.12\ e^2/\hbar$.

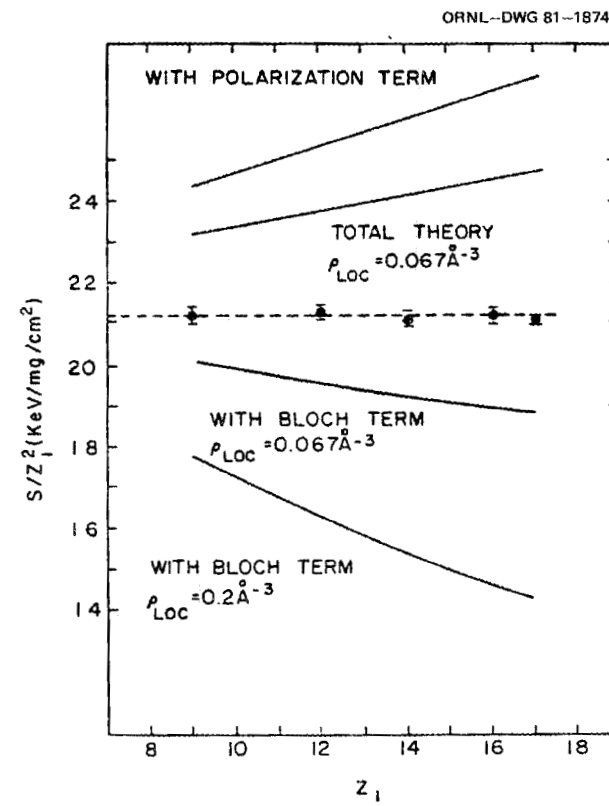


Fig. 8.4. Bare-ion experimental results compared with estimate including Bloch correction and/or polarization term.

from ions having only K-shell electrons and ions having three or more electrons.

1. Bell Laboratories, Murray Hill, N.J.
2. Brookhaven National Laboratory, Upton, N.Y.

3. Aarhus University, Dept. of Physics, DK-8000, Aarhus C, Denmark.
4. J. C. Ashley, R. H. Ritchie, and W. Brandt, *Phys. Rev. B* **5**, 2393 (1972).
5. W. H. Barkas, N. J. Dyer, and H. H. Heckman, *Phys. Rev. Lett.* **11**, 26 (1963).
6. F. Bloch, *Ann. Phys. (Leipzig)* **16**, 285 (1933).
7. J. Lindhard, *Nucl. Instrum. Methods* **132**, 1 (1976).
8. H. H. Andersen, J. F. Bak, H. Knudsen, P. Møller Petersen, and B. R. Nielsen, *Nucl. Instrum. Methods* **140**, 537 (1977).

SINGLE AND MULTIPLE ELECTRON-LOSS CROSS-SECTION MEASUREMENTS

G. D. Alton, P. D. Miller
L. B. Bridwell[1], C. M. Jones
M. Lucas[2], Q. C. Kessel[3]
C. D. Moak, A. A. Antar[3]
M. D. Brown[4]

Experimental studies of projectile-electron-loss processes resulting from interactions between 20-MeV Fe^{4+} and a variety of gaseous targets have been continued. The principal emphasis was placed on molecular-target effects with the objective of delineation of differences in electron-loss processes of atomic and molecular targets. Studies were conducted with a variety of targets including He, Ne, Ar, Kr, Xe, H_2, N_2, O_2, CH_4, CO_2, CHF_3, CF_4, and SF_6. The experimental arrangement was identical to that used in similiar studies previously described.[5-9] Several interesting target- and projectile-related effects were observed during these investigations.

Shell effects, attributable to changes in the binding energy of projectile electrons prior to and following the argon-like electronic configuration, were observed in the electron-loss cross-section data for noble-gas targets. This effect, illustrated in Fig. 8.5, is characterized by a change in shape of electron-loss cross section vs final projectile charge state q on either side of $q = 8$, which corresponds to the argon-like configuration of the projectile.

Electron-loss cross sections vs target atomic number obtained from a noble-gas target indicate a slight decrease in cross sections between $Z_2 = 18$ and $Z_2 = 54$. This effect, previously observed for other projectile-noble-gas target combinations,[10] is believed to be attributable to differences in the polarizabilities of targets in this region. The data shown in Fig. 8.6 illustrate this phenomenon.

"Nonadditivity" and "density" effects both play roles in projectile-electron-loss processes during

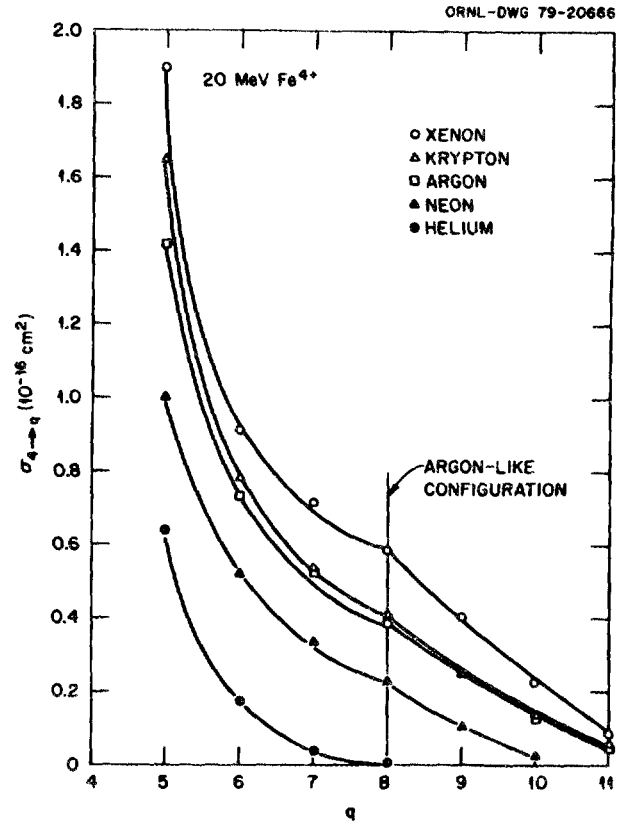


Fig. 8.5. Electron-loss cross section vs final projectile charge state produced in He, Ne, Ar, Kr, and Xe targets. The data have been plotted on a linear scale in order to illustrate the change in shape of the cross section vs projectile final charge-state curves at $q = 8$. The changes are attributable to the increase in binding energies between the $3d$ and $3p$ subshells and illustrate a so-called "shell effect."

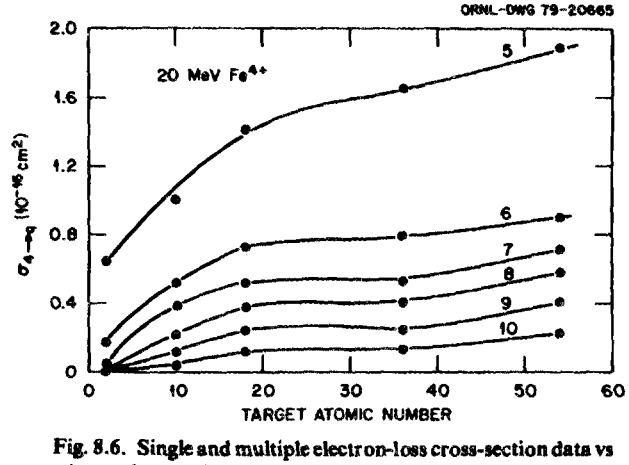


Fig. 8.6. Single and multiple electron-loss cross-section data vs atomic number for He, Ne, Ar, Kr, and Xe target gases.

interactions between high-energy multielectron projectile and gaseous molecular target as evidenced by the data shown in Fig. 8.7. A plot of electron-loss cross section per atom vs final projectile charge state indicates that the molecular targets CO_2, CF_4, and SF_6 are not as effective as neon for producing projectile charge states $q > 8$, while they are more effective for producing charge states $q > 8$, and all are approximately equal at $q = 8$. Thus these data reflect "nonadditivity" effects for $q < 8$ and "density" effects for $q > 8$. "Nonadditivity" refers to the case where the total electron-loss cross section per molecule is less than the sum of the cross sections for the individual constituents. This effect is attributable to shadowing of individual atoms by other atoms or groups of atoms during the interaction. The "density" effect occurs because the projectile can undergo multiple collisions during passage through a molecular target. Such high-frequency collisions can lead to enhanced electron loss over that which would result from the summation of individual cross sections of the constituents for a particular loss process.

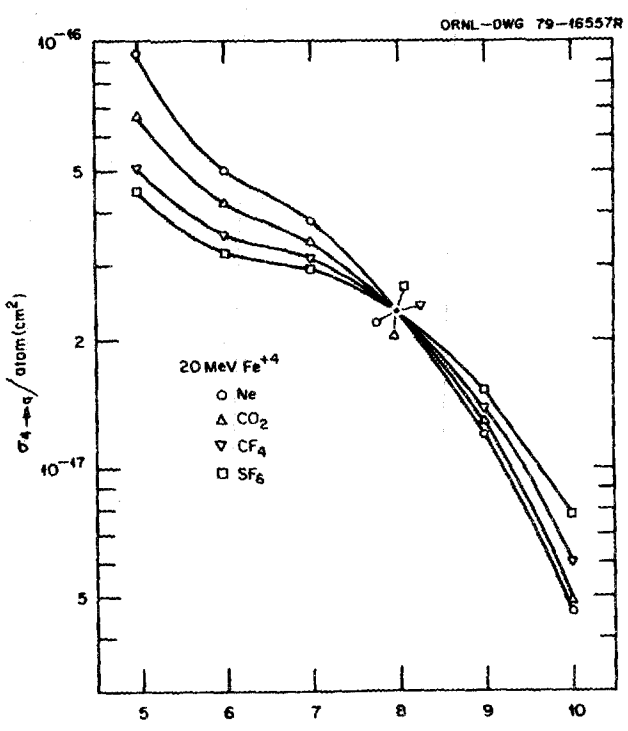


Fig. 8.7. Comparison of the electron-loss cross sections per atom data produced in CO_2, CF_4, and SF_6 with those produced in neon as a function of final projectile charge state. The data illustrate a "nonadditivity effect" observed in molecular gases for charge states $q < 8$ and a "density effect" for charge states $q > 8$.

A prescription of what is termed the mean atomic number which the target appears to possess during interactions with molecular targets, leading to single-electron loss, has also been deduced. The formula is

$$Z_2/n = \Sigma z_i/n^2 , \qquad (1)$$

where n is the number of atoms in the molecule. A plot of single-electron-loss cross sections vs the mean atomic number per atom calculated from expression (1) is shown in Fig. 8.8. We note that all measured molecular target data increase monotonically with $\bar{Z}_2/n$ and fall along a curve which passes through the noble-gas data. The solid line in Fig. 8.8 represents cross-section values calculated from a modified Bohr formula.[8,9]

---

1. Murray State University, Murray, Ky.
2. University of Sussex, Sussex, Brighton, England.
3. University of Connecticut, Storrs, Conn.
4. Naval Surface Weapons, White Oak, Silver Spring, Md.
5. *Phys. Div. Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5498.
6. C. D. Moak, L. B. Bridwell, H. A. Scott, G. D. Alton, C. M. Jones, P. D. Miller, R. O. Sayer, Q. C. Kessel, and A. Antar, *Nucl. Instrum. Methods* **150**, 529 (1978).
7. H. Knudsen, C. D. Moak, C. M. Jones, P. D. Miller, R. O. Sayer, G. D. Alton, and L. B. Bridwell, *Phys. Rev. A* **19**, 1029 (1979).

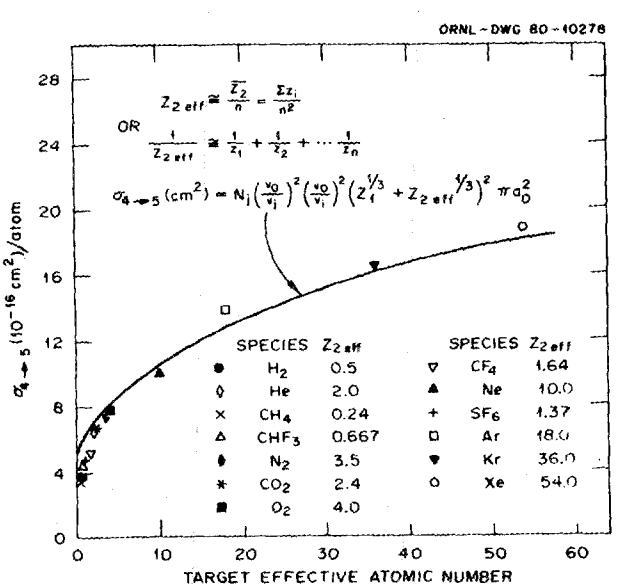


Fig. 8.8. Comparisons of single electron-loss cross sections per atom computed from the modified Bohr formula as a function of average effective atomic number per atom with those experimentally measured.

8. G. D. Alton, L. B. Bridwell, M. Lucas, C. D. Moak, P. D. Miller, C. M. Jones, Q. C. Kessel, A. A. Antar, and M. D. Brown, *Phys. Rev. A* **23**, 2340 (1981).
9. G. D. Alton, *IEEE Trans. Nucl. Sci.* **NS-28**, 1043 (1981).
10. V. S. Nikolaev, *Sov. Phys.—Usp.* **8**, 265 (1965).

FORWARD EJECTED ELECTRON SPECTROSCOPY

I. A. Sellin[1] R. Marrus[6]
M. Breinig[2] R. Laubert[7]
S. B. Elston[1] M. M. Schauer[2]
L. Liljeby[3] M. Suter[8]
R. S. Thoe[4] S. Huldt[2]
C. R. Vane[5] S. Datz[9]
H. Gould[6] S. Overbury[9]

An experiment was performed to make initial tests of a possible second Born term as the source of asymmetry in forward electron ejection by fast bare nuclei. The shapes of continuum capture cusps arising from ejection of target electrons by 15- to 18-a.u. Ar^{18+} nuclei transversing He, Ne, and Ar were investigated. Observed asymmetries were then compared with the second-Born-term asymmetry conjecture by Shakeshaft and Spruch[10] and with the alternative first-Born-term asymmetry counter-conjecture by Chan and Eichler.[11] Present evidence favors the former conjecture, as shown in Fig. 8.9.

In a second experiment the velocity dependence of the widths of electron-loss cusps in the range 7 to 12.5 a.u. was investigated. For Si^{q+}, O^{q+}, and C^{q+} projectiles traversing He, Ne, and Ar targets in the velocity range 7 to 12.5 a.u., the FWHM was found to be independent of the ion velocity. These results disagree with theoretical predictions predating those of Day[12] and restrict the velocity dependence of the anisotropy parameter β in Day's theory.

In a third experiment, the spectrum and yield for convoy electrons produced by 1- to 8.5-MeV/u C^{q+}, O^{q+}, and Ni^{q+} ions traversing equilibrium-thickness polycrystalline C, Al, Ag, and Au targets, and ⟨110⟩ and ⟨100⟩ axial channels in thin gold monocrystals, were measured. By studying convoy electron production in coincidence with emergent ions of charge state q_e, it was found that the yield integrated over electron velocity for channeled ions depends strongly on q_e, but the shape was found to be independent of q_e, v and target material. For polycrystalline and randomly oriented monocrystalline targets, the yield was found to be independent of emergent ion charge state q_e. The data suggest that convoy electron production is a bulk process and that convoy production is initiated by capture events requiring a close approach to lattice sites (within about 0.65 Å for gold). The similarity of the convoy spectra to analogous spectra observed for projectile electron loss in gases suggests that subsequent electron-loss collisions determine the basic shape of the convoy spectrum, which is then modified by electron scattering out of the forward direction in such a way as to yield a skew toward high electron energy.

ORNL-DWG 81-18749

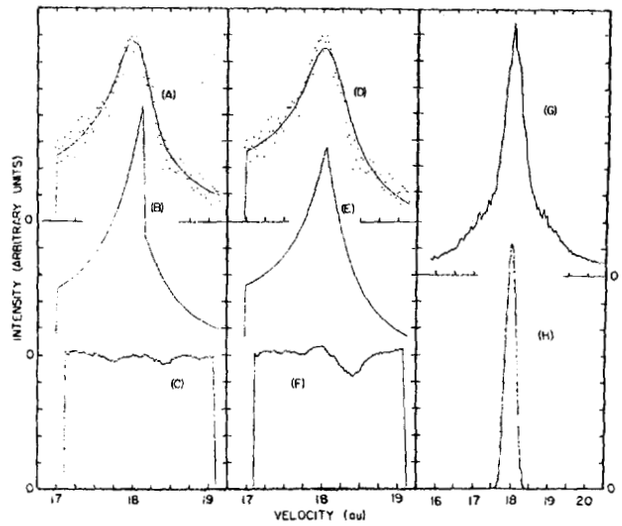


Fig. 8.9. Comparison of the central portion of ECC cusps obtained for 18.1-a.u. Ar^{18+} on He with the overlaid convoluted line shapes read from ref. 10 (*A*) and ref. 11 (*D*). The respective best-fit theoretical shapes (*B*) and (*E*), when convoluted with the measured apparatus function (curve *H*), produce fits (*A*) and (*D*). A narrower more symmetric ECC spectrum for 8.5-MeV/u Ar^{13+} on He is shown in (*G*). Curves (*C*) and (*F*) display ten-channel moving averages of the corresponding deviation spectra ($y_i - y_{fit}$ vs i).

---

1. Part-time employee from the University of Tennessee, Knoxville.
2. University of Tennessee, Knoxville.
3. University of Tennessee, now at the Inst. Atomfysik, Stockholm, Sweden.
4. University of Tennessee, now at Lawrence Livermore Laboratory, Calif.
5. Lawrence Berkeley Laboratory, now at ORNL Physics Division.
6. Lawrence Berkeley Laboratory, Calif.
7. East Carolina University, now deceased.
8. Eidgenossische Technische Hochschule, Zurich, Switzerland.

9. Chemistry Division.

10. R. Shakeshaft and L. Spruch, *Phys. Rev. Lett.* **41**, 1037 (1978).

11. F. T. Chan and J. Eichler, *Phys. Rev. A* **20**, 367 (1979); R. Shakeshaft and L. Spruch, *Phys. Rev. A* **20**, 376 (1979); K. Dettmann, K. G. Harrison, and M. W. Lucas, *J. Phys.* **B7**, 269 (1974); K. C. R. Chiu, W. Meckbach, G. Sanchez Sarmiento, and J. E. McGowan, *J. Phys.* **B12**, L147 (1979).

12. M. H. Day, *J. Phys.* **B13**, L65-8 (1980); J. S. Briggs and M. H. Day, Harwell Theoretical Physics Report TP 856, submitted for publication.

STORED HIGHLY IONIZED PARTICLE SPECTROSCOPY (SHIPS)

S. L. A. Huldt[1] S. B. Elston[3]
S. D. Berry[1] G. A. Glass[1]
M. Breinig[1] R. M. Holmes[1]
W. S. Burns[2] R. A. Kennefick[2]
D. A. Church[2] I. A. Sellin[3]

The preliminary goal for this project is to confine slow (~10 eV), multiply charged ions in a volume (~1 cm^3) for times limited only by charge-changing collisions with the residual gas atoms. Ions are produced in the center of a trap in collisions between a target gas and a beam of highly stripped projectiles with energy of ~1 MeV/u. The trap is of the Penning type, which utilizes a combination of magnetic and electrostatic fields. The motion of the trapped ions is characterized by three distinct frequencies related to the trap parameters and to the charge-to-mass ratio of the ions. These frequencies are utilized both for the detection of ions and for selectively expelling one or more unwanted constituents by exciting the trap at a corresponding frequency.

In a run during April 1981, neon gas with pressure in the range 10^{-8} Torr was ionized by a 30-MeV chlorine beam traversing the trap along the direction of the magnetic field. Peaks in the trap frequency spectrum corresponding to Ne^{q+}, $q = 2, 3, 4$, and 5, were identified, and the confinement time as a function of gas pressure was measured. These results are shown in Fig. 8.10. The times ranged from ~50 to ~800 ms and indicated that, in spite of the crude electrode geometry of the present trap, the escape mechanisms due to imperfections in the field configuration are of little significance on this time scale.

Efforts are being directed toward further developing the ion detection scheme and toward including provisions to momentarily increase the gas pressure by letting a "gas puff" into the trap with a duration much shorter than typical confinement times.

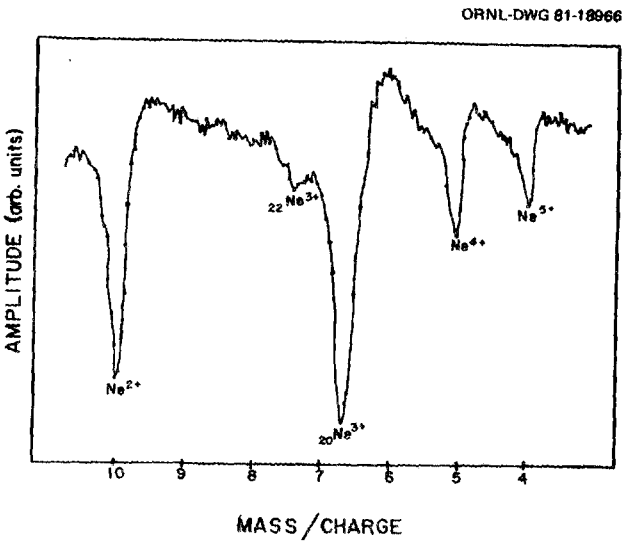


Fig. 8.10. Power absorption spectrum of a trapped population of Ne^{20} (91% natural abundance) and Ne^{22} (9%).

1. University of Tennessee, Knoxville.
2. Texas A&M University, College Station.
3. Part-time employee from the University of Tennessee, Knoxville.

RESONANT COHERENT EXCITATION OF CHANNELED IONS

C. D. Moak J. Gomez del Campo
J. A. Biggerstaff P. Hvelplund[2]
O. H. Crawford[1] H. Knudsen[2]
P. F. Dittner H. F. Krause[1]
S. Datz[1] P. D. Miller
S. H. Overbury[1]

Hydrogenic ions of B, C, N, O, and F and helium-like ions of N, O, and F have been shown to exhibit resonant coherent excitation from their $n = 1$ to their $n = 2$ states caused by periodic electric potential oscillations which occur as the ion moves through axial or planar channels of a thin crystal of gold.[3] The resonance velocities of the ions exhibit shifts and splittings which are the result of the crystal fields

acting upon the one- or two-electron ions. Comparisons with theory show fairly good agreement except for certain weak resonances which do not appear or appear at unexpected values of the resonance velocity.[4] For the case of planar channeling, resonances can be tuned both by velocity variation and by variation of the planar channel geometry.[5] Two identical geometries with trajectory path lengths which differ by 41% were used for the data in Figs. 8.11 and 8.12. The increase of path length did not strengthen the resonances but only produced a slight increase in resonance width, and the conclusion is that the thin-side path length is enough to produce the maximum effect and that particles passing through additional path length have lost too much energy to remain in resonance.

In Fig. 8.13, planar resonances appear for both hydrogenic ions and helium-like ions. The input ions were all helium-like; the figure demonstrates that an ion can change charge in the crystal and then undergo resonant coherent excitation.

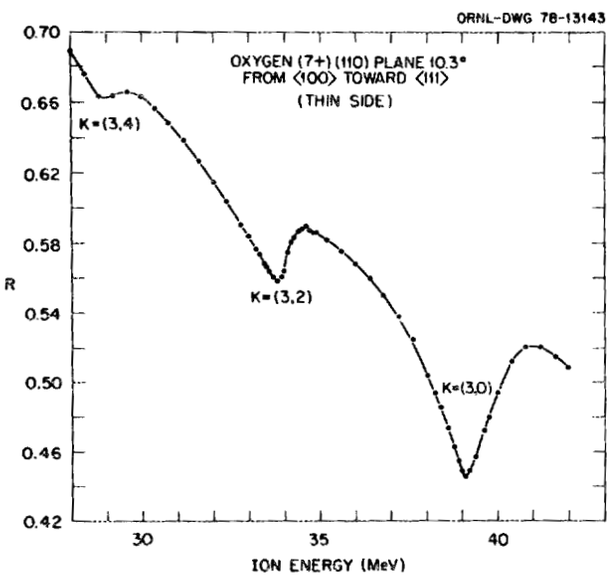


Fig. 8.11. (100) planar resonances of O^{7+} in gold. Path length, 1190 Å 10.3° from ⟨100⟩.

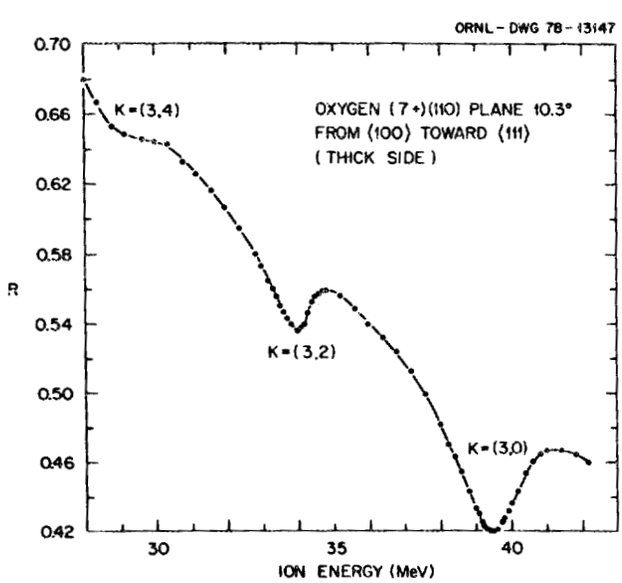


Fig. 8.12. (110) planar resonances of O^{7+} in gold. Path length 2014 Å 10.3° from ⟨100⟩.

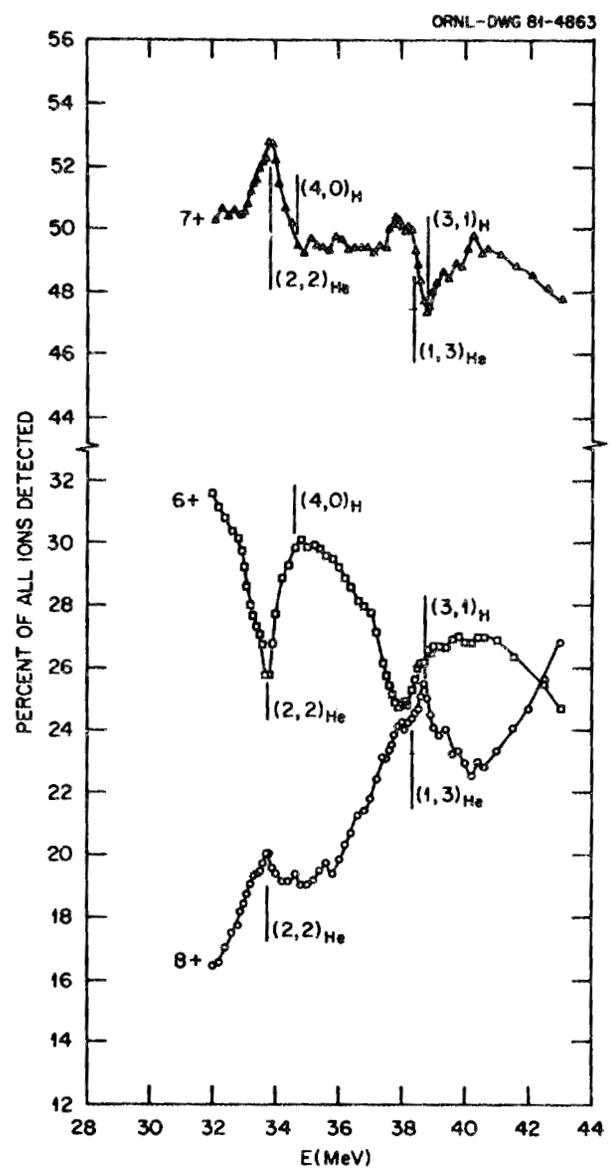


Fig. 8.13. Oxygen 6+ ions on gold 38° from 100 axis in 100 plane (tilt angle = 0°).

The process of "planar tipping" has been used to gradually eliminate ion trajectories of small transverse amplitude and cause extinction of the resonances. The data shown in Figs. 8.13 to 8.15 indicate that different parts of the resonance profile do not come from different trajectories, since no shift or shape change occurs as the crystal tilt is increased.

1. Chemistry Division.
2. Aarhus University, Dept. of Physics, DK-8000, Aarhus C, Denmark.

3. C. D. Moak, S. Datz, O. H. Crawford, H. F. Krause, P. F. Dittner, J. Gomez del Campo, J. A. Biggerstaff, P. D. Miller, P. Hvelplund, and H. Knudsen, *Phys. Rev. A* **19**, 977 (1979).
4. O. H. Crawford and R. H. Ritchie, *Phys. Rev. A* **20**, 1848 (1979).
5. S. Datz, C. D. Moak, O. H. Crawford, H. F. Krause, P. D. Miller, P. F. Dittner, J. Gomez del Campo, J. A. Biggerstaff, H. Knudsen, and P. Hvelplund in *Atomic Collisions in Solids*, ed. D. P. Jackson, J. E. Robinson, and D. A. Thompson, North-Holland, Amsterdam, 1980.

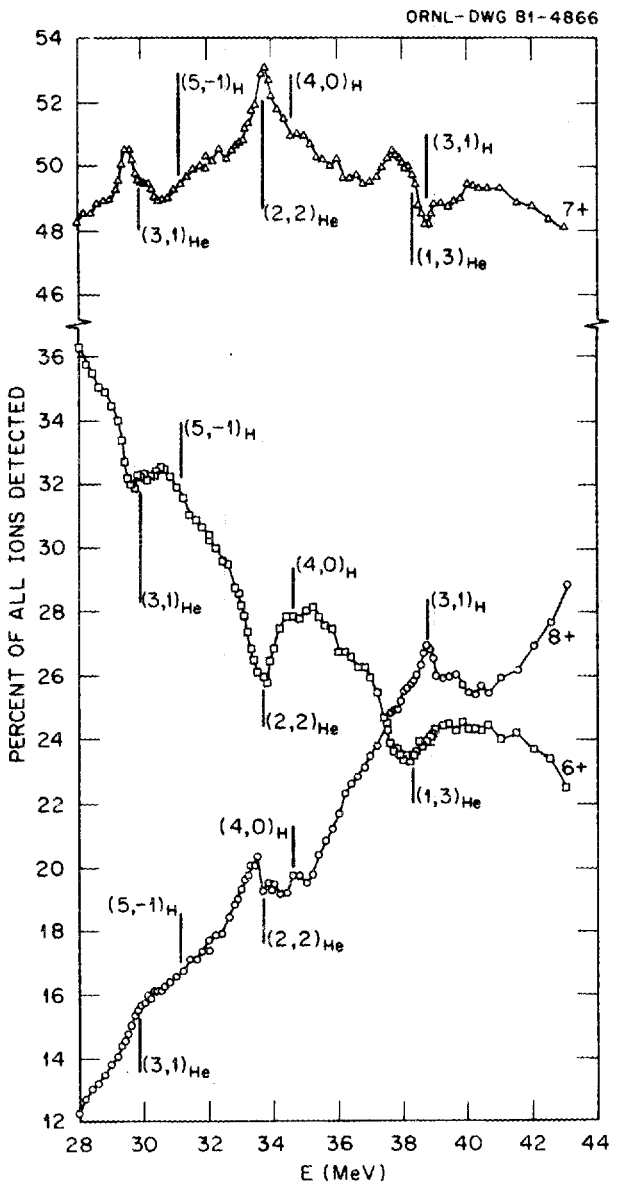


Fig. 8.14. Oxygen 7+ ions on gold 38° from 100 axis in 100 plane (tilt angle = 0.096°).

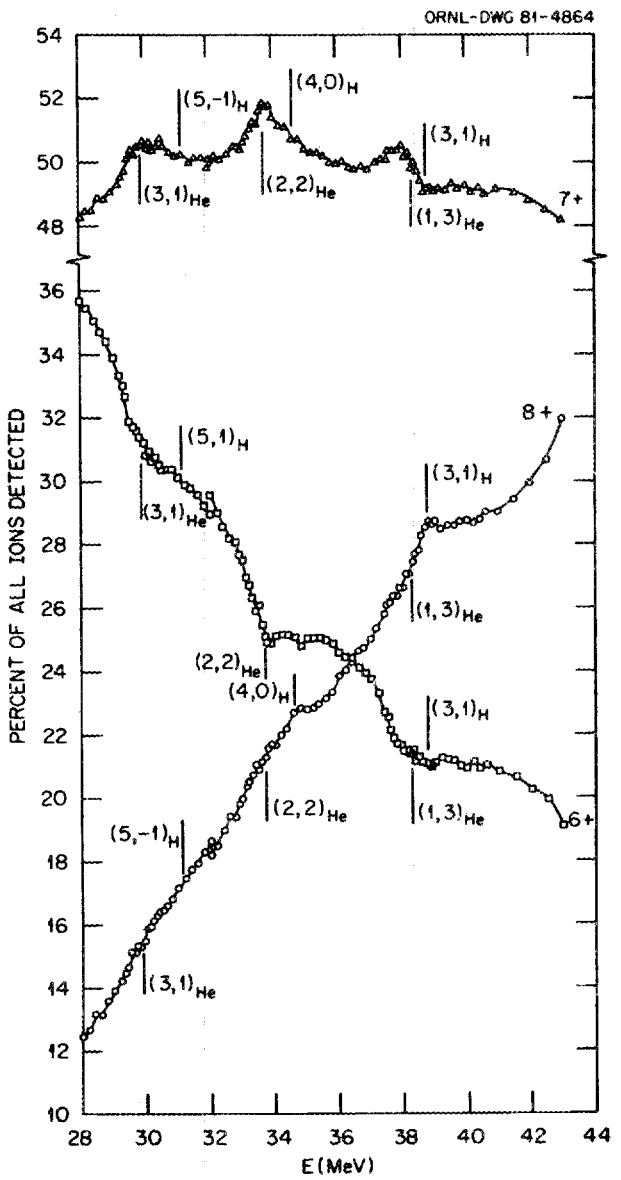


Fig. 8.15. Oxygen 6+ ions on gold 38° from 100 axis in 100 plane (tilt angle = 0.146°).

INTERPLANAR POTENTIALS DERIVED FROM TRANSVERSE OSCILLATIONS OF 3.5-MeV/amu HELIUM AND LITHIUM NUCLEI IN PLANAR CHANNELS OF SILICON

C. D. Moak
J. Gomez del Campo
J. A. Biggerstaff
S. Datz[1]
P. F. Dittner
H. F. Krause[1]
P. D. Miller

Transverse oscillations of ions moving in the planar channels of a crystal give information about their stopping powers vs amplitude of oscillation and about the restoring forces operating on the ions. In a previous paper, M. T. Robinson analyzed data on 3-MeV alpha particles, 10-MeV oxygen ions, and 15- to 60-MeV iodine ions in crystals of gold; at these energies, the effective charges of the ions were unknown and had to be inferred by analysis of the channeling data.[2] In this study we have used light ions at high enough energy to assure that each ion is a bare nucleus. Ions of ^{3}He, ^{4}He, ^{6}Li, and ^{7}Li at 3.5 MeV/amu have been used to give both a change of charge and change of charge-to-mass ratio. Robinson's analysis has been recast, since in this case the ions' effective charges are known. A new procedure has been utilized to examine how well various approximations for interplanar potentials can be made to fit the data.

Figure 8.16 illustrates the selection of energy-loss groups according to angle of emergence of channeled particles, and Fig. 8.17 shows that as the crystal is rotated for increased path length, the geometry selects particles of longer oscillation wavelength and smaller energy loss. The data in Fig. 8.18 show the variation of stopping power in various groups as path length is increased; the upper part of the figure shows the result of computer analysis to give unambiguous identification of the various loss groups.

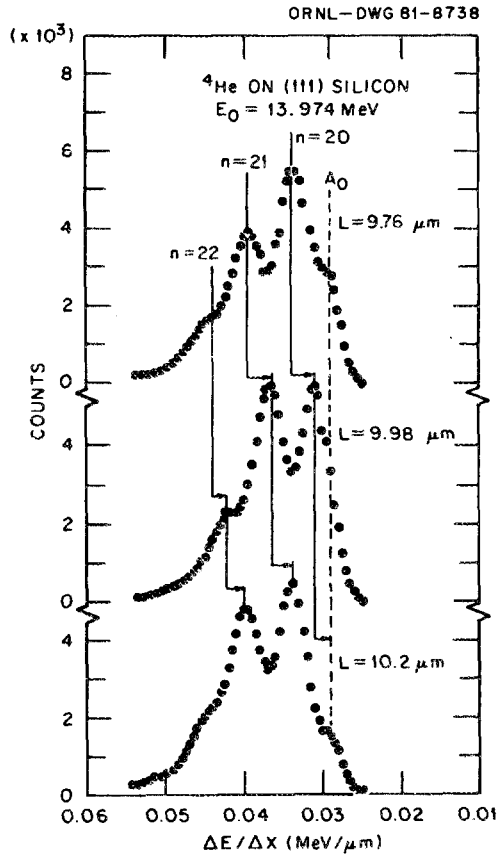
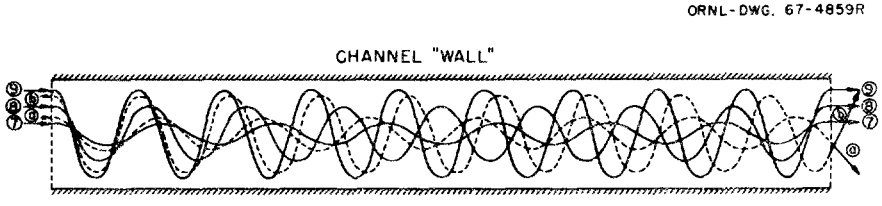


Fig. 8.17. Shifts of planar channel energy-loss groups vs crystal thickness.



1. DETECTOR ALIGNED TO BEAM AXIS.
2. PATHS ⑦ ⑧ AND ⑨ EMERGE WITH DIRECTION UNCHANGED.
3. PATHS SUCH AS ⓐ AND ⓑ EMERGE WITH ALTERED DIRECTION.
4. AN IDENTICAL SET OF PATHS (OMITTED HERE) EXISTS FOR ENTRY BELOW MID-CHANNEL.
5. $(\Delta E)_9 > (E\Delta)_8 > (\Delta E)_7$ etc.
   $(\Delta E)_a$ AND $(\Delta E)_b$ ARE UNOBSERVED.
6. FOR THE CASE DRAWN HERE λ DECREASES WITH INCREASING OSCILLATION AMPLITUDE.

Fig. 8.16. Selection of energy-loss groups according to angle of emergence of channeled particles.

ORNL-DWG 81-4905

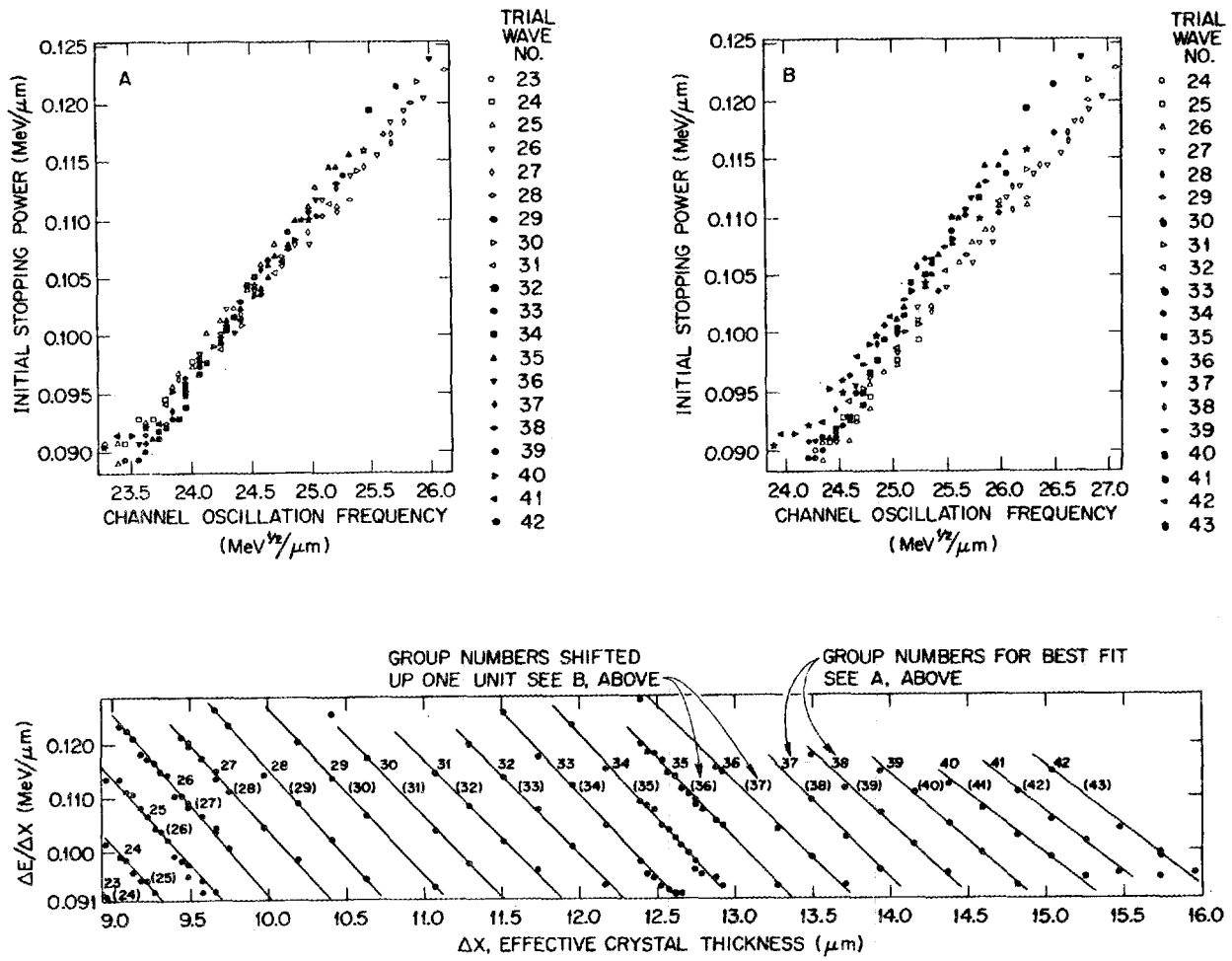


Fig. 8.18. Stopping power vs planar channel thickness, 21-MeV ^{6}Li in (100) channel in silicon. (*A*) Oscillation frequency vs stopping power for trial first wave number 23; (*B*) oscillation frequency vs stopping power for trial first wave number 24.

The results demonstrate that planar channeling energy-loss groups provide a very sensitive test of the form and size of the interplanar potentials, provided that the particles are totally stripped of electrons. Almost all of the data indicate that, as expected, different isotopes behave identically in planar channeling oscillations [i.e., $\nu_A(m_A)^{1/2} = \nu_B(m_B)^{1/2}$, where ν is the oscillation frequency and m the ion mass]. The data prove that the Moliere potential, as it is commonly used, does not fit the correct form or size of the real interplanar potentials in silicon. In contrast, the Hartree-Fock potential provides an accurate fit to the data. The absence of any differences between helium and lithium indicates that, within the experimental errors, both nuclei behave as good test charges for the crystalline potentials in silicon.

1. Chemistry Division.
2. M. T. Robinson, *Phys. Rev. B* **4**, 1461 (1971).

L- AND *M*-SHELL VACANCY PRODUCTION BY DIRECT IONIZATION AND ELECTRON CAPTURE TO THE PROJECTILE *K* SHELL

F. D. McDaniel[1] P. D. Miller
R. G. Albridge[2] R. S. Peterson[3]
M. C. Andrews[1] A. Ramyya[2]
F. Breyer[1] P. V. Rao[4]
J. L. Duggan[1] L. Rayburn[5]
A. Hamdi[1] Y. P. Sangsingkeow[1]
R. Mehta[1] A. Zander[6]

During the past two years we have made a great deal of progress in our study of inner-shell ionization in ion-atom collisions. We have determined the projectile charge-state dependence of inner-shell ionization for *L*-[7] and *M*-shell[8] ionizations by measuring both the direct ionization (DI) and electron capture (EC) contributions for selected collision systems. Previously, it was thought that inner-shell ionization depended on the nuclear charge of the ion and was independent of the number of electrons the ion possessed. Earlier measurements by the present authors[9] and others[10] showed that the number of electrons on the ion was very important primarily due to EC mechanisms from the target atom to the high-velocity ion. These EC transitions were possible only if inner-shell vacancies existed on the ion at the time of the collision. In fact, for some collision systems, the EC mechanism can be dominant over the DI mechanism for producing inner-shell vacancies.

The DI measurements have been compared with perturbed stationary-state calculations recently presented by the present authors.[11] We have just published an extensive comparison of our EC calculations in the perturbed stationary-state approximation with binding and Coulomb deflection to all of the available EC data in the literature for the *K* shell for fully stripped ions.[12] These EC calculations have provided very good agreement with other data in the literature as well as our own data for projectile atomic number (Z_1) to target atomic number (Z_2) ratios $\leqslant 0.5$ for low to intermediate projectile energies. Beyond $Z_1/Z_2 \cong 0.5$ the calculations and measurements begin to diverge for the *K* shell.

Figures 8.19 and 8.20 show the EC results obtained for the *L* shell for $^{19}_{9}$F and $^{28}_{14}$Si ions, respectively, incident on $_{60}$Nd, $_{67}$Ho, and $_{79}$Au targets. The dashed curve represents the Oppenheimer-Brinkman-Kramers calculations of Nikolaev,[13] while the solid curve shows the present perturbed stationary-state calculations.[8]

ORNL-DWG. 81-13150

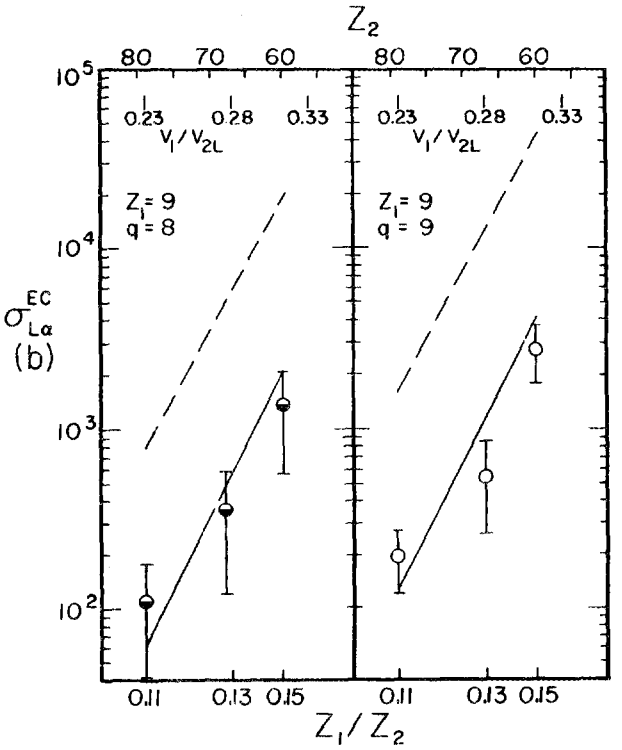


Fig. 8.19. Electron capture results for the L-shell for $^{19}_{9}$F ions incident on ^{60}Nd, ^{67}Ho and ^{79}Au targets

We are attempting to extend these measurements to larger Z_1/Z_2 ratios and to higher velocities to further test these theoretical approaches to inner-shell ionization.

---

1. North Texas State University, Denton.
2. Vanderbilt University, Nashville, Tenn.
3. University of Tennessee at Chattanooga.
4. Emory University, Atlanta, Ga.
5. University of Texas at Arlington.
6. East Texas State University, Commerce.

7. F. D. McDaniel, A. Toten, R. S. Peterson, J. L. Duggan, S. R. Wilson, J. D. Gressett, P. D. Miller, and G. Lapicki, *Phys. Rev. A* **19**, 1517 (1979).
8. R. Mehta, J. L. Duggan, F. D. McDaniel, M. C. Andrews, R. M. Wheeler, R. P. Chaturvedi, P. D. Miller, and G. Lapicki, *IEEE Trans. Nucl. Sci.* **NS-28**, 1122 (1981).
9. F. D. McDaniel, J. L. Duggan, G. Basbas, P. D. Miller, and G. Lapicki, *Phys. Rev. A* **16**, 1375 (1977).
10. T. J. Gray, P. Richard, G. Gealy, and J. Newcomb, *Phys. Rev. A* **19**, 1424 (1979).
11. R. Rice, G. Basbas, and F. D. McDaniel, *At. Data Nucl. Data Tables* **20**, 503 (1977).
12. G. Lapicki and F. D. McDaniel, *Phys. Rev. A* **22**, 1896 (1980).
13. V. S. Nikolaev, Zh. Eksp. Teor. Fiz. **51**, 1263 (1966) [*Sov. Phys.-JETP* **24**, 847 (1967)].

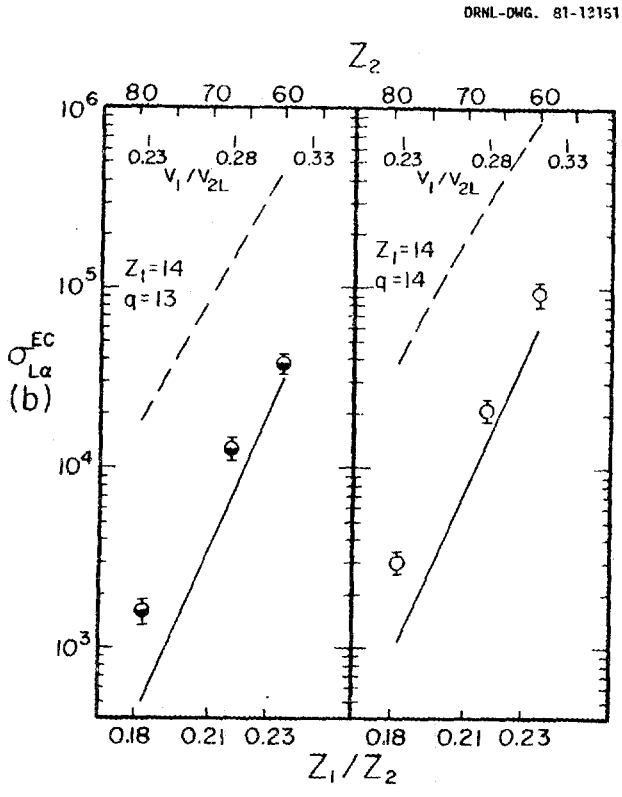


Fig. 8.20. Electron capture results for the L-shell for $^{28}_{14}$Si ions incident on ^{60}Nd, ^{67}Ho and ^{79}Au targets.

STUDIES OF THE LIFETIME, PHOTODETACHMENT, AND COLLISIONAL DETACHMENT OF He⁻

G. D. Alton R. N. Compton[1]
D. J. Pegg[2]

A rather comprehensive research effort has been initiated which is designed to study auto-, photo-, and collisional-detachment processes involving interactions with He^-. These investigations were initially motivated by a controversy between experiment[3-6] and theory[7] over the possibility of a long-lived doublet state of He^-. The required mechanism for production of the doublet He^- state is through single-event collisional processes in which two electrons are transferred to an energetic He^+ ion from an electron donor such as an alkali or alkaline-earth metal. Doublet He^- is expected to be produced predominately in single collisions between He^+ and an exchange vapor provided that multiple collisional processes are negligible and that the Wigner spin rule is not violated. The process can be described by the following reaction:

$$He^+ + X \rightarrow He^- + X^{++} . \qquad (1)$$

While experimental results[3-6] suggest the possibility of reaction (1), they are in direct conflict with the theoretical results of ref. 7.

The use of an alkaline-earth metal (Ca^0) exchange vapor is routinely used for the production of He^- at ORNL, and therefore this particular experiment, which involved use of the negative-ion injector for the 6-MV tandem accelerator, was particularly suited for existing facilities. The negative-ion source used was a duoplasmatron charge exchange source which utilizes a Ca^0 vapor exchange cell. The experimental apparatus used for lifetime determinations is illustrated schematically in Fig. 8.21. The auto-detachment lifetime is determined by measuring the ratio of the electron current collected on a 26-cm-long, positively biased plate to the He^- current arriving at the Faraday cup. The ion transit time across the parallel plate arrangement is varied by changing the ion beam energy. The range of energies used spans the energy region from 40 to 100 keV. In order to eliminate background electrons resulting from interactions with the residual gas ($P_0 \cong 1 \times 10^{-7}$ Torr), measurements were made as a function of N_2 pressure. The extrapolated ordinate intercept at zero pressure was then used to determine the lifetime of He^-. The results of these measurements are shown in Table 8.1 along with other reported values. The results of these measurements are in good agreement with the lifetime of the known $(1s2s2p)4P^0$ state, which has been shown to be produced in sequential collisions.

Table 8.1. Measured lifetimes of He⁻

Source of He	Lifetime (μs)	Reference
$He^+ + He$	18.2	11
$He^+ + N_2$	9^{+5}_{-3}	12
$He^+ + K$	11.5 ± 5, 345 ± 90	13
$He^+ + K$	10 ± 2, 16 ± 4, 500 ± 200	14
$He^+ + Ca$	10.5 ± 2	Present

The experimental apparatus shown in Fig. 8.21 is compatible without modification for the determination of He^- photodetachment cross sections, and therefore little effort was required to initiate these

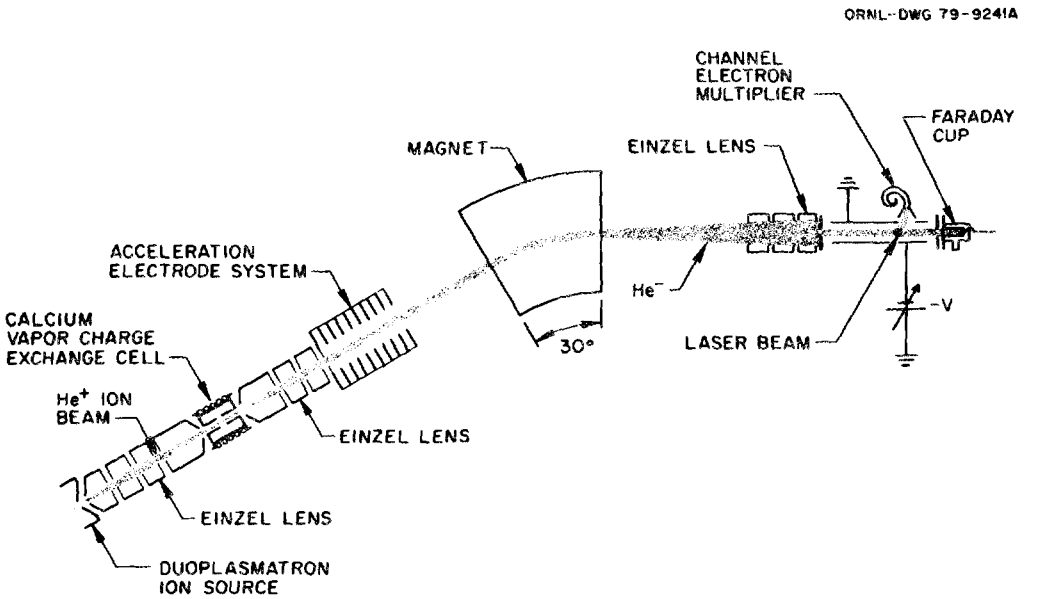


Fig. 8.21. Experimental apparatus. Not shown are the flash-lamp-pumped dye laser, optical multichannel analyzer, and photodiode. The autodetached electron energies were determined with a double-focusing electronstatic energy analyzer inserted in place of the parallel-plate detector.

experiments. The mechanism of He^- production was via the two-step collisional process

$$He^+ + X \rightarrow He(1s2s)^3S + X^+ ,$$

$$He(1s2s)^3S + X \rightarrow He^-(1s2s2p)^4P + X^+ ,$$

where X is the exchange vapor (Ca^0). The negative-ion source used in these experiments was also the duoplasmatron-charge exchange source with a Ca^0 vapor exchange cell.

A flash lamp tunable dye laser ($\Delta\lambda \cong 1.6$ Å) was used in a crossed-beam configuration to produce photodetached electrons from an He^- ion beam which were detected in a channel electron multiplier as shown in Fig. 8.21. The range of photon energies employed (in these experiments, 1.77 to 2.5 eV) was sufficient to detach either of the $2s$ or $2p$ electrons which are bound by 1.22 and 0.077 eV, respectively, and therefore detachment into either continuum $He(^3S)$ or $He(^3P) + e$ is possible. Typical ion currents of 10^{-7} to 10^{-6} A of momentum-analyzed He^- were focused through a collimation system into a Faraday cup by means of an einzel lens. The photodetached electrons, produced during interactions between the photon and He^- beams, were swept into a channel electron multiplier by applying a negative potential to the bottom parallel plate. Background problems were essentially eliminated by gating a boxcar signal averager during the firing of the laser. Absolute photodetachment cross sections were determined by calibration of the data with known cross sections for O^- having reported accuracies of ±3%. Beams of He^- and O^- were alternately introduced into the experimental arrangement, and the $S(He^-)$ and $S(O^-)$ electron signals were measured. Cross sections for He^- were then determined from the following simple relation:

$$\sigma_{He^-} = \frac{S(He^-)\, I(O^-)\, v_{He^-}}{S(O^-)\, I(He^-)\, v_{O^-}}\, \sigma_{O^-} , \qquad (2)$$

where $I(He^-)$ and $I(O^-)$ are the beam intensities of O^- and He^-, respectively, and v_{He^-} and v_{O^-} are the respective velocities of the two species. The results of these measurements, reported in ref. 9 and shown in Fig. 8.22, are the first photodetachment measurements made over an extensive photon energy range (1.77 to 2.5 eV).

In addition to the previously reported experimental results, studies have been implemented to investigate the energies associated with the auto-ejected electrons as well as to study collisional-ejected ("cusp") electron phenomena. For these experiments the parallel plate arrangement was replaced with a high-resolution spherical-sector analyzer (not

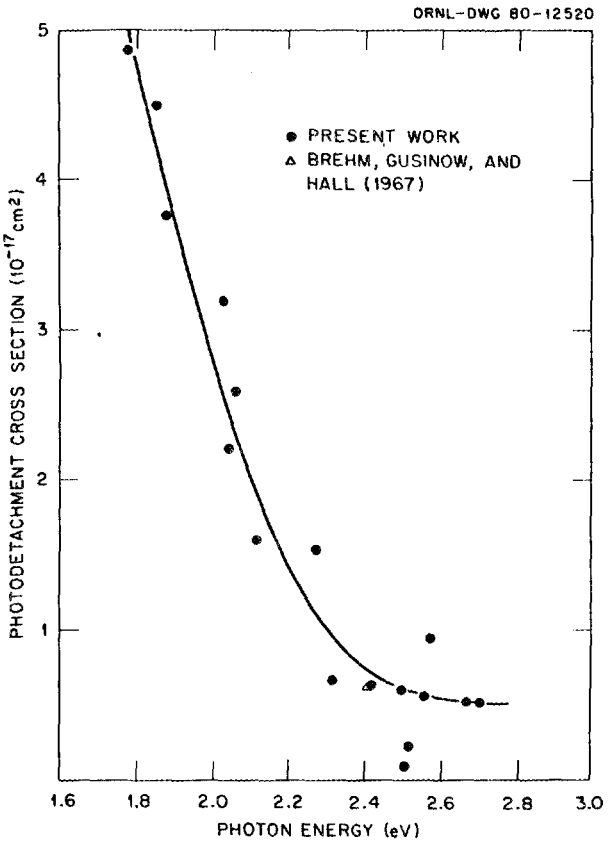


Fig. 8.22. Photodetachment cross section for $He^-(1s2s2p)^4P^o$ plotted against photon energy.

shown). The autoionizing state for He^- was found to agree within experimental error to that associated with the He^- $(1s2s2p)^4P$ electronic configuration. No other energy levels were detected indicating the existence of a single He^- metastable state. A significant group of electrons with energies corresponding to the velocity of the ion beam was observed in addition to the autodetached electrons at 19.74 eV. Some of these electrons are undoubtedly due to photodetachment by background black-body radiation as well as collisionally produced. The number of such photoejected electrons can be calculated from known photodetachment cross sections. Calculations indicate that a significant number of this group of electrons may be attributed to background radiation. Experiments are being planned to determine the mechanisms responsible for these electrons. As well, further photo- and collisional-detachment experiments are in progress involving He^- and other ions.

1. Health and Safety Research Division.
2. Part-time employee from the University of Tennessee, Knoxville.
3. R. A. Baragiola, abstracts of papers, VIII ICPEAC (Belgrade) 827 (1973).
4. E. H. Pedersen, F. R. Simpson, and P. Hvelplund, *J. Phys.* **B 7**, 1294 (1974); *Phys. Rev. A* **11**, 516 (1975).
5. R. A. Baragiola and E. R. Salvatelli, *J. Phys.* **B8**, 382 (1975).
6. K. F. Dunn, B. J. Gilmore, F. R. Simpson, and H. B. Gilbody, *J. Phys.* **B11**, 1797 (1978).
7. A. V. Bunge and C. F. Bunge, *Phys. Rev.* **19**, 452 (1979).
8. R. N. Compton, G. D. Alton, A. D. Williamson, and A. E. Carter, abstracts of papers, XI International Conference on Physics of Electronic and Atomic Collisions (Kyoto, Japan), p. 68 (1979).
9. R. N. Compton, G.D. Alton, and D. J. Pegg, J. Phys. **B13**, L651 (1980).
10. R. N. Compton, G. D. Alton, and D. J. Pegg, *IEEE Trans. Nucl. Sci.* **NS-28**, 1198 (1981).
11. D. J. Nichols, C. W. Trowbridge, and W. D. Allen, *Phys. Rev.* **167**, 38 (1968).
12. F. R. Simpson, R. Browning, and H. B. Gilbody, *J. Phys.* **B4**, 106 (1971).
13. L. M. Blau, R. Novick, and D. Weinflash, *Phys. Rev. Lett.* **24**, 1268 (1970).
14. R. Novick and D. Weinflash, Proc. Int. Conf. Precision Measurement and Fundamental Constants (Gaithersburg, Md.), ed. D. N. Langenberg and B. N. Baylor, NRS Spec. Pub. 343, p. 403.

EN TANDEM OPERATIONS (COVERING PERIOD—JANUARY 1979 TO APRIL 1981)

G. F. Wells P. D. Miller

The period covered by this report marked the conclusion of the era during which the EN tandem was operated primarily as a nuclear physics facility and marked the commencement of the era of its operation as a primarily atomic physics facility. In Table 8.2, for example, the first activity, Heavy-Ion Reaction Studies, was concluded during 1979, whereas the second activity, Merged Electron-Heavy-Ion Beams, was not started until 1980. During this period 5002 operating hours were provided to the experimental groups. A major "down period" was experienced in July–August 1980 to replace the accelerator main tubes. Considerable time was spent conditioning the new tubes before satisfactory 6-MV operation was achieved. During 1979 the Enge spectrometer magnet was removed from the EN tandem experimental area and reinstalled at the Holifield Heavy-Ion Research Facility. Conceptual

Table 8.2. Research activities on the tandem Van de Graaff accelerator (January 1979 through April 30, 1981)

Type	Investigators	Approximate percent of utilized beam time
Heavy-Ion Reaction Studies	Ford, Shapira, Bomar,[a] Dacal,[b] Ortiz,[b] Gomez del Campo	18.6
Merged Electron–Heavy-Ion Beams	Dittner, Dress, Moak, Miller, Datz,[c]	16.9
Heavy-Ion Vacancy Production	McDaniel,[d] Duggan,[d] Miller, Zander,[d]	15.5
Hydrogen Depth Profiling	Moak, Miller, Sellschop,[e] Tsong,[f]	10.5
Forward Ejected Electrons and Trapped, Slow, Highly Charged Heavy Ions	Sellin,[g] Pegg,[g] Thoe,[h] Elston,[g] Glass,[i] Breinig,[i] Berry,[i] Schauer,[i] Holmes,[i] Rozet,[i] Liljeby,[i] Latz,[i]	10.3
Gas Jet Development	Ford, Shapira, Park,[j] Thornton[j]	8.6
Radiation Damage Studies	Appleton,[k] Noggle[k]	8.2
Radiative Electron Capture in Diamond	Moak, Lucas,[l] Bridwell,[m] Miller, Sellschop[e]	5.7
Carbon Foil Lifetimes	Bair, Jones, Stelson	3.6
(*p,n*) Reaction Yields Leading to Positron Emitters	Bair, Miller	0.8
HHIRF Buncher Prototype Development	Milner, Ziegler	0.5
Radiation-Induced Creep	Reiley,[n] Cook[n]	0.4
X-Ray Satellites for the Study of Chemical Environment	Vane, McDaniel,[d] Raman, Kim, O'Kelly,[c] Young,[o] Hulett[o]	0.4

[a]Vanderbilt University, Nashville, Tenn.
[b]University of Mexico, Mexico City.
[c]Chemistry Division.
[d]North Texas State University, Denton.
[e]University of Witwatersrands, Johannesburg, S. Africa.
[f]Pennsylvania State University, University Park.
[g]Part-time employee from the University of Tennessee, Knoxville.
[h]Lawrence Livermore Laboratory, Livermore, Calif.
[i]University of Tennessee, Knoxville.
[j]University of Virginia, Charlottesville.
[k]Solid State Division.
[l]University of Sussex, Sussex, England.
[m]Murray State University, Murray, Ky.
[n]Metals and Ceramics Division.
[o]Analytical Chemistry Division.

design engineering has been completed for the installation of an Elbek spectrometer magnet in its place.

Improvement of the beam lines and their vacuum cleanliness has continued with the completion of a cryogenic-pumped, copper-seal beam line from the main analyzing magnet to the switching magnet in the Low-Mass Target Room experimental area. This area serves the merged electron–heavy-ion beams experiment. A cryogenic pump and associated copper-seal beam line has also been installed at the output of the 90° binding magnet in the Shielded-Target Room experimental area, which serves the rest of the experiments on the accelerator.

9. High-Energy Physics

H. O. Cohn
W. M. Bugg[1]
G. T. Condo[1]
T. Handler[2]
E. L. Hart[1]
H. R. Brashear[3]

Due to the long lead time required in executing a high-energy experiment, several experiments of a diverse nature were being worked on during the past year. Work was completed on the interaction of π^+d at 15 GeV/c in collaboration with Florida State University. Papers published were on multipion production, neutral three-pion resonance formation, and on the investigation of higher-mass even-G parity states.

This last publication presented evidence, to more than $4^1/_2$ standard deviation significance, for the existence of two previously unreported broad dipion states with masses in excess of that of the g (1700). In addition to the fit of the dipion mass spectrum to a Breit-Wigner shape with a smooth polynomial background, our evidence for the existence for these higher-mass states was augmented by the fact that they were virtually mandated by the previously determined branching ratio for the g^0 decay into $\pi^+\pi^-$ relative to $\pi^+\pi^-\pi^0\pi^0$. That is to say, that without higher-mass states and with the assumption of a smooth background, our derived branching ratio, as well as the mass and width of the g^0, would not be reconciled with previous experiments. Analysis of the reaction $\pi^+d \rightarrow p\,p\pi^+\pi^-$(MM) also suggested that the g^0 meson may have nonzero branching ratios into $\eta(550)\pi^+\pi^-$ and into $\eta'(958)\pi^+\pi^-$. Since publication of this work, a high-statistics study of the reaction $\pi^-p \rightarrow K + K^-n$ at 62 GeV/c π^- momentum[4] has also found evidence for two, probably $I^G = 1^+$, states beyond the g, with masses and widths substantially equivalent to the values deduced in our paper.

Another conventional bubble chamber experiment done in collaboration with MIT and Tohoku University concerns the π^-p interactions at 8 GeV/c. This film represents the largest single data sample of medium-energy π^-p interactions in existence (~800,000 events). Results relating to the decay modes of the charged g (1700) meson are discussed in detail later. Study of the reaction $\pi^-p \rightarrow \pi^-p\pi^+\pi^-$ at 8 GeV/c shows that it is dominated by ρ^0, f^0, and Δ^{++} production, much of which is a product of the decays of A_2, A_3, and N^* (1470) resonances. Considerable double-resonance production [$\rho^0\Delta^0$, $f^0\Delta^0$, ρ^0N^* (1520)] and ρ^0N^* (1698) have also been isolated and analyzed by double-Regge exchange models.

A π^+p interaction experiment at 16 GeV/c in the SLAC Hybrid Facility with a lead-glass detector has been worked on in collaboration with Duke University and Florida State University. All of the film has been scanned, and over 50,000 events have been measured on the spiral reader at ORNL. The software analysis system is in the final stages of development. Events have been successfully passed through to the data summary tape level.

During 1980 several papers were published from our 147-GeV/c π^-p experiment and our 147-GeV/c $\pi^+/K^+/p$–proton interaction experiment. The Fermilab Hybrid Bubble Chamber Experiment is a collaboration of the International Hybrid Spectrometer Consortium. From the π^- experiment, a study of leading particles and diffractive dissociation of both beam and target particles was affected. The observation of the beamlike leading pion signal was possible only because of the improved momentum resolution provided by the downstream PWCs of the hybrid system. Among the principal results presented here was the measured equality of beam and target dissociation—both being equal to 1750 μb to within our experimental errors. It was also observed that Δ^{++} (1216) production occurred predominantly in the target dissociation channel $p \rightarrow p\pi^+\pi^-$.

The π^- experiment also was the basis of a study of multiparticle correlations and high transverse momentum "jets."

During the past year, papers were also published whose theses were studies of inclusive Δ^{++} production and of inclusive neutral-strange particle production

from 147-GeV/c $\pi^+/K^+/p$ interaction in hydrogen. In the former paper it was shown that only Pomeron exchange was important at the beam vertex at our energy. Data concerning the inclusive distributions of the variables x,y,t' and p_t^2 showed that they all had very similar shapes for the different reactions: $\pi^+p \rightarrow \Delta^{++}x$, $K^+p \rightarrow \Delta^{++}x$, and $pp \rightarrow \Delta^{++}x$. Furthermore, the integrated Δ^{++} inclusive cross sections were proportional to the total cross sections. This result is consistent, not only with Pomeron exchange at the beam vertex, but also with the same exchange mechanism for all of the reactions at the p, Δ^{++} vertex. This latter exchange was found to be in good agreement with the exchange of a pion trajectory.

The inclusive neutral strange-particle paper presented our study of K_s, Λ, and $\bar{\Lambda}$ production from the interactions of protons with each of the positive beam particles. Cross sections were given for all nine inclusive reactions. The invariant cross-section distributions were also presented as a function of the Feynman scaling variable x and the C.M. rapidity y. The P_t^2 distributions with their fitted slopes indicated that the slopes of Λ, $\bar{\Lambda}$ production from π^+p interactions were somewhat larger than those from π^- beams at higher energies (>150 GeV/c).

We have taken data for a charm search and vector meson production experiment in 20-GeV γ-p collisions in the SLAC 40-in. hybrid bubble chamber facility. This experiment is done with a large international collaboration. Nearly monochromatic gammas are obtained from a backscattered laser beam. For secondary particle identification and triggering downstream PWCs, a two-stage segmented gas Cerenkov counter and a 2.8 × 1.2 × 14 radiation length lead-glass Cerenkov counter are employed. In addition to the conventional photographs, a high-resolution camera takes pictures of the interaction vertex region to detect short decays of charmed particles. Several thousand events have been measured on the ORNL spiral reader, and preliminary results have been presented on the charmed production cross section and the lifetimes of charged and neutral D mesons.

New 1.2 × 1.2 m drift chambers and 1-m-square PWCs have been built at ORNL to improve the downstream hybrid system at FNAL for a new 200-GeV experiment. A test run with several of these counters was completed in May 1981. The complete system will include 16 large position-sensitive counter planes designed and constructed at ORNL.

Design of a neutron-antineutron transition experiment in collaboration with Harvard University has progressed to the stage where a proposal has been prepared. A detailed discussion of this proposal is given in a subsequent section.

---

1. Part-time employee from the University of Tennessee, Knoxville.
2. University of Tennessee, Knoxville.
3. Instrumentation and Controls Division.
4. B. Alper et al., *Phys. Lett.* **94B**, 422 (1980).

SOME g (1700) DECAY MODES

W. M. Bugg[1] H. O. Cohn
G. T. Condo[1] E. L. Hart[1]
T. Handler[2]

Although the even-G parity mass region from 1.5 to 1.8 GeV/c^2 has been exhaustively investigated, the precise physical interpretation of the experimental data has yet to be delineated. The current assessment of this mass region would appear to be that of the Particle Data Group,[3] whereby all even-G parity resonances in this region are assumed to be various manifestations of the g (1700) unless proved otherwise. Because of the wide divergence of the various parameters reported for the g in different experiments, the experimental situation is far from resolved. We present our data from a rather large 8-GeV/c π^-p experiment done in collaboration with MIT and Tohoku University, where we establish that the $\omega\gamma$-decay mode of the g^- is one of its more substantial channels. This decay channel has, in the past, been controversial, even though the narrow width of the ω should permit an unambiguous determination of the magnitude of its presence. We also show that the $\omega\pi$-branching fraction is more significant than that of the $(A_2\pi)^-$ and present our data concerning the production of ρ mesons as decay products of the g^-.

Our data derives from a 780,000-picture study of π-p interactions at 8 GeV/c taken at the SLAC 82-in. hydrogen bubble chamber. The sample reported consists of the following numbers of events:

1. π-$p \rightarrow \pi$-$\pi^0 p$ (12,055 events, $\sigma = 0.733 \pm 0.020$ mb),
2. π-$p \rightarrow \pi$-π-$\pi^0 \pi^+ p$ (22,969 events, $\sigma = 1.60 \pm 0.04$ mb).

The full, uncut bosonic mass spectra from these channels are presented in Fig. 9.1. Both spectra have been fitted with Breit-Wigner resonances superimposed upon fourth-order polynonial backgrounds. The parameters derived from these fits, together with their associated errors, are given in Table 9.1. The

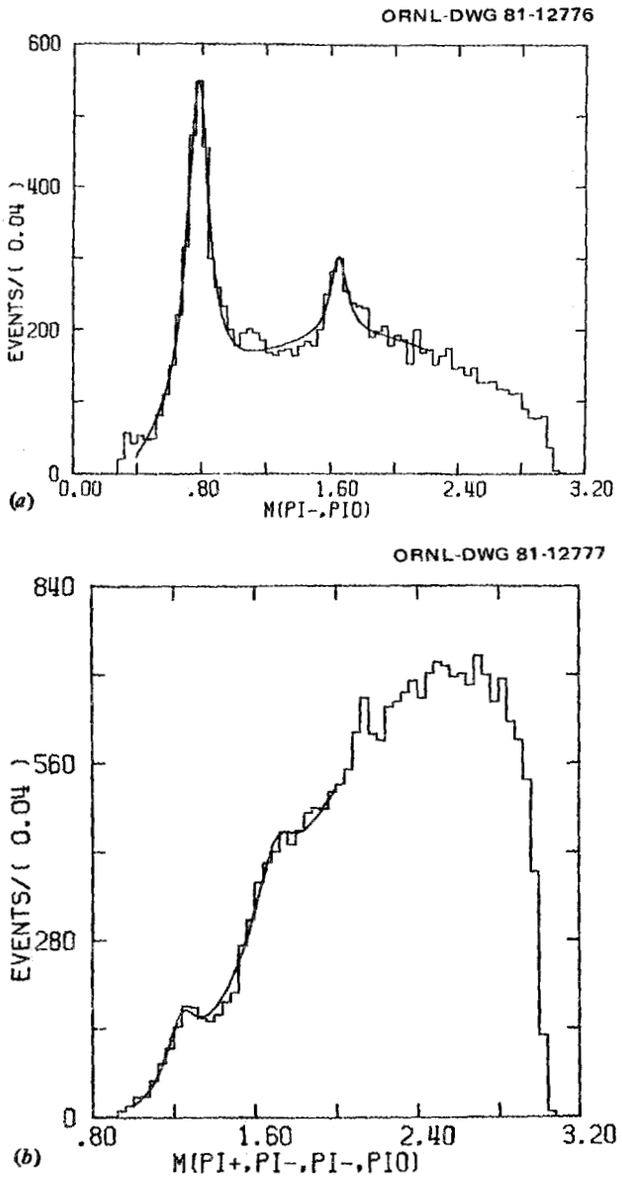


Fig. 9.1. (*a*) Full $\pi^-\pi^0$ mass spectrum from $\pi^-p \to \pi^-\pi^0 p$; (*b*) full $\pi^+\pi^-\pi^-\pi^0$ mass spectrum from $\pi^-p \to \pi^+\pi^-\pi^-\pi^0 p$.

Table 9.1. Meson production data from the reactions $\pi^-p \to \pi^-\pi^0 p$, $\pi^+\pi^-\pi^-\pi^0 p$

Final state	Mass (MeV)	Width (MeV)	Cross section (μb)	χ^2 per n deg freedom
ρ-p	777 ± 3	161.6	176 ± 5	1.6/37
g^--p	1654 ± 9	126 ± 22	34 ± 4	
B^--p	1239 ± 8	185 ± 20	50 ± 4	
g-p	1699 ± 13	239 ± 34	85 ± 9	1.1/31

gross fraction of two-pion decays of the g^- is 0.40 ± 0.07, which agrees well with the world average reported by the Particle Data Group.[3] This number ignores any contribution from the possible decay mode $\pi^-\pi^0\pi^0\pi^0$. It should be noted that the mass and width of the 4π g^- decays exceed the values determined in the dipion decays—a fact we attribute to the relatively larger background present in the 4π spectrum. The g^- and B^- (1235) are, however, both present in the 4π spectrum at approximately the 10σ level.

The neutral 3π mass spectrum is dominated by the presence of the ω. The observed cross section, mass, and width (Γ) of the ω, determined without regard to our resolution, are 185 ± 7 μb, 783 ± 1 MeV, and 33 ± 1 MeV respectively. Probably the most striking aspect of g^+ decay is the wide divergence reported in the $\omega\pi^+$ decay fractions. Since the ω is a narrow resonance, produced in moderate-energy pion-induced reactions with minimal background, the determination of the $\omega\pi^\pm$ decay fraction would appear to be straightforward. However, the reported $\omega\pi^\pm$ to all $\pi^\pm\pi^-\pi^+\pi^0$ decay fractions often stand in stark contrast with one another. These range from 0.33 ± 0.07 (ref. 4) to an upper limit only of 0.09 (ref. 5). The most recent high-statistics determination was in the form of an upper limit[6] whereby the $\omega\pi$ fraction was found to be less than 0.11 at a 95% confidence level. In Fig. 9.2 we plot the $\omega\pi^-$ and $\pi^+\pi^-\pi^-\pi^0$ spectra at low-momentum transfers to the 4π system. Also shown in Fig. 9.2 are the results of our fits to these data. The 4π spectrum was fit with Breit-Wigner resonances for the B and g superimposed on a fourth-order polynomial in the mass. The parameters for the B and g as well as the quality of the fits are given in Table 9.2. The relevant branching ratio is thus found to be $g^- \to \omega\pi^-/g^- \to \pi^+\pi^-\pi^-\pi^0 = 0.38 \pm 0.07$.

Close inspection of Table 9.2 shows that while the widths of the g in the $\omega\pi$ and 4π channels are comparable, the mass of the $\omega\pi$ signal in the g region is significantly lower than in the full 4π spectrum. To further investigate whether the observed $\omega\pi$ state is appropriately identified with the g, we looked at the $\pi\pi$ scattering angular distributions obtained in the Gottfred-Jackson frame, for the B, g, and a higher-mass background region (1.8 to 2.0 GeV/c^2). The $\cos\theta$ distribution for the B is substantially flat, thereby being consistent with a predominantly S-wave $\omega\pi$ decay. In the g and the 1.9 ± 0.1 GeV/c^2 regions, a bump near $\cos\theta = 0$ suggests the involvement of higher partial waves. These distributions are quite similar to those obtained by Thomp-

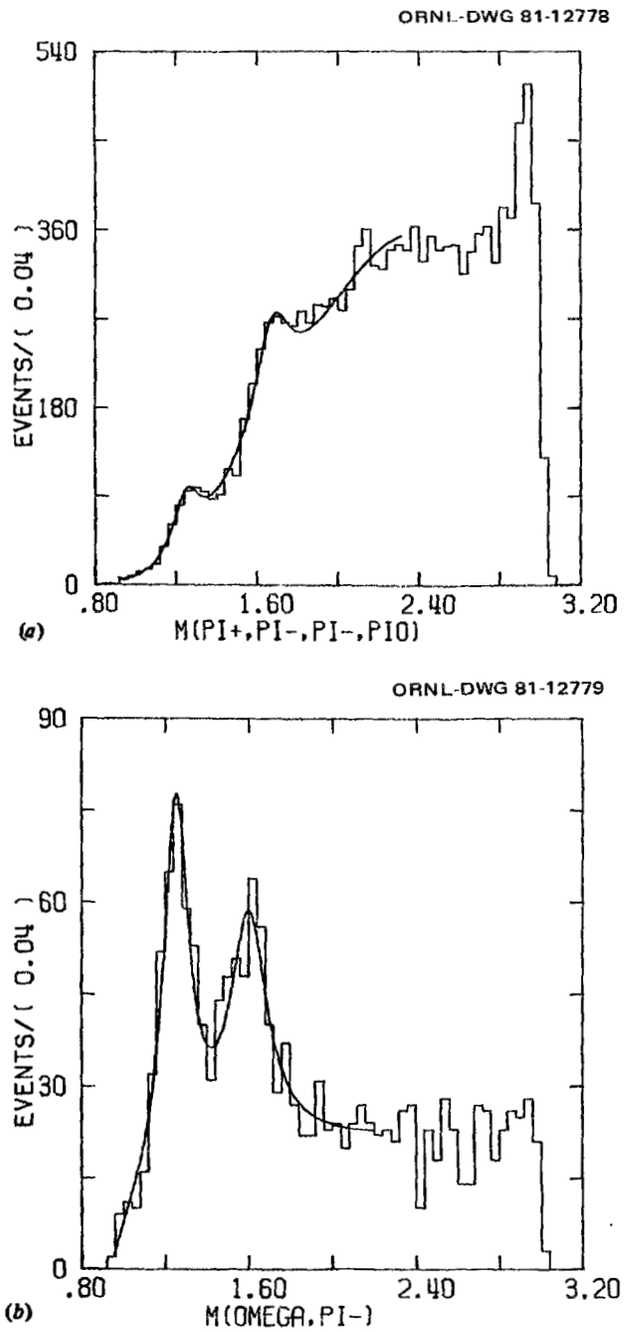


Fig. 9.2. (*a*) Four-π mass spectrum from reaction 2 with $|t'p_{\perp}p| < 0.2$ GeV^2; (*b*) $\omega\pi$ mass spectrum from reaction 2 with $|t'p_{\perp}p| < 0.2$ GeV^2.

son et al.,[4] who found the mass of their second $\omega\pi$ enhancement to be 1686 $\pm$9 MeV/c^2—a value wholly compatible with that of the g. A similar peak in the $\omega\pi^-$ mass at 1690 $\pm$ 15 MeV/c^2 has recently been reported by Evangelista et al.[7] from an ~200-event/μb experiment, using the CERN Omega Spectrometer.

Table 9.2 B^- **and** g^- **production parameters from the** $\pi^+\pi^-\pi^-\pi^0$ **and** $\omega\pi^-$ **final states**

Meson	Mass (MeV)	Width (MeV)	Cross section (μb)	χ^2 per n deg freedom
$B^-(4\pi)$	1250 $\pm$ 10	163 $\pm$ 21	26.4 $\pm$ 25	0.77/36
$g^-(4\pi)$	1675 $\pm$ 10	215 $\pm$ 30	64 $\pm$ 4.5	
$B^-(\omega\pi)$	1253 $\pm$ 8	145 $\pm$ 20	27 $\pm$ 3	0.78/30
$g^-(\omega\pi)$	1601 $\pm$ 16	212 $\pm$ 42	24 $\pm$ 3.5	

Our data also yield information on the other purported decay channels of the g involving A_2 and ρ mesons. Because of the strong high-quality $\omega\pi^-$ signal in the g^- region and because the exclusion of ω events can scarcely affect the amounts of ρ production (or A_2 production if restricted to the $\rho\pi$ decay mode), the remainder of our discussion of the $\pi^+\pi^-\pi^-\pi^0$ channel will devolve from data from which ω events have been purged. The $\pi^+\pi^-\pi^0$ spectrum when the other neutral three-pion combination is in the ω region displays a small enhancement in the neighborhood of 1 GeV/c^2 as well as a smallish ω signal over a rather flat background extending beyond 1.6 GeV/c^2. The elimination of ω events has the additional benefit of reducing the large low-mass backgrounds.

Reported values for the branching ratio of the $g^{\pm}$ into $(A_2\pi)^{\pm}$ are also in rather broad disagreement. Although some authors[8,9] have found the $A_2\pi$ decay channel to represent a rather insignificant fraction of charge g decays, others have reported[6,10] it to account for fractions as large as 0.60 $\pm$ 0.15 and 0.66 $\pm$ 0.08. Our data support the former results. In Fig. 9.3 we present the 3π spectra ($\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^-$) for those events whose 4π mass is in the g region ($1.56 \leq M_{4\pi} \leq 1.78$ GeV/c). Since the 3π decay of the A_2 has not been observed except through the intermediate $\rho\pi$ state,[3,11] these spectra are restricted to those events for which the appropriate dipion combinations contain a ρ of the proper charge, that is, ρ^+ or ρ^- in the $\pi^+\pi^-\pi^0$ spectrum and ρ^0 in the $\pi^+\pi^-\pi^-$ spectrum. The mass cut used to define the ρ meson is 0.66 to 0.86 GeV/c^2. The histograms clearly indicate that the fraction of A_2 events, in the g region, which subsequently decay into the $\rho\pi$ channel is quite small. The fits shown in Fig. 9.3 have been constrained so that the A_2 width is at least 50 MeV. Neither fit yields an A_2 intensity as large as 8% of the g^- signal. Furthermore, both fits have a lower confidence level with the inclusion of the A_2 than they did when the fit

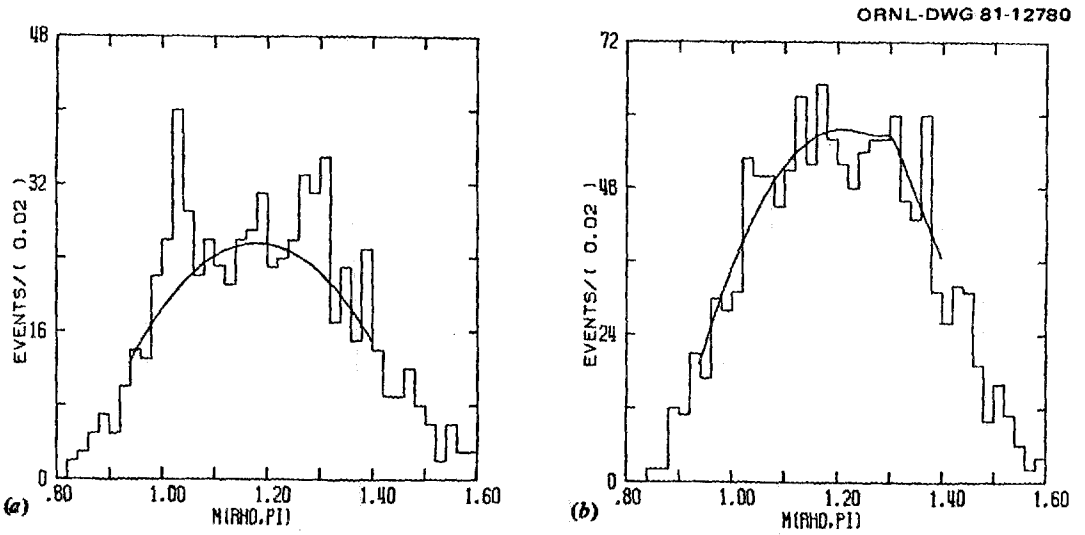


Fig. 9.3. For events with a 4π mass in the g^- region, $|t'p_{\omega}p| < 0.2$ GeV^2 with neither $\pi+\pi-\pi^\circ$ mass combination in the ω region: (*a*) $\rho \pm \pi$ + mass, (*b*) $\rho^\circ \pi^-$ mass.

was purely of the form of a quadratic background. To more accurately quantify the $A_2\pi$ branching fraction, we have added the two histograms together. The resulting fit (to a quadratic background and Breit-Wigner A_2) has an intensity of 33 ± 22 events, with a χ^2 per 26 degrees of freedom of 1.1. Correcting for the fraction of ρ mesons excluded by our mass cuts (36%), our $A_2\pi$ branching fraction becomes

$$g^- \to (A_2\pi)^- \to (\rho\pi\pi)^-$$
$$\to \pi+\pi-\pi-\pi^\circ \;/\; (g- \to \pi+\pi-\pi-\pi^\circ) = 0.08 \pm 0.13.$$

It is felt that this number is truly an upper limit, since the existence of any $\rho+$ signal from g^- decay is quite tenuous. The $\rho+$ appears as a somewhat less than 3σ enhancement and then, at that level, only when the mass and width of the ρ are permitted rather wide latitude in their definition. From another point of view, it would peccant, on the basis of our data, to proclaim a $\rho+$ signal from g^- decay. Nevertheless, in order to set an upper limit to the $A_2\pi$ branching fraction, the $\rho+$, as determined by our fits, was treated on a basis identical to that for the ρ° and ρ^-. Because of the tiny A_2 signal, a background subtraction was deemed superfluous.

The degree of involvement of ρ mesons in charged g decays has been another controversial feature of this resonance. The branching fractions reported for the $\rho\pi\pi$ state relative to all 4π decays have mostly been near unity,[6,12,13] although Thompson et al.[4] suggest that this ratio is "probably <0.40." Because of our exclusion of $\omega\pi$ events, the $\rho\pi\pi/4\pi$ branching ratio cannot, perforce, exceed ~0.62. As has been emphasized by several groups,[4,6] the determination of the appropriate ρ content of g decay products requires a careful consideration of the nonresonant background contributions to the ρ signals. Our procedure is to determine the intensity of ρ^+, ρ°, and ρ events in the g region and in a background region (1.35 to 1.55 and 1.8 to 2.0 GeV/c^2). The lower-mass part of the background region has too few events to allow a meaningful assessment of the various ρ signals in it by itself. From a fit to the 4π mass spectrum, antiselected on ω events, the number of g events and background events in the g and background regions is known. If we now assume that the ρ signals have only two sources, namely, from g decay and from background production, the number of ρ events associated with g^- decays can be determined:

$$g- \to \rho-\pi+\pi-/g- \to 4\pi = 0.36 \pm 0.12,$$
$$g- \to \rho^\circ\pi-\pi^\circ/g- \to 4\pi = 0.47 \pm 0.11$$
$$g- \to \rho+\pi-\pi-/g- \to 4\pi = 0.13 \pm 0.10.$$

As mentioned in connection with the $A_2\pi$ branching ratio determination, the $\rho+$ fraction, while finite, is of inferior statistical quality. The weak $\rho+$ signal from g^- decay is entirely consonant with a negligible $(A_2\pi)^-$ decay fraction.

The final g^- decay fraction in the $\pi+\pi-\pi-\pi^\circ$ channel to which we address overselves is that fraction which decays simultaneously to ρ^- and ρ° mesons. Over the years the fractions of 4π decays which proceed through the channel $g- \to \rho^-\rho^\circ$ has

plummeted from more than 70% (refs. 9, 10, 14) to the more recent determination[4,6] of 0.13 ± 0.19 and 0.12 ± 0.11. At least part of the cause of these rather divergent values would appear to derive from the $\rho\rho$ decay appearing as a threshold enhancement in the g region of the 4π spectrum and from the necessity of executing a background subtraction. The number of ρ events in the $\pi^+\pi^-$ and $\pi^-\pi^\circ$ spectra for events which have a 4π mass in the g^- region is given in Table 9.3. Because our 4π g signal extends to 1.56 GeV/c^2, no meaningful background region subtraction is possible from the mass region beneath the g region. Correcting for the number of g events lying outside the g mass limits and the number of ρ events not included by our ρ mass cuts 37% ρ^- and 29% of ρ°. We find the branching ratio.

$$g \to \rho^-\rho^\circ / g \to \pi^+\pi^-\pi^-\pi^\circ|\text{all} = 0.31 \pm 0.15.$$

The large error derives principally from the indicated background subtractions and the ~10% errors in the determinations of the ρ signals. It should be noted that the determination of the $\rho^-\pi^+\pi^-$ and $\rho^\circ\pi^-\pi^\circ$ given above was relevant to the entire g signal, including the $\omega\pi$ fraction. With the $\omega\pi$ events excluded, the fractions of the remaining g's which decay to ρ^- and ρ° are 0.68 ± 0.22 and 0.81 ± 0.19 respectively. Although the errors are not insubstantial, these data are clearly consistent with a significant fraction of simultaneous $\rho^-\rho^\circ$ decays.

Table 9.3. Decay branching ratios for g^- meson

$g^- \to \pi^-\pi^\circ/g \to \pi^+\pi^-\pi^-\pi^\circ$	=	0.40 ± 0.07
$g^- \to \omega\pi^-/g^- \to \pi^+\pi^-\pi^-\pi^\circ$	=	0.38 ± 0.07
$g^- \to (A_2\pi)^- \to (\rho\pi\pi)^-$ $\to \pi^+\pi^-\pi^-\pi^\circ/g^- \to \pi^+\pi^-\pi^-\pi^\circ$	=	0.08 ± 0.13
$g^- \to \rho^-\pi^+\pi^-/g^- \to (4\pi)^-$	=	0.36 ± 0.12
$g^- \to \rho^+\pi^-\pi^-/g^- \to (4\pi)^-$	=	0.13 ± 0.10
$g^- \to \rho^\circ\pi^\circ\pi^-/g^- \to (4\pi)^-$	=	0.47 ± 0.11
$g^- \to \rho^-\rho^\circ/g^- \to (4\pi)^-$	=	0.31 ± 0.15

For ease of reference, the principal results are collected in Table 9.3, where it should be emphasized that all fractions are relative to the entire g signal in the $\pi^+\pi^-\pi^-\pi^\circ$ spectrum.

1. Part-time employee from the University of Tennessee, Knoxville.
2. University of Tennessee, Knoxville.
3. Particle Data Group, *Rev. Mod. Phys.* **52**(2), Part II, (1980).
4. G. Thompson et al., *Nucl. Phys.* **B69**, 220 (1974).

5. G. K. Kliger et al., *Sov. J. Nucl. Phys.* **19**, 428 (1974).
6. B. Baltay et al., *Phys. Rev. D* **17**, 62 (1978).
7. C. Evangelista et al., *Nucl. Phys.* **B178**, 197 (1981).
8. T. F. Johnston et al., *Phys. Rev. Lett.* **20**, 1414 (1968).
9. N. M. Cason et al., *Phys. Rev. D* **7**, 1971 (1973).
10. J. Bartsch et al., *Nucl. Phys.* **B22**, 109 (1970).
11. M. Abramovich et al., *Nucl. Phys.* **B29**, 466 (1970).
12. C. Caso et al., *Nuovo Cimento* **54A**, 983 (1968).
13. J. Ballam et al., *Phys. Rev. D* **3**, 2606 (1971).
14. N. Armenise et al., *Lett. Nuovo Cimento* **4**, 205 (1972).

A PROPOSED NEUTRON-ANTINEUTRON TRANSITION EXPERIMENT

W. M. Bugg[1] E. L. Hart[1]
H. O. Cohn R. A. Lillie[2]
G. T. Condo[1] P. D. Miller
T. A. Gabriel[2] F. E. Obenshain
M. S. Goodman[3] R. Wilson[3]
T. Handler[4] G. R. Young

Baryon number has long been assumed to be an absolutely conserved quantity; no strong experimental evidence suggests otherwise. Experimental observation of its violation would have important implications for our understanding of nature and for efforts to describe all forces in one unified theory. Extensive theoretical effort is being expended to extend the unification of electromagnetic and weak forces to include strong interactions as well.[5] An almost universal prediction of these grand unified theories (GUT) is the existence of processes which do not conserve baryon number, $\Delta B \neq 0$, notably the prediction of the decay of the proton. Once one considers possible extensions of minimal GUT to include a nonminimal Higgs sector,[6,7] or if one considers partial unification schemes which do not contradict present data on electroweak interactions,[8] it is found that $\Delta B = 2$ processes may exist, notably the process $n \leftrightarrow \bar{n}$. Experimental verification of the existence of $n \leftrightarrow \bar{n}$ transitions would constitute a most fundamental discovery about the behavior of matter and would serve to discriminate among general classes of unification schemes. We propose to search for these transitions, using the Oak Ridge Research Reactor (ORR).

If one considers the following mass matrix for n and $\bar{n}$ states,

$$H = \begin{pmatrix} X & \alpha \\ \alpha & Y \end{pmatrix}, \quad \psi = \begin{pmatrix} n \\ \bar{n} \end{pmatrix},$$

where $X = M_n + V_n$, $Y = M_{\bar{n}} + V_{\bar{n}}$, M_n is the neutron mass, V_n is the external potentials experienced by a

neutron, and $\alpha = \hbar / T_{n\bar{n}}$, $T_{n\bar{n}}$ being the $n - \bar{n}$ mixing time, one sees that diagonalizing yields eigenvalues $\lambda_{1,2} = M_n \pm \sqrt{V_n^2 + \alpha^2}$, and the resultant transition probability becomes $P(t)_{n\bar{n}} = 2(1 - \cos \omega t)\sin^2\theta \cos^2\theta$, where we have taken $M_n = M_{\bar{n}}$, $V_n = -V_{\bar{n}}$, and one has $\omega = 2\sqrt{V_n^2 + \alpha^2}/\hbar^2$, $\tan \theta = \alpha / V_n^2 + \alpha^2$. Since one can estimate[6] from observed matter stability on the order of $\tau \geqslant 10^{30}$ years that $\alpha \leqslant 10^{-22}$ eV $\ll V_n$, the eigenstates of the diagonalized Hamiltonian are n and $\bar{n}$ to good approximation, and the expression for $P(t)_{n\bar{n}}$ can be expanded for small ω and θ to give

$$P(t)_{n\bar{n}} = \frac{2\alpha^2}{(2V_n)^2}(1 - \cos \omega t) \cong \frac{\alpha^2 t^2}{\hbar^2} .$$

This yields a maximum transition probability $P_{max} = \alpha^2 / V_n^2$.

A convenient figure of merit to employ for comparison of various experimental arrangements is Nt^2, where N is the number of neutrons observed, and t is the observation time. A comparison of reactor- and accelerator-produced neutrons from various existing facilities that might be available to us showed that the ORR with a flux of 15×10^{13} neutrons cm^{-2} sec^{-1} at the "goat hole" port with an area of 1400 cm^2 has the highest figure of merit of any facility considered.

Since neutrons have a magnetic moment $\mu_n = -1.91\mu_N$ and since $\vec{\mu}_n = -\vec{\mu}_{\bar{n}}$, any external magnetic fields remove the $n - \bar{n}$ degeneracy. Writing $P(t)_{n\bar{n}} = \alpha^2/(\mu B)^2 \sin^2 (\mu Bt)$, that is, assuming removal of the $n,\bar{n}$ degeneracy by magnetic field perturbations only, one sees that a gain in $P(t)_{n\bar{n}}$ is realized by decreasing the perturbing magnetic field B until $\mu Bt \ll 1$. At that point, expanding $\sin^2 (\mu Bt)$ yields $P(t)_{n\bar{n}} \cong [\alpha^2/(\mu B)^2] \times (\mu Bt)^2 = (\alpha t)^2$. The maximum field allowed to attain $\mu Bt < 1$ for thermal neutrons traveling a 20-m flight path is $B < 11$ mG.

We propose to use the ORR to introduce as many free neutrons as possible into a magnetic-field-free region, meeting the above criterion for a relatively long time (10^{-2} s). We then would search for the presence of antineutrons. This is most easily done by allowing any antineutrons present to annihilate on matter and searching for the characteristic $2M_nc^2$ ($\cong$2 GeV) of energy released. The vast majority of annihilation products are pions with a mean multiplicity of about 4.5 per annihilation. Since one-third of the pions are neutral and decay immediately to two gammas, we should on the average have three charged pions and three high-energy gammas originating from an annihilation. We estimate from the figure of merit and an observation time of 120 days that we can observe neutron-antineutron transitions if the period is less than 10^8 s. The current best estimate for the n-$\bar{n}$ transition time is of the order of $10^{7\pm1}$ s.

Many questions need to be answered before this experiment can be undertaken. The most serious are: (1) Can the reactor-associated and the cosmic-ray backgrounds be overcome so as to allow signal detection with the sensitivity indicated? (2) Can a detector be designed to accomplish this aim? To answer these and other questions, a preliminary design of the experiment and detector has been made. The experimental layout (see Fig. 9.4) shows some of the design considerations that will be incorporated. The reactor neutron flux will be further moderated with D_2O and a bismuth gamma-ray shield. From calculations using a one-dimensional radiation transport code, it appears possible to decrease the fast (+ epithermal) neutron/thermal neutron flux ratio by a factor of 20 and to decrease the gamma-ray flux by at least a factor of 1000 over the open-port values, while maintaining a current of 2×10^{13} thermal neutrons/s on target. Next there will be a floodable section of beam pipe and a movable lead gamma-beam stop so the neutron and gamma beams can be stopped as desired. A 20-m-long drift pipe will be magnetically shielded with several layers of mu metal to reduce the field to less than 1 mG. Inside the pipe there will be a coil so that a magnetic field can be introduced at will in order to kill the n-$\bar{n}$ transition effect. This will greatly aid in identifying the genuine effect when it is observed. The pipe will also be evacuated so that the gas should not serve as an annihilation target. The annihilation cross section for thermal neutrons is unknown, but is estimated to be at least of the order of 10^4 b. The target is chosen to be very thin to minimize neutron and gamma scattering into the annular detector. It will be a thin CD_2 plastic 2.5×10^{-3} g/cm^2 thick covering a 1-m^2 area of the beam. The beam will be transmitted through the target and dissipated in a beam dump (not shown). Surrounding the beam pipe and detector is a 3- to 5-ft-thick concrete shield. The detector is further shielded by 3 ft of steel that serves to reduce the cosmic-ray background. Between the concrete and steel shields is a scintillation veto counter. Charged cosmic-ray particles that penetrate the outer steel shield will be vetoed by this counter with an effectiveness of 10^{-4} or 10^{-5}.

The detector (Fig. 9.5) will consist of an array of 64 lead-glass Cerenkov counters surrounding the target and further segmented scintillation lead sandwiches. The lead glass was chosen because it is

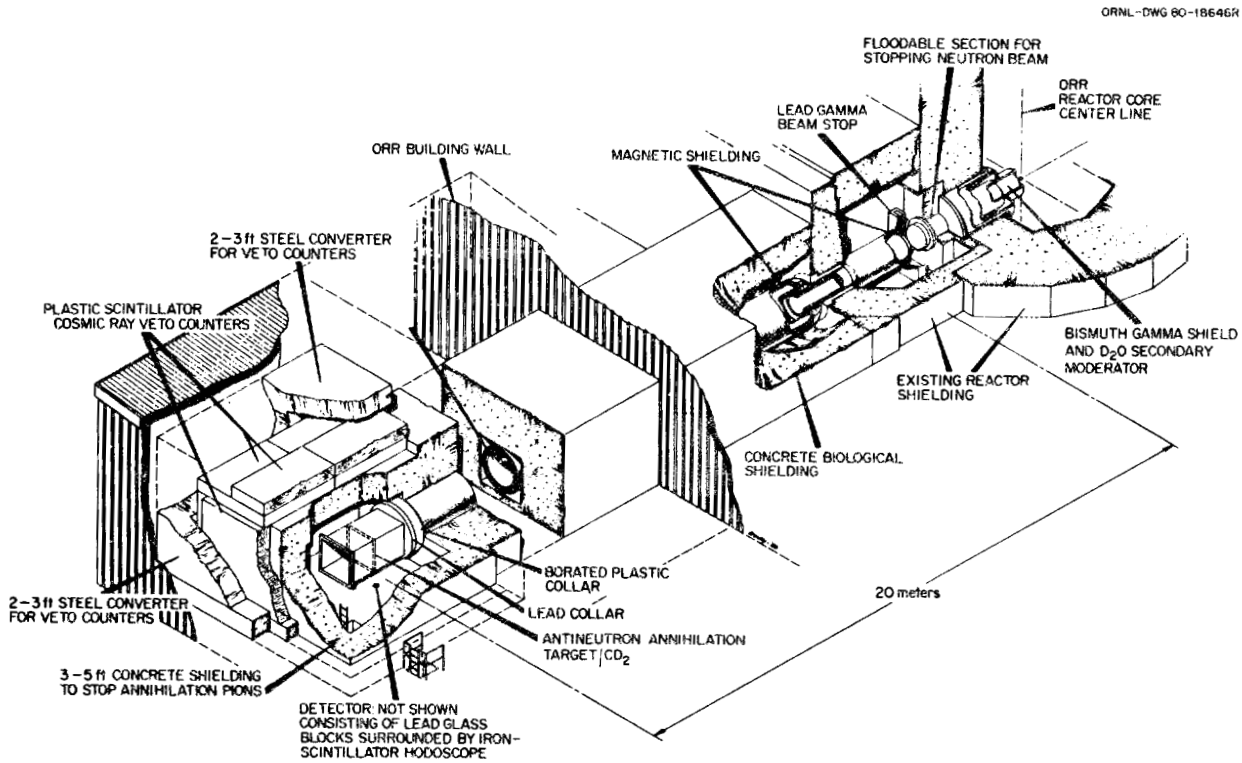


Fig. 9.4. Isometric view of the proposed $n - \bar{n}$ mixing experiment at the Oak Ridge Research Reactor.

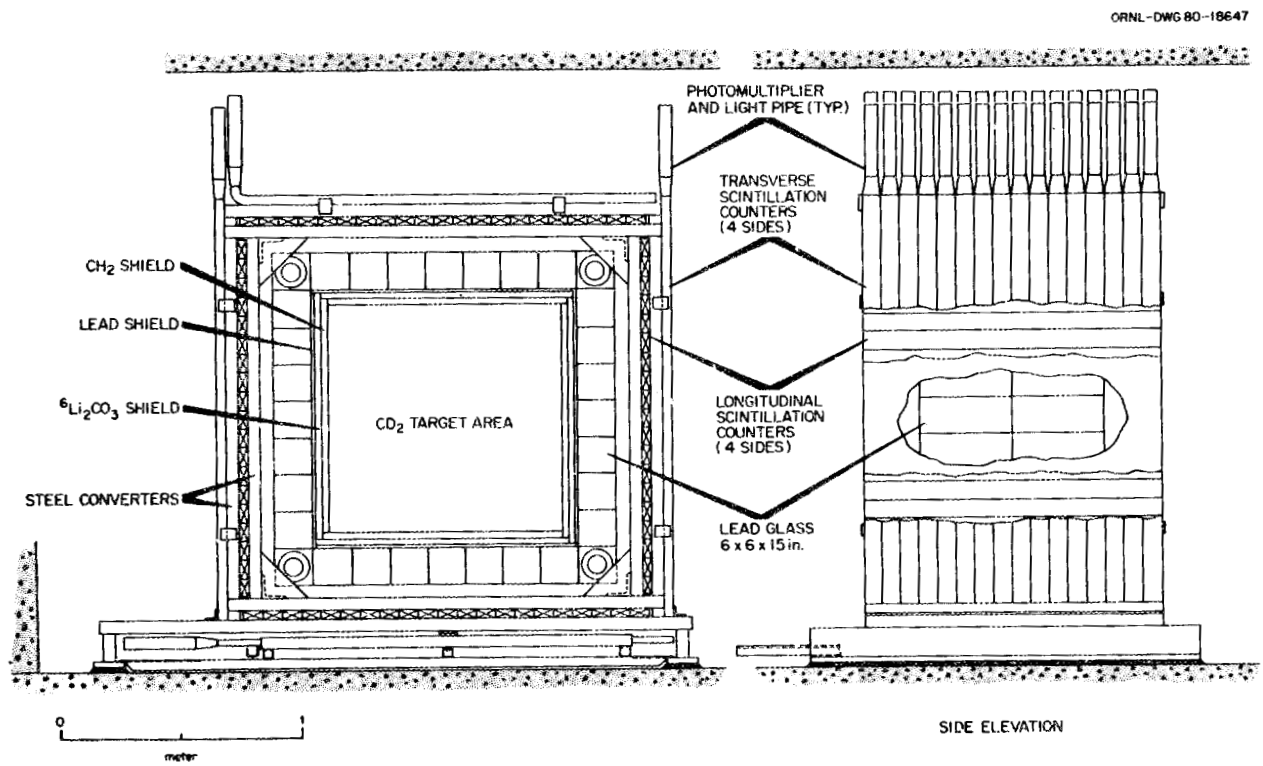


Fig. 9.5. Sketches of detector layout: beam view (left) and side view (right).

very insensitive to low-energy neutrons and gammas but will efficiently detect the gammas from the $\bar{n}$ annihilation. It also will detect the charged pions. The scintillation lead counters will further serve for particle identification and give directional information essential for background reduction.

Several tests have been undertaken in connection with the design of the neutron-antineutron mixing experiment. Radiation damage tests have been made on several materials to be used in the detector. The innermost active layer of the detector in the present design is a set of lead-glass blocks. A small block of the correct type of lead glass was exposed to a 3000-rad dose from an intense ^{60}Co source located at ORNL. Some yellowing of the glass was observed. A second, 60,000-rad, exposure was made, completely darkening the block. It was then demonstrated that the glass could be cured by exposure to the ultraviolet radiation in sunlight. The expected dose to the lead glass in one year of running is less than 50 rads of gamma-ray flux, considerably less than the above doses.

Blocks of lead glass, plastic scintillator, and Lucite were exposed to radiation from the Pool Critical Assembly at ORNL, a 10-kW training reactor. All blocks were encased in 0.05 in. of cadmium to absorb thermal neutrons. This was done to simulate the experiment environment in which layers of $^{6}Li_2CO_3$ and boron will be used to absorb thermal neutrons before they reach the detector. Exposures were made at total fast-neutron fluences between 2×10^{8} and 5×10^{11} neutrons/cm^2, thus exceeding the calculated fast-neutron dose in the detector for a one-year run by a factor of 100. No increase in light absorption below 6000 Å, as measured with a spectrophotometer, was found for the plastic scintillator or the Lucite at the maximum fluence used. For the lead-glass samples, no increase in light attenuation below 6000 Å was found for a fluence of 5×10^{10} neutrons/cm^2, while a 10% increase in attenuation was found for 5×10^{11} neutrons/cm^2.

Tests of the pulse-height response of the lead glass to neutrons in the energy range 10 keV to 100 MeV were made at the Oak Ridge Electron Linear Accelerator 85-m beam line. Neutron response of the SF_5 lead glass was observed for neutrons above $T_n =$ 7 MeV; it was checked that the response was due to neutrons by using the lead glass to measure the absorption of 7- to 100-MeV neutrons by paraffin and comparing the results with calculated values of the absorption. It is hypothesized that the observed response is due to an $(n,n'\gamma)$ process, with subsequent detection of the Cerenkov radiation from Compton electrons produced by the gamma rays emitted. No detectable response was found for neutrons of 10 keV $< T_n <$ 2 MeV. The pulse heights for even 100-MeV neutrons are quite small, corresponding to those of low-energy gamma rays. This indicates that pulse pileup due to neutron response of the innermost detector will not be a problem for the experiment.

Tests of the lead-glass pulse-height response to the neutrons and gamma rays emitted by a ^{252}Cf fission source and by a ^{60}Co source were also made. An integral efficiency of $\sim 10^{-3}$ was obtained, again suggesting that pileup of soft reactor gamma rays will not be a problem.

Monte Carlo studies of the event signature of the annihilation of an antineutron have been carried out to the level of computing all particle momenta and determining detector acceptance and efficiency of possible trigger schemes. The output of this program is being used as input to a high-energy-particle transport code. From this calculation the response of the detector to real events is being determined. The results of the acceptance calculations show that a triggering multiplicity of three or greater can be used while retaining an overall detection efficiency of ~50%, which will aid greatly in cosmic-ray rejection.

We are setting up a program to carry through studies that would finalize the design of the experiment within a year. The various tasks are:

1. Detailed engineering design studies in order to arrive at a conceptual design for the experiment and to obtain a reliable cost estimate for the experiment.
2. Safety analysis of the experiment in conjunction with the engineering design to ensure the project meets all safety requirements. Potential hazards from reactor-produced radiation could be especially severe for this experiment.
3. Detailed neutron and gamma-ray transport calculations to determine necessary shielding arrangements and to evaluate induced activation throughout the considerable length of the experiment apparatus.
4. Monte Carlo calculations to design and study the performance of the proposed detection apparatus. Event signatures and cosmic-ray rejection capabilities will be studied.
5. Measurements of detector element performance done in small-scale mock-ups at the reactor in

radiation environments similar to conditions existing in the experiment. Particular attention will be given to reactor-associated backgrounds and reactor-induced activities.

---

1. Part-time employee from the University of Tennessee, Knoxville.
2. Engineering Physics Division.

3. Harvard University, Cambridge, Mass.
4. University of Tennessee, Knoxville.
5. S. Weinberg, *Rev. Mod. Phys.* **52**, 515 (1980) and references therein: A. Salam, ibid, p. 525; S. L. Glashow, ibid, p. 539.
6. S. L. Glashow, Harvard Preprints HUTP-59, HUTP-79, 1980.
7. N. P. Chang, AIP Conference Proceedings No. 72, VPI 1980, p. 142; J. C. Pati, ibid, p. 84.
8. R. E. Marshak, R. N. Mahapatra, Riazuddin, VPI Preprint VPI-HEP-80/7.

10. Publications

List Prepared by Shirley J. Ball

The following list of publications includes primarily those articles by Physics Division staff members and associates *which have appeared in print from January 1979 through April 1981.* A few articles published in 1977 and 1978, not previously reported in the Division's Progress Report, are also included. Articles pending publication as of June 15, 1981, are listed immediately following this section.

BOOK, JOURNAL, AND PROCEEDINGS ARTICLES

Aleonard, M. M., Y. El Masir, I. Y. Lee, F. S. Stephens, M. A. Deleplanque, and R. M. Diamond, "Experimental Study of ^{136}Nd at High Angular Momentum," *Nucl. Phys.* **A350**, 190–204 (1981).

Allen, B. J., J. W. Boldeman, A. R. de L. Musgrove, and R. L. Macklin, *Resonance Neutron Capture in the Isotopes of Titanium*, Australian Atomic Energy Commission Report AAEC/E-402 (1977).

Allen, B. J., A. R. de L. Musgrove, R. L. Macklin, and R. R. Winters, "Neutron Sensitivity of Capture Gamma-Ray Detectors," p. 506 in *Neutron Data of Structural Materials for Fast Reactors* (Proceedings, Specialists' Meeting, Geel, Belgium, December 1977), Pergamon, New York, 1978.

Allen, B. J., A. R. de L. Musgrove, R. Taylor, and R. L. Macklin, "Neutron Capture Cross Section of ^{57}Fe," p. 476 in *Neutron Data of Structural Materials for Fast Reactors* (Proceedings, Specialists' Meeting, Geel, Belgium, December 1977), Pergamon, New York, 1978.

Allen, B. J., and R. L. Macklin, "Resonance Neutron Capture in ^{58}Fe," *J. Phys.* (*London*) **G6**, 381–92 (1980).

Allred, D. D., D. C. Booth, B. R. Appleton, P. D. Miller, C. D. Moak, J. P. F. Sellschop, C. W. White, and A. L. Wintenberg, "The Hydrogen Content of Multicomponent Amorphous Silicon Alloys by ^{19}F Nuclear Reaction Analysis," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1838–40 (1981).

Alton, G. D. (invited paper), "Recent Negative Ion Source Developments," Proceedings, Fifth Conference on Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 1542–48 (1979).

Alton, G. D., "A Universal Positive or Negative Ion Source," Proceedings, 1979 Particle Accelerator Conference (San Francisco, Calif., March 1979), *IEEE Trans. Nucl. Sci.* **NS-26**, 3708–12 (1979).

Alton, G. D., "Recent Negative Ion Source Developments at ORNL," pp. 168–86 in *Proceedings, Symposium of Northeastern Accelerator Personnel* (Oak Ridge, Tenn., October 1978), CONF-781051, U.S. Government Printing Office, Washington, D.C. (1979).

Alton, G. D., "Single and Multiple Electron Loss Processes in MeV Heavy Ion–Target Collisions," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1043–52 (1981).

Alton, G. D., J. K. Bair, J. A. Benjamin, C. M. Jones, R. C. Juras, J. E. Mann, W. T. Milner, C. D. Moak, R. O. Sayer, and G. F. Wells, eds., *Proceedings, Symposium of Northeastern Accelerator Personnel* (Oak Ridge, Tenn., October 1978), CONF-781051, U.S. Government Printing Office, Washington, D.C. (1979).

Alton, G. D., and G. C. Blazey, "Studies Associated with the Development of a Modified University of Aarhus Negative Ion Source," *Nucl. Instrum. Methods* 166, 105–16 (1979).

Alton, G. D., J. B. Roberto, C. W. White, and R. A. Zhur, "Design Features and Focal Properties of Simple Three-Element Two- or Three-Dimensional Lens System for Decelerating Intense Ion Beams to Very Low Energies," *Nucl. Instrum. Methods 177*, 273–80 (1980).

Appleton, B. R., R. H. Ritchie, J. A. Biggerstaff, T. S. Noggle, S. Datz, C. D. Moak, H. Verbeek, and V. N. Neelavathi, "Radiative Electron Capture by Oxygen Ions in Single-Crystal Channels: Experiment and Theory," *Phys. Rev. B* 19, 4347–62 (1979).

Auble, R. L., "Nuclear Data Sheets for $A = 119$," *Nucl. Data Sheets* 26, 207–79 (1979).

Auble, R. L., "Nuclear Data Sheets for $A = 60$," *Nucl. Data Sheets* 28, 103–78 (1979).

Auble, R. L., "Nuclear Data Sheets for $A = 63$," *Nucl. Data Sheets* 28, 559–618 (1979).

Auble, R. L., J. K. Bair, D. M. Galbraith, C. M. Jones, P. H. Stelson, and D. C. Weisser, "Evaluation of Carbon Stripper Foils for Heavy-Ion Accelerators," *Nucl. Instrum. Methods* 177, 289–94 (1980).

Bainum, D. E., J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, and C. A. Goulding, "Observation of Giant Particle-Hole Resonances in ^{90}Zr$(p,n)^{90}$Nb," *Phys. Rev. Lett.* 44, 1751–55 (1980).

Bair, J. K., "Progress on the Oak Ridge Tandem," pp. 223–29 in *Proceedings, Symposium of Northeastern Accelerator Personnel* (Los Alamos, N.Mex., September 1977), Los Alamos Scientific Laboratory Report LA-7445-C (1978).

Bair, J. K., and J. Gomez del Campo, "Neutron Yields from Alpha-Particle Bombardment," *Nucl. Sci. Eng.* 71, 18–28 (1979).

Baker, F. T., A. Scott, T. P. Cleary, J. L. C. Ford, E. E. Gross, and D. C. Hensley, "^{194}Pt(^{12}C,^{12}C′) Reaction and the Triaxial-Rotor Model," *Nucl. Phys. A* 321, 222–30 (1979).

Baker, F. T., A. Scott, E. E. Gross, D. C. Hensley, and D. L. Hillis, "^{30}Si(^{12}C,^{12}C′) Reaction at 41.3 MeV," *Nucl. Phys. A* 325, 525–32 (1979).

Ball, J. B., E. D. Hudson, R. S. Lord, J. W. Johnson, J. A. Martin, G. S. McNeilly, W. T. Milner, S. W. Mosko, R. O. Sayer, and R. L. Robinson, "The Holifield Heavy-Ion Research Facility — Phase II," Proceedings, 1979 Particle Accelerator Conference (San Francisco, Calif., March 1979), *IEEE Trans. Nucl. Sci.* NS-26, 3727–29 (1979).

Ball, J. B., E. D. Hudson, R. S. Lord, J. A. Martin, G. S. McNeilly, and S. W. Mosko (invited paper), "Status of the Holifield Heavy-Ion Research Facility Phase II Booster," Proceedings, Eighth International Conference on Cyclotrons and Their Applications (Bloomington, Ind., September 1978), *IEEE Trans. Nucl. Sci.* NS-26, 2055–60 (1979).

Barker, J. H., J. R. Beene, M. L. Halbert, D. C. Hensley, M. Jääskeläinen, D. G. Sarantites, and R. Woodward, "Direct Evidence for a Narrow Window at High Angular Momentum in Incomplete-Fusion Reactions," *Phys. Rev. Lett.* 45, 424–26 (1980).

Barnett, C. F., D. H. Crandall, B. J. Farmer, H. B. Gilbody, P. M. Hafford, M. I. Kirkpatrick, E. W. McDaniel, R. H. McKnight, F. W. Meyer, T. J. Morgan, R. A. Phaneuf, and E. W. Thomas, *1979 Bibliography of Atomic and Molecular Processes*, DOE Report DOE/ER-0074, U. S. Government Printing Office, Washington, D.C. (1980).

Barnett, C. F., D. H. Crandall, B. J. Farmer, H. B. Gilbody, S. W. Hawthorne, M. I. Kirkpatrick, E. W. McDaniel, R. H. McKnight, F. W. Meyer, T. J. Morgan, R. A. Phaneuf, and E. W. Thomas, *1978 Bibliography of Atomic and Molecular Processes*, DOE Report DOE/ER-0044, U. S. Government Printing Office, Washington, D.C. (1980).

Barnett, C. F., and J. A. Ray, "Progress in Extending Neutral-Pipe Detection Down to 10eV Using a Cs Heat Pipe for Electron Detachment," pp. 2.1–2.12 in *Proceedings, Workshop on New Diagnostics Related to Impurity Release* (Germantown, Md., May–June 1979), CONF-790585, U.S. Government Printing Office, Washington, D.C. (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 4, No. 6 (1978).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 4, Index (1978).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, No. 1 (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, No. 2 (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, No. 3 (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, No. 4 (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, No. 5 (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, No. 6 (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 5, Index (1979).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 6, No. 1 (1980).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 6, No. 2 (1980).

Barnett, C. F., and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 6, No. 3 (1980).

Bart, S. M., E. V. Hungerford, J. A. Vrba, C. R. Bingham, T. P. Cleary, E. E. Gross, and D. C. Hensley, "A Trajectory Detector for the Measurement of Short-Lived Activity by Decay in Flight," *Nucl. Instrum. Methods* 167, 209–14 (1979).

Becker, R. L., A. L. Ford, and J. F. Reading, "Contributions of Multielectron Processes in Inner-Shell Charge Transfer and Vacancy Production: Projectile Charge Dependence in Collisions of Bare Nuclei with Argon," *J. Phys. (London)* **B13**, 4059–77 (1980).

Becker, R. L., and A. D. MacKellar, "Classical Four-Body Calculations of $^4He^+$ + H and H + H Collisions," *J. Phys. (London)* **B12**, 345–50 (1979).

Becker, R. L., J. F. Reading, and A. L. Ford, "Nonstatistical Theory of Multiple Vacancy Production in Atomic Collisions," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1092–94 (1981).

Beene, J. R., R. M. de Vries, D. Shapira, and M. R. Clover, "*m*-Substate Populations in Resonant Heavy-Ion Reactions," *Phys. Rev. C* **21**, 167–74 (1980).

Beene, J. R., M. L. Halbert, D. C. Hensley, D. G. Sarantites, L. W. Westerberg, K. Geoffroy, and R. Woodward, "Gamma-Ray Continuum Spectra from Heavy-Ion Reactions," pp. 503–10 in *Proceedings, Symposium on High-Spin Phenomena in Nuclei* (Argonne, Ill., March 1979), Argonne National Laboratory Report ANL/PHY-79-4 (October 1979).

Bemis, C. E., J. R. Beene, J. P. Young, and S. D. Kramer, "Optical Isomer Shift for the Spontaneous-Fission Isomer ^{240m}Am," *Phys. Rev. Lett.* **43**, 1854–58 (1979).

Bemis, C. E., Jr., J. R. Beene, J. P. Young, and S. D. Kramer, "Laser-Induced Nuclear Polarization (LINUP): Application to the Study of Short-Lived Nuclides," Proceedings, XI International Quantum Electronics Conference (Boston, Mass., June 1980), IEE Catalog No. 80, CH-1561-0, p. 643 and *J. Opt. Soc. Am.* **70**, 643 (1980).

Bemis, C. E., Jr., P. F. Dittner, R. L. Ferguson, D. C. Hensley, F. Plasil, and F. Pleasonton, "Spontaneous-Fission Branching in the Decay of ^{259}104," *Phys. Rev. C* 23, 555–58 (1981).

Bemis, C. E., Jr., R. J. Silva, D. C. Hensley, O. L. Keller, Jr., J. R. Tarrant, L. D. Hunt, P. F. Dittner, R. L. Hahn, and C. D. Goodman, "X-Ray Identification of Element 104," *Phys. Rev. Lett.* **31**, 647 (1973); reprinted in *Benchmark Papers in Physical Chemistry and Chemical Physics*, Vol. 1, Transuranium Elements: Products of Modern Alchemy, Dowden, Hutchinson, and Ross, Stroudsburg, Pa., 1979.

Bertrand, F. E. (invited paper), "The New Giant Resonances — An Experimental Review," pp. 417–51 in *Common Problems in Low- and Medium-Energy Nuclear Physics* (Proceedings, NATO Advanced Study Institute on Theoretical Methods in Medium-Energy Physics, Banff, Canada, August–September 1978), Plenum, New York, 1979.

Bertrand, F. E. (invited paper). "Giant Multipole Resonances and Inelastic Pion Scattering," pp. 230–51 in *Proceedings, Second International Conference on Meson-Nuclear Physics* (Houston, Tex., March 1979), American Institute of Physics, New York, 1979.

Bertrand, F. E. (invited paper), "Giant Multipole Resonances — Perspectives after Ten Years," Proceedings, International Conference on Nuclear Physics (Berkeley, Calif., August 1980), *Nucl. Phys. A* **354**, 129c-56c (1981).

Bertrand, F. E., J. R. Beene, C. E. Bemis, Jr., E. E. Gross, D. J. Horen, J. R. Wu, and W. P. Jones, "Measurement of the Fission Decay of the Giant Quadrupole Resonance in ^{238}U," *Phys. Lett.* **99B**, 213–17 (1981).

Bertrand, F. E., G. R. Satchler, D. J. Horen, and A. van der Woude, "Systematics of the Isoscalar Giant Monopole Resonance from 60-MeV Inelastic Proton Scattering," *Phys. Lett.* **80B**, 198–202 (1979).

Bertrand, F. E., G. R. Satchler, D. J. Horen, J. R. Wu, A. D. Bacher, G. T. Emery, W. P. Jones, D. W. Miller, and A. van der Woude, "Systematic Investigation of Giant Multipole Resonances from Inelastic Scattering of 152-MeV Alpha Particles," *Phys. Rev. C* **22**, 1832–47 (1980).

Blann, M., and R. L. Ferguson, "Ambiguities in the Inference of Precompound Emission from Excitation Function Analysis," *Phys. Rev. C* **19**, 289–90 (1979).

Blann, M., R. H. Stokes, B. Erkkila, H. C. Britt, P. D. Goldstone, R. L. Ferguson, F. Plasil, and H. H. Gutbrod, "Final and Primary Yields and Dispersions for Strongly Damped Reaction of ^{86}Kr + ^{124}Sn," *Phys. Rev. C* **19**, 1288–94 (1979).

Blecher, M., K. Gotow, D. Jenkins, F. Milder, F. E. Bertrand, T. P. Cleary, E. E. Gross, C. A. Ludemann, M. A. Moinester, R. L. Burman, M. Hamm, R. P. Redwine, M. Yates-Williams, S. Dam, C. W. Darden III, R. D. Edge, D. J. Malbrough, T. Marks, and B. M. Preedom, "Positive Pion-Nucleus Elastic Scattering at 40 MeV," *Phys. Rev. C* **20**, 1884–90 (1979).

Bonche, P., K. T. R. Davies, B. Flanders, H. Flocard, B. Grammaticos, S. E. Koonin, S. J. Krieger, and M. W. Weiss, "Time-Dependent Hartree-Fock Calculations of Fusion Cross Sections for ^{16}O + ^{40}Ca and ^{28}Si + ^{28}Si," *Phys. Rev. C* **20**, 641–47 (1979).

Bottcher, C., "Energy Transfer in Ion-Polar Molecule Collisions," *Chem. Phys. Lett.* **66**, 126–30 (1979).

Bottcher, C., "Excited State Potential Surfaces and Their Applications," pp. 169–206 in *Advances in Chemical Physics*, Vol. XLII, Wiley, New York, 1980.

Bottcher, C., Ionization of Rydberg Atoms by Moderately Fast Charged Particles," pp. 222–23 in Proceedings, Seventh International Conference on Atomic Physics, Abstracts (Cambridge, Mass., August 1980), 1980.

Bottcher, C. (invited paper), "Theory of Recombination Processes," pp. 267–312 in *Proceedings, NATO Advanced Study Institute on Atomic and Molecular Processes in Controlled Thermonuclear Fusion* (Toulouse, France, August 1979), Plenum, New York, 1980.

Bottcher, C. (invited paper), "Coherence Effects in Heavy Ion-Atom Collisions," pp. 403–11 in *Coherence and Correlation in Atomic Collisions* (Proceedings, International Workshop on Coherence and Correlation in Atomic Collisions, London, England, September 1978), Plenum, New York, 1980.

Bottcher, C., and B. D. Buckley, "Dissociative Electron Attachment to the Metastable $c^3\pi_u$ State of Molecular Hydrogen," *J. Phys. (London)* **B12**, L497–L500 (1979).

Bottcher, C., and C. Feuillade, "Coherent Pumping of Microwave Transitions between Highly Excited States," *Chem. Phys.* **54**, 227–40 (1981).

Bottcher, C., H. J. Kim, F. W. Meyer, R. A. Phaneuf, P. H. Stelson, and P. Hvelplund, "Observation of Coulomb Interference in Total Electron-Capture Cross Sections," pp. 304–5 in *Proceedings, Sixth International Conference on Atomic Physics*, Contributed Papers (Riga, U.S.S.R., August 1978), Physics Inst. Latvian Academy of Sciences, U.S.S.R., 1978.

Braga, R. A., W. R. Western, J. L. Wood, R. W. Fink, R. Stone, C. R. Bingham, and L. L. Riedinger, "Very Slow *M*4 Transitions and Shell-Model Intruder States in ^{199,201}Bi," *Nucl. Phys. A* **349**, 61–67 (1980).

Braga, R. A., J. L. Wood, G. M. Gowdy, and R. W. Fink, "Decay of Mass-Separated ^{197}Tl (2.83 *h*) to ^{197}Hg," *Phys. Rev. C* 19, 2305–13 (1979).

Breinig, M., S. B. Elston, I. A. Sellin, L. Liljeby, R. Thoe, C. R. Vane, H. Gould, R. Marrus, and R. Laubert, "Initial Tests of Possible Second-Born-Term Source of Asymmetry in Forward Electron Ejection by Fast Bare Nuclei," *Phys. Rev. Lett.* **45**, 1689–92 (1980).

Brick, D., D. Fong, M. Heller, A. M. Shapiro, M. Widgoff, F. Bruyant, D. Bogert, M. Johnson, R. Burnstein, C. Fu, D. Petersen, M. Robertson, H. Rubin, R. D. Sard, A. Snyder, J. Tortora, E. D. Alyea, Jr., C.-Y. Chien, P. Lucas, A. Pevsner, R. Zdanis, F. Barreiro, O. Benary, J. E. Brau, C. E. DeTar, J. Grunhaus, E. S. Hafen, R. I. Hulsizer, U. Karshon, V. Kistiakowsky, A. Levy, A. Napier, I. A. Pless, J. P. Silverman, T. Stoughton, P. C. Trepagnier, J. Wolfson, R. K. Yamamoto, H. O. Cohn, P. F. Jacques, T. C. Ou, R. J. Plano, T. L. Watts, E. B. Brucker, E. Koller, P. Stamer, S. Taylor, W. M. Bugg, G. Condo, T. Handler, E. L. Hart, H. Kraybill, D. Ljung, T. Ludlam, and H. D. Taft, "Average Charged-Particle Multiplicities in $\pi^- p$ Inclusive Reactions at 147 GeV/*c*," *Phys. Rev. D* 19, 743–63 (1979).

Brick, D., D. Fong, M. Heller, A. M. Shapiro, M. Widgoff, F. Bruyant, D. Bogert, M. Johnson, R. Burnstein, C. Fu, D. Petersen, M. Robertson, H. Rubin, R. Sard, A. Snyder, J. Tortora, E. D. Alyea, Jr., C.-Y. Chien, P. Lucas, A. Pevsner, R. Zdanis, F. Barreiro, O. Benary, J. E. Brau, J. Grunhaus, E. S. Hafen, R. I. Hulsizer, U. Karshon, V. Kistiakowsky, A. Levy, A. Napier, I. A. Pless, J. P. Silverman, P. C. Trepagnier, J. Wolfson, R. K. Yamamoto, H. Cohn, P. F. Jacques, T. C. Ou, R. J. Plano, T. L. Watts, E. B. Brucker, E. L. Koller, P. Stamer, S. Taylor, W. Bugg, G. Condo, T. Handler, E. Hart, K. Kraybill, D. Ljung, T. W. Ludlam, and H. D. Taft, "Neutral-Particle Production in $\pi^- p$ Interactions at 147 GeV/*c* and Comparison to Charged-Particle Production," *Phys. Rev. D* 20, 2123–34 (1979).

Brick, D., D. G. Fong, M. Heller, A. M. Shapiro, M. Widgoff, F. Bruyant, D. Bogert, M. Johnson, R. A. Burnstein, C. Fu, D. V. Petersen, M. Robertson, H. A. Rubin, A. E. Snyder, J. O. Tortora, E. D. Alyea, Jr., C.-Y. Chien, P. Lucas, A. Pevsner, R. A. Zdanis, F. Barreiro, O. Benary, J. E. Brau, J. E. Grunhaus, E. S. Hafen, R. I. Hulsizer, U. Karshon, V. Kistiakowsky, A. Levy, A. Napier, I. A. Pless, J. P. Silverman, P. C. Trepagnier, J. Wolfson, R. K. Yamamoto, H. O. Cohn, P. F. Jacques, T. C. Ou, R. J. Plano, T. L. Watts, E. B. Brucker, E. L. Koller, P. E. Stamer, S. Taylor, W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, H. Kraybill, D. A. Ljung, T. W. Ludlam, and H. D. Taft, "Triple-Regge Analysis of the Reactions $\pi^- p \to p_{\text{slow}} + X$ and $\pi^- p \to \pi^-_{\text{fast}} + X$ at 147 GeV/*c*," *Nucl. Phys. B* 150, 109–18 (1979).

Brick, D., D. Fong, M. Heller, A. M. Shapiro, M. Widgoff, F. Bruyant, P. Lucas, D. Bogert, M. Johnson, R. Burnstein, C. Fu, D. Petersen, M. Robertson, H. Rubin, R. Sard, A. Snyder, J. Tortora, E. D. Alyea, Jr., C.-Y. Chien, A. Pevsner, R. Zdanis, F. Barreiro, O. Benary, J. E. Brau, J. Grunhaus, E. S. Hafen, R. I. Hulsizer, U. Karshon, V. Kistiakowsky, A. Levy, A. Napier, I. A. Pless, J. P. Silverman, P. C. Trepagnier, J. Wolfson, R. K. Yamamoto, H. O. Cohn, P. F. Jacques, T. C. Ou, R. J. Plano, T. L. Watts, E. B. Brucker, E. L. Koller, P. E. Stamer, S. Taylor, W. Bugg, G. Condo, T. Handler, E. Hart, H. Kraybill, D. Ljung, T. Ludlam, and H. D. Taft, "Leading Particles and Diffraction Dissociation in 150-GeV/*c* $\pi^- p$ Interactions," *Phys. Rev. D* 21, 1726–43 (1980).

Brick, D., A. M. Shapiro, M. Widgoff, R. E. Ansorge, J. R. Carter, W. W. Neale, J. G. Rushbrooke, D. R. Ward, B. M. Whyman, R. A. Burnstein, H. A. Rubin, J. W. Cooper, R. L. Plumer, R. D. Sard, J. O. Tortora, E. D. Alyea, L. Bachman, C.-Y. Chien, A. Pevsner, J. E. Brau, E. S. Hafen, D. Hochman, R. I. Hulsizer, V. Kistiakowsky, A. Levy, P. Lutz, A. Napier, I. A. Pless, J. P. Silverman, P. C. Trepagnier, R. K. Yamamoto, F. Grard, J. Hanton, V. Henri, P. Herquet, J. M. Lesceux, R. Windmolders, F. Crijns, H. de Bock, W. Kittel, W. Metzger, C. Pols, M. Schouten, R. Van de Walle, H. O. Cohn, G. Bressi, E. Calligarich, C. Castoldi, G. Cecchet, R. Dolfini, S. Liguori, S. Ratti, P. J. Jacques, M. Kalelkar, R. J. Plano, P. Stamer, T. L. Watts, E. B. Brucker, E. L. Koller, S. Taylor, L. Berny, S. Dado, J. Goldberg, S. Toaff, G. Alexander,

O. Benary, S. Dagan, J. Grunhaus, D. Lissauer, Y. Oren, W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, Y. Eisenberg, U. Karshon, E. E. Ronat, A. Shapira, R. Yaari, G. Yekutieli, D. A. Ljung, T. W. Ludlam, and H. D. Taft, "Inclusive π^{++} Production in pp, K^+p, π^+p, and π^-p, Interactions at 147 GeV/c," *Phys. Rev. D* **21**, 632–40 (1980).

Brick, D., A. M. Shapiro, M. Widgoff, R. E. Ansorge, J. R. Carter, W. W. Neale, J. G. Rushbrooke, D. R. Ward, B. M. Whyman, R. A. Burnstein, H. A. Rubin, J. W. Cooper, R. L. Plumer, R. D. Sard, J. O. Tortora, E. D. Alyea, L. Bachman, C.-Y. Chien. A. Pevsner, J. E. Brau, E. S. Hafen, D. Hochman, R. I. Hulsizer, V. Kistiakowsky, A. Levy, P. Lutz, A. Napier, I. A. Pless, J. P. Silverman, P. Trepagnier, R. K. Yamamoto, F. Grard, J. Hanton, V. Henri, P. Herquet, J. M. Lesceux, R. Windmolders, H. deBock, F. Crijns, W. Metzger, C. Pols, M. Schouten, R. Van de Walle, H. O. Cohn, G. Bressi, E. Calligarich, C. Castoldi, G. Cecchet, R. Dolfini, G. Liguori, S. Ratti, P. F. Jacques, M. Kalelkar, R. J. Plano, P. Stamer, T. L. Watts, E. B. Brucker, E. L. Koller, S. Taylor, L. Berny, S. Dado, J. Goldberg, S. Toaff, G. Alexander, O. Benary, J. Grunhaus, W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, Y. Eisenberg, U. Karshon, E. E. Ronat, A. Shapira, R. Yaari, G. Yekutieli, D. Ljung, T. Ludlam, and H. Taft, "Exclusive Production of Neutral Strange Particles by 147 GeV/c $\pi^+/K^+/p$ Interactions in Hydrogen," *Nucl. Phys. B* **164**, 1–24, (1980).

Brink, D. M., and G. R. Satchler, "The Role of the Attractive Nuclear Potential in Determining Reaction Cross Sections," *J. Phys. (London)* G7, 43–52 (1981).

Brisson, D., F. W. Baity, B. H. Quon, J. A. Ray, and C. F. Barnett, "Low-Energy H-Atom Analyzer Using a Cesium Heat Pipe," *Rev. Sci. Instrum.* **51**, 511–15 (1980).

Brown, G. E., and S. Raman, "Where Have All the $M1$ Strengths Gone in ^{208}Pb?," *Comments Nucl. Part. Phys.* **9**, 79–88 (1980).

Bugg, W. M., G. T. Condo, T. Handler, E. L. Hart, H. O. Cohn, S. Hagopian, V. Hagopian, and J. E. Lannutti, "Neutral Three-Pion Resonance Production in 15-GeV/c π^+–Deuteron Collisions," *Phys. Rev. D* **21**, 623–27 (1980).

Bugg, W. M., G. T. Condo, T. Handler, E. L. Hart, H. O. Cohn, S. Hagopian, V. Hagopian, J. E. Lannutti, and B. Wind, "Investigation of Higher-Mass Even-G States from 15-GeV/c π^+d Collisions," *Phys. Rev. D* **21**, 1744–49 (1980).

Button, T. M., R. S. Peterson, F. D. McDaniel, A. Toten, M. C. Andrews III, R. Rice, J. D. Gressett, J. L. Duggan, R. S. Thoe, G. D. Alton, and P. D. Miller, "Radiative Electron Capture X-Ray Profiles from Fast Collisions of F^{+q} on He," Proceedings, Fifth Conference on Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl, Sci.* **NS–26**, 1157–58 (1979).

Carlson, T. A., "Primary Processes in Hot-Atom Chemistry," pp. 11–37 in Chapter 2 of *Chemical Effects of Nuclear Transformations in Inorganic Systems*, North-Holland, Amsterdam, 1979.

Carlson, T. A., "Hot-Atom Chemistry," pp. 418–19 in *Encyclopedia of Physics*, Addison-Wesley, Reading, Mass., 1981.

Carlson, T. A., N. Duric, P. Erman, and M. Larson, "Collisional Transfer to the B State in N_2," *Phys. Scr.* **19**, 25–28 (1979).

Carlton, R. F., J. A. Harvey, N. W. Hill, M. S. Pandey, and R. W. Benjamin, "Neutron Total Cross-Section Measurements on ^{249}Cf," pp. 707–10 in *Proceedings, International Conference on Nuclear Cross Sections for Technology* (Knoxville, Tenn., October 1979), U.S. National Bureau of Standards Special Publication 594 (1980).

Carlton, R. F., S. Raman, and E. T. Jurney, "The ^{115}Sn(n,γ) Reaction with Thermal Neutrons," pp. 571–72 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Carter, H. K. (invited paper), "The UNISOR Isotope Separator Facility," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1481–84 (1981).

Carter, H. K., and C. R. Bingham (invited paper), "Plans for Laser Hyperfine Structure Measurement at UNISOR," pp. 83–88 in *Proceedings, International Symposium on Future Directions in Studies of Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980.

Castel, B., and G. R. Satchler, "Giant EO Resonances and Their Effects on the Lifetime of Excited 0^+ States," *Phys. Lett.* **80B**, 13–16 (1978).

Castel, B., G. R. Satchler, and K. Goeke, "Core Polarization Effects and Giant Quadrupole Resonances in the $A \approx 90$ Region," *Phys. Lett.* **91B**, 185–88 (1980).

Ceyzeriat, P., D. J. Pegg, M. Carre, M. Druetta, and M. L. Gaillard, "A Precision Measurement and a Theoretical Calculation of Lifetimes in the $4p^5 5p$ Configuration of Singly Ionized Rubidium," *J. Opt. Soc. Am.* **70**, 901–11 (1980).

Cisneros, C., I. Alvarez, R. Garcia, C. F. Barnett, J. A. Ray, and A. Russek, "Electron Capture to D_3^- and D_3^0 Repulsive States by D_3^+ in Cs," *Phys. Rev. A* **19**, 631–40 (1979).

Cleary, T. P., "Implementation of the ORIC Magnetic Field Measurements," Proceedings, 1979 Particle Accelerator Conference (San Francisco, Calif., March 1979), *IEEE Trans. Nucl. Sci.* **NS-26**, 3907–9 (1979).

Cleary, T. P., J. L. C. Ford, Jr., E. E. Gross, D. C. Hensley, C. R. Bingham, and J. A. Vrba, "Mutual Excitation of ^{22}Ne and ^{126}Te in Inelastic Scattering," *Phys. Lett.* **83B**, 51–54 (1979).

Clover, M. R., R. M. De Vries, B. Fulton, R. Ost, N. J. A. Rust, N. Anantaraman, J. L. C. Ford, Jr., and D. Shapira, "Elastic Back Angle Scattering of ^{12}C," pp. 598–99 in *Proceedings, International Conference on Clustering Aspects of Nuclear Structure and Nuclear Reactions* (Winnipeg, Canada, June 1978), American Institute of Physics, New York, 1978.

Compton, R. N., G. D. Alton, and D. J. Pegg, "Photodetachment Cross Sections for $He^-(^4p^0)$," *J. Phys. (London)* **B13**, L651–55 (1980).

Compton, R. N., G. D. Alton, and D. J. Pegg, (invited paper), "Photodetachment Cross Sections for $He^-(^4p^0)$," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1198–202 (1981).

Compton, R. N., G. D. Alton, A. D. Williamson, and A. E. Carter, "Lifetime of He^- Formed through Collisions of He^+ and Ca Vapor," pp. 68–69 in *Proceedings, XI International Conference on the Physics of Electronic and Atomic Collisions*, Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Cordell, K. R., S. T. Thornton, L. C. Dennis, P. G. Lookadoo, T. C. Schweizer, J. L. C. Ford, Jr., J. Gomez del Campo, and D. Shapira, "The $^{12}C(^{13}C,\alpha)^{21}Ne$ Reaction: High-Spin States, Resonances, and Coherent Widths," *Nucl. Phys. A* **323**, 147–60 (1979).

Cotanch, S. R., and G. R. Satchler, "Reciprocity Relation for Multichannel Coupling Kernels," *Phys. Rev. C* **23**, 566–68 (1981).

Cowley, A. A., C. C. Chang, H. D. Holmgren, J. D. Silk, D. L. Hendrie, R. W. Koontz, P. G. Roos, C. Samanta, and J. R. Wu, "Energy Dissipation Process for 100-MeV Protons and the Nucleon-Nucleon Interactions in Nuclei," *Phys. Rev. Lett.* **45**, 1930–33 (1980).

Crandall, D. H. (invited paper), "Electron Capture by Multicharged Ions Colliding with Atomic Hydrogen," pp. 90–97 in *Proceedings, Sixth International Seminar on Ion-Atom Collisions* (Tokai-mura, Japan, September 1979), Japan Atomic Energy Research Institute Report JAERI-M8489 (1979).

Crandall, D. H. (invited paper), "Introductory Remarks on Electron Capture by Multicharged Ions," pp. 387–89 in *Proceedings, XI International Conference on Electronic and Atomic Collisions*, Invited Papers (Kyoto, Japan, August–September 1979), North-Holland, Amsterdam, 1980.

Crandall, D. H. (invited paper), "Electron Impact Ionization of Multicharged Ions," Proceedings, Second Technical Committee Meeting on Atomic and Molecular ($A + M$) Data for Fusion (Paris, France, May 1980), *Phys. Scr.* 23, 153–62 (1981).

Crandall, D. H., C. F. Barnett, and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 6, No. 4 (1980).

Crandall, D. H., C. F. Barnett, and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 6, No. 5 (1980).

Crandall, D. H., C. F. Barnett, and W. L. Wiese, "Atomic Data for Fusion," Bimonthly Bulletin — Vol. 6, No. 6 (1980).

Crandall, D. H., and F. W. Meyer (invited paper), "Hydrogen Negative Ions and Collisions of Atomic Particles," pp. 1–9 in *Proceedings, Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions* (Upton, N.Y., October 1980), Brookhaven National Laboratory Report BNL-51304 (1980).

Crandall, D. H., and R. A. Phaneuf, "Electron Impact Ionization of Oxygen Ions — O^{3+}, O^{4+}, O^{5+}," pp. 226–27 in *Proceedings, XI International Conference on the Physics of Electronic and Atomic Collisions*, Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Crandall, D. H., R. A. Phaneuf, B. E. Hasselquist, and D. C. Gregory, "Measured Cross Sections for Ionization of C^{3+}, N^{4+}, and O^{5+} Ions with Contribution Due to Excitation-Autoionization," *J. Phys. (London)* **B12**, L249–56 (1979).

Crandall, D. H., R. A. Phaneuf, and F. W. Meyer, "Electron Capture by Slow Multicharged Ions in Atomic and Molecular Hydrogen, *Phys. Rev. A* 19, 504–14 (1979).

Crandall, D. H., R. A. Phaneuf, and F. W. Meyer, "Electron Capture by Heavy Multicharged Ions from Atomic Hydrogen at Low Velocities," *Phys. Rev. A* 22, 379–87 (1980).

Cusson, R. Y., and B. Castel, "Isospin Mixing in ^{16}O by Use of Pion and Deuteron Probes," *Phys. Rev. C* 23, 1279–81 (1981.

Cusson, R. Y., J. Gomez del Campo, and H. W. Meldner, "Heavy-Ion Clusters in the TDHF Approximation," pp. 35–44 *in Proceedings, Third International Conference on Clustering Aspects of Nuclear Structure and Nuclear Reactions* (Winnipeg, Canada, June 1978), American Institute of Physics, 1978.

Cusson, R. Y., J. A. Maruhn, H. Stocker, and A. Gobbi, "Collision of $^{234}U + ^{238}U$ Using a Three-Dimensional TDHF-BCS Model," *Z. Phys.* **A294**, 257–60 (1980).

Dabbs, J. W. T. (invited paper). "Instrumentation for Fission Cross-Section Measurements on Actinides," pp. 313–26 in *Proceedings, Specialists' Meeting on Nuclear Data of Plutonium and Americium Isotopes for Reactor Applications* (Upton, N. Y., November 1978), Brookhaven National Laboratory Report BNL-50991 (1979).

Dabbs, J. W. T. (invited paper), "Neutron Cross-Section Measurements at ORELA," pp. 929–35 in *Proceedings, International Conference on Nuclear Cross Sections for Technology* (Knoxville, Tenn., October 1979), U.S. National Bureau of Standards Special Publication 594 (1980).

Dabbs, J. W. T. (invited paper), "The Actinide Cross-Section Program at ORELA," pp. 605–28 in *Proceedings, International Conference on Nuclear Waste Transmutation* (Austin, Tex., July 1980), University of Texas, Austin, 1981.

Dam, S. H., R. D. Edge, B. M. Preedom, F. E. Bertrand, E. E. Gross, M. Clecher, K. Goto, R. L. Burman, E. Carlini, M. E. Hamm, R. P. Redwine, M. A. Yates-Williams, and M. Moinester, "π^+ and π^- Elastic Scattering from ^{40}Ca at 65 MeV," pp. 525–26 in *Proceedings, Second Conference on Meson-Nuclear Physics* (Houston, Tex., March 1979), American Institute of Physics, New York, 1979.

Datz, S., C. D. Moak, O. H. Crawford, H. F. Kraus, P. D. Miller, P. F. Dittner, J. Gomez del Campo, J. A. Biggerstaff, H. Knudsen, and P. Hvelplund, "Resonant Coherent Excitation in Planar Channeling," Proceedings, International Conference on Atomic Collisions in Solids (Hamilton, Ontario, August 1979), *Nucl. Instrum. Methods* **170**, 15–20 (1980).

Davies, K. T. R. (invited paper), "TDHF Calculations of Kr-Induced Strongly Damped Collisions," pp. 331–55 in Vol. 1 of *Proceedings, EPS Topical Conference on Large-Amplitude Collective Nuclear Motion* (Keszthely, Hungary, June 1979), 1979.

Davies, K. T. R. (invited paper), "Time-Dependent Hartree-Fock Studies of the Scattering of Kr Ions from Pb, Bi, and La," pp. 185–93 in Proceedings, Workshop on the Time-Dependent Hartree-Fock Method (Orsay, France, May–June 1979), 1980.

Davies, K. T. R., H. Flocard, S. J. Krieger, and M. S. Weiss, "Application of the Imaginary Time Step Method to the Solution of the Static Hartree-Fock Problem," *Nucl. Phys. A* **342**, 111–23 (1980).

Davies, K. T. R., V. Maruhn-Rezwani, S. E. Koonin, and J. W. Negele, "Time-Dependent Hartree-Fock Calculations of Kr-Induced Strongly Damped Collisions," pp 76–79 in Proceedings, Workshop on High-Resolution Heavy Ion Physics at 20-100 MeV/*a*(Saclay, France, May–June 1978), 1979.

Davies, K. T. R., K. R. Sandhya Devi, and M. R. Strayer, "Time-Dependent Hartree-Fock Calculations of ^{86}Kr + ^{139}La at E_{lab} = 505, 610, and 710 MeV," *Phys. Rev. C* **20**, 1372–82 (1979).

Davies, K. T. R., K. R. Sandhya Devi, and M. R. Strayer, "Time-Dependent Hartree-Fock Fusion Calculations for ^{86}Kr + ^{139}La and ^{84}Kr + ^{209}Bi Collisions," *Phys. Rev. Lett.* **44**, 23–26 (1980).

Dayras, R. A., R. G. Stokstad, C. B. Fulmer, D. C. Hensley, M. L. Halbert, R. L. Robinson, A. H. Snell, D. G. Sarantites, L. Westerberg, and J. H. Barker, "Randomly Oriented Angular Momentum in Strongly Damped Collisions," *Phys. Rev. Lett.* **42**, 697–700 (1979).

Dayras, R. A., R. G. Stokstad, D. C. Hensley, M. L. Halbert, D. G. Sarantites, L. Westerberg, and J. H. Barker, "Angular Momentum Transfer in the Reactions Induced by 166-MeV ^{20}Ne on ^{63}Cu," *Phys. Rev. C* **22**, 1485–508 (1980).

de Lima, A. P., J. H. Hamilton, A. V. Ramayya, B. Van Nooijen, R. M. Ronningen, H. Kawakami, R. H. Piercey, E. de Lima, R. L. Robinson, H. J. Kim, W. K. Tuttle, and L. K. Peker, "Evidence for Ground and Both Neutron and Proton Rotational Aligned Bands in ^{68}Ge," *Phys. Lett.* **83B**, 43–47 (1979).

de Lima, A. P., J. H. Hamilton, A. V. Ramayya, B. van Nooijen, R. M. Ronningen, H. Kawakami, R. B. Piercey, R. L. Robinson, H. J. Kim, W. K. Tuttle, L. K. Peker, F. A. Rickey, and R. Popli, "Multiple Band Structure in ^{68}Ge and the $g_{9/2}$ Orbital," p. 402 in *Lecture Notes in Physics*, Vol. 92 (Proceedings, International Conference on Nuclear Interactions, Canberra Australia, August–September 1978), Springer-Verlag, Berlin, 1979.

de Lima, A. P., A. V. Ramayya, J. H. Hamilton, B. Van Nooijen, R. M. Ronningen, H. Kawakami, R. B. Piercey, E. de Lima, R. L. Robinson, H. J. Kim, L. K. Peker, F. A. Rickey, R. Popli, A. Caffrey, and J. C. Wells, "Multiple Band Structures in ^{68}Ge," *Phys. Rev. C* **23**, 213–27 (1981).

de L. Musgrove, A. R., B. J. Allen, J. W. Boldeman, and R. L. Macklin, "Recent Measurements of Neutron Capture Cross Sections in the Fission Product Mass Region," pp. 449–71 in *Proceedings, International Conference on Nuclear Data for Reactors and Other Applied Purposes* (Harwell, England, September 1978), OECD Nuclear Energy Agency, 1978).

de L. Musgrove, A. R., B. J. Allen, and R. L. Macklin, "Resonance Neutron Capture in ^{23}Na and ^{27}Al from 3 to 600 keV," pp. 426–31 in *Proceedings, International Conference on Nuclear Data for Reactors and Other Applied Purposes* (Harwell, England, September 1978), OECD Nuclear Energy Agency, 1978.

de L. Musgrove, A. R., B. J. Allen, and R. L. Macklin, "Neutron-Capture Resonance Parameters and Cross Sections from the Even-*A* Isotopes of Cadmium," *J. Phys. (London)* GA, 771–85 (1978).

de L. Musgrove, A. R., B. J. Allen, and R. L. Macklin, "Resonance Neutron Capture in ^{138}Ba and ^{140}Ce and the Prompt Neutron Correction to γ-Ray Detectors," *Aust. J. Phys.* **32**, 213–21 (1979).

Denne, B., D. J. Pegg, K. Ishii, E. Alvarex, R. Hallin, J. Phil, and R. Sjodin, "Radiative Lifetimes of Highly Ionized and Foil-Excited Al," Proceedings, Fifth International Conference on Beam-Foil Spectroscopy (Lyon, France, September 1978), *J. Phys. (Paris), Colloq.* 40, C1-183-85 (1979),

Dennis, L. C., K. R. Cordell, R. R. Doering, R. L. Parks, S. T. Thornton, J. L. C. Ford, Jr., J. Gomez del Campo, and D. Shapira, "Search for Resonances in $^{12}C(^{9}Be,\alpha)^{17}O$," *Nucl. Phys. A* 357, 521-32 (1981).

Dittner, P. F., C. E. Bemis, Jr., D. C. Hensley, R. J. Silva, and C. D. Goodman, "Identification of the Atomic Number of Nobelium by an X-Ray Technique," *Phys. Rev. Lett.* 26 1037 (1971); reprinted in *Benchmark Papers in Physical Chemistry and Chemical Physics*, Vol. 1, Transuranium Elements: Products of Modern Alchemy, Dowden, Hutchinson, and Ross, Stroudsburg, Pa., 1979.

Do Dang, G., and S. Ramavataram, "The Center-of-Mass Spuriosity in Continuum Shell-Model Calculations," *J. Phys. (London)* G6, 47-58 (1980).

Eck, J. S., T. R. Ophel, P. D. Clark, D. C. Weisser, and G. R. Satchler, "Inelastic Scattering of ^{9}Be Projectiles to Low-Lying Collective States in ^{28}Si and ^{40}Ca at $E(^{9}Be) = 45$ and 60 MeV," *Nucl. Phys. A* 341, 178-88 (1980).

Eck, J. S., T. R. Ophel, P. D. Clark, D. C. Weisser, and G. R. Satchler, "Elastic and Inelastic Scattering Measurements for the $^{24}Mg + ^{208}Pb$ and $^{28}Si + ^{208}Pb$ Systems," *Phys. Rev. C* 23, 228-35 (1981).

Ellis, Y. A., "Nuclear Data Sheets for $A = 105$," *Nucl. Data Sheets* 27, 1-95 (1979).

Ellis, Y. A., "Nuclear Data Sheets for $A = 213$," *Nucl. Data Sheets* 28, 619-38 (1979).

Ellis, Y. A., "Nuclear Data Sheets for $A = 217$," *Nucl. Data Sheets* 28, 639-53 (1979).

Ellis, Y. A., J. F. Emery, and K. S. Toth, "^{233}U Levels Populated in the α Decay of ^{237}Pu," *Phys. Rev. C* 20, 799-804 (1979).

Ellis, Y. A., and K. S. Toth, "Determination of Q Values for Electron-Capture Decay of ^{172}Hf and ^{188}Pt from X-Ray Intensities," pp. 459-64 in *Atomic Masses and Fundamental Constants 6* (Proceedings, Sixth International Conference on Atomic Masses, East Lansing, Mich., September 1979), Plenum, New York, 1980.

Ellis-Akovali, Y. A., K. S. Toth, C. R. Bingham, H. K. Carter, and D. C. Sousa, "Electron-Capture and Alpha-Particle Decay of ^{190}Pb," *Phys. Rev. C* 23, 480-86 (1981).

Elston, S. B. (invited paper), "Failure of Single Electron Descriptions of Molecular Orbital Collision Processes," Proceedings, Fifth Conference on the Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* NS-26, 1037-41 (1979).

Elston, S. B., S. Schumann, and C. R. Vane, "Many-Electron Aspects of Molecular Promotion in Ion-Atom Collisions, Production of Core-Excited States of Li in Li^{+}-He Collisions, *Phys. Rev. A* 19, 962-69 (1979).

Elston, S. B., I. A. Sellin, M. Breinig, S. Huldt, L. Liljeby, R. S. Thoe, S. Datz, S. Overbury, and R. Laubert, "Coincidence Experiments Concerning Convoy-Electron Production by 1- to 8.5-MeV/u Highly Ionized Ions Traversing Polycrystalline Solids and Axial Channels in Gold," *Phys. Rev. Lett.* 46, 321-23 (1981).

Ewbank, W. B. "Versatile Output from a Simple Numeric Data File," pp. 359-69 in *Proceedings, Sixth International CODATA Conference*, (Santa Flavia, Palermo, Italy, May 1978), Pergamon, New York, 1979.

Ewbank, W. B. (invited paper), "Status of Transactinium Nuclear Data in the Evaluated Nuclear Structure Data File," pp. 109-41 in *Proceedings, IAEA Advisory Group Meeting on Transactinium Isotope Nuclear Data* (Cadarache, France, May 1979), Report IAEA-TECDOC-232 (1980).

Ewbank, W. B., R. L. Haese, F. W. Hurley, M. R. McGinnis, and S. Ramavataram, "1978 Recent References (Cumulation)," *Nucl. Data Sheets* 26, 525-778 (1979).

Ewbank, W. B., F. W. Hurley, M. R. McGinnis, and S. Ramavataram, "Recent References, January through April 1979," *Nucl. Data Sheets* 27, 229-338 (1979).

Ewbank, W. B., F. W. Hurley, M. R. McGinnis, and S. Ramavataram, "Recent References, May through August 1979," *Nucl. Data Sheets* **28**, 1–102 (1979).

Ewbank, W. B., F. W. Hurley, M. R. McGinnis, and S. Ramavataram, "1979 Recent References (Cumulation)," *Nucl. Data Sheets* **29**, 169–452 (1980).

Ewbank, W. B., F. W. Hurley, M. R. McGinnis, and S. Ramavataram, "Recent References, January through April 1980," *Nucl. Data Sheets* **30**, 171–303 (1980).

Ewbank, W. B., F. W. Hurley, M. R. McGinnis, and S. Ramavataram, "Recent References, May through August 1980," *Nucl. Data Sheets* **31**, 1–102 (1980).

Ferguson, R. L., A. I. Gavron, F. E. Obenshain, F. Plasil, R. L. Robinson, D. Shapira, A. H. Snell, and G. R. Young, "Distribution of Products in the Reaction ^{20}Ne + Al," pp. 21–25 in *Proceedings, Workshop on Nuclear Dynamics* (Granlibakken, Calif., March 1980), Lawrence Berkeley Laboratory Report LBL-10688 (1980).

Feuillade, C., and C. Bottcher, "A Multipole Treatment of the Degenerate Maser Problem," *Chem. Phys. Lett.* **77**, 195–201 (1981).

Ford, A. L., R. L. Becker, G. L. Swafford, and J. F. Reading, "Proton-Impact Argon Inner-Shell Charge Transfer and Ionization: Importance of Couplings to Target-Centered *d*-States," *J. Phys.* (*London*) **B12**, L491–96 (1979).

Ford, A. L., J. F. Reading, and R. L. Becker, "Charge Transfer and Ionization in Collisions of 2.5- to 9-MeV Protons with Argon," *J. Phys.* (*London*) **B12**, 2905–11 (1979).

Ford, A. L., J. F. Reading, and R. L. Becker, "Inner-Shell Capture and Ionization in Collisions of H^+, He^{2+}, and Li^{3+} Projectiles with Neon and Carbon," *Phys. Rev. A* **23**, 510–18 (1981).

Ford, J. L. C., Jr., "Position-Sensitive Proportional Counters as Focal Plane Detectors," Detectors in Nuclear Science, *Nucl. Instrum. Methods* **162**, 277–304 (1979).

Ford, J. L. C., Jr., T. P. Cleary, J. Gomez del Campo, D. C. Hensley, D. Shapira, and K. S. Toth, "First 8^+ State in ^{28}Si and Level Systematics of *sd*-Shell Nuclei," *Phys. Rev. C* **21**, 764–67 (1980).

Ford, J. L. C., Jr., J. Gomez del Campo, D. Shapira, M. R. Clover, R. M. DeVries, B. R. Fulton, R. Ost, and C. F. Maguire, "Systematics of Back Angle ^{12}C Scattering — The ^{12}C + ^{20}Ne and ^{12}C + ^{24}Mg Systems," *Phys. Lett.* **89B**, 48–52 (1979).

Forester, J. P., D. J. Pegg, P. M. Griffin, G. D. Alton, S. B. Elston, H. C. Hayden, R. S. Thoe, C. R. Vane, and J. J. Wright, "A Systematic Study of $2s^2\ 2p^k - 2s2p^{k+1} - 2p^{k+2}$ Transitions in Multiply Charged Cl Ions," Proceedings, Fifth International Conference on Beam-Foil Spectroscopy (Lyon, France, September 1978), *J. Phys.* (*Paris*), *Colloq.* **40**, C1–208–10 (1979).

Fulmer, C. B., J. B. Ball, R. L. Ferguson, R. L. Robinson, and J. R. Wu, "Light-Particle Emission from Reactions of 208-MeV ^{16}O Ions with ^{12}C, ^{56}Fe, and ^{91}Zr," *Phys. Lett.* **100B**, 305–9 (1981).

Fulmer, C. B., H. M. Butler, W. F. Ohnesorge, and S. W. Mosko, "Fast Neutron Dose Equivalent Rates in Heavy-Ion Target Areas," Proceedings, Eighth International Conference on Cyclotrons and Their Applications (Bloomington, Ind., September 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 2216–18 (1979).

Fulmer, C. B., R. L. Robinson, J. B. Ball, R. L. Ferguson, R. L. Auble, F. E. Bertrand, I. Y. Lee, M. J. Martin, J. R. Wu, G. R. Young, J. C. Wells, and H. Yamada, "Light-Particle Emission from Heavy-Ion Reactions," pp. 255–60 in Vol. 2 of *Nuclear Science Research Conference Series* (Proceedings, International Symposium on Continuum Spectra of Heavy-Ion Reactions, San Antonio, Tex., December 1979), Harwood Academic, New York, 1980.

Fulmer, C. B., G. R. Satchler, E. E. Gross, F. E. Bertrand, C. D. Goodman, D. C. Hensley, J. R. Wu, N. M. Clarke, and M. F. Steeden, "Elastic and Inelastic Scattering of 88-MeV ^{6}Li Ions," *Nucl. Phys. A* **356**, 235–59 (1981).

Fulmer, C. B., R. M. Wieland, D. C. Hensley, S. Raman, G. R. Satchler, A. H. Snell, P. H. Stelson, and R. G. Stokstad, "^{12}C + ^{12}C Transfer Reactions at 93.8 MeV," *Phys. Rev. C* **20**, 670–82 (1979).

Gardner, L. D., J. E. Bayfield, P. M. Koch, I. A. Sellin, D. J. Pegg, R. S. Peterson, M. L. Mallory, and D. H. Crandall, "Electron-Capture Collisions at keV Energies of Boron and Other Multiply Charged Ions with Atoms and Molecules, I: Ar, H_2, and He," *Phys. Rev. A* **20**, 766–78 (1979).

Gardner, L. D., J. E. Bayfield, P. M. Koch, I. A. Sellin, D. J. Pegg, R. S. Peterson, and D. H. Crandall, "Electron-Capture Collisions at keV Energies of Boron and Other Multiply Charged Ions with Atoms and Molecules. II: Atomic Hydrogen," *Phys. Rev. A* **21**, 1397–1402 (1980).

Gardner, W. H., C. Ferraro, D. D. Bluhm, J. F. Burdoin, M. Cowen, D. A. Davis, E. C. Hartwig, H. Kacinskas, S. Mosko, J. G. Murray, M. Plotkin, T. M. Putnam, A. Tseng, and V. P. Zernoski, *Electrical Safety Criteria for Research and Development Activities*, U.S. Department of Energy Report DOE/EV-0051/1 (1979).

Garg, J. B., V. K. Tikku, J. Halperin, and R. Macklin, "Neutron Capture Cross Section in ^{64}Zn," *Phys. Rev. C* **23**, 683–94 (1981).

Garg, J. B., V. K. Tikku, and J. A. Harvey, "Neutron Widths and Level Spacings of ^{64}Zn + *n*," *Phys. Rev. C* **23**, 671–82 (1981).

Gavron, A., R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, G. A. Petitt, K. A. Geoffroy, D. G. Sarantites, and C. F. Maguire, "Neutron Emission in Deep-Inelastic Collisions of ^{16}O on ^{93}Nb at 204 MeV," *Phys. Rev. Lett.* **46**, 8–11 (1981).

Geoffroy, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, "Angular Momentum Transfer in Incomplete-Fusion Reactions," *Phys. Rev. Lett.* **43**, 1303–6 (1979).

Geoffrey, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, "Angular Momentum Transfer in Incomplete Fusion Reactions," p. 267 in *Lecture Notes in Physics*, Vol. 117 (Proceedings, Symposium on Deep-Inelastic and Fusion Reactions with Heavy Ions, Berlin, Germany, October 1979), Springer-Verlag, Berlin, 1980.

Geoffroy, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker (invited paper), "Angular Momentum Transfer in Incomplete Fusion Reactions," pp. 875–76 in Vol. 2 of *Proceedings, Symposium on Heavy-Ion Physics from 10 to 200 MeV/AMU* (Upton, N.Y., July 1979), Brookhaven National Laboratory Report BNL-51115 (1979).

Gomez, del Campo, J. (invited paper), "Comparison of Fusion Cross Sections for ^{10}B + ^{16}O and ^{12}C + ^{14}N Systems," Proceedings, Third Symposium on Nuclear Physics (Oaxtepec, Mexico, January 1980), *Notas Fis.* **3**, 74–98 (1980).

Gomez del Campo, J., (invited paper), "The Observation of a Random Component of Transferred Angular Momentum in the Reaction ^{20}Ne + ^{63}Cu," pp. 93–116 in Vol. 1 of *Proceedings, Symposium on Heavy-Ion Physics from 10 to 200 MeV/AMU* (Upton, N.Y., July 1979), Brookhaven National Laboratory Report BNL-51115 (1979).

Gomez del Campo, J., R. A. Dayras, J. A. Biggerstaff, D. Shapira, A. H. Snell, P. H. Stelson, and R. G. Stokstad, "Comparison of Fusion Cross Sections for ^{10}B + ^{16}O → ^{26}Al and ^{12}C + ^{14}N → ^{26}Al," *Phys. Rev. Lett.* **43**, 26–28 (1979).

Gomez del Campo, J., R. G. Stokstad, J. A. Biggerstaff, R. A. Dayras, A. H. Snell, and P. H. Stelson, "Fusion and Peripheral Reactions of ^{12}C + ^{14}N at Energies up to 13 MeV/*a*," *Phys. Rev. C* **19**, 2170–85 (1979).

Goodman, C. D. (invited paper), "The (*p*,*n*) Reaction at Intermediate Energy," pp. 149–77 in *Proceedings, Conference on the (p,n) Reaction and the Nucleon-Nucleon Force* (Telluride, Colo., March 1979), Plenum, New York, 1980.

Goodman, C. D. (invited paper), "Excitation of Giant Resonances via Charge-Exchange Reactions," pp. 419–32 in Vol. 1 of *Nuclear Science Research Conference Series* (Proceedings, Giant Multipole Resonances Topical Conference, Oak Ridge, Tenn., October 1979), Harwood Academic, New York, 1980.

Goodman, C. D., C. C. Foster, M. B. Greenfield, C. A. Goulding, D. A. Lind, and J. Rapaport, "A Facility for Studying Neutron Energy Spectra at Intermediate Energies," Proceedings, Eighth International Conference on Cyclotrons and Their Applications (Bloomington, Ind., September 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 2248–52 (1979).

Goodman, C. D., C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, C. C. Foster, W. G. Love, and F. Petrovich, "Gamow-Teller Matrix Elements from O^0 (p,n) Cross Sections," *Phys. Rev. Lett.* **44**, 1755–59 (1980).

Goulding, C. A., M. B. Greenfield, C. C. Foster, T. E. Ward, J. Rapaport, D. E. Bainum, and C. D. Goodman, "Comparison of the $^{12}C(p,n)^{12}N$ and $^{12}C(p,p')$ Reactions at E_p = 62 and 120 MeV," *Nucl. Phys. A* 331, 29–38 (1979).

Gowdy, G. M., J. L. Wood, and R. W. Fink, "Decay of Mass-Separated ^{195}Tl (1.13 h) to ^{195}Hg," *Nucl. Phys. A* 312, 56–80 (1978).

Greene, G. L., N. F. Ramsey, W. Mampe, J. M. Pendlebury, K. Smith, W. B. Dress, P. D. Miller, and P. Perrin, "A Measurement of the Neutron Magnetic Moment," *Phys. Rev. D* 20, 2139–53 (1979).

Greenwood, L. R., R. R. Heinrich M. J. Saltmarsh, and C. B. Fulmer, "Integral Tests of Neutron Activation Cross Sections in a $^9Be(d,n)$ Field at E_d = 40 MeV," *Nucl. Sci. Eng.* 72, 175–90 (1979).

Gregory, D., G. H. Dunn, R. A. Phaneuf, and D. H. Crandall, "Absolute Cross Sections for $2s$-$2p$ Excitation of N^{4+} by Electron Impact," *Phys. Rev. A* 20, 410–20 (1979).

Grimm, F. A., T. A. Carlson, W. B. Dress, P. Agron, J. O. Thomson, and J. W. Davenport, "Use of the Multiple-Scattering Method for Calculating the Asymmetry Parameter in the Angle-Resolved Photoelectron Spectroscopy of N_2, CO, CO_2, COS, and Cs_2," *J. Chem. Phys.* 72, 3041–48 (1980).

Guidry, M. W., I. Y. Lee, N. R. Johnson, P. A. Butler, D. Cline, P. Colombani, R. M. Diamond, and F. S. Stephens, "Reduced Transition Probabilities and Energies of High-Spin States in ^{162}Dy," *Phys. Rev. C* 20, 1814–18 (1979).

Hagopian, V., D. Gluch, S. Hagopian, C. P. Horne, M. Jenkins, J. E. Lannutti, P. K. Williams, B. Wind, H. O. Cohn, W. M. Bugg, G. T. Condo, T. Handler, and E. L. Hart, "Many-Pion Production in π^+d Reactions at 15 GeV/c," *Phys. Rev. D* 20, 2113–22 (1979).

Hahn, R. L., K. S. Toth, C. Cabot, H. Gauvin, and Y. LeBeyec, "Remeasurement of ^{40}Ar and ^{84}Kr Excitation Functions Leading to the Same Compound Nucleus, ^{158}Er," *Phys. Rev. Lett.* **42**, 218–20 (1979).

Hahn, R. L., K. S. Toth, R. L. Ferguson, and F. Plasil, "Energy Loss and Straggling of 7.3-MeV/Nucleon ^{84}Kr Ions in Ni, Al, and Ti," *Nucl. Instrum. Methods* 180, 581–88 (1981).

Halbert, E. C., "Density Patterns and Energy-Angle Distributions from a Simple Cascade Scheme for Fast ^{20}Ne + ^{238}U Collisions," *Phys. Rev. C* 23, 295–330 (1981).

Halbert, M. L., "Nuclear Data Sheets for A = 64," *Nucl. Data Sheets* 28, 179–266 (1979).

Halbert, M. L., R. A. Dayras, J. R. Beene, D. C. Hensley, L. Westerberg, D. G. Sarantites, K. A. Geoffroy, and J. H. Barker, "Studies of the Gamma Continuum from ^{20}Ne on ^{150}Nd," P. 430 in *Lecture Notes in Physics*, Vol. 92 (Proceedings, International Conference on Nuclear Interactions, Canberra, Australia, August–September 1978), Springer-Verlag, Berlin, 1979.

Halperin, J., "Nuclear Data Sheets for A = 196," *Nucl. Data Sheets* 28, 485–558 (1979).

Halperin, J., C. E. Bemis, Jr., J. W. T. Dabbs, B. H. Ketelle, R. W. Stoughton, R. W. Hoff, and R. J. Dougan, "Prompt Neutron Multiplicity Distribution in the Spontaneous Fission of Curium-242," *Nucl. Sci. Eng.* 75, 56–59 (1980).

Halperin, J., C. H. Johnson, R. R. Winters, and R. L. Macklin, "Resonance Structure of ^{32}S + n from Measurements of Neutron Total and Capture Cross Sections," *Phys. Rev. C* 21, 545–62 (1980).

Hamilton, J. H., R. L. Robinson, and A. V. Ramayya, "Discovery of Multiple Collective Band Structures in Nuclei with A = 60–80," *Phys. Energ. Fortis Phys. Nucl.* 3, 355–81 (1979).

Hamilton, J. H., R. L. Robinson, and A. V. Ramayya, "Collective Motions and Band Structures in A = 60–80 Even-Even Nuclei," pp. 253–68 in *Lecture Notes in Physics*, Vol. 92 (Proceedings, International Conference on Nuclear Interactions, Canberra, Australia, August–September 1978), Springer-Verlag, Berlin, 1979.

Hamilton, J. H., E. H. Spejewski, C. R. Bingham, and E. F. Zganjar, eds., *Proceedings, International Symposium on Future Directions in Studies of Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980, 424 pp.

Harakeh, M. N., H. P. Morsch, K. van der Weg, A. van der Woude, and F. E. Bertrand, "Isoscalar Giant Resonances in ^{232}Th," *Phys. Rev. C* 21, 768–71 (1980).

Harmatz, B., "Nuclear Data Sheets for A = 154," *Nucl. Data Sheets* 26, 281–384 (1979).

Harmatz, B., "Nuclear Data Sheets for A = 111," *Nucl. Data Sheets* 27, 453–516 (1979).

Harmatz, B., "Nuclear Data Sheets for A = 101," *Nucl. Data Sheets* 28, 343–402 (1979).

Harmatz, B., "Nuclear Data Sheets for A = 103," *Nucl. Data Sheets* 28, 403–83 (1979).

Harmatz, B., "Nuclear Data Sheets for A = 106," *Nucl. Data Sheets* 30, 305–412 (1980).

Harmatz, B., "Nuclear Data Sheets for A = 115," *Nucl. Data Sheets* 30, 413–99 (1980).

Harvey, J. A., and N. W. Hill, "Scintillation Detectors for Neutron Physics Research," Detectors in Nuclear Science, *Nucl. Instrum. Methods* 162, 507–29 (1979).

Harvey, J. A., C. L. Moore, and N. W. Hill, "Neutron Total Cross Section of ^{233}U from 0.01 to 1.0 eV," pp. 690–91 in *Proceedings, International Conference on Nuclear Cross Sections for Technology* (Knoxville, Tenn., October 1979), U.S. National Bureau of Standards Special Publication 594 (1980).

Hensley, D. C., "The Event Handler – A Fast, Programmable, CAMAC-Coupled Data Acquisition Interface," Proceedings, 1978 Nuclear Science Symposium (Washington, D.C., October 1978), *IEEE Trans. Nucl. Sci.* NS-26, 710–16 (1979).

Hensley, D. C., "The Event Handler II – A Fast, Programmable, CAMAC-Coupled Data Acquisition Interface," Proceedings, Topical Conference on Computerized Data-Acquisition Systems in Particle and Nuclear Physics (Santa Fe, N.Mex., May 1979), *IEEE Trans. Nucl. Sci.* NS-26, 4454–58 (1979).

Hershbarger, R. L., D. S. Flynn, F. Gabbard, and C. H. Johnson, "Systematics of Proton Absorption Deduced from (p,p) and (p,n) Cross Sections for 2.0- to 6.7-MeV Protons on ^{107,109}Ag and ^{115}In," *Phys. Rev. C* 21, 896–901 (1980).

Hjorth, S. A., I. Y. Lee, J. R. Beene, C. Roulet, D. R. Haenni, N. R. Johnson, F. E. Obenshain, and G. R. Young, "Interpretation of the 21-*ns* Isomer in ^{190}Hg as $(\nu i_{13/2})^2$ from a g-Factor Measurement," *Phys. Rev. Lett.* 45, 878–79 (1980).

Horen, D. J. (invited paper), "Survey of Ground-State Magnetic Dipole Strength," pp. 299–316 in Vol. 1 of *Nuclear Science Research Conference Series* (Proceedings, Giant Multipole Resonance Topical Conference, Oak Ridge, Tenn., October 1979), Harwood Academic, New York, 1980.

Horen, D. J. (invited paper), "Search for Magnetic Dipole Strength and Giant Spin-Flip Resonances in Heavy Nuclei," pp. 223–49 in *Proceedings, 1980 RCNP International Symposium on Highly Excited States in Nuclear Reactions* (Osaka, Japan, May 1980), Research Center for Nuclear Physics, Osaka, 1980.

Horen, D. J., C. D. Goodman, D. E. Bainum, C. C. Foster, C. Gaarde, C. A. Goulding, M. B. Greenfield, J. Rapaport, T. N. Taddeucci, E. Sugarbaker, T. Masterson, S. M. Austin, A. Galonsky, and W. Sterrenberg, "Energy Systematics of the Giant Gamow-Teller Resonance and a Charge-Exchange Dipole Spin-Flip Resonance," *Phys. Lett.* **99B**, 383–86 (1981).

Horen, D. J., C. D. Goodman, C. C. Foster, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, E. Sugarbaker, T. G. Masterson, F. Petrovich, and W. G. Love, "Search for Isobaric Analogues of $M1$ States and Giant Spin-Flip Resonances in the ^{208}Pb(p,n) Reaction," *Phys. Lett.* **95B**, 27–30 (1980).

Horen, D. J., and J. A. Harvey, "Unique Contribution of High-Resolution Neutron Scattering Measurements to the Understanding of $M1$ Radiative Strength in ^{207,208}Pb," p. 5.3 in *Proceedings, International Conference on Nuclear Physics with Electromagnetic Interactions*, Contributed Papers (Mainz, W. Germany, June 1979), Max-Planck-Institut fur Chemie, Mainz, 1979.

Horen, D. J., J. A. Harvey, and N. W. Hill, "Parity Assignments from High-Resolution Neutron Scattering $M1$ Radiative Strength in ^{208}Pb," pp. 632–33 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Horen, D. J., J. A. Harvey, and N. W. Hill, "^{206}Pb + n Resonances for $E = 25$–600 keV; s- p-, and d-Wave Doorway States and $M1$ Ground-State Radiative Strength in ^{207}Pb," *Phys. Rev. C* **20**, 478–96 (1979).

Horen, D. J., R. T. Kouzes, D. Mueller, F. Calaprice, and R. P. Hall, "Evidence for Negative Parity for the 7064-keV Level in ^{208}Pb," *Phys. Rev. C* **19**, 549–51 (1979).

Horn, D., G. R. Young, C. I. Lister, and C. Baktash, "High-Spin Isomers in ^{153}Er," pp. 81–82 in *Proceedings, International Conference on Nuclear Behavior at High Angular Momentum*, Contributed Papers (Strasbourg, France, April 1980), Centre de Recherches de Strasbourg, 1980.

Horn, D., G. R. Young, C. I. Lister, and C. Baktash, "High-Spin Isomers in ^{153}Er," Proceedings, International Conference on Nuclear Behavior at High Angular Momentum (Strasbourg, France, April 1980), *J. Phys. (Paris), Colloq.* **41**, C10–39–42 (1980).

Horn, D., G. R. Young, C. J. Lister, and C. Baktash, "High-Spin Single-Particle States in ^{152,153}Er," *Phys. Rev. C* **23**, 1047–55 (1981).

Huber, W. A., and C. Bottcher, "Dielectronic Recombination in a Magnetic Field," *J. Phys. (London)* **B13**, L399–404 (1980).

Hubert, Ph., C. Roulet, H. Sergolle, P. Colombani, J. M. Lagrange, J. Vanhorenbeeck, and N. R. Johnson, "Coulomb Excitation Study of ^{182,184,186}W Isotopes," *Nucl. Phys. A* **321**, 213–21 (1979).

Hughes, R. H., T. A. Heumier, and P. M. Griffin, "Vacuum UV and Soft X-Ray Optical Emissions from Electron Impact on Metals," *Appl. Opt.* **20**, 1350–54 (1981).

Huldt, S. (invited paper), "Convoy-Electron Production in Polycrystalline and Monocrystalline Targets," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS–28**, 1139–42 (1981).

Johnson, B. M., D. C. Gregory, K. W. Jones, D. J. Pegg, P. M. Griffin, T. H. Kruse, J. L. Cecchi, and J. O. Ekberg (invited paper), "Anomalies in the Beam-Foil Measurements for $\Delta n = 0$ Transitions in Highly Ionized Members of the Li, Na, and Cu Sequences," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS–28**, 1159–61 (1981).

Johnson, C. H., "(p,n) Reactions for $89 < A < 130$ and an Anomalous Optical Model Potential for Sub-Coulomb Protons," *Phys. Rev. C* **22**, 899–900 (1980).

Johnson, C. H., J. L. Fowler, N. W. Hill, and J. M. Ortolf, "Measurement off the 2.35-MeV Window in O + n," pp. 807–11 in *Proceedings, International Conference on Nuclear Cross Sections for Technology* (Knoxville, Tenn., October 1979), U.S. National Bureau of Standards Special Publication 594 (1980).

Johnson, C. H., A. Galonsky, and R. L. Kernell, "(p,n) Reaction for $89 < A < 130$ and an Anomalous Optical Model Potential for Sub-Coulomb Protons," *Phys. Rev. C* **20**, 2052–71 (1979).

Johnson, C. H., and R. R. Winters, "Neutron Total Cross Section of Sulfur: Single Level to Multilevel to Optical Model," *Phys. Rev. C* **21**, 2190–98 (1980).

Johnson, N. R., M. W. Guidry, R. J. Sturm, E. Eichler, R. O. Sayer, D. C. Hensley, and N. C. Singhal, "Lifetimes of Rotational States in ^{154}Sm," *Phys. Rev. C* **22**, 2416–19 (1980).

Junker, B. R., "Fourier Transform of Two Center Charge Distribution," *J. Phys. (London)* **B13**, 1049–56 (1980).

Juras, R. C., and N. F. Ziegler, "A Single-Crate Stand-Alone CAMAC Control System for a Negative Ion Source Test Facility," Proceedings, 1979 Particle Accelerator Conference (San Francisco, Calif., March 1979), *IEEE Trans. Nucl. Sci.* **NS–26**, 3442–44 (1979).

Kawakami, H., A. P. de Lima, R. M. Ronningen, A. V. Ramayya, J. H. Hamilton, R. L. Robinson, H. J. Kim, and L. K. Peker, "High-Spin States in ^{65}Ga and Possible Triaxial Structure," *Phys. Rev. C* **21**, 1311–20 (1980).

Kim, H. J., and F. W. Meyer, "n-Scaling of Electron-Loss Cross Sections for Fast $H(n)^0$ N^{3+} Collisions," pp. 962–63 in *Proceedings, XI International Conference on the Physics of Electronic and Atomic Collisions*, Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Kim, H. J., and F. W. Meyer, "Electron Loss from Highly Excited States of H^0 in Collisions with N^{3+}," *Phys. Rev. Lett.* **44**, 1047–49 (1980).

Knudsen, H., C. D. Moak, C. M. Jones, P. D. Miller, R. O. Sayer, G. D. Alton, and L. B. Bridwell, "Total Electron-Loss Cross Sections and Absolute Charge-State Yields of 20-MeV Fe Ions Transmitted Through Gaseous Targets," *Phys. Rev. A* **19**, 1029–37 (1979).

Kocher, D. C., W. B. Ewbank, and M. J. Martin, "Standardized Radioactive Decay Data Sets for Use in Radiation Dosimetry," pp. 139–45 in Vol. II of *National and International Standardization of Radiation Dosimetry* (Proceedings, IAEA Symposium on National and International Standardization of Radiation Dosimetry, Atlanta, Ga., December 1977), IAEA, Vienna, 1978.

Kratz, J. V., W. Bruchle, H. Gaggeler, K. Schadel, K. Summerer, G. Wirth, G. Herrmann, G. Tittel, N. Trautmann, R. Stakemann, E. K. Hulet, R. W. Lougheed, J. M. Nitschke, R. L. Hahn, and R. L. Ferguson (invited paper), "Heavy Actinide Cross Sections in the ^{238}U + ^{248}Cm Reaction," pp. 65–69 in *Proceedings, International Workshop on Gross Properties of Nuclei and Nuclear Excitations* (Hirschegg, Austria, January 1981), Institut fur Kernphysik, Darmstadt, 1981.

Krieger, S. J., and K. T. R. Davies, "Time-Dependent Hartree-Fock Calculation of Fusion Cross Sections for the Reactions ^{18}O + ^{12}C and ^{16}O + ^{12}C," *Phys. Rev. C* **20**, 167–70 (1979).

Kröger, H., "Classical Dynamical Description of Heavy-Ion Sequential Fission," pp. 375–81 in Vol. 2 of *Nuclear Science Research Conference Series* (Proceedings, International Symposium on Continuum Spectra of Heavy-Ion Reactions, San Antonio, Tex., December 1979), Harwood Academic, New York, 1980.

Kröger, H., "Finite Region Density Increase Effects in the Lee-Wick Model," *Phys. Lett.* **97B**, 346–50 (1980).

Kröger, H., "Hilbert Space Approach to the Three- and Four-Nucleon System," *J. Math. Phys.* **22**, 185–98 (1981).

Kröger, H., and R. Perne, "An N-Body Scattering Equation Approach Using a Pole Decomposition of the Green's Function," *Lett. Nuovo Cimento* **27**, 406–8 (1980).

Kruse, H., W. T. Pinkston, W. Greiner, and V. Oberacker, "How Prompt is Coulomb Fission?," *J. Phys. (London)* **G5**, L105–11 (1979).

Kruse, H., W. T. Pinkston, W. Greiner, and V. Oberacker, "Dynamics of Coulomb Fission," *Phys. Rev. C* **22**, 2465–84 (1980).

Larson, J. D., "Thoughts on Accelerator Tubes," pp. 249–65 in *Proceedings, Symposium of Northeastern Accelerator Personnel* (Los Alamos, N.Mex., September 1977), Los Alamos Scientific Laboratory Report LA-7445-C (1978).

Laubert, R.., S. Huldt, M. Breinig, L. Liljeby, S. Elston, R. S. Thoe, and I. A. Sellin, "Convoy Electrons from Solids in Coincidence with Emergent Projectile Charge State," *J. Phys. (London)* **B14**, 859–62 (1981).

Laubert, R., S. Huldt, M. Breinig, L. Liljeby, S. Elston, R. S. Thoe, and I. A. Sellin, "Convoy Electrons from Solids in Coincidence with the Final Projectile Charge State," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1143–45 (1981).

Laubert, R., I. A. Sellin, C. R. Vane, M. Suter, S. B. Elston, G. D. Alton, and R. S. Thoe, "Yield of Convoy Electrons from Solids," Proceedings, International Conference on Atomic Collisions in Solids (Hamilton, Ontario, August 1979), *Nucl. Instrum. Methods* **170**, 557–60 (1980).

Lemmer, R. H., and C. Toepffer, "Fusion Doorway States in the $^{12}C + ^{12}C$ System," *Phys. Rev. Lett.* **44**, 26–29 (1980).

Liljeby, L., S. Mannervik, S. Hultberg, and I. A. Sellin, "Coherent Electron Density Distributing Oscillations in Electron Capture by Fast Protons in He," *Z. Phys.* **A288**, 321–22 (1978).

Liljeby, L., S. Mannervik, S. Hultberg, and I. A. Sellin, "Orbital Angular Momentum State Coherence in Charge Transfer to the $n = 2$ Hydrogen Levels by Fast Protons in Gases," pp. 447–56 in *Coherence and Correlation in Atomic Collisions* (Proceedings, International Workshop on Coherence and Correlation in Atomic Collisions, London, England, September 1978), Plenum, New York, 1980.

Lister, C. J., G. R. Young, D. Cline, J. Srebrny, D. Elmore, P. A. Butler, R. Ledoux, and R. Frideau, "High Spin States and Isomers in ^{151}Dy," *Phys. Rev. C* **20**, 605–18 (1979).

Ma, C. H., D. P. Hutchinson, and K. L. Vander Sluis, "A Modulated Submillimeter-Laser Polarimeter for the Measurement of the Faraday Rotation by a Plasma," *Appl. Phys. Lett.* **34**, 218–20 (1979).

Macklin, R. L., "Neutron Capture in Reactor Structural Materials," pp. 63–72 in *Neutron Capture in the keV Energy Range in Structural Materials for Fast Reactors* (Proceedings, NEACRP/NEANDC Specialists Meeting, Karlsruhe, Germany, May 1973), Report KFK-2046 (1975).

Macklin, R. L. (invited paper), "Resonance Capture Reactions with a Total Energy Detector," pp. 475–84 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Macklin, R. L., and J. Halperin, "$^{100,101,102,104}Ru(n,\gamma)$ and $^{103}Rh(n,\gamma)$ Cross Sections above 2.6 keV," *Nucl. Sci. Eng.* **73**, 174–85 (1980).

Macklin, R. L., J. Halperin, and R. R. Winters, "$^{104,105,106,108,110}Pd(n,\gamma)$ Cross Sections above 2.6 keV," *Nucl. Sci. Eng.* **71**, 182–91 (1979).

Macklin, R. L., J. Halperin, and R. R. Winters, "Absolute Neutron Capture Yield Calibration," *Nucl. Instrum. Methods* **164**, 213–14 (1979).

Macklin, R. L., R. W. Ingle, and J. Halperin, "$^{6}Li(n,\alpha)T$ Cross Section from 70 to 3000 keV from the $^{235}U(n,f)$ Calibration of a Thin Glass Scintillator," *Nucl. Sci. Eng.* **71**, 205–8 (1979).

Macklin, R. L., and R. R. Winters, "Stable Isotope Capture Cross Sections from Oak Ridge Electron Linear Accelerator," *Nucl. Sci. Eng.* **78**, 110–11 (1981).

Macklin, R. L., R. R. Winters, and J. Halperin (invited paper), "Recent Capture Cross-Section Data from ORELA above 2.6 MeV," pp. 103–12 in *Proceedings, NEANDC Specialists' Meeting on Neutron Cross Sections of Fission Product Nuclei* (Bologna, Italy, December 1979), CONF-791223, 1979.

Maguire, C. F., G. L. Bomar, A. V. Ramayya, R. B. Piercey, J. L. C. Ford, Jr., J. Gomez del Campo, D. Shapira, and D. Hensley, "Comparison of the Single-Proton Pickup Reactions $^{40}Ca(^{11}B,^{12}C)^{39}K$ and $^{40}Ca(^{13}C,^{14}N)^{39}K$ at Low and High Bombarding Energies," *Phys. Rev. C* **22**, 1097–103 (1980).

Martin, J. A. (invited paper), "Status of the Holifield Heavy-Ion Research Facility," Proceedings, Fifth Conference on Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 1439–44 (1979).

Martin, J. A. (invited paper), "Conference Summary," Proceedings, Eight International Conference on Cyclotrons and Their Applications (Bloomington, Ind., September 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 1863 (1979).

Martin, J. A. (compiled by), "Cyclotrons — 1978," Proceedings, Eighth International Conference on Cyclotrons and Their Applications (Bloomington, Ind., September 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 2443–651 (1979).

Martin, J. A. (invited paper), "Recent Advances in Design for Low- and Medium-Energy Heavy-Ion Accelerators," Proceedings, 1979 Particle Accelerator Conference (San Francisco, Calif., March 1979), *IEEE Trans. Nucl. Sci.* **NS-26**, 3645–52 (1979).

Martin, M. J., Editor, "Nuclear Decay Data for Selected Radionuclides," pp. 306–441 in *A Handbook of Radioactivity Measurements Procedures*, NCRP Report No. 58, Washington, D.C. (1978).

Martin, M. J., "Nuclear Data Sheets for $A = 212$," *Nucl. Data Sheets* **27**, 637–79 (1979).

Martin, M. J., "ENSDF — Its Structure, Contents, and Use in Applied Research," pp. 2–16 in *Proceedings, 1979 Seminar on Nuclear Data, Japanese Nuclear Data Committee* (Tokai-mura, Ibaraki-ken, Japan, December 1979), Japanese Atomic Energy Research Institute Report JAERI-M8769 (1980).

Maruhn, J. A. (invited paper), "Time-Dependent Hartree-Fock Theory for Heavy Ions," pp. 381–94 in *Lecture Notes in Physics*, Vol. 117 (Proceedings, International Symposium on Deep-Inelastic and Fusion Reactions with Heavy Ions, Berlin, West Germany, October 1979), Springer-Verlag, Berlin, 1980.

Maruhn, J. A., V. E. Oberacker, and V. Maruhn-Rezwani, "Muon-Induced Fission as a Probe for Fission Dynamics," *Phys. Rev. Lett.* **44**, 1576–78 (1980).

McDaniel, F. D., D. A. Toten, R. S. Peterson, J. L. Duggan, S. R. Wilson, J. D. Gressett, P. D. Miller, and G. Lapicki, "Projectile-Charge-State Dependence of Target *L*-Shell Ionization by 1.86-MeV/amu Fluorine and Silicon Ions and 1.8-MeV/amu Chlorine Ions," *Phys. Rev. A* **19**, 1517–24 (1979).

McGowan, F. K., C. E. Bemis, Jr., J. L. C. Ford, Jr., W. T. Milner, D. Shapira, and P. H. Stelson, "Coulomb Excitation of ^{183}W," *Phys. Rev. C* **20**, 2093–2100 (1979).

McGowan, F. K., W. T. Milner, and P. H. Stelson, "Reduced, *E*1, *E*2, and *E*3 Transition Probabilities for Transitions in $^{156-160}$Gd and $^{160-164}$Dy," published in Vol. 1, *Proceedings, International Conference on Band Structure and Nuclear Dynamics* (New Orleans, La., February–March 1980), Tulane University Press, New Orleans, 1980.

McGrory, J. B. (invited paper), "The Role of the *n-p* Interaction in Microscopic Calculations of Collective Motion," pp. 257–72 in *Proceedings, Conference on the (p,n) Reaction and the Nucleon-Nucleon Force* (Telluride, Colo., March 1979), Plenum, New York, 1980.

McGrory, J. B., and S. Raman, "Shell Structure of Collective States in ^{56}Fe, ^{58}Fe, and ^{60}Fe," *Phys. Rev. C* **20**, 830–41 (1979).

McGrory, J. B., and B. H. Wildenthal, "Large-Scale Shell-Model Calculations," *Ann. Rev. Nucl. Part. Sci.* **30**, 383–436 (1980).

Mehta, R., J. L. Duggan, F. D. McDaniel, M. C. Andrews, R. M. Wheeler, R. P. Chaturvedi, P. D. Miller, and G. Lapicki, "Projectile Charge-State Dependence of *M*-Shell Ionization of Au, Pb, Bi, and U by 1.42-MeV/amu Fluorine Ions," Proceedings, Sixth Conference of the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1122–25 (1981).

Mehta, R., F. D. McDaniel, J. L. Duggan, and P. D. Miller, "*K*-Shell Ionization of Elements $_{29}$Cu to $_{37}$Rb for 0.4- to 3.8-MeV/amu $^{10}_{5}$B-Ion Bombardment," *Phys. Rev. A* **19**, 1363–66 (1979).

Melin, R. C., R. M. Ronningen, J. A. Nolen, Jr., G. M. Crawley, C. H. King, J. E. Finck, and C. E. Bemis, Jr., "Multipole Moments of ^{232}Th and ^{234,236,238}U from Proton Inelastic Scattering," pp. 69–71 in Vol. 1 of *Proceedings, International Conference on Band Structure and Nuclear Dynamics* (New Orleans, La., February–March 1980), Tulane University Press, New Orleans, 1980.

Meyer, F. W., "Cross-Section Measurements Using a Cs Vapor Target of Novel Design," *Rev. Sci. Instrum.* **51**, 1295–98 (1980).

Meyer, F. W., "Single Electron Capture and Loss by H^+, H^0 and H^- in Cs Vapor in the Energy Range 0.1–2.0 keV," *J. Phys. (London)* **B13**, 3823–28 (1980).

Meyer, F. W., "Single Electron Capture and Loss by H^+, H^0, and H^- in Cs Vapor in the Energy Range 0.1–2.0 keV," pp. 129–30 in Proceedings, Seventh International Conference on Atomic Physics, Abstracts (Boston, Mass., August 1980), 1980.

Meyer, F. W., and H. J. Kim, "Measurement of H Atom Rydberg-State Population by a Transmission Method," pp. 552–53 in *Proceedings, XI International Conference on the Physics of Electronic and Atomic Collisions*, Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Meyer, F. W., R. A. Phaneuf, H. J. Kim, P. Hvelplund, and P. H. Stelson, "Single-Electron-Capture Cross Sections for Multiply Charged O, Fe, Mo, Ta, W, and Au Ions Incident on H and H_2 at Intermediate Velocities," *Phys. Rev. A* **19**, 515–25 (1979).

Middleton, R., R. R. Betts, H. T. Fortune, and R. G. Stokstad, "Energy-Averaged Angular Distributions for $^{16}O + {}^{12}C + a + {}^{24}Mg$," *Phys. Rev. C* **19**, 100–203, (1979).

Miller, P. D. (invited paper), "Multiple Electron Loss Cross Sections for Heavy Ions Incident on Various Atomic and Molecular Gases," Proceedings, Fifth Conference on the Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 111–17 (1979).

Milner, W. T., "Double-Drift Beam Bunching Systems," Proceedings, Fifth Conference on the Applications of Small accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, (1979).

Milner, W. T., J. A. Biggerstaff, D. C. Hensley, and R. O. Sayer, "Data Acquisition and Analysis System for the Holifield Heavy-Ion Research Facility," Proceedings, Topical Conference on Computerized Data Acquisition Systems in Particle and Nuclear Physics (Santa Fe, N.Mex., May 1979), *IEEE Trans. Nucl. Sci.* **NS-26**, 4399–404 (1979).

Milner, W. T., and N. F. Ziegler, "Buncher Development for ORIC Injection," pp. 124–28 in *Proceedings, Symposium of Northeastern Accelerator Personnel* (Los Alamos, N.Mex., September 1977), Los Alamos Scientific Laboratory Report LA-7445-C (1978).

Mizumoto, M., J. H. Hamilton, S. Raman, R. L. Macklin, G. G. Slaughter, and J. A. Harvey, "Enhanced Primary *M*1 Transitions in ^{207}Pb," pp. 699–700 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Mizumoto, M., S. Raman, R. L. Macklin, G. G. Slaughter, J. A. Harvey, and J. H. Hamilton, "Low-Energy Neutron Resonances in ^{206}Pb," *Phys. Rev. C* **19**, 335–41 (1979).

Mlekodaj, R. L., E. H. Spejewski, and B. G. Ritchie, "A New High-Temperature ISOL Ion Source," *Nucl. Instrum. Methods* 171, 451–55 (1980).

Moak, C. D., "Channeling in Solids," pp. 9–10 in Vol. 3, *McGraw-Hill Encyclopedia of Science and Technology*, Fourth Edition, McGraw-Hill, New York, 1977.

Moak, C. D., "Proton Sources," p. 280 in Vol. 7, *McGraw-Hill Encyclopedia of Science and Technology*, Fourth Edition, McGraw-Hill, New York, 1977.

Moak, C. D., "Absolute Charge-State Yields of 20-MeV ^{127}I Ions Emerging from a Gas Stripper," pp. 3–14 in *Proceedings, Symposium of Northeastern Accelerator Personnel* (Los Alamos, N. Mex., September 1977), Los Alamos Scientific Laboratory Report LA-7445-C (1978).

Moak, C. D., S. Datz, O. H. Crawford, H. F. Krause, P. F. Dittner, J. Gomez del Campo, J. A. Biggerstaff, P. D. Miller, P. Hvelplund, and H. Knudsen, "Resonant Coherent Excitation of Channeled Ions," *Phys. Rev. A* **19**, 977–93 (1979).

Morgan, T. J., C. F. Barnett, J. A. Ray, and A. Russek, "Investigation of Nonadiabatic Effects in Molecular-Hydrogen Rydberg States by Electric Field Ionization," *Phys. Rev. A* **20**, 1062–72 (1979).

Müller, B., and V. Oberacker, "Influence of Nuclear-Trajectory Variations on Atomic-Excitation Probabilities," *Phys. Rev. C.* **22**, 1909–13 (1980).

Neese, R. E., M. W. Guidry, R. Donangelo, and J. O. Rasmussen, "Surface Structure of Deformed Nuclei by Radial and Angular Localization in Heavy-Ion Scattering," *Phys. Lett.* **85B**, 201–5 (1979).

Nettles, W. G., A. V. Ramayya, J. H. Hamilton, F. T. Avignone III, and H. K. Carter (invited paper), "Subnanosecond Lifetime Measurements of Excited States in Nuclei Far from Stability," pp. 77–81 in *Proceedings, International Symposium on Future Directions in Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980.

Nitschke, J. M., M. Fowler, A. Ghiorso, R. E. Leber, M. E. Leino, M. J. Nurmia, L. P. Somerville, K. E. Williams, E. K. Hulet, J. H. Landrum, R. W. Lougheed, J. F. Wild, C. E. Bemis, Jr., R. J. Silva, and P. Eskola, "Search for an 80-ms Spontaneous-Fission Activity in Bombardments of ^{249}Bk with ^{15}N," *Nucl. Phys. A* **352**, 138–46 (1981).

Noid, D. W., C. Bottcher, and M. L. Koszykowski, "Comparison of Quantal and Classical Calculations of Infrared Multiphonon Dissociation," *Chem. Phys. Lett.* 72, 397–400 (1980).

Oberacker, V., W. Greiner, H. Kruse, and W. T. Pinkston, "Characteristics of Coulomb, Fission," *Phys. Rev. C* 20, 1453–66 (1979).

Oberacker, V., H. Kruse, W. T. Pinkston, and W. Greiner, "Signatures of Coulomb Fission — A Theoretical Study," pp. 369–74 in Vol. 2 of *Nuclear Science Research Conference Series* (Proceedings, International Symposium on Continuum Spectra of Heavy-Ion Reactions, San Antonio, Tex., December 1979), Harwood Academic, New York, 1980.

Ohnesorge, W. F., H. M. Butler, J. K. Bair, and J. F. Alexander, "Some Aspects of Radiation Safety at the Holifield Heavy-Ion Facility," Proceedings, Fifth Conference on the Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 1587 (1979).

Ohnesorge, W. F., H. M. Butler, C. B. Fulmer, and S. W. Mosko, "Heavy-Ion Target Area Fast-Neutron Dose Equivalent Rates," *Health Phys.* **39**, 633–36 (1980).

Ortiz, M. E., E. Andrade, M. Cardenas, A. Dacal, A. Menchaca-Rocha, J. L. C. Ford, Jr., J. Gomez del Campo, R. L. Robinson, D. Shapira, and E. Aguilera, "Nonstatistical Effects in the ^{12}C(^{13}N,α) Reaction," *Phys. Rev. C* 22, 1104–20 (1980).

Pegg, D. J., "Radiative and Auger Beam Foil Measurements," pp. 529–606 in *Methods of Experimental Physics,* Vol. 17, Academic, New York, 1980.

Pegg, D. J., J. P. Forester, P. M. Griffin, G. D. Alton, S. B. Elston, B. M. Johnson, M. Suter, R. S. Thoe, and C. R. Vane, "Time-Resolved Spectroscopic Measurements on Multiply Charged Si, P, and Cl Ions," p. 63 in Proceedings, European Conference on Atomic Spectroscopy (Munich, West Germany, July 1978).

Pegg, D. J., J. P. Forester, P. M. Griffin, G. D. Alton, S. B. Elston, B. M. Johnson, M. Suter, R. S. Thoe, and C. R. Vane, "Oscillator Strength Determination for Δn = O Transitions in Be-Like Ions of the Third-Period Elements," Proceedings, Fifth International Conference on Beam-Foil Spectroscopy (Lyon, France, September 1978), *J. Phys. (Paris), Colloq.* **40**, C1–205–7 (1979).

Pegg, D. J., and M. L. Gaillard (invited paper), "Time-Resolved Spectroscopy of Ions Using CW Laser Excitation," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1186–89 (1981).

Perez, R. B., G. de Saussure, R. L. Macklin, and J. Halperin, "Statistical Tests for the Detection of Intermediate Structure: Application to the Structure of the ^{238}U Neutron Capture Cross Section between 5 keV and 0.1 MeV," *Phys. Rev. C* 20, 528–45 (1979).

Peterson, R. S., F. D. McDaniel, J. L. Duggan, R. S. Thoe, and P. D. Miller, "Mo X-Ray Production in Collisions of F^{+q} with Ne," Proceedings, Fifth International Conference on the Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* **NS-26**, 1159–61 (1979).

Petitt, G. A., R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, G. R. Young, K. A. Geoffroy, D. G. Sarantites, and C. F. Maguire, "Neutron Emission in Deeply Inelastic and Fusion-Evaporation Reactions of 208-MeV ^{16}O with ^{93}Nb," pp. 319–24 in Vol. 2 of *Nuclear Science Research Conference Series* (Proceedings, International Symposium on Continuum Spectra of Heavy-Ion Reactions, San Antonio, Tex., December 1979), Harwood Academic, New York, 1980.

Phaneuf, R. A. (invited paper), "Production of High-Q Ions by Laser Bombardment Method," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1182–85 (1981).

Phaneuf, R. A., D. H. Crandall, and F. W. Meyer, "Low-Energy Electron Capture by Multicharged Ions from Hydrogen," Proceedings, Second Technical Committee Meeting on Atomic and Molecular ($A + M$) Data for Fusion (Paris, France, May 1980), *Phys. Scr.* 23, 188–89 (1981).

Phaneuf, R. A., and L. Krause, "$5^2p_{1/2} \leftrightarrow 5^2p_{3/2}$ Excitation Transfer in Rubidium Induced in Collisions with CH_4, CH_2D_2, and CD_4 Molecules," *Can. J. Phys.* **58**, 1047–48 (1980).

Piercey, R. B., A. V. Ramayya, J. H. Hamilton, C. F. Maguire, R. L. Robinson, H. J. Kim, and J. C. Wells, "Band Structures in ^{74,76}Kr," p. 404 in *Lecture Notes in Physics*, Vol. 92 (Proceedings, International Conference on Nuclear Interactions, Canberra, Australia, August–September 1978), Springer-Verlag, Berlin, 1979.

Piercey, R. B., A. V. Ramayya, J. H. Hamilton, R. L. Robinson, L. K. Peker, D. L. Sastry, A. Ahmed, H. Kawakami, A. P. de Lima, H. L. Crowell, H. J. Kim, R. O. Sayer, J. C. Wells, W. T. Milner, and C. F. Maguire, "Band Structures in ^{76,78,80}Kr," p. 405 in *Lecture Notes in Physics*, Vol. 92 (Proceedings, International Conference on Nuclear Interactions, Canberra, Australia, August–September 1978), Springer-Verlag, Berlin, 1979.

Piercey, R. B., A. V. Ramayya, R. M. Ronningen, J. H. Hamilton, V. Maruhn-Rezwani, R. L. Robinson, and H. J. Kim, "In-Beam Gamma-Ray Spectroscopy of ^{74}Se Following the ^{60}Ni(^{16}O,2*p*), ^{64}Ni(^{12}C,2*n*), and ^{65}Cu(^{11}B,2*n*) Reactions," *Phys. Rev. C* **19**, 1344–55 (1979).

Plasil, F. (invited paper), "Angular Momentum Effects in Fusion-Fission and Fusion-Evaporation Reactions," Proceedings, International Conference on Nuclear Behavior at High Angular Momentum (Strasbourg, France, April 1980), *J. Phys. (Paris), Colloq.* **41**, C10–183–99 (1980).

Plasil, F., J. R. Beene, R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, G. R. Young, M. P. Webb, G. A. Petitt, K. A. Geoffroy, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire, "Light-Particle Emission in Reactions Induced with Carbon and Oxygen Ions," pp. 1–7 in *Proceedings, Workshop on Nuclear Dynamics* (Granlibakken, Calif., March 1980), Lawrence Berkeley Laboratory Report LBL-10688 (1980).

Plasil, F., J. R. Beene, R. L. Ferguson, A. Gavron, F. E. Obenshain, G. R. Young, G. A. Petitt, K. G. Young, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire (invited talk), "Nonequilibrium Neutron Emission from ^{12}C + ^{158}Gd and ^{13}C + ^{157}Gd Reactions," pp. 97–106 in *Proceedings, International Workshop on Gross Properties of Nuclei and Nuclear Excitations* (Hirschegg, Austria, January 1981), Institut fur Kernphysisch, Darmstadt, 1981.

Plasil, F., and R. L. Ferguson (invited paper), "Heavy-Ion-Induced Fission following Fusion," pp. 521–50 in *Proceedings, IAEA International Symposium on the Physics and Chemistry of Fission* (Julich, West Germany, May 1979), International Atomic Energy Agency, Vienna, 1980.

Plasil, F., R. L. Ferguson, K. A. Geoffroy, D. C. Hensley, F. E. Obenshain, C. F. Maguire, G. A. Petitt, D. C. Sarantites, A. H. Snell, and G. R. Young, "Neutron Emission in Reactions between ^{16}O and ^{93}Nb at 12.75 MeV/Nucleon," pp. 873–74 in Vol. 2 of *Proceedings, Symposium on Heavy-Ion Physics from 10 to 200 MeV/AMU* (Upton, N.Y., July 1979), Brookhaven National Laboratory Report BNL-51115 (1979).

Plasil, F., R. L. Ferguson, R. L. Hahn, F. E. Obenshain, F. Pleasonton, and G. R. Young, "Fission Barrier of ^{153}Tb," *Phys. Rev. Lett.* **45**, 333–36 (1980).

Plattard, S., G. F. Auchampaugh, N. W. Hill, G. de Saussure, J. A. Harvey, and R. B. Perez, "Some Spectroscopic Properties of Fine Structures Observed near the ^{231}Pa(*n*,*f*) Fission Threshold," *Phys. Rev. Lett.* **46**, 633–36 (1981).

Plattard, S., G. F. Auchampaugh, N. W. Hill, G. de Saussure, R. B. Perez, and J. A. Harvey, "High-Resolution Fission Cross Section of ^{231}Pa," pp. 491–95 in *Proceedings, International Conference on Nuclear Cross Sections for Technology* (Knoxville, Tenn., October 1979), U.S. National Bureau of Standards Special Publication 594 (1980).

Preedom, B. M., S. H. Dam, C. W. Darden III, R. D. Edge, D. J. Malbrough, T. Marks, R. L. Burman, M. Hamm, M. A. Moinester, R. P. Redwine, M. A. Yates, F. E. Bertrand, T. P. Cleary, E. E. Gross, N. W. Hill, C. A. Ludemann, M. Blecher, K. Gotow, D. Jenkins, and F. Milder, "Positive Pion-Nucleus Scattering at 30 and 50 MeV," *Phys. Rev. C* **23**, 1134–40 (1981).

Raman, S., "Dipole and Quadrupole Radiation Strengths from Discrete States of ^{208}Pb," p. 331 in Proceedings, Second International Symposium on Neutron-Induced Nuclear Reactions (Smolenice, Czechoslovakia, June 1979).

Raman, S. (invited paper), "Localized Dipole and Quadropole Radiation Strengths in ^{208}Pb," pp. 193–220 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York 1979.

Raman, S., Editor, "Actinide Newsletter," Issue 2 (February 1979).

Raman, S., Editor, "Actinide Newsletter," Issue 3 (March 1980).

Raman, S., Editor, "Actinide Newsletter," Issue 4 (March 1981).

Raman, S., and G. E. Brown, "Present Status of the Magnetic Dipole Strengths in ^{208}Pb," p. 1.33 in *Proceedings, International Conference on Nuclear Physics with Electromagnetic Interactions*, Contributed Papers (Mainz, W. Germany, June 1979), Max-Planck-Institut fur Chemie, Mainz, 1979.

Raman, S., and E. T. Jurney, "The ^{59}Ni(n,γ) Reaction with Thermal Neutrons," pp. 571–72 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Raman, S., G. G. Slaughter, J. C. Wells, Jr., and B. J. Allen, "Valence Neutron Capture γ-Ray Spectrum in ^{54}Fe," *Phys. Rev. C* **22**, 328–34 (1980).

Ramavataram, K., R. Larue, V. Turcotte, C. St.-Pierre, and S. Ramavataram, "Study of the ^{11}B(p,n) ^{11}C Reaction below the Giant Dipole Resonance in ^{12}C," *Nuovo Cimento* **58A**, 342–54 (1980).

Ramavataram, S., and G. Do Dang, "A Coupled-Channels Treatment of the Positive-Parity Resonances in ^{4}He," *Z. Phys.* **A298**, 225–34 (1980).

Rao, P. V., R. G. Albridge, A. V. Ramayya, M. C. Andrews, R. Mehta, F. D. McDaniel, and P. D. Miller, "*L*-Shell Ionization in High-*Z* Targets by Carbon and Silicon Ions," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1112–13 (1981).

Rapaport, M. S., R. W. Fink, L. L. Riedinger, L. L. Collins, and G. D. O'Kelley, "Half-Lives and Decay of ^{197}Pb Isomers," *Nucl. Phys. A* **315**, 163–68 (1979).

Ray, J. A., C. F. Barnett, and B. Van Zyl, "Absolute Measurement of Low-Energy H^0 by a Secondary Emission Detector," *J. Appl. Phys.* **50**, 6516–19 (1979).

Reading, J. F., A. L. Ford, and R. L. Becker (invited paper), "Fast Numerical Calculations of Ion-Atom Collisions," Proceedings, Workshop on Inner-Shell Processes (Linz, Austria, May 1979), *Nucl. Instrumen. Methods* **169**, 273–79 (1980).

Reading, J. F., A. L. Ford, and R. L. Becker, "A One and a Half Centered Expansion for Ion-Atom Collisions," Proceedings, Sixth Conference on the Application of Accelerators in Research and Industry (Denton, Tex., November 1980), *IEEE Trans. Nucl. Sci.* **NS-28**, 1089–91 (1981).

Reiley, T. C., R. L. Auble, and R. H. Shannon, "Irradiation Creep under 60-MeV Alpha Irradiation," *J. Nucl. Mater.* **90**, 271–81 (1980).

Rester, A. C., J. B. Ball, and R. L. Auble, "Nuclear Structure Study of States in ^{72}Ge and ^{74}Ge with (p,t) Reactions," *Nucl. Phys. A* **346**, 371–96 (1980).

Ritchie, B. G., F. T. Avignone III, H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, "Electron Capture and Positron Decay of ^{206}Fr and ^{208}Fr and the Energy Levels of ^{206}Rn and ^{208}Rn," *Phys. Rev. C* **23**, 1717–25 (1981).

Ritchie, Burke, "'Optical Activity' in the Scattering of Neutrons from Chiral Molecules," *Phys. Rev. A* **20**, 1915–21 (1979).

Robinson, R. L., Editor, "Heavy-Ion Research Facility (September–December 1978)," Newsletter No. 13 (1978).

Robinson, R. L., Editor, "Holifield Heavy-Ion Research Facility (January–April 1979)," Newsletter No. 14 (1979).

Robinson, R. L., Editor, "Holifield Heavy-Ion Research Facility (May–August 1979)," Newsletter No. 15 (1979).

Robinson, R. L., Editor, *Holifield Heavy-Ion Research Facility Users Handbook*," U.S. Government Printing Office, Washington, D.C., 1980.

Robinson, R. L., Editor, "Holifield Heavy-Ion Research Facility (September 1, 1979–May 15, 1980)," Newsletter No. 16 (1980).

Robinson, R. L., Editor, "Holifield Heavy-Ion Research Facility," Newsletter No. 17 (1980).

Robinson, R. L., and J. H. Hamilton (invited paper, "Band Structure in Even-Mass Nuclei around $A = 70$," Proceedings, Second Symposium on Nuclear Physics (Oaxtepec, Mexico, January 1979), *Notas Fis.* 2, 358–73 (1979).

Robinson, R. L., H. J. Kim, R. O. Sayer, W. T. Milner, R. B. Piercey, J. H. Hamilton, A. V. Ramayya, J. C. Wells, Jr., and A. J. Caffrey, "High-Spin Levels and Band Structure in ^{78}Kr," *Phys. Rev. C* **21**, 603–13 (1980).

Robinson, R. L., H. J. Kim, R. O. Sayer, W. T. Milner, R. B. Piercey, A. V. Ramayya, J. H. Hamilton, and J. C. Wells, Jr., "In-Beam Gamma Rays from ^{78}Kr," p. 406 in *Lecture Notes in Physics*, Vol. 92 (Proceedings, International Conference on Nuclear Interactions, Canberra, Australia, August–September 1978), Springer-Verlag, Berlin, 1979.

Rudolf, G., A. Gobbi, H. Stelzer, U. Lynen, A. Olmi, H. Sann, R. Stokstad, and D. Pelte, "Energy Loss and Nucleon Exchange in the Reaction of ^{86}Kr with ^{166}Er," *Nucl. Phys. A* **330**, 243–52 (1979).

Sandhya Devi, K. R., M. R. Strayer, J. M. Irvine, and K. T. R. Davies, "Time-Dependent Hartree-Fock Collisions of ^{16}O + ^{93}Nb at $E_{lab} = 204$ MeV," *Phys. Rev. C* 23, 1064–73 (1981).

Sarantites, D. G., M. Jääskeläinen, J. T. Hood, R. Woodward, J. H. Barker, D. C. Hensley, M. L. Halbert, and Y. D. Chan (invited paper), "The Spin Spectrometer at the Holifield Heavy-Ion Research Facility and Some Planned Experiments," Proceedings, International Conference on Nuclear Behavior at High Angular Momentum (Strasbourg, France, April 1980), *J. Phys. (Paris), Colloq.* **41**, C10-269–80 (1980).

Satchler, G. R. (invited paper), "Microscopic, Semirealistic Interactions for Both Light- and Heavy-Ion Scattering," pp. 305–31 in *Proceedings, 1978 INS International Symposium on Nuclear Direct Reaction Mechanism* (Fukuoka, Japan, October 1978), Institute for Nuclear Study, University of Tokyo, 1979.

Satchler, G. R. (invited paper), "Excitation of the Giant Momopole Resonance by Protons of about 60 MeV," pp. 77–79 in *Proceedings, RCNP Seminar on Nuclear Reactions* (Osaka, Japan, October 1978), Research Center for Nuclear Physics, Osaka, 1979.

Satchler, G. R., "The Optical Potential for ^{9}Be Scattering: Another Anomaly," *Phys. Lett.* **83B**, 284–88 (1979).

Satchler, G. R. (invited paper), "Some Aspects of Heavy-Ion Scattering," Proceedings, Sixth INS Summer School on Nuclear Physics (Dogashima, Japan, October 1978), *Genshikaku Kenkyu* **23**, 45–128 (1979).

Satchler, G. R., "A Comparative Study of the Scattering of Light Heavy Ions Using a Folding Model," *Nucl. Phys. A* **329**, 233–58 (1979).

Satchler, G. R. (invited paper), "Semirealistic Interactions for Scattering from Nuclei," Proceedings, Third Symposium on Nuclear Physics (Oaxtepec, Mexico, January 1980), *Notas Fis.* **3**, 268–304 (1980).

Satchler, G. R., "Elastic and Inelastic Scattering of ^{6}Li at about 74 MeV and the Folding Model," *Phys. Rev. C* **22**, 919–21 (1980).

Satchler, G. R., M. L. Halbert, R. G. Stokstad, R. M. DeVries, D. A. Goldberg, and J. G. Cramer, "Energy Dependence in $^{12}C + ^{28}Si$ Elastic Scattering," *Nucl. Phys. A* **346**, 179–90 (1980).

Satchler, G. R., and W. G. Love, "Folding Model Potentials from Realistic Interactions for Heavy-Ion Scattering," *Phys. Rep.* **55**, 183–254 (1979).

Schmorak, M. R., "Nuclear Data Sheets for $A = 204$," *Nucl. Data Sheets* **27**, 581–635 (1979).

Schmorak, M. R., "Systematics of Nuclear Level properties in the Lead Region," *Nucl. Data Sheets* **31**, 283–380 (1980).

Schmorak, M. R. "Nuclear Data Sheets for $A = 246$ through $A = 262$ (even-A)," *Nucl. Data Sheets* **32**, 87–209 (1981).

Schumann, S., I. A. Sellin, R. Mann, H. J. Frischkorn, D. Rosich, G. Szabo, and K. O. Groeneveld, "Delayed Coincidence Auger Electron Lifetime Measurements," Proceedings, Fifth International Conference on Beam-Foil Spectroscopy (Lyon, France, September 1978), *J. Phys. (Paris), Colloq.* **40**, C1–221–24 (1979).

Scott, H. A., L. B. Bridwell, C. D. Moak, G. D. Alton, C. M. Jones, P. D. Miller, R. O. Sayer, Q. C. Kessel, and A. Antar, "Electron Loss Cross Sections for 20-MeV Cl^{+4} and I^{+5} Ions Incident on Thin Gaseous Experimental Measurements and Potential Model Data Analyses," *Phys. Rev. A* **18**, 2459–63 (1978).

Sellin, I. A., "Continuum Electron Capture," p. 25 in *Physics News, 1979*, American Institute of Physics, New York, 1979.

Sellin, I. (invited paper), "Electron 'Cusp' Spectroscopy of the Forward Peak in Continuum Electron Capture and Loss in Gases and Solids," Proceedings, Fifth International Conference on Beam-Foil Spectroscopy (Lyon, France, September 1978), *J. Phys. (Paris), Colloq.* **40**, C1–2251–35 (1979).

Sellin, I. A. (invited paper), "Coincidence Spectroscopy of Continuum Electron Transfer in Heavy-Ion Collisions," pp. 2–14 in *Proceedings, Sixth International Seminar on Ion-Atom Collisions* (Tokai-mura, Japan, September 1979), Japan Atomic Energy Research Institute, Tokai-mura, 1979.

Sellin, I. A., L. Liljeby, S. Mannervik, and S. Hultberg, "Observation of Mixed Parity Electric Dipole Oscillations in Charge-Transfer to the $n = 2$ Hydrogen Levels by Fast Proton in Gases," *Phys. Rev. Lett.* **42**, 570–72 (1979).

Sellin, I. A., and J. R. Mowat, "Many-Electron Transitions in Violent Encounters of Highly Ionized Ions with Atoms and Molecules," *Comments At. Mol. Phys.* **8**, 21–27 (1978).

Sellin, I. A., M. Suter, C. R. Vane, S. B. Elston, R. S. Thoe, and G. D. Alton, "Coincidence Experiments Concerning Forward Electron Ejection," pp. 754–55 in *Proceedings*, XI International Conference on the Physics of Electronic and Atomic Collisions, Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Shapira, D., G. L. Bomar, J. L. C. Ford, Jr., J. Gomez del Campo, and L. C. Dennis, "Improving the Electric Field Uniformity in Large Hybrid Focal Plane Detectors," *Nucl. Instrum. Methods* **169**, 77–81 (1980).

Shapira, D., R. Dayras, J. L. C. Ford, Jr., J. Gomez del Campo, A. H. Snell, P. H. Stelson, and R. G. Stokstad, "A Gas Cell Target for Studying Fusion and Damped Collisions of Light Nuclei," *Nucl. Instrum. Methods* **163**, 325–30 (1979).

Shapira, D., J. L. C. Ford, Jr., J. Gomez del Campo, and P. H. Stelson, "Backward Angle Cross Sections for $^{27}Al + ^{16}O$ Reaction Products," *Phys. Rev. C* **21**, 1824–27 (1980).

Shapira, D., J. L. C. Ford, Jr., J. Gomez del Campo, R. G. Stokstad, and R. M. DeVries, "Orbiting in the $^{12}C + ^{20}Ne$ System," *Phys. Rev. Lett.* **43**, 1781–84 (1979).

Sjoreen, T. P., U. Garg, D. B. Fossan, J. R. Beene, T. K. Alexander, E. D. Earle, O. Hausser, and A. B. McDonald, "High-Spin States in the Odd-Odd Nucleus ^{212}At," *Phys. Rev. C* **20**, 960–68 (1979).

Soff, G., W. Greiner, W. Betz, and B. Muller, "Electrons in Superheavy Quasimolecules," *Phys. Rev. A* **20**, 169–93 (1979).

Sparks, C. J., Jr., S. Raman, E. Ricci, M. O. Krause, and R. V. Gentry (invited paper), "X-Ray Fluorescence with Synchrotron Radiation," Proceedings, Fifth Conference on the Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* NS-26, 1368–72 (1979).

Spejewski, E. H., and R. L. Mlekodaj (invited paper), "The UNISOR Facility: Recent Developments and Future Directions," pp. 63–69 in *Proceedings, International Symposium on Future Directions in Studies of Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980.

Stelson, P. H., "Coulomb Excitation," pp. 572–73 in Vol. 3, *McGraw-Hill Encyclopedia of Science and Technology*, Fourth Edition, McGraw-Hill, New York, 1977.

Stokstad, R. G., "Resonances and Backward-Angle Scattering," Proceedings, International Conference on Dynamical Properties of Heavy-Ion Reactions (Johannesburg, South Africa, August 1978), *S. Afr. J. Phys.* 1, 191–201 (1978).

Stokstad, R. G. (invited paper), "The Influence of Nuclear Structure on Heavy-Ion Fusion at Sub-barrier Energies," Proceedings, Third Symposium on Nuclear Physics (Oaxtepec, Mexico, January 1980), *Notas Fis.* 3, 305–40 (1980).

Stokstad, R. G., Y. Eisen, S. Kaplanis, D. Pelte, U. Smilansky, and I. Tserruya, "Fusion of $^{16}O + ^{148,150,152,154}Sm$ at Sub-barrier Energies," *Phys. Rev. C* 21, 2427–35 (1980).

Stokstad, R. G., and E. E. Gross, "Analysis of the Sub-barrier Fusion of $^{16}O + ^{148,150,152,154}Sm$," *Phys. Rev. C* 23, 281–94 (1981).

Stokstad, R. G., R. M. Wieland, G. R. Satchler, C. B. Fulmer, D. C. Hensley, S. Raman, L. D. Rickertsen, A. H. Snell, and P. H. Stelson, "Elastic and Inelastic Scattering of ^{12}C by ^{12}C from $E_{c.m.} = 35$–63 MeV," *Phys. Rev. C* 20, 655–69 (1979).

Suter, M., C. R. Vane, S. B. Elston, G. D. Alton, P. M. Griffin, R. S. Thoe, L. Williams, and I. A. Sellin, "Observation of Intense Low-Energy Autoionization Lines in the Wings of the Forward Peak from Fast Ion-Atom Collisions," *Z. Phys.* **A289**, 433–34 (1979).

Suter, M., C. R. Vane, S. B. Elston, I. A. Sellin, R. S. Thoe, and G. D. Alton, "*K*-Auger Electrons Observed in Coincidence with Final Projectile Charge State in Ion-Atom Collisions," pp. 762–63 in *Proceedings, XI International Conference on the Physics of Electronic and Atomic Collisions*, Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Tang, H. H. K., and C. Y. Wong, "Exactly Central Heavy-Ion Collisions by Nuclear Hydrodynamics," *Phys. Rev. C* 21, 1846–63 (1980).

Taylor, P. O., R. A. Phaneuf, and G. H. Dunn, "Absolute Cross Sections and Polarization for Electron-Impact Excitation of the Resonance Multiplet of the Be^+ Ion," *Phys. Rev. A* 22, 435–44 (1980).

Tikku, V. K., J. B. Garg, R. L. Macklin, and J. Halperin, "Neutron Capture Cross Sections in ^{66}Zn and ^{68}Zn," pp. 776–78 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Toten, A., F. D. McDaniel, R. S. Peterson, J. L. Duggan, S. R. Wilson, J. D. Gressett, P. D. Miller, and G. Lapicki, "Projectile Charge-State Dependence of Target *Lα* X-Ray Production," Proceedings, Fifth Conference on the Applications of Small Accelerators (Denton, Tex., November 1978), *IEEE Trans. Nucl. Sci.* NS-26, 1143–46 (1979).

Toth, K. S., "Nuclear Data Sheets for $A = 225$," *Nucl. Data Sheets* 27, 701–17 (1979).

Toth, K. S., "Investigation of Nuclei near $N = 82$ and $Z = 64$ via Radioactive Decay of High-Spin Isomers," pp. 413–420 in *Proceedings, Symposium on High-Spin Phenomena in Nuclei* (Argonne, Ill., March 1979), Argonne National Laboratory Report ANL/PHY-79-4 (October 1979).

Toth, K. S. (invited paper), "Alpha-Decay Studies in the Lead Region," pp. 71–76 in *Proceedings, International Symposium on Future Directions in Studies of Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980).

Toth, K. S., "Alpha-Decay Systematics for Elements with $50 < Z < 83$," pp. 409–18 in *Atomic Masses and Fundamental Constants 6* (Proceedings, Sixth International Conference on Atomic Masses, East Lansing, Mich., September 1979), Plenum, New York, 1980).

Toth, K. S., "Decay of ^{146}Tb and the Lowest 2^+ State in ^{146}Gd," *Phys. Rev, C* 22, 1341–43 (1980).

Toth, K. S., C. R. Bingham, H. K. Carter, B. G. Ritchie, D. C. Sousa, and D. R. Zolnowski, "Decay of the High-Spin Isomers in ^{150,151,152}Ho," *Phys. Rev. C* 20, 298–306 (1979).

Toth, K. S., C. R. Bingham, D. R. Zolnowski, S. E. Cala, H. K. Carter, and D. C. Sousa, "Identification of ^{148}Ho and ^{149}Ho," *Phys. Rev. C* 19, 482–86 (1979).

Toth, K. S., and Y. A. Ellis, "Nuclear Data Sheets for $A = 221$," *Nucl. Data Sheets* 27, 681–700 (1979).

Toth, K. S., Y. A. Ellis, D. C. Sousa, H. K. Carter, D. Sen, and E. F. Zganjar, "Decay of ^{172}Hf to Levels in ^{172}Lu," *Phys. Rev. C* 20, 190–7 (1979).

Toth, K. S., Y. A. Ellis-Akovali, D. M. Moltz, C. R. Bingham, H. K. Carter, and D. C. Sousa, "The α-Decay Rate of ^{188}Pb," *Nucl. Phys. A* 356, 26–32 (1981).

Toth, K. S., M. A. Ijaz, C. R. Bingham, L. L. Riedinger, H. K. Carter, and D. C. Sousa, "Anomalous α-Decay Rate of ^{192}Pb," *Phys. Rev. C* 19, 2399–2402 (1979).

Van Bibber, K., D. L. Hendrie, D. K. Scott, H. H. Wieman, L. S. Schroeder, J. V. Geaga, S. A. Cessin, R. Treuhaft, Y. J. Grossiord, J. O. Rasmussen, and C. Y. Wong, "Evidence for Orbital Dispersion in the Fragmentation of ^{16}O at 90 and 120 MeV/Nucleon," *Phys. Rev. Lett.* 43, 840–44 (1979).

van der Borg, K., M. N. Harakeh, A. van der Woude, and F. E. Bertrand, "On the Excitation of Isovector Dipole Strength by Inelastic Proton Scattering in the Giant Resonance Region in Light Nuclei," *Nucl. Phys. A* 341, 219–28 (1980).

Vander Sluis, K. L., D. P. Hutchinson, and P. A. Staats, "The Evaluation of a High-Power Submillimeter Pulsed Laser System," *Summary, Japan-U.S.A. Workshop* (Boston, Mass., January 1980), Informal Report, Massachusetts Institute of Technology, Cambridge (1980).

Vane, C. R., I. A. Sellin, S. B. Elston, M. Suter, R. S. Thoe, G. D. Alton, S. D. Berry, and G. A. Glass, "Coincidence Observations of Strong Correlations between Bound- and Continuum-State Electron Capture by Fast, Highly Ionized Ions in Gases," *Phys. Rev. Lett.* 43, 1388–91 (1979).

Vane, C. R., I. A. Sellin, M. Suter, S. B. Elston, G. D. Alton, R. S. Thoe, and R. Laubert, "Target Dependences for Continuum Capture Processes in Ion-Atom Collisions," pp. 752–53 in *Proceedings, XI International Conference on the Physics of Electronic and Atomic Collisions,* Contributed Papers (Kyoto, Japan, August–September 1979), The Society for Atomic Collision Research, Japan, 1979.

Vaz, L. C., J. M. Alexander, and G. R. Satchler, "Fusion Barriers, Empirical and Theoretical: Evidence for Dynamic Deformation in Sub-barrier Fusion," *Phys. Rep.* 69, 373–99 (1981).

Visvanathan, A., E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, and F. E. Turner, "Fast Beta Transition in ^{183}Pt and the Systematics of Nilsson States in the $N = 105$ Isotones," *Phys. Rev. C* 19, 282–86 (1979).

Vrba, J. A., C. R. Bingham, M. W. Guidry, R. E. Neese, E. E. Gross, T. P. Cleary, D. C. Hensley, and E. V. Hungerford, "A Search for a Decay of High-Spin Isomers in Rare-Earth Nuclei," *Phys. Rev. C* 22, 755–66 (1980).

Weigmann, H., J. A. Harvey, R. L. Macklin, S. Raman, and G. G. Slaughter, "Resonance Parameters, Capture Gamma Rays, and Reaction Mechanism in ^{100}Mo + n," p. 739 in *Neutron Data of Structural Materials for Fast Reactors* (Proceedings, Specialists' Meeting, Geel, Belgium, December 1977), Pergamon, New York, 1978.

Weigmann, H. , S. Raman, J. A. Harvey, R. L. Macklin, and G. G. Slaughter, "Capture Gamma Rays and Reaction Mechanism in ^{100}Mo + n," pp. 797–99 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Weigmann, H., S. Raman, J. A. Harvey, R. L. Macklin, and G. G. Slaughter, "Neutron Resonances in ^{100}Mo and Valence Neutron Capture," *Phys. Rev. C* **20**, 115–27 (1979).

Wells, J. C., Jr., S. Raman, and G. G. Slaughter, "Correlation of the Primary Gamma-Ray Intensities Following *s*- and *p*-Wave Neutron Capture in ^{58}Fe," pp. 800–801 in *Neutron Capture Gamma-Ray Spectroscopy* (Proceedings, Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, N.Y., September 1978), Plenum, New York, 1979.

Wells, J. C., Jr., R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, J. H. Hamilton, and C. F. Maguire, "High-Spin States and Band Structure in ^{76}Se," *Phys. Rev. C* **22**, 1126–37 (1980).

Welton, T. A., "A Computational Critique of an Algorithm for Image Enhancement in Bright-Field Electron Microscopy," pp. 37–101 in *Advances in Electronics and Electron Physics*, Vol. 48, Academic Press, New York, 1979.

Wharton, W. R., C. D. Goodman, and D. C. Hensley, "Gamow-Teller Sum Rules and the ^{14}C(^{6}Li, ^{6}He)^{14}N Reaction," *Phys. Rev. C* **22**, 1138–44 (1980).

Winters, R. R., N. W. Hill, R. L. Macklin, J. A. Harvey, D. K. Olsen, and G. L. Morgan, "Uranium-238 Inelastic Neutron Scattering at 82 keV," *Nucl. Sci. Eng.* **78**, 147–53 (1981).

Winters, R. R., R. L. Macklin, and J. Halperin, "^{186,187,188}Os(n,γ) Cross Sections and Galactic Nucleosynthesis," *Phys. Rev. C* **21**, 563–73 (1980).

Wong, C. Y., "Superheavy Torodial Nuclei," pp. 524–33 in *Superheavy Elements* (Proceedings, International Symposium on Superheavy Elements, Lubbock, Tex., March 1978), Pergamon, New York, 1978.

Wong, C. Y., "Selection of Central Events in Intermediate-Energy Heavy-Ion Collisions," *Phys. Lett.* **85B**, 39–42 (1979).

Wong, C. Y. (invited paper), "Central Collisions in Intermediate-Energy Heavy-Ion Reactions," pp. 329–63 in Vol. 1 of *Proceedings, Symposium on Heavy-Ion Physics from 10 to 200 MeV/AMU* Upton, N.Y., July 1979), Brookhaven National Laboratory Report BNL 51115 (November 1979).

Wong, C. Y., "Classical Transcription of the TDHF Approximation," pp. 205–11 in Proceedings, Workshop on the Time-Dependent Hartree-Fock Method (Orsay, France, May–June 1979), 1980.

Wong, C. Y., and R. Blankenbecler, "Nuclear Momentum Distribution and Relativistic Heavy-Ion Reactions," pp. 105–8 in *Proceedings, Workshop on Nuclear Dynamics* (Granlibakken, Calif., March 1980), Lawrence Berkeley Laboratory Report LBL-10688 (1980).

Wong, C. Y., and R. Blankenbecler, "Scaling Phenomenon in Relativistic Nucleus-Nucleus Collisions," pp. 109–12 in *Proceedings, Workshop on Nuclear Dynamics* (Granlibakken, Calif., March 1980), Lawrence Berkeley Laboratory Report LBL-10688 (1980).

Wong, C. Y. and R. Blankenbecler, "Direct Fragmentation and Hard-Scattering Processes in Relativistic Heavy-Ion Reactions," *Phys. Rev. C* **22**, 2433–48 (1980).

Wong, C. Y., and K. T. R. Davies, "Influence of Particle Collisions on the Time-Dependent Hartree-Fock Fusion Window in ^{16}O ^{40}Ca," *Phys. Lett.* **96B**, 258–60 (1980).

Wong, C. Y., and H. H. K. Tang, "Dynamics of Nuclear Fluid. V. Extended Time-Dependent Hartree-Fock Approximation Illuminates the Approach to Thermal Equilibrium," *Phys. Rev. C* **20**, 1419–52, (1979).

Wong, C. Y., and H. H. K. Tang, (invited paper), "Extended TDHF Approximation Illuminates the Approach to Thermal Equilibrium," pp. 212–17 in Proceedings, Workshop on the Time-Dependent Hartree-Fock Method (Orsay, France, May–June 1979), 1980.

Wong, C. Y., and C. Toepffer (invited paper), "Approach to Thermal Equilibrium," pp. 400–409 in Vol. 1 of *Proceedings, EPS Topical Conference on Large-Amplitude Collective Nuclear Motion* (Keszthely, Hungary, June 1979), 1979.

Wood, J. L. (invited paper), "The Use of Systematics in the Interpretation of Nuclear Structure Far from the Beta-Stable Region," pp. 37–48 in *Proceedings, International Symposium on Future Directions in Studies of Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980.

Wu, J. R., "Mechanism for (p,p') Reactions in the Continuum," *Phys. Lett.* **91B**, 169–72 (1980).

Wu, J. R., and I. Y. Lee, "Projectile Fragmentation Accompanied by Incomplete Fusion," *Phys. Rev. Lett.* **45**, 8–10 (1980).

Yates, S. W., I. Y. Lee, N. R. Johnson, E. Eichler, L. L. Riedinger, M. W. Guidry, A. C. Kahler, D. Cline, R. S. Simon, P. A. Butler, P. Colombani, F. S. Stephens, R. M. Diamond, R. M. Ronningen, R. D. Hichwa, J. H. Hamilton, and E. L. Robinson, "High-Spin Properties of ^{164}Er in the Multiple Band Crossing Region," *Phys. Rev. C* **21**, 2366–84 (1980).

Young, G. R., R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, M. P. Webb, C. F. Maguire, and G. A. Petitt, "Alpha-Particle Emission in Deeply Inelastic Reactions of 204-MeV, ^{16}O + ^{93}Nb," *Phys. Rev. Lett.* **45**, 1380–92 (1980).

Zganjar, E. F. (invited paper), "The Structure of Neutron-Deficient Odd-Proton Nuclei near the Shell Closure at $Z = 82$," pp. 49–62 in *Proceedings, International Symposium on Future Directions in Studies of Nuclei Far from Stability* (Nashville, Tenn., September 1979), North-Holland, Amsterdam, 1980.

Ziegler, N. F. (invited paper), "The Holifield Heavy-Ion Research Facility 25-MV Tandem Accelerator Control System," pp. 379–85 in *Proceedings, Symposium of Northeastern Accelerator Personnel* (Oak Ridge, Tenn., October 1978), CONF-781051, U.S. Government Printing Office, Washington, D.C. (1979).

Ziegler, N. F., "Control System for the Holifield Heavy-Ion Research Facility Beam Buncher," Proceedings, 1979 Particle Accelerator Conference (San Francisco, Calif., March 1979), *IEEE Trans. Nucl. Sci.* NS-26, 3304–6 (1979).

ANNUAL REPORT

Stelson, P. H., Editor, *Physics Division Annual Progress Report for Period Ending December 31, 1978*, ORNL-5498 (May 1979).

TOPICAL REPORTS

Barnett, C. F., J. A. Ray, E. Ricci, M. I. Wilker, E. W. McDaniel, E. W. Thomas, and H. B. Gilbody, *Atomic Data for Controlled Fusion Research*, ORNL-5207/R2 (October 1980).

Crandall, D. H., P. M. Hafford, and Y. Itikawa, eds., *U.S.-Japan Workshop on Atomic Collision Data for Fusion*, ORNL/TM-7675 (April 1981).

Crandall, D. H., R. A. Phaneuf, and D. C. Gregory, *Electron Impact Ionization of Multicharged Ions*, ORNL/TM-7020 (September 1979).

Davis, K. T. R., *Time-Dependent Hartree-Fock Calculations of the Scattering of Kr Ions from ^{208}Pb*, ^{209}Pb, and ^{139}*La*, ORNL/TM-7000 (August 1979).

Ewbank, W. B., *Graphical Comparison of Calculated Internal Conversion Coefficients*, ORNL-5704 (November 1980).

Fulmer, C. B., N. M. Clarke, E. E. Gross, F. E. Bertrand, C. D. Goodman, D. C. Hensley, G. R. Satchler, M. F. Steeden, and J. R. Wu, *Elastic Scattering and Inelastic Scattering of 88-MeV* ^{6}Li, ORNL/TM-7510 (October 1980).

Hutchinson, D. P., P. A. Staats, K. L. Vander Sluis, and J. B. Wilgen, *A Multichannel Submillimeter Interferometer for Tokamak Density Measurements*, ORNL/TM-7015 (September 1979).

Macklin, R. L., *Thorium Resonance Neutron Capture (2.6–10 keV*, ORNL/TM-7732 (April 1981).

Macklin, R. L., R. R. Winters, and J. Halperin, *Recent Capture Cross-Section Data from ORELA above 2.6 keV*, ORNL/TM-7058 (October 1979).

Milora, S. L., C. A. Foster, C. E. Thomas, C. E. Bush, J. B. Wilgen, E. A. Lazarus, J. L. Dunlap, P. H. Edmonds, W. A. Houlberg, H. C. Howe, D. P. Hutchinson, T. C. Jernigan, M. Murakami, G. H. Neilson, J. A. Rome, and M. J. Saltmarsh, *Results of Hydrogen Pellet Injection into ISX-B*, ORNL/7422 (September 1980).

Thomas, E. W., S. W. Hawthorne, F. W. Meyer, and B. J. Farmer, *Atomic Data for Controlled Fusion Research (Revisions and Additions to Sections D.1. Sputtering, D.5 Ion Reflection from Surfaces, and D.6. Trapping*, ORNL-5207/R1 (November 1979).

Wu, J. R., HIFI – *A Computer Code for Projectile Fragmentation Accompanied by Incomplete Fusion*, ORNL/TM-7424 (July 1980).

THESIS

Bart, S., "Measurement of Short Alpha Half-Lives by a Decay-in-Flight Technique," M.S. degree, University of Houston, June 1979.

ARTICLES PENDING PUBLICATION AS OF JUNE 15, 1981

Ahmed, A., A. V. Ramayya, D. L. Sastry, J. H. Hamilton, R. B. Piercey, H. Kawakami, A. P. de Lima, C. F. Maguire, R. L. Robinson, H. J. Kim, J. C. Wells, and A. C. Rester, "Level Structure of ^{70}Se," *Physical Review C.*

Alton, G. D. (invited paper), "Aspects of the Physics, Chemistry, and Technology of High-Intensity Heavy-Ion Sources," *Proceedings, Third International Conference on Ion Implantation: Equipment and Technique* (Kingston, Ontario, July 1980).

Alton, G. D., J. K. Bair, J. A. Benjamin, J. A. Biggerstaff, C. M. Jones, R. C. Juras, J. E. Mann, E. G. Richardson, D. C. Weisser, and N. F. Ziegler, "Summary Report on the Oak Ridge 25-MV Tandem Accelerator," *Proceedings, Symposium of Northeastern Accelerator Personnel* (Philadelphia, Pa., October 1979).

Alton, G. D., L. B. Bridwell, M. Lucas, C. D. Moak, P. D. Miller, C. M. Jones, Q. C. Kessel, A. A. Antar, and M. D. Brown, "Single and Multiple Electron-Loss Cross-Section Measurements from 20-MeV Fe^{4+} on Thin Gaseous Targets," *Physical Review A.*

Auble, R. L., "Radiation Lifetimes and Failure Mechanisms of Carbon Stripper Foils," *Proceedings, Third International Conference on Electrostatic Accelerator Technology* (Oak Ridge, Tenn., April 1981).

Auble, R. L., and D. M. Galbraith, "A Procedure for the Rapid Evaluation of Carbon Stripper Foils," *Proceedings*, Ninth World Conference of the International Nuclear Target Development Society (Gatlinburg, Tenn., October 1980).

Bair, J. K., P. D. Miller, and B. W. Wieland, "Neutron Yields from the 4- to 12-MeV Proton Bombardment of ^{11}B, ^{13}C, and ^{18}O as Related to the Production of $^{11}C^{+}$, 13N, and ^{18}F," *International Journal of Applied Radiation and Isotopes.*

Ball, G. C., O. Hausser, T. K. Alexander, W. G. Davies, J. S. Forster, I. V. Mitchell, J. R. Beene, and D. Horn, "Electric Quadrupole Moments of First Excited States in ^{28}Si, ^{32}S, and ^{34}S," *Nuclear Physics A.*

Ball, J. B. (invited paper), "The New Large Tandem Electrostatic Accelerators," *Proceedings, 1981 Particle Accelerator Conference* (Washington, D.C., March 1981).

Barnett, C. F., "Atomic and Molecular Collision Formulae," *American Institute of Physics 50th Anniversary Handbook.*

Barnett, C. F., "Dissociation and Electron Capture Collisions of Diatomic and Triatomic Hydrogen Ions in H_2 and Xe," *Proceedings, U.S.-Mexico Cooperative Joint Workshop on Atomic Physics* (Galindo, Mexico, April 1981).

Barnett, C. F., D. P. Hutchinson, K. L. Vander Sluis, and P. A. Staats (invited paper), "Status of the U.S.A. Program on the Development of Submillimeter Lasers to Measure Ion Temperatures," *Proceedings, Second Conference on Hot Plasma Diagnostics* (Kharkov, U.S.S.R., September 1977).

Becker, R. L., J. F. Reading, and A. L. Ford, "Nonstatistical Theory of Multiple Vacancy Production in Atomic Collisions," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Beene, J. R., and C. E. Bemis, Jr., "Nuclear Orientation with Lasers," *McGraw-Hill 1982 Yearbook of Science and Technology.*

Beene, J. R., C. E. Bemis, Jr., J. P. Young, and S. D. Kramer, "Study of the Fission Isomer ^{240m}Am(SF) Using Laser-Induced Nuclear Polarization," *Proceedings, Fifth International Conference on Hyperfine Interactions* (Berlin, W. Germany, July 1980).

Beene, J. R., M. L. Halbert, D. C. Hensley, R. A. Dayras, K. G. Young, D. G. Sarantites, and J. H. Barker, "Fusion-Like Reactions of ^{16}O with ^{154}Sm:γ-Ray Multiplicity vs Bombarding Energy," *Physical Review C.*

Berry, S. D., and C. Bottcher, "Time-Dependent Response of a Two-Level System with Degenerate Levels to Coherent Radiation," *Chemical Physics Letters.*

Bertrand, F. E., "Giant Multipole Resonances — An Experimental Review," *Proceedings, Varenna Summer School on Nuclear Structure and Heavy-Ion Collisions* (Varenna, Italy, July 1979).

Bertrand, F. E., E. E. Gross, D. J. Horen, J. R. Wu, J. Tinsley, D. K. McDaniels, L. W. Swenson, and R. Liljestrand, "Excitation of Giant Resonance Modes in ^{90}Zr and ^{120}Sn by 200-MeV Protons," *Physics Letters.*

Biggerstaff, J. A. (invited paper), "New Developments in Electrostatic Accelerator Control Systems," *Proceedings, Third International Conference on Electrostatic Accelerator Technology* (Oak Ridge, Tenn., April 1981).

Biswas, N. N., ..., W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, H. O. Cohn, and other collaborators, "Neutral-Particle Production in 4.1-GeV/c $\bar{p}p$ Interactions Using the 12-ft Bubble Chamber with TST," *Proceedings, Fourth International Conference on $\bar{N}N$ Interactions* (Strasbourg, France, June 1978).

Bottcher, C., "Transition-State Theory of Charge Capture by Highly Stripped Heavy Ions," *Physical Review A.*

Bottcher, C., "Coherence in Heavy Ion–Molecule Scattering at Intermediate Energies," *Journal of Physics (London) B.*

Bottcher, C., "Numerical Solution of the Peterkop-Rabik Temkin-Hahn Model of Electron-Impact Ionization," *Journal of Physics (London) B.*

Bottcher, C., "Numerical Calculation of Electron-Impact Ionization," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Bottcher, C., "Numerical Solution of the Time-Dependent Schrödinger Equation with Coulomb Interactions," *International Journal of Quantum Chemistry.*

Bottcher, C., and C. Feuillade, "Microscopic Derivation of Block Equations and Relaxation Times," *Proceedings, Tenth International Quantum Electronics Conference* (Atlanta, Ga., May–June1978).

Bottcher, C., and T. G. Heil, "Fully Quantal Studies of Charge Capture by Highly Stripped Ions from Atomic Hydrogen," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Breinig, M., M. M. Schauer, I. A. Sellin, S. B. Elston, C. R. Vane, R. S. Thoe, and M. Suter, "Velocity Dependence of the Widths of Electron Loss Cusps in the Range 7–12.5 au," *Journal of Physics (London) B.*

Brick, D., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, and other collaborators, "The Fitted Channels $\pi^-p \to \pi^-p\pi^+\pi^-$ and $\pi^-p \to \pi^-p2\pi^+2\pi^-$ at 147-GeVc Incident Momentum," *Proceedings, XXIX International Conference on High-Energy Physics* (Tokyo, Japan, August 1978).

Brick, D., ..., H. O. Cohn, G. T. Condo, E. L. Hart, and other collaborators, "A Comparison of Δ^{++} Production in π^+p and pp," *Proceedings, XXIX International Conference on High-Energy Physics* (Tokyo, Japan, August 1978).

Brick, D., ..., H. O. Cohn, G. T. Condo, E. L. Hart, and other collaborators, "Topological Cross Section for K^+p Interactions at 147 GeV/c," *Proceedings, XXIX International Conference on High-Energy Physics* (Tokyo, Japan, August 1978).

Collins, L. L., L. L. Riedinger, G. D. O'Kelley, C. R. Bingham, M. S. Rapaport, J. L. Wood, and R. W. Fink, "Studies of $Z = 81$ Transitional Nuclei. I. ^{197}Pb Decay," *Physical Review C.*

Crandall, D. H., C. F. Barnett, and W. L. Wiese, "Atomic Data for Fusion," Vol. 6, Index (January–December 1980).

Cusson, R. Y., J. Gomez del Campo, J. A. Maruhn, and V. Maruhn-Rezwani, "Analysis of the ^{14}N + ^{12}C Heavy-Ion Reaction," *Physical Review Letters.*

Cusson, R. Y., J. A. Maruhn, W. Greiner, and H. Stocker, "Time-Dependent Hartree-Fock Study of Angular Momentum Transfer in 6 and 12 MeV/A Heavy-Ion Reactions of ^{86}Kr on ^{166}Er," *Physical Review Letters.*

Davies, K. T. R., and S. E. Koonin, "Skyrme-Force Time-Dependent Hartree-Fock Calculations with Axial Symmetry," *Physical Review C.*

Davies, K. T. R., and S. J. Krieger, "Transformation between Harmonic Oscillator Wave Functions in Different Coordinate Bases," *American Journal of Physics.*

Davies, K. T. R., K. R. Sandhya Devi, and M. R. Strayer, "Fusion Behavior in Time-Dependent Hartree-Fock Calculations of ^{86}Kr + ^{139}La and ^{84}Kr +^{209}Bi Collisions," *Physical Review C.*

de Lima, A. P., J. H. Hamilton, A. V. Ramayya, H. Kawakami, E. de Lima, R. M. Ronningen, A. C. Rester, R. L. Robinson, and H. J. Kim, "In-Beam Spectroscopy Studies of Levels in ^{72}Ge," *Journal of the Korean Physical Society.*

de L. Musgrove, A. R., B. J. Allen, J. W. Boldeman, and R. L. Macklin, "Nonstatistical Neutron Capture in ^{140}Ce," *Australian Journal of Physics.*

Dhar, A. K., B. S. Nilsson, K. T. R. Davies, and S. E. Koonin, "Time-Dependent Hartree-Fock Study of ^{136}Xe + ^{208}Bi Collisions," *Nuclear Physics A.*

Donangelo, R., M. W. Guidry, R. E. Neese, and M. J. Rhoades-Brown, "Angular Localization and Approximations to the Deformed Nuclear Potential in Heavy-Ion Reactions," *Physics Letters B.*

Dress, W. B., "A Position-Sensitive Detector for Photoelectron Spectroscopy," *Proceedings, Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy* (Cleveland, Ohio, March 1979).

Elston, S. B. (invited paper), "Multiple Ionization and Excitation Processes in Single Ion-Atom Collisions," *Proceedings, International Conference on X-Ray Processes and Inner-Shell Ionization* (Stirling, Scotland, August 1980).

Ewbank, W. B., "Evaluated Data Collections from ENSDF," *Proceedings, International Conference on Nuclear Cross Sections for Technology* (Knoxville, Tenn., October 1979).

Falk, R. A., G. H. Dunn, D. C. Gregory, and D. H. Crandall, "Excitation-Autoionization in Electron Impact Ionization of Ti^{+3} and Zr^{+3}," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Falk, R. A., G. H. Dunn, D. C. Griffin, C. Bottcher, D. C. Gregory, D. H. Crandall, and M. S. Pindzola, "Excitation-Autoionization Contributions to Electron Impact Ionization," *Physical Review Letters.*

Feuillade, C., and C. Bottcher, "Double Resonance and Relaxation in a Three-Level System," *Proceedings, Seventh International Conference on Molecular Spectroscopy* (Tours, France, September 1979).

Feuillade, C., and C. Bottcher, "Double Resonance and Relaxation in a Three-Level System," *Chemical Physics.*

Ford, A. L., J. F. Reading, and R. L. Becker, "Calculations of the Impact Parameter Dependence of Ionization and Charge Transfer in Ion-Atom Collisions," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Fuller, E. L., Jr., S. D. Clinton, K. J. Fallon, C. M. Jones, S. M. Senkan, and J. S. Watson, "Sorption of SF_6 by Activated Charcoal," *Journal of Chemical and Engineering Data.*

Garg, J. B., V. K. Tikku, J. A. Harvey, R. L. Macklin, and J. Halperin, "Statistical Properties of Complex States of $^{67}_{30}$Zn," *Physical Review C.*

Gavron, A., J. R. Beene, R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, G. A. Petitt, K. G. Young, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire, "Neutron Emission in ^{12}C + ^{158}Gd and ^{13}C + ^{157}Gd Reactions between 8 and 12 MeV/Nucleon," *Physical Review C.*

Golovchenko, J. A., A. N. Goland, J. S. Rosner, C. E. Thorn, H. E. Wegner, H. Knudsen, and C. D. Moak, "Charge-State Dependence of Channeled Ion Energy Loss," *Physical Review A.*

Goodman, C. D., "The (*p,n*) Reaction at Intermediate Energy," *Proceedings, LAMPF Workshop on Pion Single Charge Exchange* (Los Alamos, N.Mex., January 1979).

Goodman, C. D., "Charge Exchange Probes of Nuclear Structure and Interactions with Emphasis on (*p,n*)," *Proceedings, Workshop on Nuclear Structure with Intermediate Energy Probes* (Los Alamos, N.Mex., January 1980).

Greene, G. L., N. F. Ramsey, W. Mampe, J. M. Pendlebury, K. Smith, W. B. Dress, P. D. Miller, and P. Perrin, "Determination of the Neutron Magnetic Moment," *Proceedings, Second International Conference on Precision Measurements and Fundamental Constants* (Gaithersburg, Md., June 1981).

Gregory, D. C., P. F. Dittner, and D. H. Crandall, "Electron-Impact Ionization of Xe^{3+}," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Griffin, D. C., C. Bottcher, and M. S. Pindzola, "Contributions of Autoionization to Ionization Cross Sections in Ions of the Transition Series Elements," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Gross, E. E., "Nuclear Moments from Heavy-Ion Inelastic Scattering above the Coulomb Barrier," *Proceedings, Fourth Symposium on Nuclear Physics* (Oaxtepec, Mexico, January 1981).

Hamilton, J. H., R. L. Robinson, and J. B. Ball, "The Holifield Heavy-Ion Research Facility," *Proceedings, Fourth International Summer School on Nuclear Physics – Neutron Physics and Nuclear Energy* (Varan, Bulgaria, 1979).

Hamilton, J. H., R. L. Robinson, and A. V. Ramayya, "Discovery of Multiple Collective Band Structures in Nuclei with $A = 60$–80," *Journal of High Energy and Nuclear Physics.*

Harvey, J. A., "Neutron Spectroscopy (Spectrometry)," *McGraw-Hill Encyclopedia of Science and Technology.*

Hill, N. W., J. A. Harvey, D. J. Horen, G. L. Morgan, and R. R. Winters, "Majority-Logic NE-110 Detector for keV Neutrons," *Nuclear Instruments and Methods.*

Hjorth, S. A., I. Y. Lee, J. R. Beene, C. Roulet, D. R. Haenni, N. R. Johnson, F. E. Obershain, and G. R. Young, "Interpretation of the 21-ns Isomer in ^{190}Hg as $(\nu i_{13/2})^2$ from a *g*-Factor Measurement," *Proceedings, Workshop on Nuclear Physics* (Philadelphia, Pa., September 1980).

Horen, D. J., J. A. Harvey, and N. W. Hill, "Parity and Spin Dependence of Level Densities in ^{207}Pb," *Proceedings, International Conference on Theory and Applications of Moment Methods in Many-Fermion Systems* (Ames, Iowa, September 1979).

Horen, D. J., J. A. Harvey, and N. W. Hill, "^{206}Pb + n Resonances for $E = 600$-900 keV: Neutron Strength Functions," *Physical Review C.*

Hulet, E. K., R. W. Lougheed, J. M. Nitschke, R. L. Hahn, R. L. Ferguson, W. Brüchle, H. Gäggeler, J. V. Kratz, M. Schädel, G. Wirth, G. Hermann, G. Tittel, and N. Trautmann, "Recent Searches for Superheavy Elements in Deep-Inelastic Reactions," *Proceedings, International Symposium on the Synthesis and Properties of New Elements* (Dubna, U.S.S.R., September 1980).

Hussein, A. R. Z., J. A. Harvey, N. W. Hill, and J. R. Patterson, "Neutron Total Cross Section and Resonance Parameters of ^{231}Pa + n," *Nuclear Science and Engineering.*

Hutchinson, D. P., C. H. Ma, P. A. Staats, and K. L. Vander Sluis, "The Simultaneous Measurement of Electron Density and Faraday Rotation in the ISX-B Tokamak," *Nuclear Fusion.*

Hutchinson, D. P., C. H. Ma, P. A. Staats, and K. L. Vander Sluis, "Characteristics of a Submillimeter-Wave Electro-optic Modulator," *Proceedings, International Conference on Lasers '80* (New Orleans, La., December 1980).

Johnson, B. M., D. C. Gregory, K. W. Jones, J. T. Sample, D. A. Hutcheon, R. Abegg, and G. J. Basbas, "*K*-, *L*-, and *M*-Shell Vacancy Production by 500-MeV Protons," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Johnson, D. E., F. D. McDaniel, G. Basbas, and P. D. Miller, "X-Ray Measurement and Theory of *M*-Shell Vacancy Production in Light Ions by Heavy Targets," *Physical Review A.*

Jones, C. M., "Recovery of SF_6 from Air-SF_6 Mixtures Using Sorption on Activated Charcoal," *Proceedings, Symposium of Northeastern Accelerator Personnel* (Philadelphia, Pa., October 1979).

Jones, C. M., "The 25-MV Tandem Accelerator at Oak Ridge," *Proceedings, Fifth Tandem Conference* (Catania, Italy, June 1980).

Jones, C. M., "Notes on Stripper Foil Lifetimes," *Proceedings, Symposium of Northeastern Accelerator Personnel* (Madison, Wis., October 1980).

Jones, C. M., "The Oak Ridge 25-MV Tandem Accelerator," *Proceedings, Third International Conference on Electrostatic Accelerator Technology* (Oak Ridge, Tenn., April 1981).

Juras, R. C., "A Small Microcomputer-Based CAMAC Controller, *Proceedings, Symposium of Northeastern Accelerator Personnel* (Philadelphia, Pa., October 1979).

Kappeler, F., H. Beer, K. Wisshak, D. D. Clayton, R. L. Macklin, and R. A. Ward, "*s*-Process Studies in the light of New Experimental Cross Sections Distribution of Neutron Fluences and *r*-Process Radials," *Astrophysical Journal.*

Kawakami, H., A. P. de Lima, J. H. Hamilton, A. V. Ramayya, R. M. Ronningen, A. C. Rester, M. D. Barker, J. D. Galambos, H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, "Absolute Cross Sections for the ^{64}Zn(^{12}C,X) and ^{58}Ni(^{12}C,X) Reactions," *Physical Review C.*

Keveloh, C., H. P. Hellmeister, K. P. Lieb, J. B. McGrory, and I. P. Johnstone, "Weak *E*2 Transitions in ^{56}Fe and ^{57}Co," *Journal of Physics (London) G.*

Kim, H. J., "A Novel Apparatus for Studying Ion-Ion Collisions," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Kitagaki, T., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, T. Handler, and E. L. Hart, "Study of Two-Charged Particle Final States of 8-GeV/c $\pi^- p$ Interactions," *Proceedings, XXIX International Conference on High-Energy Physics* (Tokyo, Japan, August 1978).

Kröger, H., and R. Perne, "Few-Body Binding Energy Correlations," *Proceedings, Ninth International Conference on the Few-Body Problem* (Eugene, Oreg., August 1980).

Kröger, H., and R. Perne, "Efimov Pathology in Effective Two-Body Systems," *Proceedings, Ninth International Conference on the Few-Body Problem* (Eugene, Oreg., August 1980).

Kröger, H., and R. Perne, "A Few-Body Scattering Integral Equation Approach," *Proceedings, Ninth International Conference on the Few-Body Problem* (Eugene, Oreg., August 1980).

Kröger, H., and R. Perne, "Few-Body Binding Energy Correlations," *Physical Review C.*

Lee, I. Y., N. R. Johnson, F. K. McGowan, G. R. Young, M. W. Guidry, and S. W. Yates, "Isomeric and High-Spin States of ^{94}Tc and the Search for Yrast Isomers near $N \sim 50$," *Physical Review C.*

Lord, R. S., J. B. Ball, R. M. Beckers, T. P. Cleary, E. D. Hudson, C. A. Ludemann, J. A. Martin, W. T. Milner, S. W. Mosko, and N. F. Ziegler, "Coupled Operation of the Oak Ridge Isochronous Cyclotron and the 25-MV Tandem," *Proceedings, 1981 Particle Accelerator Conference* (Washington, D.C., March 1981).

Macklin, R. L., "Thorium Resonance Neutron Capture (2.6–10 keV)," *Nuclear Science and Engineering.*

Macklin, R. L., "Gold Neutron Capture Cross Section from 100 to 2000 keV," *Nuclear Science and Engineering.*

Martin, J. A., J. B. Ball, T. P. Cleary, E. D. Hudson, R. S. Lord, C. A. Ludemann, S. W. Mosko, T. A. Welton, S. W. Schwenterly, J. K. Ballou, R. L. Brown, W. H. Gray, G. S. McNeilly, and F. W. Nehring, "Superconducting Conversion of the Oak Ridge Isochronous Cyclotron," *Proceedings, 1981 Particle Accelerator Conference* (Washington, D.C., March 1981).

Martin, M. J., "Radioisotopes," *Encyclopedia of Chemical Technology.*

Martir, N., J. F. Reading, A. L. Ford, and R. L. Becker, "Coupled-Channels Calculations of Excitation and Ionization in Collisions of Negatively Charged Projectiles with Atoms," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Mateja, J. F., L. R. Medsker, C. P. Browne, J. D. Zumbro, H. T. Fortune, R. Middleton, and J. B. McGrory, "(t,p) Studies of ^{52}Ti, ^{53}V, and ^{57}Mn and Tests of Mixed-Configuration Shell Model Calculations," *Physical Review C.*

McGowan, F. K., "Interacting Boson Approximation Model Analysis of $E2$ Transition Probabilities for Transitions in $^{166-170}$Er," *Physical Review C.*

McGowan, F. K., and W. T. Milner, "Reduced $M1$, $E1$, $E2$, and $E3$ Transition Probabilities for Transitions in $^{156-160}$Gd and $^{160-164}$Dy," *Physical Review C.*

McGrory, J. B. (invited paper), "Shell-Model Origins of Collective Effects in Light- and Medium-Weight Nuclei," *Proceedings, Symposium on Shell-Model Investigations of Medium-Weight Nuclei* (Tokyo, Japan, September 1977).

McGrory, J. B. (invited paper), "Shell-Model Tests of the Interacting Boson Model Description of Nuclear Collective Motion," *Proceedings, Workshop on the "Interacting Boson Model"* (Erice, Italy, June 1978).

McGrory, J. B. (invited paper), "Application of the Shell Model to Nuclear Spectroscopy," *Proceedings, International Summer School on Nuclear Structure* (Dronten, The Netherlands, August 1980).

McGrory, J. B., and B. H. Wildenthal, "Shell-Model Calculations of $M1$ Scattering Strengths in ^{42,44,48}Ca," *Physics Letters.*

Mehta, R., F. D. McDaniel, J. L. Duggan, M. C. Andrews, P. D. Miller, L. A. Rayburn, and A. R. Sander, "Projectile Charge-State Dependence of M-Shell Ionization of Au, Pb, Bi, and U by 25- and 35-MeV Fluorine Ions," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Meyer, F. W., and H. J. Kim, "Electron Loss From Ryberg States of Atomic Hydrogen in Collisions with Multi-charged Ions," *Proceedings, First European Conference on Atomic Physics* (Heidelberg, W. Germany, April 1981).

Meyer, F. W., and H. J. Kim, "Electron Loss from Atomic Hydrogen in Collisions with N^{+3}," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Mlekodaj. R. L., "A New High-Temperature ISOL Ion Source with an Electron-Extracting Grid," *Nuclear Instruments and Methods.*

Mlekodaj, R. L., E. F. Zganjar, and J. C. Cole, "A New Concept for a Compact Tape Transport System," *Nuclear Instruments and Methods.*

Moak, C. D., J. Gomez del Campo, J. A. Biggerstaff, S. Datz, P. F. Dittner, H. F. Krause, and P. D. Miller, "Interplanar Potentials Derived from Transverse Oscillations of 3.5 MeV/amu He and Li Nuclei in Planar Channels of Silicon," *Physical Review A.*

Moltz, D. M., "The Helium-Jet Coupled Mass Separator – Advances and Directions," *Proceedings, Tenth International Conference on Electromagnetic Isotope Separators* (Zinal, Switzerland, September 1980).

Needham, G. A., F. P. Brady, D. H. Fitzgerald, J. L. Romero, J. L. Ullmann, J. W. Watson, C. Zanelli, N. S. P. King, and G. R. Satchler, "Analog Isovector Giant Resonance Excitation via the (n,p) Reaction on ^{14}N and ^{16}O at 60 MeV," *Nuclear Physics A*.

Pegg, D. J., "Beam-Foil Spectroscopy," *Scientific American*.

Peterson, R. S., F. D. McDaniel, J. L. Duggan, R. S. Thoe, and P. D. Miller, "The Charge-State Dependence of Mo X-Ray Production in Collisions of F^{+q} with Ne," *Physical Review Letters*.

Phaneuf, R. A., "Electron Capture in Very Slow C^{+q} + H Collisions," *Physical Review Letters*.

Phaneuf, R. A., "Electron Capture in Slow C^{+q} + H Collisions," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Piercey, R. B., J. H. Hamilton, R. Soundranayagam, A. V. Ramayya, C. F. Maguire, X. J. Sun, Z. Z. Zhao, R. L. Robinson, H. J. Kim, L. Funke, G. Winter, J. Doring, F. Dubbers, P. Kemnitz, E. Will, S. Frauendorf, J. Roth, L. Cleeman, J. Eberth, W. Neumann, J. C. Wells, J. Lin, A. C. Rester, and H. K. Carter, "Irregular Behavior of the Low-Spin Yrast and First Excited O_2^+ States in Light Kr Isotopes," *Physical Review Letters*.

Piercey, R. B., A. V. Ramayya, J. H. Hamilton, and R. L. Robinson, "Techniques of In-Beam Gamma-Ray Spectroscopy," *Proceedings, Fourth International School on Nuclear Physics* (Varna, Bulgaria, October 1979).

Plattard, S., G. F. Auchampaugh, N. W. Hill, G. de Saussure, J. A. Harvey, and R. B. Perez, "Properties Spectroscopiques de Quelques Structures Fines Observees dan le Seuil de la Reaction $^{231}Pa(n,f)$," *Journal of the Study of Fission*.

Pless, I. A., ..., H. O. Cohn, W. M. Bugg, T. Handler, and other collaborators, "Inclusive and Semi-inclusive Charge Structure in $\pi^- p$ Multiparticle Production at 147 GeV/c," *Proceedings, XXIX International Conference on High-Energy Physics* (Tokyo, Japan, August 1978).

Raman, S., O. Shahal, and G. G. Slaughter, "Test of Axel-Brink Predictions by a Discrete Approach to Resonance-Averaged (n,γ) Spectroscopy," *Physical Review C*.

Raman, S., O. Shahal, A. Z. Hussein, G. G. Slaughter, and J. A. Harvey, "Enhanced Primary Dipole Transitions in the $^{89}Y(n,\gamma)$ Reaction," *Physical Review C*.

Ramavataram, S., K. Ramavataram, and G. Do Dang, "Extended Coupled-Channels Model and the $^{11}B(p,\gamma_1)^{12}C^*$ Reaction," *Progress in Theoretical Physics*.

Rapaport, J., T. Taddeucci, C. Gaarde, C. D. Goodman, C. C. Foster, C. A. Goulding, D. Horen, E. Sugarbaker, T. G. Masterson, and D. Lind, "The $^{12}C(p,n)^{12}N$ Reaction at 120, 160, and 200 MeV," *Physical Review C*.

Reading, J. F., A. L. Ford, and R. L. Becker, "One and a Half Centered Expansion for Ion-Atom Collisions," *Proceedings, International Conference on X-Ray Processes and Inner-Shell Ionization* (Stirling, Scotland, August 1980).

Reading, J. F., A. L. Ford, and R. L. Becker, "A New Atomic Orbital Method for Ion-Atom Collisions," *Journal of Physics (London) B*.

Reading, J. F., A. L. Ford, and R. L. Becker, "One and a Half Centered Calculations of Ionization and Charge Transfer in H^+ + He^+ and He^{2+} + H Collisions," *Proceedings, XII International Conference on the Physics of Electronic and Atomic Collisions* (Gatlinburg, Tenn., July 1981).

Reading, J. F., A. L. Ford, and R. L. Becker, "Ion-Atom Collisions: The Symmetric Region," *Proceedings, International Seminar on Ion (Mainly Heavy)-Atom Collisions* (Debrecen, Hungary, March 1981).

Reinhardt, J., B. Müller, and W. Greiner, "Theory of Positron Production in Heavy-Ion Collisions," *Physical Review A*.

Rhoades-Brown, M. J., R. J. Donangelo, M. W. Guidry, and R. E. Neese, "Quantum-Mechanical and Classical-Limit Coupled-Channels Calculations for Very Heavy Systems," *Physical Review Letters*.

Riedinger, L. L., "The Limits of Studying High-Spin States by Discrete-Line Gamma-Ray Spectroscopy," *Proceedings, Nobel Symposium on Nuclei at Very High Spin* (Lund, Sweden, June 1980).

Ritchie, B. G., R. D. Edge, D. J. Malbrough, B. M. Preedom, F. E. Bertrand, E. E. Gross, F. E. Obenshain, J. R. Wu, M. Blecher, K. Gotow, R. L. Burman, R. Carlini, M. E. Hamm, M. J. Leitch, and M. A. Moinester, "The Reaction $\pi^+ + d \rightarrow p + p$ at 20 to 65 MeV," *Physical Review C.*

Ritchie, B. G., K. S. Toth, H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, "Alpha-Decay Properties of ^{205,206,207,208}Fr; Identification of ^{206m}Fr," *Physical Review C.*

Roberto, J. B., R. A. Zuhr, J. L. Moore, and G. D. Alton, "Low-Energy Hydrogen Sputtering of Au, Ni, and Stainless Steel," *Journal of Nuclear Materials.*

Sastry, D. L., A. Ahmed, A. V. Ramayya, R. B. Piercey, H. Kawakami, R. Soundranayagam, J. H. Hamilton, C. F. Maguire, A. P. de Lima, S. Ramavataram, R. L. Robinson, H. J. Kim, and J. C. Wells, Jr., "Band Structure in ^{80}Kr," *Physical Review C.*

Sastry, D. L., M. S. Rao, B. M. Rao, G. S. Narayana, V. S. Rao, A. V. Ramayya, J. H. Hamilton, A. P. de Lima, H. Kawakami, R. L. Robinson, and H. J. Kim, "High-Spin Levels in Kr-79," *Proceedings, International Conference on Band Structure and Nuclear Dynamics* (New Orleans, La., February–March 1980).

Sellin, I. A., S. Huldt, S. B. Elston, M. Breinig, L. Liljeby, R. S. Thoe, S. Datz, S. Overbury, and R. Laubert, "Convoy Electron Production by 1 to 8.5 MeV/u Highly Ionized Ions Traversing Polycrystalline Solids and Axial Channels in Gold," *Proceedings, Seminar on Molecular Ions, Molecular Structure, and Interaction with Matter* (Rehovot, Israel, January 1981).

Sellin, I. A., and R. Laubert, "Electron Capture and Loss to Continuum States in Gases and Solids," *Proceedings, Third International Workshop on Inelastic Ion-Surface Collisions* (Munich, W. Germany, September 1980).

Sousa, D. C., L. L. Riedinger, C. R. Bingham, F. E. Turner, K. S. Toth, H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, "Radioactive Decay of Mass-Separated ^{192}Tl and ^{192}Pb," *Physical Review C.*

Spejewski, E. H., "A D.C.-Heated Thermal-Ionization Source," *Nuclear Instruments and Methods.*

Spejewski, E. H., R. L. Mlekodaj, and H. K. Carter, "Present Status of the UNISOR Facility," *Nuclear Instruments and Methods.*

Stocker, H., R. Y. Cusson, J. A. Maruhn, and W. Greiner, "Preequilibrium Nucleon Jets in TDHF Calculations of Medium-Energy Heavy-Ion Collisions," *Physical Review Letters.*

Stokstad, R. G., W. Reisdorf, K. D. Hildenbrand, J. V. Kratz, G. Wirth, R. Lucas, and J. Poitou, "The Subbarrier Fusion of ^{40}Ar with ^{144,148,154}Sm," *Zeitschrift fuer Physik.*

Suter, M., I. A. Sellin, C. R. Vane, R. S. Thoe, S. B. Elston, G. D. Alton, S. D. Berry and G. A. Glass, "Electron-Ion Coincidence Spectroscopy o f Multielectron K-Ionizing Binary Collision Events in 7-9 au Velocity C^{q+}, O^{q+} Projectiles Traversing Air," *Physical Review Letters.*

Tang, H. H. K., and C. Y. Wong, "Reply to the Comment on 'Exactly Central Heavy-Ion Collisions by Nuclear Hydrodynamics,'" *Physical Review C.*

Toepffer, C., and B. J. Cole, "Inversion of Nuclear Molecules," *Physical Review Letters.*

Toepffer, C., and C. Y. Wong, "Relaxation in a Dilute Homogeneous Fermion System," *Physical Review.*

Tsong, I. S. T., M. D. Monkowski, J. R. Monkowski, P. D. Miller, C. D. Moak, B. R. Appleton, and A. L. Wintenberg, "Investigation of Hydrogen and Chlorine at the SiO_2/Si Interface," *Proceedings, Conference on the Physics of MOS Insulator* (Chapel Hill, N.C., June 1980).

Tsong, I. S. T., M. D. Monkowski, J. R. Monkowski, A. L. Wintenberg, P. D. Miller, and C. D. Moak, "Hydrogen and Chlorine Detection at the SiO_2/Si Interface," *Proceedings, Fifth International Conference on Ion Beam Analysis* (Sydney, Australia, February 1981).

Tsong, I. S. T., G. A. Smith, J. W. Michels, A. L. Wintenberg, P. D. Miller, and C. D. Moak, "Dating of Obsidian Artifacts by Depth-Profiling of Artificially Hydrated Surface Layers," *Proceedings, Fifth International Conference on Ion Beam Analysis* (Sydney, Australia, February 1981).

Wells, J. C., Jr., R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, J. H. Hamilton, and C. F. Maguire, "High-Spin States and Band Structure in ^{76}Se," *Proceedings, International Conference on Band Structure and Nuclear Dynamics* (New Orleans, La., February–March 1980).

Wells, J. C., R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, J. H. Hamilton, C. F. Maguire, K. Kumar, R. W. Eastes, M. E. Barclay, and A. J. Caffrey, "High-Spin States and Band Structure in ^{76}Br," *Physical Review C.*

Welton, T. A., "A Rapidly Pulsed Synchrotron for Heavy-Ion Acceleration," *Proceedings, 1981 Particle Accelerator Conference* (Washington, D.C., March 1981).

Welton, T. A., and T. Nichols, "Orbit Dynamics in Isochronous Cyclotrons," *Proceedings, 1981 Particle Accelerator Conference* (Washington, D.C., March 1981).

Wong, C. Y., "Dynamics of Nuclear Fluid. VI. The Time-Dependent Hartree-Fock Approximation from a Classical Viewpoint," *Physical Review C.*

Wong, C. Y., "Dynamics of Nuclear Fluid. VIII. Giant Isovector, Spin-Vector, and Spin-Isovector Multipole Resonances as Elastic Vibrations," *Physical Review C.*

Wong, C. Y., and N. Azziz, "Dynamics of Nuclear Fluid. VII. Nuclear Giant Resonances as Elastic Vibrations," *Physical Review C.*

Wong, C. Y., and R. Blankenbecler, "Scaling Phenomenon in Relativistic Nucleus-Nucleus Collisions," *Physical Review Letters.*

Wong, C. Y., and R. Y. Cusson, "Microscopic Calculations of Superheavy Bubble Nuclei," *Physical Review C.*

Wood, J. L., "Dynamical Supersymmetries and the Positive-Parity States in ^{193}Au," *Physical Review Letters.*

Wood, J. L., "Testing the Interacting-Boson and Interacting-Boson-Fermion Approximations by the Study of Radioactive Decay Schemes with the UNISOR On-Line Isotope Separator," *Proceedings, Workshop on Nuclear Physics* (Philadelphia, Pa., September 1980).

Wood, M. H., S. M. Blankenship, T. P. Lang, F. T. Avignone III, G. L. Morgan, and S. Raman, "Low-Energy Proton and Electron Responses of an *n*-Octane Liquid Scintillator," *Nuclear Instruments and Methods.*

Wu, C. L., D. H. Feng, J. Q. Chen, and M. W. Guidry, "Boson Degrees of Freedom and Nuclear Shell Model," *Physical Review Letters.*

Wu, J. R., J. R. Beene, C. E. Bemis, Jr., F. E. Bertrand, E. E. Gross, D. J. Horen, and W. P. Jones, "The Fission Probability of ^{239}U at High Excitation Measured with the ^{238}U(a, ^{3}He f) Reaction," *Physical Review C.*

Yamada, H., C. F. Maguire, J. H. Hamilton, A. V. Ramayya, D. C. Hensley, M. L. Halbert, R. L. Robinson, F. E. Bertrand, and R. Woodward, "Localized ℓ-Window from Partial Fusion Reactions Accompanied by Proton, Deuteron, and Triton Emission," *Physical Review Letters.*

Young, G. R., H. O. Cohn, T. A. Gabriel, R. A. Lillie, P. D. Miller, R. R. Spencer, M. S. Goodman, R. Wilson, W. M. Bugg, G. T. Condo, T. Handler, and E. L. Hart (invited paper), "A Proposed Experiment for a Sensitive Search for $\Delta B = 2$ Transitions via *n-n* Mixing," *Proceedings, Conference on Weak Interactions as Probes of Unification* (Blacksburg, Va., December 1980).

Young, G. R., K. A. Van Bibber, A. J. Lazzarini, S. G. Steadman, and F. Videbaek, "Gamma-Ray Deexcitation Following Deeply Inelastic Collisions of 100-MeV ^{16}O with ^{27}Al," *Physical Review C.*

Young, K. G., D. G. Sarantites, J. R. Beene, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, "Nonequilibrium Emission of Neutrons from Fusion-Like Reactions of ^{16}O with ^{154}Sm: Neutron Spectra at 152 MeV," *Physical Review C.*

Zganjar, E. F., J. D. Cole, and J. L. Wood, "The Investigation of Complex Radioactive Decay Schemes Far from Beta Stability: The Structure of 187-Au," *Proceedings, International Conference on Nuclei Far from Stability* (Helsingör, Denmark, June 1981).

Zhao, Z. Z., X. J. Sun, R. B. Piercey, J. H. Hamilton, C. F. Maguire, A. V. Ramayya, R. L. Robinson, H. J. Kim, and J. C. Wells, "Lifetime Measurements of Excited States in ^{76}Kr," *Chinese Journal of Nuclear Physics.*

Ziegler, N. F., E. G. Richardson, J. E. Mann, R. C. Juras, C. M. Jones, J. A. Biggerstaff, and J. A. Benjamin, "Status of the Oak Ridge 25-MV Tandem Accelerator," *Proceedings, Symposium of Northeastern Accelerator Personnel* (Madison, Wis., October 1980).

Ziegler, N. F., E. G. Richardson, J. E. Mann, R. C. Juras, C. M. Jones, J. A. Biggerstaff, and J. A. Benjamin, "Status of the Oak Ridge 25-MV Tandem Accelerator," *Proceedings, 1981 Particle Accelerator Conference* (Washington, D.C., March 1981).

11. Papers Presented at Scientific and Technical Meetings January 1979 through April 1981

Prepared by Shirley J. Ball

1979

Second Symposium on Nuclear Physics, Oaxtepec, Mexico, January 3–6, 1979

Robinson, R. L., and J. H. Hamilton (invited paper), "Band Structure in Nuclei around $A = 70$."

Topical Conference on Atomic Processes in High-Temperature Plasmas, Boulder, Colorado, January 17–19, 1979

Crandall, D. H., R. A. Phaneuf, B. E. Hasselquist, and D. C. Greogry, "Experimental Electron Impact Ionization Cross Sections and Rates," *Bull. Am. Phys. Soc.* **24**, 776 (1979).

Kim, H. J., and F. W. Meyer, "Excited-State Contribution to the Electron-Loss Collisions of a Fast H^0 Beam on Multiply Charged Heavy Ions," *Bull. Am. Phys. Soc.* **24**, 765 (1979).

MacKellar, A. D., and R. L. Becker, "Classical Trajectory Study of Neutral H-Atom–H-Atom Collisions," *Bull. Am. Phys. Soc.* **24**, 765 (1979).

Phaneuf, R. A. (invited talk), "Measurements of Atomic Collision Cross Sections for High-Temperature Plasma Applications," *Bull. Am. Phys. Soc.* **24**, 764 (1979).

LAMPF Workshop on Pion Single Charge Exchange, Los Alamos, New Mexico, January 22–24, 1979

Goodman, C. D., "*p,n* Reactions at Intermediate Energies."

American Physical Society, New York, New York, January 29–February 1, 1979

Backman, L., ..., H. O. Cohn, T. Handler, E. Hart, and other collaborators, "Neutral Strange Particle Production in $\pi^+/K^+/p$ Collisions on Hydrogen at 147 GeV/c," *Bull. Am. Phys. Soc.* **24**, 45 (1979).

Ellis, Y. A., K. S. Toth and H. K. Carter, "Decay of 10.2-Day ^{188}Pt," *Bull. Am. Phys. Soc.* **24**, 53 (1979).

Fulmer, C. B., J. B. Ball, R. L. Ferguson, and R. L. Robinson, "Protons, Deuterons, Tritons, and Alpha Particles Emitted from Reactions of 208-MeV ^{16}O, with ^{12}C, ^{56}Fe, and ^{91}Zr," *Bull. Am. Phys. Soc.* **24**, 13 (1979).

Hulsizer, R., ..., H. O. Cohn, E. L. Hart, and other collaborators, "Topological Cross Sections for K^+p, π^+p, and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **24**, 44 (1979).

Levy, A., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, and other collaborators, "Comparison of Δ^{++} Production in π^+p, K^+p, and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **24**, 45 (1979).

Napier, A., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, and other collaborators, "Forward Gamma Production in π^+p and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **24**, 45 (1979).

Toth, K. S., R. L. Hahn, H. Gauvin, Y. LeBeyec, and C. Cabot, "Remeasurement of ^{40}Ar and ^{84}Kr Excitation Functions Leading to the Same Compound Nucleus, ^{158}Er," *Bull. Am. Phys. Soc.* **24**, 14 (1979).

Trepagnier, P. C., ..., H. O. Cohn, W. M. Bugg, G. T. Condo, and other collaborators, "The Four-Prong, Four-Constraint Final State in $\pi^+/K^+/p$-p Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **24**, 44 (1979).

30th Pittsburgh Conference on Analytical Chemical and Applied Spectroscopy, Cleveland, Ohio, March 4–9, 1979

Dress, W. B., "A Position-Sensitive Detector for Photoelectron Spectroscopy."

Second Conference on Meson-Nuclear Physics, Houston, Texas, March 5–8, 1979

Bertrand, F. E. (invited talk), "Giant Multipole Resonances and Inelastic Pion Scattering."

Dam, S. H., R. D. Edge, B. M. Preedom, F. E. Bertrand, E. E. Gross, M. Blecher, K. Gotow, R. L. Burman, R. Carlini, M. E. Hamm, R. P. Redwine, M. A. Yates-Williams, and M. Moinester, "π^+ and π^- Elastic Scattering from ^{40}Ca at 65 MeV."

1979 Particle Accelerator Conference, San Francisco, California, March 12–14, 1979

Alton, G. D., "A Universal Positive or Negative Ion Source," *Bull. Am. Phys. Soc.* 24, 148 (1979).

Ball, J. B., E. D. Hudson, R. S. Lord, J. A. Martin, G. S. McNeilly, and S. W. Mosko, "Holifield Heavy-Ion Research Facility — Phase II," *Bull. Am. Phys. Soc.* 24, 149 (1979).

Cleary, T. P., "Implementation of the ORIC Magnetic Field Measurements," *Bull. Am. Phys. Soc.* 24, 185 (1979).

Juras, R. C., and N. F. Ziegler, "A Single-Crate Stand-Alone CAMAC Control System for a Negative Ion Source," *Bull. Am. Phys. Soc.* 24, 155 (1979).

Martin, J. A. (invited talk), "Recent Advances in Design for Low- and Medium-Energy Heavy-Ion Accelerators," *Bull. Am. Phys. Soc.* 24, 172 (1979).

Ziegler, N. F., "Control System for the Holifield Heavy-Ion Research Facility Beam Buncher," *Bull. Am. Phys. Soc.* 24, 157 (1979).

Symposium on High-Spin Phenomena in Nuclei, Argonne, Illinois, March 15–17, 1979

Beene, J. R., M. L. Halbert, D. C. Hensley, D. G. Sarantites, L. W. Westerberg, K. Geoffroy, and R. Woodward, "Gamma-Ray Continuum Spectra from Heavy-Ion Reactions."

Toth, K. S., "Investigation of Nuclei near $N = 82$ and $Z = 64$ via Radioactive Decay of High-Spin Isomers."

Conference on Nuclear Structure and Elementary Particle Physics, Birmingham, England, March 28–30, 1979

Clarke, N. M., M. F. Steeden, C. B. Fulmer, C. D. Goodman, E. E. Gross, and D. C. Hensley, "Elastic Scattering of ^{6}Li at 88 MeV."

Conference on the (p,n) Reaction and the Nucleon-Nucleon Force, Telluride, Colorado, March 29–31, 1979

Goodman, C. D. (invited talk), "The (p,n) Reaction at Intermediate Energies."

McGrory, J. B. (invited talk), "The Role of the n-p Interaction in Microscopic Calculations of Collective Motion."

Department of Energy Research on High-Energy Atomic Physics, Manhattan, Kansas, April 5–7, 1979

Becker, R. L. (invited talk), "Theory of Electron Transfer and Ionization."

Crandall, D. H., and C. F. Barnett (invited talk), "Low-Energy Atomic Collisions with Multicharged Ions."

Miller, P.D., and C. D. Moak (invited talk), "Accelerator-Based Atomic Physics Program at ORNL."

American Physical Society, Washington, D.C., April 23–26, 1979

Becker, R. L., and A. D. MacKellar, "Classical Trajectory Monte Carlo Calculation of $He^+ + H$ Collisions," *Bull. Am. Phys. Soc.* 24, 581 (1979).

Dabbs, J. W. T., "^{6}Li(n,α)-Xe Gas Scintillator Neutron Beam Monitor," *Bull. Am. Phys. Soc.* 24, 651 (1979).

Dam, S. H., R. D. Edge, B. M. Preedom, R. L. Burman, M. E. Hamm, R. P. Redwine, M. A. Yates-Williams, F. E. Bertrand, E. E. Gross, M. Blecher, K. Gotow, and M. A. Moinester, "π^+ and π^- Scattering from ^{40}Ca at 65 MeV," *Bull. Am. Phys. Soc.* 24, 687 (1979).

Dayras, R. A., K. A. Geoffroy, D. G. Sarantites, J. H. Barker, D. C. Hensley, R. G. Stokstad, and M. L. Halbert, "Deep-Inelastic Collisions of 166-MeV ^{20}Ne + ^{63}Cu," *Bull. Am. Phys. Soc.* **24**, 630 (1979).

Dennis, L. C., S. T. Thornton, K. R. Cordell, R. R. Doering, R. L. Parks, J. L. C. Ford, Jr., J. Gomez del Campo, and D. Shapira, "Nonstatistical Structure in the ^{12}C(^{14}N,α)^{22}Na Reaction," *Bull. Am. Phys. Soc.* **24**, 666 (1979).

Ellis, Y. A., K. S. Toth, D. C. Sousa, D. Sen, and E. F. Zganjar, "Decay of ^{172}Hf to Levels in ^{172}Lu," *Bull. Am. Phys. Soc.* **24**, 668 (1979).

Ewbank, W. B., "Special Data Collections from ENSDF," *Bull. Am. Phys. Soc.* **24**, 686 (1979).

Ford, J. L. C., Jr., J. Gomez del Campo, D. Shapira, R. M. DeVries, M. R. Clover, R. Ost, and C. F. Maguire, "The ^{20}Ne + ^{12}C System: Elastic and Inelastic Scattering and Fusion Measurements," *Bull. Am. Phys. Soc.* **24**, 570 (1979).

Fowler, J. L., C. A. Uttley, J. A. Cookson, M. Hussian, M. T. Swinhoe, and R. B. Schwartz, "Absolute Neutron Flux in the 2- to 25-MeV Energy Range," *Bull. Am. Phys. Soc.* **24**, 651 (1979).

Fulmer, C. B., N. M. Clarke, C. D. Goodman, E. E. Gross, D. C. Hensley, and M. Steeden, "Target Spin Effects Observed in 88-MeV ^{6}Li Elastic Scattering," *Bull. Am. Phys. Soc.* **24**, 572 (1979).

Geoffroy, K. A., D. G. Sarantites, D. C. Hensley, M. L. Halbert, R. A. Dayras, and J. H. Barker, "Light-Particle Emission in the Reactions of ^{16}O with ^{154}Sm," *Bull. Am. Phys. Soc.* **24**, 695 (1979).

Gomez del Campo, J., R. G. Stokstad, and R. A. Dayras, "Monte Carlo Calculations of Particle-Particle Correlations in Strongly Damped Collisions," *Bull. Am. Phys. Soc.* **24**, 630 (1979).

Hochman, D., ..., H. Cohn, W. Bugg, G. Condo, T. Handler, and E. Hart, "Resonance Production in $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ at 8 GeV/c," *Bull. Am. Phys. Soc.* **24**, 674 (1979).

Johnson, C. H., and R. R. Winters, "Multilevel Analysis of Neutron Total Cross Section of Sulfur below 1.1 MeV," *Bull. Am. Phys. Soc.* **24**, 685 (1979).

Kruse, H., W. T. Pinkston, W. Greiner, and V. E. Oberacker, "A Study of the Prompt Component in Coulomb Fission," *Bull. Am. Phys. Soc.* **24**, 573 (1979).

Lee, I. Y., N. R. Johnson, M. W. Guidry, R. M. Diamond, F. S. Stephens, and C. Roulet, "Coulomb Excitation of Gd Isotopes," *Bull. Am. Phys. Soc.* **24**, 667 (1979).

Levy, A., ..., H. Cohn, W. Bugg, and other collaborators, "Comparison of Hadron Electroproduction and Hadrons Produced by π^-, π^+, K^+, and Protons on Protons," *Bull. Am. Phys. Soc.* **24**, 636 (1979).

Lutz, P., ..., H. Cohn, W. Bugg, and other collaborators, "Multiparticle Correlations as a Link between Low p_T and High p_T Physics," *Bull. Am. Phys. Soc.* **24**, 636 (1979).

Mateja, J. F., L. R. Medsker, J. B. McGrory, J. Zumbro, C. P. Browne, H. T. Fortune, and R. Middleton, "A Study of the (t,p) Reaction on Nuclei in the $f_{7/2}$ Shell," *Bull. Am. Phys. Soc.* **24**, 631 (1979).

Mlekodaj, R. L., E. H. Spejewski, H. K. Carter, and B. G. Ritchie, "A New High-Temperature Ion Source for On-Line Isotope Separation," *Bull. Am. Phys. Soc.* **24**, 596 (1979).

Nettles, W. G., A. V. Ramayya, J. H. Hamilton, F. T. Avignone, and H. K. Carter, "Lifetime Measurements of the Excited 0^+ State in ^{186}Hf," *Bull. Am. Phys. Soc.* **24**, 684 (1979).

Oberacker, V. E., "Are There Any Characteristics of Coulomb Fission?," *Bull. Am. Phys. Soc.* **24**, 573 (1979).

Petitt, G. A., R. L. Ferguson, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, G, R. Young, J. E. Gaiser, K. A. Geoffroy, and D. G. Sarantites, "Neutron Emission from Reactions between 204-MeV ^{16}O and ^{93}Nb," *Bull. Am. Phys. Soc.* **24**, 630 (1979).

Raman, S., J. C. Wells, Jr., and G. G. Slaughter, "Valence Neutron Capture in ^{54}Fe," *Bull. Am. Phys. Soc.* **24**, 631 (1979).

Ramavataram, S., and G. Do Dang, "A Calculation of the Total Cross Section for the ^{11}B$(p,\gamma_1)^{12}$C* Reaction," *Bull. Am. Phys. Soc.* **24**, 609 (1979).

Ramavataram, S., and G. Do Dang, "A Coupled-Channel Calculation for the Positive- Parity States in ^{4}He," *Bull. Am. Phys. Soc.* **24**, 611 (1979).

Ritchie, B. G., F. T. Avignone III, H. K. Carter, R. L. Mlekodaj, and E. H. Spejewski, "Low-Lying Level Structure of ^{208}Rn and the Interacting Boson Approximation," *Bull. Am. Phys. Soc.* **24**, 685 (1979).

Stokstad, R. G., K. D. Hildebrand, J. V. Kratz, W. Reisdorf, G. Wirth, R. Lucas, and J. Poitou, "Sub-barrier Fusion of ^{40}Kr + ^{144,148,154}Sm," *Bull. Am. Phys. Soc.* **24**, 696 (1979).

Suter, M., C. R. Vane, S. B. Elston, G. D. Alton, P. M. Griffin, R. S. Thoe, L. Williams, I. A. Sellin, and R. Laubert, "*K*-Auger Electrons Observed in Coincidence with Final Projectile Charge State in ~1.5 MeV/*a* Ion-Atom Collisions," *Bull. Am. Phys. Soc.* **24**, 582 (1979).

Thoe, R. S., C. R. Vane, S. B. Elston, I. A. Sellin, M. Suter, L. Williams, G. D. Alton, P. M. Griffin, and R. Laubert, "Coincidence Experiments on Electron Loss to Low-Lying Projectile-Centered Continuum States of One, Two, and Three Electron Loss Events in High-Velocity C + Ar Collisions," *Bull, Am. Phys. Soc.* **24**, 581 (1979).

Toth, K. S., R. L. Hahn, Y. LeBeyec, and M. W. Guidry, "^{200}Po Compound Nuclei Formed by ^{40}Ar and ^{84}Kr Ions," *Bull. Am. Phys. Soc.* **24**, 696 (1979).

Wells, J. C., Jr., R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, and C. F. Maguire, "High-Spin States in ^{76}Se," *Bull. Am. Phys. Soc.* **24**, 637 (1979).

Widgoff, M., ..., H. Cohn, G. Condo, and other collaborators, "K^{+} Proton Single-Particle Inclusive Production at 147 GeV/*c*," *Bull. Am. Phys. Soc.* **24**, 637 (1979).

Winters, R. R., R. L. Macklin, and J. Halperin, "^{186,187,188}Os(n,γ) Cross-Section Measurements at ORELA," *Bull. Am. Phys. Soc.* **24**, 684 (1979).

Wood, M. H., S. M. Blankenship, T. P. Long, F. T. Avignone, G. L. Morgan, and S. Raman, "The Low-Energy Electron and Proton Responses of an *n*-Octane-Based Liquid Scintillator," *Bull. Am. Phys. Soc.* **24**, 651 (1979).

Young, G. R., R. L. Ferguson, F. E. Obenshain, F. Plasil, D. Shapira, and A. H. Snell, "Correlated Mass and Charge Distributions of Evaporation Residue Products from Reactions Between 160-MeV ^{40}Ar and ^{27}Al," *Bull. Am. Phys. Soc.* **24**, 695 (1979).

IAEA Advisory Group on Transactinium Isotope Nuclear Data, Cadarache, France, May 2–5, 1979

Ewbank, W. B. (invited talk), "Status of Transactinium Nuclear Data in the Evaluated Nuclear Structure Data File (ENSDF)."

Topical Conference on Computerized Data Acquisition Systems in Particle and Nuclear Physics, Sante Fe, New Mexico, May 14–17, 1979

Hensley, D. C., "The Event Handler II — A Fast, Programmable CAMAC-Coupled Data Acquisition Interface."

Milner, W. T., J. A. Biggerstaff, D. C. Hensley, and R. O. Sayer, "Data Acquisition and Analysis System for the Holifield Heavy-Ion Research Facility."

IAEA International Symposium on the Physics and Chemistry of Fission, Julich, West Germany, May 14–18, 1979

Plasil, F., and R. L. Ferguson (invited talk), "Heavy-Ion-Induced Fission following Fusion."

Workshop on Inner-Shell Proccesses, Linz, Austria, May 14–18, 1979

Reading, J. F., A. L. Ford, and R. L. Becker (invited talk), "Fast Numerical Calculations of Ion-Atom Collisions."

Workshop on the Time-Dependent Hartree-Fock Method, Orsay, France, May 28–June 1, 1979

Davies, K. T. R. (invited talk), "TDHF Calculations of Kr-Induced Strongly Damped Collisions."

Davies, K. T. R. (invited talk), "Time-Dependent Hartree-Fock Studies of the Scattering of Kr Ions from Pb, Bi, and La."

Wong, C. Y., "Classical Transcription of the TDHF Approximation."

Wong, C. Y., and H. H. K. Tang (invited talk), "Extended TDHF Approximation Illuminates the Approach to Thermal Equilibrium."

DOE Workshop on New Diagnostic Related to Impurity Release, Germantown, Maryland, May 31–June 1, 1979

Barnett, C. F., and J. A. Ray, "Progress in Extending Neutral-Pipe Detection Down to 10 eV using a Cs Heat Pipe for Electron Detachment."

International Conference on Nuclear Physics with Electromagnetic Interactions, Mainz, West Germany, June 5–9, 1979

Horen, D. J., and J. A. Harvey, "Unique Contribution of High-Resolution Neutron Scattering to the Understanding of $M1$ Radiation Strength in ^{207,208}Pb."

Raman, S., and G. E. Brown, "Present Status of the Magnetic Dipole Strength in ^{208}Pb."

Conference on Large-Amplitude Collective Nuclear Motion, Lake Balaton, Hungary, June 10–16, 1979

Davies, K. T. R. (invited talk), "TDHF Calculations of Kr-Induced Strongly Damped Collisions."

Wong, C. Y., and H. H. K. Tang (invited talk), "Extended TDHF Approximation Illuminates the Approach to Thermal Equilibrium."

Wong, C. Y., and C. Toepffer (invited talk), "Approach to Thermal Equilibrium."

Sixteenth European Cyclotron Progress Meeting, Baden, Switzerland, June 21–22, 1979

Martin, J. A. (invited talk), "Review of Cyclotron Development Activities in United States Laboratories."

Second International Symposium on Neutron-Induced Nuclear Reactions, Smolenice, Czechoslovakia, June 25–29, 1979

Raman, S. (invited talk), "Dipole and Quadrupole Radiation Strengths from Discrete States of ^{208}Pb."

Twenty-fourth Annual Meeting of the Health Physics Society, Philadelphia, Pennsylvania, July 8–13, 1979

Ohnesorge, W. F., H. M. Butler, C. B. Fulmer, and S. W. Mosko, "Heavy-Ion Target Area for Fast-Neutron Dose Equivalent Rates."

Varenna Summer School on Nuclear Structure and Heavy-Ion Collisions, Varenna, Italy, July 9–20, 1979

Bertrand, F. E., "Giant Multipole Resonances — An Experimental Review."

Symposium on Heavy-Ion Physics from 10 to 200 MeV/AMU, Upton, New York, July 16–20, 1979

Geoffroy, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker (invited talk), "Angular Momentum Transfer in Incomplete-Fusion Reactions."

Gomez del Campo, J. (invited talk), "The Observation of a Random Component of Transferred Angular Momentum in the Reaction ^{20}Ne + ^{63}Cu."

Plasil, F., R. L. Ferguson, K. A. Geoffroy, D. C. Hensley, F. E. Obenshain, C. F. Maguire, G. A. Petitt, D. G. Sarantites, A. H. Snell, and G. R. Young, "Neutron Emission in Reactions Between ^{16}O and ^{93}Nb at 12.75 MeV/Nucleon."

Wong, C. Y. (invited talk), "Central Collisions in Intermediate-Energy Heavy-Ion Reactions."

International Conference on Atomic Collisions in Solids, Hamilton, Ontario, August 12–17, 1979

Datz, S., C. D. Moak, O. H. Crawford, H. F. Krause, P. D. Miller, P. F. Dittner, J. Gomez del Campo, J. A. Biggerstaff, H. Knudsen, and P. Hvelplund, "Resonant Coherent Excitation in Planar Channeling."

Laubert, R., I. A. Sellin, C. R. Vane, M. Suter, S. B. Elston, G. D. Alton, and R. S. Thoe, "Yield of Convoy Electrons from Solids."

Eighth International Conference on High-Energy Physics and Nuclear Structure, Vancouver, Canada, August 13–17, 1979

Goodman, C. D., D. E. Bainum, C. C. Foster, C. A. Goulding, M. B. Greenfield, D. J. Horen, W. G. Love, T. Masterson, F. Petrovich, J. Rapaport, E. Sugarbaker, and J. Watson, "Isospin-Dependent Terms in the N-N Force at Low q from (p,n) Reactions."

NATO Advanced Study Institute on Atomic and Molecular Processes in Controlled Thermonuclear Fusion, Toulouse, France, August 13–24, 1979

Bottcher, C. (invited talk), "Theory of Recombination Processes."

Nordic Symposium on Nuclear Physics, Lysekil, Sweden, August 20–24, 1979

Westerberg, L., J. R. Beene, M. L. Halbert, D. C. Hensley, D. G. Sarantites, K. Geoffroy, R. Woodward, and R. J. Liotta, "Continuum Conversion-Electron and Gamma-Ray Spectra from the $^{20}Ne + ^{150}Nd$ Reaction at 115- and 130-MeV Bombarding Energy."

XI International Conference on the Physics of Electronic and Atomic Collisions, Kyoto, Japan, August 29–September 4, 1979

Compton, R. N., G. D. Alton, A. D. Williamson, and A. E. Carter, "Lifetime of He^- Formed through Collisions of He^+ and Ca Vapor."

Crandall, D. H. (invited talk), "Introductory Remarks on Electron Capture by Multicharged Ions."

Crandall, D. H., and R. A. Phaneuf, "Electron Impact Ionization of Oxygen Ions — O^{3+}, O^{4+}, O^{5+}."

Kim, H. J., and F. W. Meyer, "n-Scaling of Electron-Loss Cross Sections for Fast $H(n)^0 + N^{3+}$ Collisions."

Meyer, F. W., and H. J. Kim, "Measurement of H-Atom Rydberg-State Population by a Transmission Method."

Sellin, I. A., M. Suter, C. R. Vane, S. B. Elston, R. S. Thoe, and G. D. Alton, "Coincidence Experiments Concerning Forward Electron Ejection."

Suter, M., C. R. Vane, S. B. Elston, I. A. Sellin, R. S. Thoe, and G. D. Alton, "K-Auger Electrons Observed in Coincidence with Final Projectile Charge State in Ion-Atom Collisions."

Vane, C. R., I. A. Sellin, M. Suter, S. B. Elson, G. D. Alton, R. S. Thoe, and R. Laubert, "Target Dependences for Continuum Capture Processes in Ion-Atom Collisions."

Sixth International Seminar on Ion-Atom Collisions, Tokai-mura, Japan, September 6–7, 1979

Crandall, D. H. (invited talk), "Electron Capture by Multicharged Ions Colliding with Atomic Hydrogen."

Sellin, I. A. (invited talk), "Coincidence Spectroscopy of Continuum Electron Transfer in Heavy-Ion Collisions."

International Conference on Theory and Applications of Moments Methods in Many-Fermion Systems, Ames, Iowa, September 10–13, 1979

Horen, D. J., J. A. Harvey, and N. W. Hill, "Parity and Spin Dependence of Level Densities in ^{207}Pb."

International Symposium on Future Directions in Studies of Nuclei Far from Stability, Nashville, Tennessee, September 10–13, 1979

Carter, H. K., and C. R. Bingham (invited talk), "Plans for Laser Hyperfine Structure Measurement at UNISOR."

Nettles, W. G., A. V. Ramayya, J. H. Hamilton, F. T. Avignone, and H. K. Carter (invited talk), "Subnanosecond Lifetime Measurements of Excited States in Nuclei Far from Stability."

Spejewski, E. H., and R. L. Mlekodaj (invited talk), "The UNISOR Facility: Recent Developments and Future Directions."

Toth, K. S. (invited talk), "Alpha-Decay Studies in the Lead Region."

Wood, J. L. (invited talk), "The Use of Systematics in the Interpretation of Nuclear Structure Far from the Beta-Stable Region."

Zganjar, E. F. (invited talk), "The Structure of Neutron-Deficient Odd-Proton Nuclei near the Shell Closure at $Z = 82$."

American Chemical Society, Washington, D.C., September 10–14, 1979

Beene, J. R., M. L. Halbert, D. C. Hensley, K. A. Geoffroy, and D. G. Sarantites (invited talk), "Incomplete-Fusion Reactions and Fast-Neutron Emission."

Beene, J. R., M. L. Halbert, D. C. Hensley, I. Y. Lee, D. G. Sarantites, K. A. Geoffroy, L. Westerberg, and J. H. Barker (invited talk), "Gamma-Ray Continuum Studies of Nuclei at High Spin."

Geoffroy, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker (invited talk), "Equilibrium and Nonequilibrium Particle Emission from the Reactions of ^{16}O and ^{154}Sm."

Gomez del Campo, J., R. G. Stokstad, and R. A. Dayras (invited talk), "Angular-Momentum Transfer and Alignment in Strongly Damped Collisions of Ne + Cu."

Halbert, M. L., R. A. Dayras, D. C. Hensley, K. A. Geoffroy, D. G. Sarantites, and J. H. Barker (invited talk), "Emission of Light Charged Particles in Reactions of $^{16}O + {}^{154}Sm$."

Johnson, N. R. (invited talk), "Investigations of High Angular-Momentum States in Nuclei."

Robinson, R. L., and J. H. Hamilton (invited talk), "Band Structure in Even-Mass Nuclei around $A = 70$."

Young, G. R., R. L. Ferguson, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, M. P. Webb, G. A. Petitt, K. A. Geoffroy, and D. G. Sarantites (invited talk), "Heavy-Ion–Light-Particle Coincidence Measurements of Products from 204-MeV $^{16}O + {}^{93}Nb$ Reactions."

Seventh International Colloquium on Molecular Spectroscopy, Tours, France, September 17–21, 1979

Feuillade, C., and C. Bottcher, "Double-Resonance and Relaxation in a Three-Level System."

Sixth International Conference on Atomic Masses, East Lansing, Michigan, September 18–21, 1979

Ellis, Y. A., "Determination of Q Values for Electron-Capture Decay of ^{188}Pt and ^{172}Hf from X-Ray Intensities."

Toth, K. S., "Alpha-Decay Systematics for Elements with $50 < Z < 83$."

World Conference of the International Target Development Society, Boston, Massachusetts, October 1–3, 1979

Auble, R. L., D. M. Galbraith, C. M. Jones, J. K. Bair, P. H. Stelson, and D. C. Weisser, "Lifetime Measurements on Carbon Stripper Foils."

Symposium of Northeastern Accelerator Personnel, Philadelphia, Pennsylvania, October 8–10, 1979

Alton, G. D., J. K. Bair, J. A. Benjamin, J. A. Biggerstaff, C. M. Jones, R. C. Juras, J. E. Mann, E. G. Richardson, D. C. Weisser, and N. F. Ziegler, "Summary Report on the Oak Ridge 25-MV Tandem Accelerator."

Jones, C. M., "Recovery of SF_6 from Air-SF_6 Mixtures Using Sorption on Activated Charcoal."

Juras, R. C., "A Small, Microcomputer-Based CAMAC Controller."

Mid-southeast Chapter of Association for Computing Machinery, Gatlinburg, Tennessee, October 12, 1979

Ewbank, W. B., "Versatile Output from a Simple Numeric Data File."

Giant Multipole Resonances Topical Conference, Oak Ridge, Tennessee, October 15–17, 1979

Goodman, C. D. (invited talk), "Excitation of Giant Resonances via Charge-Exchange Reactions."

Horen, D. J. (invited talk), "Survey of Ground-State Magnetic Dipole Strength."

American Physical Society (Division of Nuclear Physics), Knoxville, Tennessee, October 18–20, 1979

Bainum, D. E., J. Rapaport, C. D. Goodman, D. J. Horen, C. C. Foster, M. B. Greenfield, and C. A. Goulding, "Excitations in ^{90}Nb Observed via the (p,n) Reaction at Intermediate Incident Energy," *Bull. Am. Phys. Soc.* **24**, 830 (1979).

Bomar, G. L., C. F. Maguire, J. L. C. Ford, Jr., J. Gomez del Campo, and D. Shapira, "Investigation of the $^{40}Ca(^{10}B, {}^{11}C)^{39}K$ Reaction," *Bull. Am. Phys. Soc.* **24**, 842 (1979).

Braga, R. A., W. R. Western, J. L. Wood, and R. W. Fink, "$M4$ Isomerism and the Observation of the $s_{1/2}$ Shell-Model Intruder State in ^{201}Bi," *Bull. Am. Phys. Soc.* **24**, 836 (1979).

Carlton, R. F., S. Raman, and E. T. Jurney, "The ^{32}S(n,γ) Reaction with Thermal Neutrons," *Bull. Am. Phys. Soc.* **24**, 818 (1979).

Comfort, J. R., G. Moake, C. Foster, J. Rapaport, and C. D. Goodman, "The ^{12}C$(\vec{p},p')$ ^{12}C Reaction at 120 MeV and Microscopic Effective Interactions," *Bull. Am. Phys. Soc.* **24**, 829 (1979).

Dabbs, J. W. T., and C. H. Johnson, "Measurement of Fission Cross Section of ^{241}Am," *Bull. Am. Phys. Soc.* **24**, 855 (1979).

Eck, J. S., T. R. Ophel, P. D. Clark, D. C. Weisser, and G. R. Satchler, "Classical and Potential Descriptions of ^{9}Be + ^{28}Si and ^{9}Be + ^{40}Ca Elastic Scattering Cross Sections at $E(^{9}\text{Be}) = 45$ and 60 MeV," *Bull. Am. Phys. Soc.* **24**, 842 (1979).

Ewbank, W. B., "Special Data Collections from ENSDF," *Bull. Am. Phys. Soc.* **24**, 837 (1979).

Ferguson, R. L., R. L. Hahn, F. E. Obenshain, F. Plasil, F. Pleasonton, A. H. Snell, and G. R. Young, "Fission Barrier of ^{153}Tb," *Bull. Am. Phys. Soc.* **24**, 825 (1979).

Ford, J. L. C., Jr., D. Shapira, J. Gomez del Campo, and R. G. Stokstad, "Orbiting in the ^{12}C + ^{20}Ne System," *Bull. Am. Phys. Soc.* **24**, 852 (1979).

Foster, C. C., T. E. Ward, C. A. Goulding, M. B. Greenfield, J. Rapaport, C. D. Zafiratos, S. D. Schery, and C. D. Goodman, "Activation Measurements of ^{7}Li$(p,n)^{7}$Be Total Reaction Cross Sections for $60 \leqslant E_p \leqslant 200$ MeV," *Bull. Am. Phys. Soc.* **24**, 828 (1979).

Garg, J. B., V. K. Tikku, and J. A. Harvey, "Statistical Distributions of Spacings of Resonances in ^{64}Zn, ^{66}Zn, ^{68}Zn, and ^{70}Zn Nuclei," *Bull. Am. Phys. Soc.* **24**, 853 (1979).

Geoffroy, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, "Angular Momentum Transfer in Incomplete-Fusion Reactions," *Bull. Am. Phys. Soc.* **24**, 835 (1979).

Gomez del Campo, J. (invited talk), "Fusion and Peripheral Reactions for 'Light' Heavy-Ion Systems at Energies up to 13 MeV/n," *Bull. Am. Phys. Soc.* **24**, 814 (1979).

Goodman, C. D., D. J. Horen, F. Petrovich, W. G. Love, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. Bainum, and C. C. Foster, "Proportionality of O° (p,n) Cross Sections to Beta-Decay Matrix Elements," *Bull. Am. Phys. Soc.* **24**, 830 (1979).

Goulding, C. A., M. B. Greenfield, C. C. Foster, C. D. Goodman, D. J. Horen, J. Rapaport, T. Masterson, J. W. Watson, and D. E. Bainum, "The ^{13}C(p,n) ^{13}N Reaction at $E_p = 80$ and 120 MeV," *Bull. Am. Phys. Soc.* **24**, 829 (1979).

Harvey, J. A., V. K. Tikku, and J. B. Garg, "High-Resolution Neutron Total Cross Section in ^{67}Zn," *Bull. Am. Phys. Soc.* **24**, 854 (1979).

Horen, D. J., J. A. Harvey, and N. W. Hill, "$M1$ Ground-State Radiative Strength in ^{207}Pb for $E_x = 6.74$ MeV," *Bull. Am. Phys. Soc.* **24**, 837 (1979).

Horen, D. J., C. Goodman, C. Foster, C. Goulding, M. Greenfield, J. Rapaport, E. Sugarbaker, T. Masterson, and D. Bainum, "Isobaric Analogue of $\Delta T = 0$, Isovector $M1$ Strength in ^{208} Pb," *Bull. Am. Phys. Soc.* **24**, 845 (1979).

McGowan, F. K., W. T. Milner, and P. H. Stelson, "Reduced $E1$ Matrix Elements for Transitions in $^{156-160}$Gd and ^{160}Dy," *Bull. Am. Phys. Soc.* **24**, 836 (1979).

Melin, R. C., R. M. Ronningen, J. A. Nolen, Jr., G. M. Crawley, J. E. Finck, and C. E. Bemis, Jr., "Proton Scattering at 35 MeV to Ground Band States in ^{232}Th and ^{234,236,238}U," *Bull. Am. Phys. Soc.* **24**, 837 (1979).

Neese, R. E., M. W. Guidry, J. A. Vrba, C. R. Bingham, L. L. Riedinger, T. L. Nichols, I. Y. Lee, and N. R. Johnson, "Some Heavy-Ion Interaction Potentials Determined by a Semiclassical Localization Prescription," *Bull. Am. Phys. Soc.* **24**, 817 (1979).

Obenshain, F. E., R. L. Ferguson, F. Plasil, R. L. Robinson, D. Shapira, and A. H. Snell, "Correlated Mass and Charge Distributions from the Reaction ^{20}Ne + ^{27}Al at 8.4 MeV/Nucleon," *Bull. Am. Phys. Soc.* **24**, 825 (1979).

Petitt, G. A., B. Smandek, R. L. Ferguson, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, G. R. Young, K. A. Geoffroy, D. G. Sarantites, and C. F. Maguire, "Neutron and High-Energy Charged-Particle Emission from Products of Reactions between 204-MeV ^{16}O and ^{93}Nb," *Bull. Am. Phys. Soc.* **24**, 834 (1979).

Raman, S., R. S. Hicks, R. A. Lindgren, B. Parker, and G. A. Peterson, "A Search for $M1$ Excitation Strength in ^{208}Pb by 180° Inelastic Electron Scattering," *Bull. Am. Phys. Soc.* **24**, 845 (1979).

Rapaport, J., D. E. Bainum, C. D. Goodman, C. C. Foster, T. E. Ward, C. A. Goulding, and M. B. Greenfield, "The ^{6,7}Li$(p,n)^{6,7}$Be Reaction at E_p = 80 MeV," *Bull. Am. Phys. Soc.* **24**, 830 (1979).

Robinson, R. L., G. R. Young, J. B. Ball, F. E. Bertrand, C. B. Fulmer, R. L. Ferguson, I. Y. Lee, M. J. Martin, J. C. Wells, Jr., and H. Yamada, "Energetic Light Ions from the ^{12}C + ^{60}Ni Reaction," *Bull. Am. Phys. Soc.* **24**, 834 (1979).

Sarantites, D. G. (invited talk), "New Possibilities for Heavy-Ion Physics with a Nuclear-Spin Spectrometer," *Bull. Am. Phys. Soc.* **24**, 841 (1979).

Shapira, D., J. L. C. Ford, Jr., and J. Gomez del Campo, "The Strong Absorption Radius and the Critical Radius for Fusion in the ^{12}C + ^{20}Ne System," *Bull. Am. Phys. Soc.* **24**, 824 (1979).

Soundranayagam, S., R. B. Piercey, A. V. Ramayya, J. H. Hamilton, A. Y. Ahmed, H. Yamada, C. F. Maguire, G. L. Bomar, D. A. Smith, R. L. Robinson, H. J. Kim, and J. C. Wells, "In-Beam Gamma-Ray Studies of Neutron-Deficient ^{66}Ge," *Bull. Am. Phys. Soc.* **24**, 826 (1979).

Tikku, V. K., J. B. Garg, R. L. Macklin, and J. Halperin, "Neutron Capture Cross Sections in ^{67}Zn," *Bull. Am. Phys. Soc.* **24**, 854 (1979).

Winters, R. R., K. Kappeler, K. Wisshak, B. Berman, and J. Browne, "^{187}Os 30-keV Inelastic-to-Elastic Neutron Cross-Section Ratio," *Bull. Am. Phys. Soc.* **24**, 854 (1979).

Wood, J. L. (invited talk), "Decay Scheme Studies of Nuclear Structure in Very Neutron-Deficient Nuclei Using On-Line Isotope Separators," *Bull. Am. Phys. Soc.* **24**, 850 (1979).

Wu, J. R., "Mechanisms for (p,p') Reactions in the Continuum," *Bull. Am. Phys. Soc.* **24**, 831 (1979).

Young, G. R., R. L. Ferguson, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, M. P. Webb, and C. F. Maguire, "Heavy-Ion Charged Particle Coincidence Measurements of Products from ^{16}O + ^{93}Nb Reactions at 204 MeV," *Bull. Am. Phys. Soc.* **24**, 834 (1979).

International Conference on Nuclear Cross Sections for Technology, Knoxville, Tennessee, October 22–26, 1979

Carlton, R. F., J. A. Harvey, N. W. Hill, M. S. Pandey, and R. W. Benjamin, "Neutron Total Cross-Section Measurements on ^{249}Cf," *Bull. Am. Phys. Soc.* **24**, 882 (1979).

Dabbs, J. W. T. (invited talk), "Neutron Cross-Section Measurements at ORELA," *Bull. Am. Phys. Soc.* **24**, 888 (1979).

Ewbank, W. B., "Evaluated Data Collections from ENSDF," *Bull. Am. Phys. Soc.* **24**, 881 (1979).

Harvey, J. A., C. Moore, and N. W. Hill, "Neutron Total Cross Section of ^{233}U from 0.01 to 1.0 eV," *Bull. Am. Phys. Soc.* **24**, 882 (1979).

Johnson, C. H., J. L. Fowler, N. W. Hill, and J. M. Ortolf, "Measurement of the 2.35-MeV Window in ^{16}O + n," *Bull. Am. Phys. Soc.* **24**, 886 (1979).

Larson, D. C., J. A. Harvey, and N. W. Hill, "Neutron Total Cross Sections of H, C, O, and Fe from 500 keV to 60 MeV," *Bull. Am. Phys. Soc.* **24**, 862 (1979).

Plattard, S., G. F. Auchampaugh, N. W. Hill, R. B. Perez, G. de Saussure, and J. A. Harvey, "High-Resolution Neutron Fission Cross Section of ^{231}Pa," *Bull. Am. Phys. Soc.* **24**, 876 (1979).

Symposium on Deep Inelastic and Fusion Reactions with Heavy Ions, Berlin, West Germany, October 23–25, 1979

Geoffroy, K. A., D. G. Sarantites, M. L. Halbert, D. C. Hensley, R. A. Dayras, and J. H. Barker, "Angular Momentum Transfer in Incomplete-Fusion Reactions."

Maruhn, J. A., (invited talk), "Time-Dependent Hartree-Fock Theory for Heavy Ions."

Fourth International Summer School on Nuclear Physics, Varna, Bulgaria, October 1979

Hamilton, J. H., R. L. Robinson, and J. B. Ball, "The Holifield Heavy-Ion Research Facility."

Piercey, R. B., A. V. Ramayya, J. H. Hamilton, and R. L. Robinson, "Techniques of In-Beam Gamma-Ray Spectroscopy."

American Physical Society (Ohio Section), Columbus, Ohio, November 2–3, 1979

Winters, R. R., R. L. Macklin, C. H. Johnson, and J. Halperin, "Thermal Neutron Direct and Bound Resonance Capture in $^{32}S + n$," *Bull. Am. Phys. Soc.* 25, 459 (1980).

American Physical Society (Southeastern Section), Chattanooga, Tennessee, November 8–10, 1979

Crowell, H. L., J. H. Hamilton, A. V. Ramayya, R. B. Piercey, R. M. Ronningen, R. L. Robinson, and W. E. Collins, "Evidence for Band Structure in ^{72}Se," *Bull. Am. Phys. Soc.* 25, 126 (1980).

Robinson, R. L. (invited talk), "The Holifield Heavy-Ion Research Facility."

American Physical Society (Division of Plasma Physics), Boston, Massachusetts, November 12–16, 1979

Hutchinson, D. P., P. A. Staats, K. L. Vander Sluis, J. B. Wilgen, and C. H. Ma, "A Multichannel Submillimeter Interferometer for Tokamak Density Measurements," *Bull. Am. Phys. Soc.* 24, 984 (1979).

Wilgen, J. B., J. L. Dunlap, D. P. Hutchison, and D. W. Swain, "Density Behavior During Neutral Beam Injection," *Bull. Am. Phys. Soc.* 24, 1034 (1979).

International Symposium on Continuum Spectra of Heavy-Ion Reactions, San Antonio, Texas, December 3–5, 1979

Fulmer, C. B., R. L. Robinson, J. B. Ball, R. L. Ferguson, R. L. Auble, F. E. Bertrand, I. Y. Lee, M. J. Martin, J. R. Wu, G. R. Young, J. C. Wells, and H. Yamada, "Light-Particle Emission from Heavy-Ion Reactions."

Kröger, H., "Classical Dynamical Description of Heavy-Ion Sequential Fission."

Oberacker, V., W. Greiner, H. Kruse, and W. T. Pinkston, "Signatures of Coulomb Fission — A Theoretical Study."

Petitt, G. A., R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, G. R. Young, K. A. Geoffroy, D. G. Sarantites, and C. F. Maguire, "Neutron Emission in Deeply Inelastic and Fusion-Evaporation Reactions of 208-MeV ^{16}O with ^{93}Nb."

Japanese Nuclear Data Committee, 1979 Seminar on Nuclear Data, Tokai-mura, Japan, December 10–11, 1979

Martin, M. J. (invited talk), "ENSDF — Its Structure, Contents, and Use in Applied Research."

American Physical Society (Division of Electron and Atomic Physics), Houston, Texas, December 10–12, 1979

Becker, R. L., and A. D. MacKellar, "Initial ϵ-Dependence of CTMC Ion-Rydberg Atom Cross Sections," *Bull. Am. Phys. Soc.* 24, 1205 (1979).

Crandall, D. H., R. A. Phaneuf, and F. W. Meyer, "Low-Velocity Electron Capture by Xe^{q+} in H," *Bull. Am. Phys. Soc.* 24, 1176 (1979).

Elston, S. B. (invited talk), "Multielectron Processes in Electron Cusp Coincidence Spectroscopy at High Z and V," *Bull. Am. Phys. Soc.* 24, 1174 (1979).

Ford, A. L., J. F. Reading, and R. L. Becker, "K-Shell Electron Capture and Ionization for Collisions of Fully Stripped Ions with Ne," *Bull. Am. Phys. Soc.* 24, 1172 (1979).

Phaneuf, R. A., and R. H. Hughes, "Laser Plasma Ion Source for Low-Energy Charge-Transfer Cross-Section Measurements," *Bull. Am. Phys. Soc.* **24**, 1179 (1979).

Reading, J. F., A. L. Ford, and R. L. Becker, "A One and a Half Centered Expansion for Ion-Atom Collisions," *Bull. Am. Phys. Soc.* **24**, 1195 (1979).

Suter, M., C. R. Vane, I. A. Sellin, R. S. Thoe, S. B. Elston, G. D. Alton, S, D. Berry, and G. A. Glass, "Electron-Ion Coincidence Spectroscropy of Multielectron K-Ionizing Processes in Single Collisions of >1 MeV/A C^{q+} and O^{q+} Projectiles with Ar Targets," *Bull. Am. Phys. Soc.* **24**, 1179 (1979).

Vane, C. R., I. A. Sellin, S. B. Elston, M. Suter, R. S. Thoe, G. D. Alton, S. D. Berry, and G. A. Glass, "Coincident Capture of Bound and Continuum Electrons by Fully Stripped C and O Projectiles in ~1 MeV/*a* Single Collisions with Ar Targets," *Bull. Am. Phys. Soc.* **24**, 1179 (1979).

Fourth International Conference on Infrared and Near-Millimeter Waves, Miami, Florida, December 10–15, 1979

Ma, C. H., D. P. Hutchinson, K. L. Vander Sluis, and P. A. Staats, "Simultaneous Measurement of Electron Density and Plasma Current in ISX Tokamak."

Hutchinson, D. P., P. A. Staats, and K. L. Vander Sluis, "Characteristics of an Optically Pumped FIR Laser with an Integral CO_2 Pump Laser."

NEANDC Specialists' Meeting on Neutron Cross Sections of Fission Product Nuclei, Bologna, Italy, December 12–14, 1979

Macklin, R. L., R. R. Winters, and J. Halperin (invited talk), "Recent Capture Cross-Section Data from ORELA above 2.6 MeV."

Third Symposium on Nuclear Physics, Oaxtepec, Mexico, January 3–5, 1980

Gomez del Campo, J. (invited talk), "Comparison of Fusion Cross Sections for $^{10}B + {}^{16}O$ and $^{12}C + {}^{14}N$ Systems."

Satchler, G. R. (invited talk), "Semirealistic Interactions for Scattering from Nuclei."

Stokstad, R. G. (invited talk), "The Influence of Nuclear Structure on Heavy-Ion Fusion at Sub-barrier Energies."

Workshop on Nuclear Structure with Intermediate-Energy Probes, Los Alamos, New Mexico, January 14–16, 1980

Goodman, C. D., "Charge-Exchange Probes of Nuclear Structure and Interactions with Emphasis on (p,n)."

American Physical Society, Chicago, Illinois, January 21–24, 1980

Hafen, E. S., ..., H. Cohn, W. Bugg, G. Condo, and other collaborators, "Inclusive ρ^0 Production in $\pi^{\pm}p$, K^+p, and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **25**, 34 (1980).

Haridas, P., ..., H. O. Cohn, W. M. Bugg, G. Condo, T. Handler, and E. L. Hart, "Resonance Production in $\pi^-p \rightarrow p\pi^+\pi^-\pi^-\pi^0$ at 8 GeV/c," *Bull. Am. Phys. Soc.* **25**, 34 (1980)

Hockman, D., ..., H. Cohn, W. Bugg, T. Handler, and E. Hart, "Resonance Structure in the Reaction $\pi^-p \rightarrow n\pi^+\pi^+\pi^-$ at 8 GeV/c," *Bull. Am. Phys. Soc.* **25**, 34 (1980).

Hulsizer, R., ..., H. Cohn, E. Hart, and other collaborators, "Extraction of Off-Mass-Shell $\pi\pi$ and $K\pi$ Interactions," *Bull. Am. Phys. Soc.* **25**, 33 (1980).

Levy, A., ..., H. Cohn, W. Bugg, G. Condo, and other collaborators, "Study of Resonances Produced in Four-Prong $\pi^{\pm}p$, K^+p, and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **25**, 33 (1980).

Lutz, P., ..., H. Cohn, E. Hart, and other collaborators, "High Transverse Momentum Jets in 147-GeV/c Interactions," *Bull. Am. Phys. Soc.* **25**, 33 (1980).

Japan-U.S.A. Workshop, Boston, Massachusetts, January 28–31, 1981

Vander Sluis, K. L., D. P. Hutchinson, and P. A. Staats, "The Evaluation of a High-Power Submillimeter Pulsed Laser System."

Conference on Extreme States in Nuclear Systems, Dresden, West Germany, February 1980

Sterrenburg, W., S. M. Austin, D. E. Bainum, R. P. DeVito, C. C. Foster, A. Galonsky, C. D. Goodman, C. A. Goulding, M. B. Greenfield, D. J. Horen, J. Rapaport, and E. Sugarbaker, "Gamow-Teller Resonances Observed in ^{90,92,94}Zr(p,t) at 120 and 160 MeV."

International Conference on Band Structure and Nuclear Dynamics, New Orleans, Louisiana, February 28–March 1, 1980

McGowan, F. K., W. T. Milner, and P. H. Stelson, "Reduced *E*1, *E*2, *E*3 Transition Probabilities for Transitions in $^{156-160}$Gd and $^{160-164}$Dy."

Melin, R. C., R. M. Ronningen, J. A. Nolen, Jr., G. M. Crawley, C. H. King, J. E. Finck, and C. E. Bemis, Jr., "Multipole Moments of ^{232}Th and ^{234,236,238}U from Proton Inelastic Scattering."

Sastry, D. L., M. S. Rao, B. M. Rao, G. S. Narayana, V. S. Rao, A. V. Ramayya, J. H. Hamilton, A. P. de Lima, H. Kawakami, R. L. Robinson, and H. J. Kim, "High-Spin Levels in Kr-79."

Wells, J. C., Jr., R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, A. V. Ramayya, J. H. Hamilton, and C. F. Maguire, "High-Spin States and Band Structure in ^{76}Se."

Third Topical Conference on High-Temperature Plasma Diagnostics, Los Angeles, California, March 17–19, 1980

Hutchinson, D. P., C. H. Ma, P. A. Staats, and K. L. Vander Sluis (invited talk), "The Simultaneous Measurement of Electron and Current Density Profiles in the ISX-B Tokamak," *Bull. Am. Phys. Soc.* 25, 669 (1980).

Workshop on Nuclear Dynamics, Granlibakken, California, March 17–21, 1980

Ferguson, R. L., A. I. Gavron, F. E. Obenshain, F. Plasil, R. L. Robinson, D. Shapira, A. H. Snell, and G. R. Young, "Distribution of Products in the Reaction ^{20}Ne + Al."

Plasil, F., J. R. Beene, R. L. Ferguson, A. Gavron, D. C. Hensley, F, E, Obenshain, G. R. Young, M. P. Webb, G. A. Petitt, K. A. Geoffroy, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire, "Light-Particle Emission in Reactions Induced with Carbon and Oxygen Ions."

Wong, C. Y., and R. Blankenbecler, "Nuclear Momentum Distribution and Relativistic Heavy-Ion Reactions."

Wong, C. Y., and R. Blankenbecler, "Scaling Phenomenon in Relativistic Nucleus-Nucleus Collisions."

American Chemical Society, Houston, Texas, March 23–28, 1980

Toth, K. S. (invited talk), "Investigation of Nuclei Near $N = 82$; Evidence for a Shell Closure at $Z = 64$."

Wood, J. L. (invited talk), "Nuclear Structure Information from the Decay of Short-Lived Nuclei."

FISICA 80, Second National Conference on Physics, Porto, Portugal, April 16–18, 1980

de Lima, A. P., J. H. Hamilton, A. V. Ramayya, A. C. Rester, H. Kawakami, R. M. Ronningen, R. L. Robinson, and H. J. Kim, "Study of ^{69}Ga with the Reaction ^{68}Zn(Li, αn)^{69}Ga."

International Conference on Nuclear Behavior at High Angular Momentum, Strasbourg, France, April 22–24, 1980

Horn, D., G. R. Young, C. I. Lister, and C. Baktash, "High-Spin Isomers in ^{153}Er."

Plasil, F. (invited talk), "Angular Momentum Effects in Fusion-Fission and Fusion-Evaporation Reactions."

Sarantites, D. G., M. Jääskeläinen, J. T. Hood, R. Woodward, J. H. Barker, D. C. Hensley, M. L. Halbert, and Y. D. Chan (invited talk), "The Spin Spectrometer at the Holifield Heavy-Ion Research Facility and Some Planned Experiments."

American Physical Society, Washington, D.C., April 28–May 1, 1980

Auble, R. L., J. K. Bair, D. M. Galbraith, C. M. Jones, P. H. Stelson, and D. C. Weisser, "Effects of Intense Heavy-Ion Beams on Carbon Foils," *Bull. Am. Phys. Soc.* **25**, 538 (1980).

Barker, J. H., J. R. Beene, M. L. Halbert, D. C. Hensley, M. Jääskeläinen, D. G. Sarantites, and R. Woodward, "Evidence for Peripheral Collisions in Incomplete Fusion Reactions," *Bull. Am. Phys. Soc.* **25**, 522 (1980).

Beene, J. R., C. E. Bemis, Jr., J. P. Young, and S. D. Kramer, "Study of the Fission Isomer ^{240m}Am (S.F.) Using Laser-Induced Nuclear Polarization," *Bull. Am. Phys. Soc.* **25**, 487 (1980).

Bemis, C. E., Jr., and J. W. T. Dabbs, "Measurement of the Fission Cross Section of ^{249}Cf at ORELA," *Bull. Am. Phys. Soc.* **25**, 487 (1980).

Berry, S. D., C. R. Vane, M. Breinig, L. Liljeby, G. A. Glass, M. M. Schauer, and S. B. Elston, "Slitless Magnetic Spectrometer for Low-Energy Electron Spectroscopy in High Radiation Fields," *Bull. Am. Phys. Soc.* **25**, 512 (1980).

Carlton, R. F., S. Raman, and E. T. Jurney, "The ^{34}S(n, γ) Reaction with Thermal Neutrons," *Bull. Am. Phys. Soc.* **25**, 543 (1980).

Dabbs, J. W. T., C. E. Bemis, Jr., S. Raman, R. J. Dougan, and R. W. Hoff, "Measurement of Fission Cross Section of ^{242m}Am," *Bull. Am. Phys. Soc.* **25**, 487 (1980).

Davies, K. T. R., K. R. Sandhya Devi, and M. R. Strayer, "TDHF Fusion in Head-On Collisions of ^{86}Kr + ^{139}La and ^{84}Kr + ^{209}Bi," *Bull. Am. Phys. Soc.* **25**, 540 (1980).

de Bock, H., H. Cohn, G. Condo, and other collaborators, "Exclusive Final States in π^+p, K^+p, and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **25**, 580 (1980).

Digregorio, D., R. A. Dayras, J. L. C. Ford, Jr., J. Gomez del Campo, D. Shapira, A. H. Snell, P. H. Stelson, and R. G. Stokstad, "Fusion and Peripheral Reactions for ^{20}Ne + ^{20}Ne and ^{20}Ne + ^{16}O at Bombarding Energies up to 8 MeV/a," *Bull. Am. Phys. Soc.* **25**, 523 (1980).

Ellis, Y. A., K. S. Toth, C. R. Bingham, H. K. Carter, and D. C. Sousa, "Decay of ^{190}Po to Levels in ^{190}Tl," *Bull. Am. Phys. Soc.* **25**, 486 (1980).

Elston, S., I. Sellin, M. Breinig, L. Liljeby, R. Thoe, R. Marrus, H. Gould, R. Vane, and R. Laubert, "Velocity and Target Dependences for Charge Capture to Continuum in High-Velocity Ar^{18+} + Gas Target Collisions," *Bull. Am. Phys. Soc.* **25**, 511 (1980).

Forte, M., B. Heckel, N. Ramsey, K. Green, G. Greene, M. Pendlebury, T. Sumner, P. D. Miller, and W. Dress, "A First Measurement of Parity Violating Neutron Spin Precession," *Bull. Am. Phys. Soc.* **25**, 526 (1980).

Fulmer, C. B., F. E. Bertrand, N. M. Clarke, C. D. Goodman, E. E. Gross, D. C. Hensley, G. R. Satchler, and J. R. Wu, "Elastic Scattering of 88-MeV ^{6}Li from ^{197}Au, ^{206,208}Pb," *Bull. Am. Phys. Soc.* **25**, 594 (1980).

Galonsky, A., S. Austin, T. Nees, W. Sterrenburg, D. Bainum, J. Rapaport, C. Foster, C. Goodman, D. Horen, C. Goulding, and M. Greenfield, "Isovector Giant Resonances in ^{90,92,94}Zr(p,n) at 80, 120, and 160 MeV," *Bull. Am. Phys. Soc.* **25**, 602 (1980).

Gavron, A., R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, G. A. Petitt, K. A. Geoffroy, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire, "Comparison of Neutron Emission in the ^{12}C + ^{158}Gd and ^{13}C + ^{157}Gd Reactions at 12 MeV/Nucleon," *Bull. Am. Phys. Soc.* **25**, 506 (1980).

Glanzman, T., W. Walker, I. J. Kim, C.-R. Sun, H. Cohn, E. Hart, and J. Lannutti, "The Reaction $\pi^+p \to \pi^+p\pi^0$ (Fast) at 16 GeV/c," *Bull. Am. Phys. Soc.* **25**, 561 (1980).

Halperin, J., C. E. Bemis, Jr., J. W. T. Dabbs, B. H. Kettelle, R. W. Stoughton, R. W. Hoff, and R. J. Dougan, "Prompt $\bar{\nu}$ of ^{242}Cm," *Bull. Am. Phys. Soc.* **25**, 487 (1980).

Hill, N. W., J. A. Harvey, D. J. Horen, G. L. Morgan, and R. R. Winters, "Majority Logic of NE-110 Detector for keV Neutrons," *Bull. Am. Phys. Soc.* **25**, 539 (1980).

Horen, D. J., J. A. Harvey, and N. W. Hill, "Nuclear Level Densities in ^{207}Pb," *Bull. Am. Phys. Soc.* **25**, 543 (1980).

Jääskeläinen, M., D. G. Sarantites, R. Woodward, J. T. Hood, J. H. Barker, D. C. Hensley, and M. L. Halbert, "'Spin Spectrometer' — A 4π γ-Ray Multidetector System for Heavy-Ion Physics," *Bull. Am. Phys. Soc.* **25**, 538 (1980).

Jones, C. M., J. K. Bair, J. A. Benjamin, J. A. Biggerstaff, A. Ceballos, N. A. Fazzini, R. C. Juras, J. E. Mann, J. A. Nicolai, E. G. Richardson, and N. F. Ziegler, "Column Voltage Tests of the Oak Ridge 25-MV Tandem Accelerator," *Bull. Am. Phys. Soc.* **25**, 537 (1980).

Kittel, W., ..., H. Cohn, E. Hart, and other collaborators, "Inclusive Vector-Meson Production in $\pi^{\pm}p$, $K^{+}p$, and pp Interactions at 147 GeV/c," *Bull. Am. Phys. Soc.* **25**, 580 (1980).

Kröger, H., "Influence of Solitons in Abnormal Nuclear Matter," *Bull. Am. Phys. Soc.* **25**, 502 (1980).

Kröger, H., "Cauchy Approach to Nonlinear Field Quantization," *Bull. Am. Phys. Soc.* **25**, 503 (1980).

Kröger, H., and R. Perne, "Few-Body Scattering Equations without Green's Function of the Subsystems," *Bull. Am. Phys. Soc.* **25**, 557 (1980).

Larson, D. C., D. M. Hetrick, and J. A. Harvey, "Comparison of Neutron Total Cross-Section Measurements with Optical Model Predictions from 2 to 80 MeV," *Bull. Am. Phys. Soc.* **25**, 543 (1980).

Laubert, R., H. Gould, R. Marrus, C. R. Vane, I. A. Sellin, S. B. Elston, M. Breinig, L. Liljeby, S. Berry, and R. S. Thoe, "Convoy Electrons from Solid Targets for 234- and 340-MeV Argon Projectiles," *Bull. Am. Phys. Soc.* **25**, 512 (1980).

Lord, R. S., J. B. Ball, T. P. Cleary, R. M. Beckers, E. D. Hudson, C. A. Ludemann, J. A. Martin, G. S. McNeilly, S. W. Mosko, and R. O. Sayer, "The Oak Ridge Isochronous Cyclotron as an Energy Booster for the 25-MV Tandem," *Bull. Am. Phys. Soc.* **25**, 538 (1980).

Martin, M. J., J. B. Ball, F. E. Bertrand, R. L. Ferguson, C. B. Fulmer, I. Y. Lee, R. L. Robinson, G. R. Young, J. C. Wells, Jr., and H. Yamada, "Gamma Rays from the $^{12}C + {}^{60}Ni$ Reaction at 194 MeV," *Bull. Am. Phys. Soc.* **25**, 506 (1980).

McGrory, J. B., "Weak-Coupling Approximations in the s-d Shell," *Bull. Am. Phys. Soc.* **25**, 573 (1980).

Oberacker, V. E., H. Kruse, W. T. Pinkston, and W. Greiner, "Information about High-Phonon Beta Vibrations in Actinides from Coulomb Fission," *Bull. Am. Phys. Soc.* **25**, 488 (1980).

Oberacker, V. E., and J. A. Maruhn, "Muon-Induced Fission: A Probe for the Friction Coefficient?," *Bull. Am. Phys. Soc.* **25**, 488 (1980).

Ortiz, M. E., Y. D. Chan, J. L. C. Ford, Jr., J. Gomez del Campo, D. Hensley, D. Shapira, R. G. Stokstad, F. Sellschop, D. Weisser, and R. Parks, "Measurements of Fusion Cross Sections for the $^{14}N + {}^{10}B$ System," *Bull. Am. Phys. Soc.* **25**, 483 (1980).

Petitt, G. A., R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, G. R. Young, K. A. Geoffroy, D. G. Sarantites, and C. F. Maguire, "Observation of Nonequilibrium Neutron Emission in Reactions of 208-MeV ^{16}O with ^{93}Nb," *Bull. Am. Phys. Soc.* **25**, 522 (1980).

Plattard, S., G. F. Auchampaugh, N. W. Hill, G. de Saussure, R. B. Perez, and J. A. Harvey, "The Triple-Humped Fission Barrier of ^{232}Pa," *Bull. Am. Phys. Soc.* **25**, 487 (1980).

Ramavataram, S., and G. Do Dang, "A Calculation of the Total Cross Section for the $^{11}B(p,n)^{11}C$ Reaction," *Bull. Am. Phys. Soc.* **25**, 520 (1980).

Ritchie, B., F. E. Bertrand, M. Blecher, R. L. Burman, R. Carlini, R. D. Edge, K. Gotow, E. E. Gross, M. E. Hamm, M. J. Leitch, D. J. Malbrough, M. A. Moinester, F. E. Obenshain, B. M. Preedom, and J. R. Wu, "Measurements of Angular Distributions for the $\pi^{+} + d \rightarrow p + p$ Reaction in the Energy Range from 20 to 65 MeV," *Bull. Am. Phys. Soc.* **25**, 559 (1980).

Sandhya, Devi, K. R., M. R. Strayer, K. T. R. Davies, and J. M. Irvine, "TDHF Studies of the Reaction $^{16}O + {}^{93}Nb$ at $E_{lab} = 204$ MeV," *Bull. Am. Phys. Soc.* **25**, 540 (1980).

Schouten, M., ..., H. Cohn, W. Bugg, and other collaborators, "Inclusive π^{+}/π^{-} Ratios in 147 GeV/c $\pi^{+}p$, $K^{+}p$, and pp Interactions," *Bull. Am. Phys. Soc.* **25**, 580 (1980).

Shahal, O., S. Raman, and G. G. Slaughter, "Capture Gamma-Ray Studies in the $^{173}Yb/n,\gamma)^{174}Yb$ Reaction," *Bull. Am. Phys. Soc.* **25**, 543 (1980).

Shapira, D., J. L. C. Ford, Jr., J. Gomez del Campo, and P. H. Stelson, "Backward Angle Measurements of $^{27}Al + ^{16}O$ Induced Reactions," *Bull. Am. Phys. Soc.* 25, 483 (1980).

Stamer, P., ..., H. Cohn, and other collaborators, "Inclusive Strange Resonance Production in 147 GeV/c π^+, K^+p, and pp Interactions," *Bull. Am. Phys. Soc.* 25, 561 (1980).

Tinsley, J., D. K. McDaniels, F. E. Bertrand, E. E. Gross, J. R. Wu, L. W. Swenson, and R. J. Liljestrand, "Excitation of Giant Resonances with 200-MeV Protons," *Bull. Am. Phys. Soc.* 25, 601 (1980).

Toth, K. S., C. R. Bingham, D. C. Sousa, A. C. Kahler, and D. R. Zolnowski, "Investigation of Nuclei near $N = 82$ and $Z = 64$: Evidence for the New Isotopes ^{144}Tb and ^{145}Tb," *Bull. Am. Phys. Soc.* 25, 486 (1980).

Vane, C. R., R. Marrus, H. Gould, I. A. Sellin, M. Breinig, S. B. Elston, L. Liljeby, R. S. Thoe, and R. Laubert, "Shape of Electron Capture to Continuum Peaks for High-Velocity Ar^{18+} + Gas Target Collisions," *Bull. Am. Phys. Soc.* 25, 512 (1980).

Vrba, J. A., C. R. Bingham, M. W. Guidry, R. E. Neese, E. E. Gross, T. P. Cleary, D. C. Hensley, and E. V. Hungerford, "A Search for α-Decay of High-Spin Isomers in Rare-Earth Nuclei," *Bull. Am. Phys. Soc.* 25, 604 (1980).

Wells, J. C., Jr., R. W. Eastes, M. E. Barclay, R. L. Robinson, H. J. Kim, R. O. Sayer, R. B. Piercey, J. H. Hamilton, A. V. Ramayya, C. F. Maguire, and A. J. Caffrey, "High-Spin States in ^{76}Br," *Bull. Am. Phys. Soc.* 25, 578 (1980).

Widgoff, M., ..., H. Cohn, E. Hart, and other collaborators, "Average Inclusive Charged-Particle Multiplicities in π^+p, K^+p, and pp Interactions at 147 GeV/c" *Bull. Am. Phys. Soc.* 25, 561 (1980).

Winters, R. R., and C. H. Johnson, "$^{32}S + n$ Spectroscopic Factors and Neutron Widths for Unbound States below 9700 keV," *Bull. Am. Phys. Soc.* 25, 543 (1980).

Winters, R. R., G. L. Morgan, R. L. Macklin, D. K. Olsen, J. A. Harvey, and N. W. Hill, "^{238}U Neutron Inelastic Scattering at 82 MeV," *Bull. Am. Phys. Soc.* 25, 543 (1980).

Wong, C. Y., "Semiempirical Determination of Nuclear Momentum Distribution," *Bull. Am. Phys. Soc.* 25, 540 (1980).

Wood, J. L., "The Positive-Parity States in $^{193,195}Au$ and Dynamical Supersymmetries," *Bull. Am. Phys. Soc.* 25, 573 (1980).

Wu, J. R., F. E. Bertrand, D. J. Horen, G. R. Satchler, A. D. Bacher, G. T. Emery, W. P. Jones, D. W. Miller, and A. van der Woude, "Excitation of Giant Multipole Resonances in ^{46}Ti, ^{58}Ni, ^{90}Zr, ^{120}Sn, and ^{208}Pb via Inelastic Scattering of 152-MeV Alpha Particles," *Bull. Am. Phys. Soc.* 25, 602 (1980).

Wu, J. R., and I. Y. Lee, "Projectile Fragmentation Accompanied by Incomplete Fusion," *Bull. Am. Phys. Soc.* 25, 506 (1980).

Yamada, H., D. C. Hensley, M. L. Halbert, A. V. Ramayya, C. F. Maguire, R. L. Robinson, J. H. Hamilton, D. G. Sarantites, R. Woodward, I. Y. Lee, and A. Ahmed, "Discrete Transitions above 1 MeV in Er Nuclei," *Bull. Am. Phys. Soc.* 25, 596 (1980).

Yang, N. C., ..., W. M. Bugg, G. T. Condo, H. O. Cohn, and other collaborators, "Neutral Particle Production in 4.1 GeV/c $\bar{p}p$ Interactions Using the 12-Foot Bubble Chamber with TST," *Bull. Am. Phys. Soc.* 25, 562 (1980).

Young, G. R., R. L. Auble, J. B. Ball, F. E. Bertrand, R. L. Ferguson, C. B. Fulmer, I. Y. Lee, M. J. Martin, R. L. Robinson, J. R. Wu, and H. Yamada, "Light-Ion–Light-Ion Coincidence Measurements in Reactions of 194-MeV ^{12}C with ^{60}Ni," *Bull. Am. Phys. Soc.* 25, 507 (1980).

1980 RCNP International Symposium on Highly Excited States in Nuclear Reactions, Osaka, Japan, May 12–16, 1980

Horen, D. J. (invited talk), "Search for Magnetic Dipole Strength and Giant Spin-Flip Resonances in Heavy Nuclei."

Second Technical Committee Meeting on Atomic and Molecular (A + M) Data for Fusion, Paris, France, May 19–22, 1980

Crandall, D. H. (invited talk), "Electron Impact Ionization of Multicharged Ions."

Phaneuf, R. A., D. H. Crandall, and F. W. Meyer, "Low-Energy Electron Capture by Multicharged Ions from Hydrogen."

EPRI Workshop on Arc By-products in Gas-Insulated Equipment, Chicago, Illinois, June 4–5, 1980

Holmberg, R. W., J. M. Keller, and C. M. Jones, "The Problem of Sulfur Hexafluoride Impurities on the Operation of Large Electrostatic Accelerators."

Fifth Tandem Conference, Catania, Italy, June 9–12, 1980

Jones, C. M., "The 25-MV Tandem Accelerator at Oak Ridge."

Nobel Symposium on Nuclei at Very High Spin, Lund, Sweden, June 9–13, 1980

Riedinger, L. L., "The Limits of Studying High-Spin States by Discrete-Line Gamma-Ray Spectroscopy."

Gordon Research Conference on Nuclear Chemistry, New London, New Hampshire, June 16–20, 1980

Bemis, C. E., Jr. (invited talk), "Optical Isomer Shift for the Fission Isomer ^{240m}Am."

The Physics of MOS Insulator Conference, Chapel Hill, North Carolina, June 18–20, 1980

Tsong, I. S. T., M. D. Monkowski, J. R. Monkowski, P. D. Miller, C. D. Moak, B. R. Appleton, and A. L. Wintenberg, "Investigation of Hydrogen and Chlorine at the SiO_2/Si Interface."

XI International Quantum Electronics Conference, Boston, Massachusetts, June 23–26, 1980

Bemis, C. E., Jr., J. R. Beene, J. P. Young, and S. D. Kramer, "Laser-Induced Nuclear Polarization (LINUP): Application to the Study of Short-Lived Nuclides."

Third International Conference on Ion Implantation: Equipment and Technique, Kingston, Ontario, Canada, July 8–11, 1980

Alton, G. D. (invited talk), "Aspects of the Physics, Chemistry, and Technology of High-Intensity Heavy-Ion Sources."

South African Institute of Physics 25th Annual Conference, Johannesburg, R. S. Africa, July 9–12, 1980

Gomez del Campo, J. (invited talk), "Fusion of Light Heavy-Ion Systems."

Fifth International Conference on Hyperfine Interactions, Berlin, West Germany, July 21–25, 1980

Beene, J. R., C. E. Bemis, Jr., J. P. Young, and S. D. Kramer (invited talk), "Study of the Fission Isomer ^{240m}Am(S.F.) Using Laser-Induced Nuclear Polarization."

International Conference on Nuclear Waste Transmutation, Austin, Texas, July 22–24, 1980

Dabbs, J. W. T. (invited talk), "The Actinide Cross-Section Program at ORELA."

Seventh International Conference on Atomic Physics, Boston, Massachusetts, August 4–8, 1980

Bottcher, C., "Ionization of Rydberg Atoms by Moderately Fast Charged Particles."

Meyer, F. W., "Single Electron Capture and Loss by H^+, H^0, and H^- in Cs Vapor in the Energy Range 0.1–2.0 keV."

Sellin, I. A., "Continuum Capture in the Three-Body Problem."

International Summer School on Nuclear Structure, Dronten, The Netherlands, August 12–23, 1980

McGrory, J. B. (invited talk), "Application of the Shell Model to Nuclear Spectroscopy."

Ninth International Conference on the Few-Body Problem, Eugene, Oregon, August 17–23, 1980

Kröger, H., and R. Perne, "Few-Body Binding Energy Correlations."

Kröger, H., and R. Perne, "A Few-Body Scattering Integral Equation Approach."

Kröger, H., and R. Perne, "Efimov Pathology in Effective Two-Body System."

International Conference on Nuclear Physics, Berkeley, California, August 24–30, 1980

Bertrand, F. E. (invited talk), "Giant Multipole Resonances — Perspectives after Ten Years."

Blecher, M., R. Auble, F. E. Bertrand, G. Blanpied, R. L. Burman, R. Carlini, S. H. Dam, W. Gaskin, K. Gotow, E. E. Gross, M. V. Hynes, M. A. Kovash, M. J. Leitch, F. E. Obenshain, B. M. Preedom, R. P. Redwine, B. Ritchie, V. D. Sandberg, and J. Wu, "Giant Resonance Excitation of ^{40}Ca with π^+ and π^- at 80 MeV," p. 264 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Ewbank, W. B., "Systematics of Yrast Levels in Nuclei," p. 322 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Gavron, A., J. R. Beene, R. L. Ferguson, F, E. Obenshain, F. Plasil, G. R. Young, G. A. Petitt, C. F. Maguire, M. Jääskeläinen, K. A. Geoffroy, and D. G. Sarantites, "Nonequilibrium Neutron Emission in ^{12}C- and ^{13}C-Induced Fusion Reactions," p. 601 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Gomez del Campo, J., K. Geoffroy, R. A. Dayras, and R. G. Stokstad, "Modeling the Equilibrium Decay: Application of Monte Carlo Calculations to the Deep Inelastic Collision of 168-MeV ^{20}Ne on ^{63}Cu," p. 497 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Goodman, C. D., D. E. Bainum, C. C. Foster, C. Gaarde, C. A. Goulding, M. B. Greenfield, D. Horen, J. Rapaport, E. Sugarbaker, and T. Taddeucci, "Low q Giant Resonances in Medium Energy (p,n) Reactions," p. 241 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Gross, E. E., J. R. Beene, C. E. Bemis, Jr., F. E. Bertrand, D. J. Horen, J. R. Wu, and W. P. Jones, "Fission Decay of the Giant Quadrupole Resonance (GQR) in ^{238}U," p. 208 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Horen, D. J., C. D. Goodman, C. C. Foster, C. A. Goulding, M. B. Greenfield, J. Rapaport, D. E. Bainum, E. Sugarbaker, R. G. Masterson, F. Petrovich, and W. G. Love, "Search for Isobaric Analogues of $M1$ States and Spin-Flip Resonances in ^{206,208}Pb(p,n) Reactions," p. 272 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Horen, D. J., C. D. Goodman, C. C. Foster, E. Sugarbaker, J. Rapaport, D. Bainum, C. A. Goulding, C. Gaarde, M. B. Greenfield, and T. Taddeucci, "Spin-Flip Resonances Observed in the ^{169}Tm(p,n), Reaction at 200 MeV," p. 271 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Horen, D. J., C. D. Goodman, C. C. Foster, E. Sugarbaker, J. Rapaport, D. Bainum, C. A. Goulding, C. Gaarde, M. B. Greenfield, and T. Taddeucci, "Energy Systematics of a $\Delta \ell = 1$ Spin-Flip Resonance Observed in the (p,n) Reaction," p. 273 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Horen, D. J., J. A. Harvey, N. W. Hill, and C. H. Johnson, "Comparison of s-, p-, and d-Wave Neutron Strength Functions for ^{206}Pb + n Reactions with Optical-Model Calculations," p. 837 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Horen, D. J., J. A. Harvey, and N. W. Hill, "Parity Dependence of Nuclear Level Densities in the Nuclear Continuum of ^{207}Pb," p. 746 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Jääskeläinen, M., R. Woodward, D. G. Sarantites, J. H. Barker, D. C. Hensley, and M. L. Halbert, "Performance and First Experiments with the 'Spin Spectrometer' at the HHIRF," p. 665 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Kröger, H., "Nonlinear Mesonic Solutions in the Lee-Wick Model," p. 399 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Kröger, H., and R. Perne, "Few-Nucleon Binding Energy Correlations," p. 1 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Kröger, H., and R. Perne, "Efimov Pathology in Cluster Models," p. 2 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Kröger, H., and R. Perne, "N-Body Scattering Equations for Nuclear Reaction Theory," p. 67 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Lee, I. Y., N. R. Johnson, D. R. Haenni, S. A. Hjorth, W. T. Milner, R. L. Robinson, G. R. Young, L. L. Riedinger, and S. W. Yates, "High-Spin Properties of ^{132}Ce from Gamma-Ray Energy-Energy Correlation Studies," p. 493 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Leitch, M. J., M. Blecher, R. Auble, F. E. Bertrand, G. Blanpied, R. L. Burman, R. Carlini, S. H. Dam, W. Gaskin, K. Gotow, E. E. Gross, M. V. Hynes, M. A. Kovash, F. E. Obenshain, B. M. Preedom, R. P. Redwine, B. Ritchie, V. D. Sandberg, and J. R. Wu, "π^+ and π^- Elastic Scattering from ^{12}C, ^{40}Ca, ^{90}Zr, ^{208}Pb at 80 MeV," p. 716 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Neese, R. E., M. W. Guidry, C. R. Bingham, L. L. Riedinger, J. A. Vrba, T. L. Nichols, I. Y. Lee, N. R. Johnson, J. O. Rasmussen, R. Donangelo, R. M. Diamond, D. L. Hillis, and P. A. Butler, "Nuclear Surface Studies via Coulomb-Nuclear Interference," p. 589 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Obenshain, F. E., F. E. Bertrand, M. Blecher, R. L. Burman, R. D. Edge, K. Gotow, E. E. Gross, M. Hamm, M. J. Leitch, M. A. Moinester, B. M. Preedom, R. P. Redwine, and J. R. Wu, "Positive Pion-Nucleus Elastic Scattering at 20 MeV," p. 701 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Obenshain, F. E., R. L. Ferguson, A. I. Gavron, F. Plasil, R. K. Robinson, D. Shapira, A. H. Snell, and G. R. Young, "Correlated Charge and Mass Distributions in the Evaporation Residue Region from the ^{20}Ne + ^{27}Al Reaction," p. 608 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Oberacker, V. E., W. T. Pinkston, H. Kruse, and W. Greiner, "Coulomb Fission of ^{238}U and ^{232}Th by Very Heavy Projectiles," p. 642 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Oberacker, V. E., and J. A. Maruhn, "Theoretical Study of Fission Dynamics by Muon-Induced Fission," p. 854 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Plasil, F., R. L. Ferguson, R. L. Hahn, F. E. Obenshain, F. Pleasonton, and G. R. Young, "Fission Barrier of ^{153}Tb," p. 641 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Raman, S., R. F. Carlton, and E. T. Jurney, "The ^{33}S(n, γ) Reaction with Thermal Neutrons," p. 236 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Raman, S., C. P. Sargent, R. S. Hicks, R. Lindgren, B. Parker, and G. A. Peterson, "A Search for $M1$ Excitation Strength in ^{208}Pb Using 180° Inelastic Electron Scattering," p. 227 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Raman, S., O. Shahal, and G. G. Slaughter, "Discrete Approach to Resonance-Averaged (n, γ) Spectroscopy," p. 247 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Riedinger, L. L., W. K. Luk, D. R. Haenni, S. A. Hjorth, N. R. Johnson, I. Y. Lee, and R. L. Robinson, "High-Spin States in ^{160}Yb," p. 383 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Ritchie, B. G., F. E. Bertrand, M. Blecher, R. L. Burman, R. Carlini, R. D. Edge, K. Gotow, E. E. Gross, M. E. Hamm, M. J. Leitch, D. J. Malbrough, M. A. Moinester, F. E. Obenshain, B. M. Preedom, and J. R. Wu, "Angular Distribution and Total Cross Sections for the $\pi^+ + d \rightarrow p + p$ Reaction with $T = 20$ to 65 MeV," p. 712 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Robinson, R. L., R. L. Auble, J. B. Ball, F. E. Bertrand, R. L. Ferguson, C. B. Fulmer, I. Y. Lee, M. J. Martín, J. R. Wu, G. R. Young, J. C. Wells, and H. Yamada, "Energetic Protons from the ^{12}C + ^{60}Ni Reaction," p. 470 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Schmorak, M., "α-Decay Systematics in the Lead Region," p. 824 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Shapira, D., J. L. C. Ford, Jr., J. Gomez del Campo, and P. H. Stelson, "Backward-Angle Measurement of Damped Processes in Light Heavy-Ion Reactions," p. 494 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Sterrenburg, W., S. Austin, A. Galonsky, T. Nees, D. Bainum, J. Rapaport, C. Foster, C. Goodmam, D. Horen, C. Goulding, and M. Greenfield, "Isovector Giant Resonances in ^{90,92,94}Zr(p,n) at 80, 120, and 160 MeV," p. 176 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Sugarbaker, E., D. E. Bainum, C. C. Foster, D. J. Horen, C. Gaarde, C. D. Goodman, C. A. Goulding, M. Greenfield, T. Masterson, and J. Rapaport, "Giant Resonances Observed in the $^{112,124}Sn(p,n)$ $^{112,124}Sb$ Reactions," p. 207 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Wong, C. Y., and R. Blankenbecler, "Nuclear Momentum Distribution and Relativistic Heavy-Ion Reactions," p. 466 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Wong, C. Y., and R. Blankenbecler, "Scaling Phenomenon in Relativistic Nucleus-Nucleus Collisions," p. 404 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Wood, J. L., R. A. Braga, M. A. Grimm, and E. F. Zganjar, "Interacting Boson-Fermion Model of Collective States in Odd Gold Nuclei," p. 359 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Wu, J. R., J. R. Beene, C. E. Bemis, Jr., F. E. Bertrand, E. E. Gross, D. J. Horen, and W. P. Jones, "The $^{238}U(\alpha, {}^{3}He f)$ Reaction at $E = 152$ MeV," p. 450 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Wu, J. R., and I. Y. Lee, "Projectile Fragmentation Accompanied by Incomplete Fusion," p. 634 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Young, G. R., R. L. Ferguson, A. Gavron, F. E. Obenshain, F. Plasil, M. P. Webb, C. F. Maguire, and G. A. Petitt, "Heavy-Ion–Alpha Correlations in Deeply Inelastic Collisions of 204-MeV ^{16}O with ^{93}Nb," p. 602 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Zganjar, E. F., J. D. Cole, M. A. Grimm, and J. L. Wood, "Strongly Deformed States in the Neutron-Deficient Odd-Mass Au and Hg Nuclei," p. 325 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

Zhao, Z. Z., X. J. Sun, R. B. Piercey, J. H. Hamilton, C. F. Maguire, A. V. Ramayya, R. L. Robinson, H. J. Kim, and J. C. Wells, "Lifetime in Yrast Levels and Composite Side Feeding Times in ^{76}Kr," p. 310 in Lawrence Berkeley Laboratory Report LBL-11118 (1980).

International Conference on X-Ray Processes and Inner-Shell Ionization, Stirling, Scotland,, August 25–29, 1980

Elson, S. B. (invited talk), "Multiple Ionization and Excitation Processes in Single Ion-Atom Collisions."

Reading, J. F., A. L. Ford, and R. L. Becker, "One and a Half Centered Expansion for Ion-Atom Collisions."

American Chemical Society, Las Vegas, Nevada, August 25–29, 1980

W. Bruchle, H. Gaggeler, J. W. Kratz, M. Schadel, G. Wirth, G. Herrmann, G. Tittel, N. Trautmann, E. K. Hulet, R. W. Lougheed, A. Ghiorso, J. M. Nitschke, R. L. Hahn, and R. L. Ferguson, "Search for Heavy Actinides and Superheavy Elements in the $^{238}U + {}^{248}Cm$ Reaction."

Robinson, R. L., and J. B. Ball, "The Holifield Heavy-Ion Research Facility."

Young, J. P., C. E. Bemis, Jr., J. R. Beene, and S. D. Kramer (invited talk), "Study of the Fission Isomer ^{240m}Am Using Laser-Induced Nuclear Polarization."

Workshop on Nuclear Physics, Philadelphia, Pennsylvania, September 1–3, 1980

Hjorth, S. A., I. Y. Lee, J. R. Beene, C. Roulet, D. R. Haenni, N. R. Johnson, F. E. Obenshain, and G. R. Young, "Interpretation of the 21-ns Isomer in ^{190}Hg as $(\nu i_{13/2})^2$ from a g-Factor Measurement."

Wood, J. L. (invited talk), "Testing the Interacting-Boson and Interacting-Boson-Fermion Approximations by the Study of Radioactive Decay Schemes with the UNISOR On-Line Isotope Separator."

Tenth International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications, Zinal, Switzerland, September 1–6, 1980

Mlekodaj, R. L., "A New Concept for a Compact Tape Transport System."

Mlekodaj, R. L., "A New High-Temperature ISOL Ion Source with an Electron-Extracting Grid."

Moltz, D. M., "The Helium-Jet Coupled Mass Separator — Advances and Directions."

Spejewski, E. H., "A D.C.-Heated Thermal-Ionization Source."

Spejewski, E. H., "Status of the UNISOR Facility."

Third International Workshop on Inelastic Ion-Surface Collisions, Munich, West Germany, September 17–19, 1980

Sellin, I. A., and R. Laubert, "Electron Capture and Loss to Continuum States in Gases and Solids."

International Symposium on the Synthesis and Properties of New Elements, Dubna, U.S.S.R., September 23–27, 1980

Hulet, E. K., R. W. Lougheed, J. M. Nitschke, R. L. Hahn, R. L. Ferguson, W. Bruchle, H. Gaggeler, J. V. Kratz, M. Schadel, G. Wirth, G. Herrmann, G. Tittel, and N. Trautmann, "Recent Searches for Superheavy Elements in Deep-Inelastic Reactions."

American Physical Society (New England Section), Cambridge, Massachusetts, October 3–4, 1980

Huffman, R. L., R. S. Hicks, R. Lindgren, B. Parker, G. A. Peterson, S. Raman, and C. P. Sargent, "180° Inelastic Electron Scattering from ^{208}Pb," *Bull. Am. Phys. Soc.* **26**, 58 (1981).

Second International Symposium on the Production and Neutralization of Negative Hydrogen Ions and Beams, Upton, New York, October 6–10, 1980

Crandall, D. H., and F. W. Meyer (invited talk), "Hydrogen Negative Ions and Collisions of Atomic Particles."

American Physical Society (Division of Nuclear Physics), Minneapolis, Minnesota, October 9–11, 1980

Auble, R. L., C. B. Fulmer, J. B. Ball, F. E. Bertrand, R. L. Ferguson, I. Y. Lee, R. L. Robinson, J. R. Wu, G. R. Young, J. C. Wells, and H. Yamada, "Light Ions from ^{12}C Bombardment of ^{60}Ni," *Bull. Am. Phys. Soc.* **25**, 743 (1980).

Azziz, N., and C. Y. Wong, "Multipole Giant Resonances as Elastic Vibration of a Nucleus," *Bull. Am. Phys. Soc.* **25**, 746 (1980).

Ellis-Akovali, Y., and K. S. Toth, "The α-Decay Rate of ^{188}Pb," *Bull. Am. Phys. Soc.* **25**, 740 (1980).

Fulmer, C. B., F. E. Bertrand, E. E. Gross, D. C. Hensley, G. R. Satchler, J. R. Wu, N. M. Clarke, and M. F. Steeden, "Elastic Scattering of 88-MeV ^{6}Li," *Bull. Am. Phys. Soc.* **25**, 738 (1980).

Goulding, C. A., M. B. Greenfield, E. Sugarbaker, C. D. Goodman, C. C. foster, J. Rapaport, T. Taddeucci, D. J. Horen, and D. E. Bainum, "Energy Dependence of the Isospin-Dependent Interaction between 80 and 200 MeV," *Bull. Am. Phys. Soc.* **25**, 728 (1980).

Gross, E. E., F. E. Bertrand, C. B. Fulmer, C. D. Goodman, D. C. Hensley, G. R. Satchler, and J. R. Wu, "Reorientation Effects in the Scattering of 88-MeV ^{6}Li Ions from ^{24}Mg, ^{26}Mg, ^{59}Co, and ^{60}Ni," *Bull. Am. Phys. Soc.* **25**, 738 (1980).

Halbert, M. (invited paper), "Angular Momentum Effects in Incomplete-Fusion Reactions," *Bull. Am. Phys. Soc.* **25**, 720 (1980).

Horen, D. J., C. D. Goodman, C. C. Foster, J. Rapaport, C. A. Goulding, M. B. Greenfield, D. E. Bainum, E. Sugarbaker, T. G. Masterson, W. G. Love, and F. Petrovich, "Observation of a Charge-Exchange $L=1$, $S=1$ Transition in ^{208}Pb$(p,n)^{208}$Bi Reaction," *Bull. Am. Phys. Soc.* **25**, 728 (1980).

Hussein, A. Z., J. A. Harvey, and N. W. Hill, "Neutron Resonances of ^{231}Pa," *Bull. Am. Phys. Soc.* **25**, 735 (1980).

Johnson, C. H., and J. L. Fowler, "A Test of the $O(n,n)$ Phase Shifts at 2.35 MeV," *Bull. Am. Phys. Soc.* **25**, 736 (1980).

Moltz, D. M., K. S. Toth, M. D. Cable, R. F. Parry, and J. M. Wouters, "Ground-State Decay of ^{147}Dy to Levels in the $N=82$ Nucleus, ^{147}Tb," *Bull. Am. Phys. Soc.* **25**, 734 (1980).

Raman, S., O. Shahal, A. Z. Hussein, G. G. Slaughter, and J. A. Harvey, "The ^{89}Y$(n,\gamma)^{90}$Y Reaction below $E_n = 6$ MeV," *Bull. Am. Phys. Soc.* **25**, 736 (1980).

Rapaport, J., T. Taddeucci, C. C. Foster, C. D. Goodman, D. J. Horen, C. A. Goulding, E. Sugarbaker, D. E. Bainum, W. G. Love, and F. Petrovich, "The Momentum Transfer Dependence of the ^{12}C$(p,n)^{12}$N(gs) Reaction," *Bull. Am. Phys. Soc.* **25**, 728 (1980).

Robinson, R. L., R. L. Auble, I. Y. Lee, M. J. Martin, J. B. Ball, F. E. Bertrand, R. L. Ferguson, C. B. Fulmer, J. R. Wu, G. R. Young, J. C. Wells, and H. Yamada, "Fast Protons and Alpha Particles from the $^{12}C+^{60}Ni$ Reaction," *Bull. Am. Phys. Soc.* **25**, 743 (1980).

Ronningen, R. M., R. C. Melin, J. A. Nolen, Jr., G. M. Crawley, J. E. Finck, and C. E. Bemis, Jr., "Multipole Moments from Proton Scattering at 35 MeV to Ground Band States in ^{232}Th and $^{234,236,238}U$," *Bull. Am. Phys. Soc.* **25**, 740 (1980).

Wood, J. L., E. F. Zganjar, and J. D. Cole, "The Decay of Mass-Separated $^{187m,g}Tl$ and Evidence for Nilsson States in ^{187}Hg," *Bull. Am. Phys. Soc.* **25**, 739 (1980).

Ninth World Conference of the International Nuclear Target Development Society, Gatlinburg, Tennessee, October 12–16, 1980

Auble, R. L., and D. M. Galbraith, "A Procedure for the Rapid Evaluation of Carbon Stripper Foils."

Symposium of Northeastern Accelerator Personnel, Madison, Wisconsin, October 13–15, 1980

Jones, C. M., "Notes on Carbon Stripper Foils."

Ziegler, N. F., E. G. Richardson, J. E. Mann, R. C. Juras, C. M. Jones, J. A. Biggerstaff, and J. A. Benjamin, "Status of the Oak Ridge 25-MV Tandem Accelerator."

Sixth Conference on the Application of Accelerators in Research and Industry, Denton, Texas, November 3–5, 1980

Allred, D. D., D. C. Booth, B. R. Appleton, P. D. Miller, C. D. Moak, J. P. F. Sellschop, C. W. White, and A. L. Wintenberg, "The Hydrogen Content of Multicomponent Amorphous Silicon Alloys by ^{19}F Nuclear Reaction Analysis."

Alton, G. D., "Single and Multiple Electron Loss Processes in MeV Heavy Ion–Target Collisions."

Alton, G. D., L. B. Bridwell, M. Lucas, C. D. Moak, P. D. Miller, C. M. Jones, Q. C. Kessel, A. A. Antar, and M. D. Brown (invited paper), "Single and Multiple Electron Loss Cross-Section Measurements from 20-MeV Fe^{4+} on Thin Gaseous Targets."

Becker, R. L., J. F. Reading, and A. L. Ford, "Nonstatistical Theory of Multiple Vacancy Production in Atomic Collisions."

Carter, H. K. (invited talk), "Isotope Separator Experiments at the Cyclotron Facility: ORIC."

Compton, R. N., G. D. Alton, and D. J. Pegg (invited talk), "Photodetachment Cross Sections for $He^-(^4p^0)$."

Elston, S. B., I. A. Sellin, M. Breinig, S. Huldt, L. Liljeby, R. S. Thoe, S. Datz, S. Overbury, and R. Laubert, "Production of Convoy Electrons by Highly Ionized Atoms Traversing Solids."

Huldt, S. (invited talk), "Convoy Electron Production in Amorphous Solids and Monocrystalline Targets."

Johnson, B. M., D. C. Gregory, K. W. Jones, D. J. Pegg, P. M. Griffin, T. H. Kruse, J. L. Cecchi, and J. O. Ekberg (invited talk), "Anomalies in the Beam-Foil Measurements for $\Delta n = 0$ Transitions in Highly Ionized Members of the Li, Na, and Cu Sequences."

Laubert, R., S. Huldt, M. Breinig, L. Liljeby, S. Elston, R. S. Thoe, and I. A. Sellin, "Convoy Electrons from Solids in Coincidence with the Final Projectile State."

Mehta, R., J. L. Duggan, F. D. McDaniel, M. C. Andrews, R. M. Wheeler, R. P. Chaturvedi, P. D. Miller, and G. Lapicki, "Projectile Charge-State Dependence of Target *M*-Shell Ionization by 1.42-MeV/amu Fluorine Ions."

Pegg, D. J., and M. L. Gaillard (invited talk), "Time-Resolved Spectroscopy of Ions Using CW Laser Excitation."

Phaneuf, R. A. (invited talk), "Production of High-*Q* Ions by Laser Bombardment Method."

Raman, S. (invited talk), "Thermal, Resonance, and Average-Resonance Neutron-Capture Spectroscopy."

Reading, J. F., A. L. Ford, and R. L. Becker, "A One and a Half Centered Expansion for Ion-Atom Collisions."

Rao, P. V., R. D. Albridge, A. V. Ramayya, M. C. Andrews, R. Mehta, F. D. McDaniel, and P. D. Miller, "*L*-Shell Ionization in High-*Z* Targets by Carbon and Silicon Ions."

Welton, T. A. (invited talk), "Stability Studies for Orbits in an Isochronous Heavy-Ion Cyclotron."

American Physical Society (Southeastern Section), Chapel Hill, North Carolina, November 6–8, 1980

Herath-Banda, M. A., R. B. Piercey, A. V. Ramayya, J. H. Hamilton, H. Crowell, R. L. Robinson, J. Eberth, L. Cleemann, and J. Roth, "Excited Levels in ^{72}Br," *Bull. Am. Phys. Soc.* 26, 90 (1981).

American Physical Society (Division of Plasma Physics), San Diego, California, November 10–14, 1980

Hutchinson, D. P., C. H. Ma, P. A. Staats, and K. L. Vander Sluis, "A Submillimeter-Wave Interferometer Using Hollow Dielectric Waveguide," *Bull. Am. Phys. Soc.* 25, 940 (1980).

Symposium on Spin-Dependent Vibrations in Nuclei, Copenhagen, Denmark, November 1980

Horen, D. J. (invited talk), "*M*1 Resonances and Energy Systematics for GT Resonances."

American Physical Society (Division of Electron and Atomic Physics), Los Angeles, California, December 1–3, 1980

Crandall, D. H., R. A. Phaneuf, R. A. Falk, and G. H. Dunn, "Electron Impact Ionization of O^{2+}," *Bull. Am. Phys. Soc.* 25, 1141 (1980).

Meyer, F. W., and H. J. Kim, "Electron Loss from Rydberg States of Atomic Hydrogen in Fast Collisions with Multicharged Ions," *Bull. Am. Phys. Soc.* 25, 1144 (1980).

Phaneuf, R. A., "Electron-Capture Cross-Section Measurements for C^{q+} + H Collisions (q = 3, 4, 5) at $E \approx$ 10 eV/amu," *Bull. Am. Phys. Soc.* 25, 1134 (1980).

Rao, P. V., R. G. Albridge, A. V. Ramayya, M. C. Andrews, R. Mehta, F. D. McDaniel, and P. D. Miller, "Carbon- and Silicon-Ion Induced *L*-Shell Ionization in Ho, Er, Ta, W, Pt, Au, Pb, and Bi," *Bull. Am. Phys. Soc.* 25, 1147 (1980).

Stephani, G., R. Camilloni, R. A. Falk, G. H. Dunn, R. A. Phaneuf, and D. H. Crandall, "Electron Impact Ionization of B^+ and C^{2+}, Beryllium-Like Ions," *Bull. Am. Phys. Soc.* 25, 1141 (1980).

Conference on Weak Interactions as Probes of Unification, Blacksburg, Virginia, December 4–6, 1980

Young, G. R., H. O. Cohn, T. A. Gabriel, R. A. Lillie, P. D. Miller, R. R. Spencer, M. S. Goodman, R. Wilson, W. M. Bugg, G. T. Condo, T. Handler, and E. L. Hart (invited talk), "A Proposed Experiment for a Sensitive Search for $\Delta B = 2$ Transitions via n-$\bar{n}$ Mixing."

International Conference on Lasers '80, New Orleans, Louisiana, December 14–19, 1980

Hutchinson, D. P., C. H. Ma, P. A. Staats, and K. L. Vander Sluis, "Characteristics of a Submillimeter-Wave Electro-Optic Modulator."

Seminar on Molecular Ions, Molecular Structure, and Interaction with Matter, Rehovot, Israel, January 4–11, 1981

Sellin, I. A., S. Huldt, S. B. Elston, M. Breinig, L. Liljeby, R. S. Thoe, S. Datz, S. Overbury, and R. Laubert, "Convey Electron Production by 1- to 8.5-MeV/u Highly Ionized Ions Traversing Polycrystalline Solids and Axial Channels in Gold."

Fourth Symposium on Nuclear Physics, Oaxtepec, Mexico, January 5–7, 1981

Gross, E. E. (invited talk), "Nuclear Moments from Heavy-Ion Inelastic Scattering above the Coulomb Barrier."

International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, January 19–24, 1981

Kratz, J. W., W. Bruchle, H. Gaggeler, M. Schadel, K. Summerer, G. Wirth, G. Herrmann, G. Tittel, N. Trautmann, R. Stakemann, E. K. Hulet, R. W. Lougheed, J. M. Nitschke, R. L. Hahn, and R. L. Ferguson (invited talk), "Heavy-Actinide Cross Sections in the ^{238}U + ^{248}Cm Reaction."

Plasil, F., J. R. Beene, R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, G. R. Young, G. A. Petitt, K. A. Geoffroy, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire (invited talk), "Light-Particle Emission in Reactions with Carbon and Oxygen Ions."

XIX International Winter Meeting on Nuclear Physics, Bormio, Italy, January 25–31, 1981

Plasil, F., J. R. Beene, R. L. Ferguson, A. Gavron, F. E. Obenshain, G. R. Young, G. A. Petitt, K. G. Young, M. Jääskeläinen, D. G. Sarantites, and C. F. Maguire (invited talk), "Nonequilibrium Neutron Emission from $^{12}C + {}^{158}Gd$ and $^{13}C + {}^{157}Gd$ Reactions."

American Physical Society, New York, New York, January 26–29, 1981

Davies, K. T. R. (invited talk), "Time-Dependent Hartree-Fock Theory in Heavy-Ion Collisions," *Bull. Am. Phys. Soc.* **26**, 12 (1981).

Toth, K. S., C. R. Bingham, D. C. Sousa, A. C. Kahler, and D. R. Zolnowski, "Decay of ^{145}Tb to Levels in the $N + 81$ Nucleus ^{145}Gd," *Bull. Am. Phys. Soc.* **26**, 45 (1981).

Fifth International Conference on Ion Beam Analysis, Sydney, Australia, February 16–20, 1981

Tsong, I. S. T., M. D. Monkowski, J. R. Monkowski, A. L. Wintenberg, P. D. Miller, and C. D. Moak, "Hydrogen and Chlorine Detection at the SiO_2/Si Interface."

Tsong, I. S. T., G. A. Smith, J. W. Michels, A. L. Wintenberg, P. D. Miller, and C. D. Moak, "Dating of Obsidian Artifacts by Depth-Profiling of Artificially Hydrated Surface Layers."

Third Topical Conference on Atomic Processes in High-Temperature Plasmas, Baton Rouge, Louisiana, February 25–27, 1981

Bottcher, C., D. C. Griffin, and M. S. Pindzola, "Contributions of Autoionization to Electron Impact Ionization of Complex Ions."

Crandall, D. H., R. A. Phaneuf, R. A. Falk, and G. H. Dunn, "Electron Impact Ionization of Al^{2+} and Si^{3+}."

Planeuf, R. A., "Electron-Capture Cross-Section Measurements for $C^{6+} + H$ at 141 and 221 eV/amu."

Sanibel International Symposium on Atomic, Molecular, and Solid-State Physics, Palm Coast, Florida, March 9–14, 1981

Bottcher, C. (invited talk), "Numerical Solution of the Time-Dependent Schrodinger Equation with Coulomb Interactions."

1981 Particle Accelerator Conference, Washington, D. C., March 11–13, 1981

Ball, J. B. (invited talk), "The New Large Tandem Accelerators," *Bull. Am. Phys. Soc.* **26**, 126 (1981).

Lord, R. S., E. D. Hudson, J. B. Ball, R. M. Beckers, C. A. Ludemann, J. A. Martin, S. W. Mosko, and T. P. Cleary, "Coupled Operation of the Oak Ridge Isochronous Cyclotron and the 25-MV Tandem," *Bull. Am. Phys. Soc.* **26**, 99 (1981).

Martin, J. A., T. P. Cleary, E. D. Hudson, R. S. Lord, P. S. Litherland, G. S. McNeilly, S. W. Schwenterly, and T. A. Welton, "Study for Superconducting Conversion of ORIC to Increase the Energy from 100 to 300 ME/q^2," *Bull. Am. Phys. Soc.* **26**, 100 (1981).

Welton, T. A., "A Rapidly Pulsed Synchrotron for Heavy-Ion Acceleration," *Bull. Am. Phys. Soc.* **26**, 101 (1981).

Welton, T. A., and T. Nichols, "Orbit Dynamics in Isochronous Cyclotrons," *Bull. Am. Phys. Soc.* **26**, 118 (1981).

Ziegler, N. F., "Measurement of the Pulsed-Beam Velocity," *Bull. Am. Phys. Soc.* **26**, 110 (1981).

Ziegler, N. F., E. G. Richardson, J. E. Mann, R. C. Juras, C. M. Jones, J. A. Biggerstaff, and J. A. Benjamin, "Status Report on the Oak Ridge 25-MV Tandem Accelerator," *Bull. Am. Phys. Soc.* **26**, 128 (1981).

German Physical Society, Hamburg, Germany, March 23–27, 1981

Borchert, G. L., O. W. B. Schult, J. Speth, P. G. Hansen, J. B. McGrory, B. Jonson, and H. L. Ravn, "Isotope Shifts of K X-Rays of Lead."

ACS Symposium on Deep-Inelastic Reactions, Atlanta, Georgia, March 30–April 1, 1981

Young, G. R., R. L. Ferguson, A. Gavron, D. C. Hensley, F. E. Obenshain, F. Plasil, A. H. Snell, G. A. Petitt, C. F. Maguire, K. G. Young, and D. G. Sarantites (invited talk), "Equilibrium and Nonequilibrium Light-Particle Emission in Deeply Inelastic Reactions at 8–13 MeV/amu."

International Seminar on Ion (Mainly Heavy)-Atom Collisions, Debrecen, Hungary, March 1981

Reading, J. F., A. L. Ford, and R. L. Becker, "Ion-Atom Collisions: The Symmetric Region."

Atomic Physics Program Contractors' Workshop, Argonne, Illinois, April 1–2, 1981

Dittner, P. F., and W. B. Dress (invited talk), "Merged Electron Heavy-Ion Beams."

Phaneuf, R. A., and D. H. Crandall, "Collisions of Low-Energy Multicharged Ions."

Sellin, I. A., "Charge Transfer to the Continuum by Heavy Ions in Atomic Hydrogen."

U.S.-Mexico Cooperative Joint Workshop on Atomic Physics of Negative Ions, Galindo, Mexico, April 1–4, 1981

Barnett, C. F., "Dissociation and Electron Capture Collisions of Diatomic and Triatomic Hydrogen Ions in H_2 and Xe."

U.S.-Mexico Joint Seminar on the Atomic Physics of Negative Ions, Queretaro, Mexico, April 1–4, 1981

Barnett, C. F. (invited talk), "Formation of Negative Ions from Dissociative Collisions of H_3^+, D_3^+, H_2D^+, and HD_2^+ in H_2."

First European Conference on Atomic Physics, Heidelberg, West Germany, April 6–10, 1981

Meyer, F. W., and H. J. Kim, "Electron Loss from Rydberg States of Atomic Hydrogen in Collisions with Multicharged Ions."

Third International Conference on Electrostatic Accelerator Technology, Oak Ridge, Tennessee, April 13–16, 1981

Auble, R. L., "Radiation Lifetimes and Failure Mechanisms of Carbon Stripper Foils."

Biggerstaff, J. A. (invited talk), "New Developments in Electrostatic Accelerator Control Systems."

Jones, C. M., "The Oak Ridge 25-MV Tandem Accelerator."

American Physical Society, Baltimore, Maryland, April 20–23, 1981

Breinig, M., and I. A. Sellin, "Atom Capture to the Continuum," *Bull. Am. Phys. Soc.* 26, 601 (1981).

Chan, Y. D., D. E. DiGregorio, J. L. C. Ford, Jr., J. Gomez del Campo, M. E. Ortiz, and D. Shapira, "Fusion Cross Sections Induced by $^{10}B + ^{17}O$," *Bull. Am. Phys. Soc.* 26, 554 (1981).

Ford, J. L. C., Jr., R. Novotny, D. Shapira, R. L. Parks, and S. T. Thornton, "A Windowless Supersonic Gas-Jet Target for Heavy Ions," *Bull. Am. Phys. Soc.* 26, 595 (1981).

Fulmer, C. B., R. L. Auble, J. B. Ball, F. E. Bertrand, E. E. Gross, D. C. Hensley, S. Mukhopadhyay, and G. R. Satchler, "^{11}B Scattering at 79.6 MeV," *Bull. Am. Phys. Soc.* 26, 553 (1981).

Goodman, C. D., C. C. Foster, D. E. Bainum, C. Gaarde, J. Larsen, C. A. Goulding, D. J. Horen, T. Masterson, J. Rapaport, T. N. Taddeucci, and E. Sugarbaker, "The Reaction $^{14}C(p,n)\,^{14}N$ and Missing GT Strength," *Bull. Am. Phys. Soc.* 26, 634 (1981).

Goulding, C. A. C. D. Goodman, C. C. Foster, J. Rapaport, T. Taddeucci, E. Sugarbaker, C. Gaarde, J. Larsen, D. Horen, and T. Masterson, "Asymmetry Measurements of the (p,n) Reaction on Carbon Isotopes at $E_p = 160$ MeV," *Bull. Am. Phys. Soc.* 26, 623 (1981).

Hicks, R. S., R. L. Huffman, R. Lindgren, B. Parker, G. A. Peterson, S. Raman, and C. P. Sargent, "Evidence for Enhanced Electric Currents in ^{208}Pb," *Bull. Am. Phys. Soc.* 26, 591 (1981).

Horen, D. J., C. D. Goodman, J. Rapaport, T. N. Tuddeucci, C. Gaarde, D. E. Bainum, C. A. Goulding, M. B. Greenfield, E. Sugarbaker, T. Masterson, S. M. Austin, A. Galonsky, and W. Sterrenberg, "Energy Systematics of the Giant GT and the $L = 1$, $S = 1$ Resonances for $A \geqslant 90$," *Bull. Am. Phys. Soc.* 26, 535 (1981).

McGrory, J. B., and B. H. Wildenthal, "A Shell-Model Description of Giant *M*1 States in Even-Even Calcium Isotopes," *Bull. Am. Phys. Soc.* **26**, 609 (1981).

Novotny, R., Y. D. Chan, K. A. Erb, J. L. C. Ford, Jr., D. Shapira, J. D. Moses, and J. C. Peng, "^{28}Se + ^{12}C Reaction Products at Backward Angles," *Bull. Am. Phys. Soc.* **26**, 611 (1981).

Obenshain, F. E., F. E. Bertrand, M. Blecher, R. L. Burman, R. D. Edge, K. Gotow, E. E. Gross, M. Hamm, M. J. Leitch, M. A. Moinester, B. M. Preedom, R. P. Redwine, and J. R. Wu, "Positive Pion-Nucleus Elastic Scattering at 20 MeV," *Bull. Am. Phys. Soc.* **26**, 581 (1981).

Petitt, G. A., A. Gavron, J. R. Beene, B. Cheynis, R. L. Ferguson, F. E. Obenshain, F. Plasil, G. R. Young, M. Jääskeläinen, D. G. Sarantites and C. F. Maguire, "Neutron Emission Measurements in the Reactions ^{12}C + ^{158}Gd and ^{20}Ne + ^{150}Nd at 177 and 249 MeV," *Bull. Am. Phys. Soc.* **26**, 539 (1981).

Raman, S., O. Shahal, and G. G. Slaughter, "Test of Axel-Brink Predictions by a Discrete Approach to Resonance-Averaged Spectroscopy," *Bull. Am. Phys. Soc.* **26**, 535 (1981).

Rhoades-Brown, M., M. Guidry, R. Neese, and R. Donangelo, "Comparison of the Quantum and Classical *S*-Matrix Approach to Heavy-Ion Inelastic Scattering," *Bull. Am. Phys. Soc.* **26**, 623 (1981).

Riedinger, L. L., W. K. Luk, H. Ower, S. Frauendorf, D. R. Haenni, S. A. Hjorth, N. R. Johnson, and I. Y. Lee, "High-Spin States in ^{164}Hf," *Bull. Am. Phys. Soc.* **26**, 620 (1981).

Sandhya Devi, K. R., M. R. Strayer, K. T. R. Davies, A. Dhar, and S. E Koonin, "Prompt Emission of Particles in TDHF Calculations," *Bull. Am. Phys. Soc.* **26**, 591 (1981).

Schauer, M. M., M. Breinig, I. A. Sellin, S. B. Elston, C. R. Vane, R. S. Thoe, M. Suter, and R. Laubert, "Systematic Study of Electron Loss Cusps in the Velocity Range 7–12.5 A.U.," *Bull. Am. Phys. Soc.* **26**, 602 (1981).

Shapira, D., Y. D. Chan, K. A. Erb, J. L. C. Ford, Jr., R. Novotny, J. D. Moses, and J. C. Peng, "Excitation Functions for ^{28}Si + ^{12}C Reaction Products," *Bull. Am. Phys. Soc.* **26**, 611 (1981).

Silk, J. D., H. D. Holmgren, K. Van Bibber, D. L. Hendrie, T. J. Symons, G. D. Westfall, P. H. Stelson, S. Raman, R. L. Auble, and J. R. Wu, "Fragmentation of ^{16}O Projectiles at 100 MeV per Nucleon," *Bull. Am. Phys. Soc.* **26**, 540 (1981).

Soundranyagan, R., S. Ramavataram, A. V. Ramayya, J. H. Hamilton, and R. L. Robinson, "Two-Quasiparticle-Plus-Rotor-Model Calculations of ^{76,78,80}Kr," *Bull. Am. Phys. Soc.* **26**, 538 (1981).

Sugarbaker, E., D. Lind, T. Masterson, C. D. Goodman, C. C. Foster, D. J. Horen, J. Rapaport, T. Taddeucci, C. Goulding, M. Greenfield, D. Bainum, A. Galonsky, S. Austin, W. Sterrenburg, C. Gaarde, and J. Larsen, "Isovector Giant Resonances Observed in ^{112,116,124}Sn(p,n) Reactions at Intermediate Energies," *Bull. Am. Phys. Soc.* **26**, 535 (1981).

Taddeucci, T. N., J. Rapaport, D. E. Bainum, C. C. Foster, C. D. Goodman, C. Gaarde, J. Larsen, C. A. Goulding, M. B. Greenfield, D. J. Horen, T. Masterson, and E. Sugarbaker, "Neutrons Produced by Quasi-Free Scattering of Protons at 160 MeV and 200 MeV," *Bull. Am. Phys. Soc.* **26**, 636 (1981).

Wong, C. Y., "Giant Isovector, Spin Vector, and Spin-Isovector Multipole Resonances as Elastic Vibrations," *Bull. Am. Phys. Soc.* **26**, 536 (1981).

Yamada, H., A. V. Ramayya, C. F. Maguire, J. H. Hamilton, D. C. Hensley, M. L. Halbert, R. L. Robinson, F. E. Bertrand, and R. Woodward, "Partial Fusion Reactions Accompanying Proton, Deuteron, and Triton Emissions," *Bull. Am. Phys. Soc.* **26**, 554 (1981).

Young, G. R., J. B. Ball, F. E. Bertrand, B. Cheynis, R. L. Ferguson, I. Y. Lee, R. Novotny, F. E. Obenshain, D. Pelte, F. Plasil, R. L. Robinson, C. F. Maguire, and G. A. Petitt, "Coincident Light-Ion Spectra from Reactions of 204-MeV ^{16}O + ^{93}Nb," *Bull. Am. Phys. Soc.* **26**, 539 (1981).

Second Workshop on Grand Unification, Ann Arbor, Michigan, April 24–25, 1981

Cohn, H. O., T. A. Gabriel, R. A. Lillie, P. D. Miller, F. E. Obenshain, R. R. Spencer, G. R. Young, M. S. Goodman, R. Wilson, W. M. Bugg, G. T. Condo, T. Handler, and E. L. Hart, "A Sensitive Search for Neutron-Antineutron Mixing."

12. General Information

Prepared by R. L. Becker, L. J. Hawkins, J. Helton, W. L. Stair, and C. R. Wallace

SCIENTIFIC PERSONNEL

The research personnel of the Physics Division are separated here into staff, guests (including students), and consultants. Information is given regarding staff changes (new members, transfers to other divisions, and terminations), temporary assignments of staff members to other institutions, guests (including graduate students) from abroad and from U.S. institutions, undergraduate students, consultants under contract with ORNL, and consultants under contract with Oak Ridge Associated Universities (ORAU).

Staff Changes

J. K. Bair (HHIRF — Tandem Accelerator) — Retired in December 1979

C. E. Bemis (Macroscopic Reaction Studies) — Transferred from Chemistry Division to Physics Division in March 1979

R. A. Broglia (Theoretical Physics)—With Niels Bohr Institute; completed temporary appointment in May 1980; also, began three-month appointment in April 1981

T. A. Carlson (Electron Spectroscopy) — Transferred from Physics Division to Chemistry Division in March 1979

R. F. Carlton (Oak Ridge Electron Linear Accelerator) — With Middle Tennessee State University; completed temporary part-time appointment in July 1980

Y. Chan (Microscopic Reaction Studies) — Formerly with University of Washington; began two-year appointment in September 1979

H. L. Dickerson (ORIC Operations) — Retired in December 1979

D. E. DiGregorio (Microscopic Reaction Studies) —With Commisión Nacional de Energia Atomica in Buenos Aires; began two-year appointment in September 1979

P. F. Dittner (Heavy-Ion Atomic Physics) — Transferred from Chemistry Division to Physics Division in November 1979

S. Elston (High-Energy Atomic Physics) — With University of Tennessee; began part-time appointment in September 1979

K. A. Erb (Microscopic Reaction Studies) — Formerly with Yale University; began appointment in August 1980

R. L. Ferguson (Macroscopic Reaction Studies) — Transferred from Chemistry Division to Physics Division in June 1979

M. P. Fewell (Nuclear Structure Studies) — Formerly with Yale University; began two-year appointment in February 1981

L. A. Ford (Theoretical Physics) — With Texas A&M University; completed temporary summer employment in August 1979

A. I. Gavron (Macroscopic Reaction Studies) — From Weizmann Institute in Rehovot, Israel; resigned in July 1980 and now with Los Alamos National Laboratory

C. D. Goodman (Microscopic Reaction Studies) — Retired in February 1980 and now with Indiana University Cyclotron Facility

D. C. Gregory (Atomic Collisions) — Formerly with Brookhaven National Laboratory; began two-year appointment in December 1980

F. A. Grimm (Electron Spectroscopy) — With University of Tennessee; transferred from Physics Division to Chemistry Division in March 1979

M. W. Guidry (Nuclear Structure Studies) — With University of Tennessee; terminated part-time appointment in July 1979; resumed part-time appointment in August 1980

D. R. Haenni (Microscopic Reaction Studies) — Resigned in December 1980 and now with Texas A&M University

J. S. Hattula (Nuclear Structure Studies) — With University of Jyvaskyla in Finland; began part-time appointment in September 1980

S. A. Hjorth (Nuclear Structure Studies) — With Research Institute of Physics in Stockholm; completed temporary appointment in September 1980

W. A. Huber (Atomic Theory) — With Columbia University; completed appointment as ORNL Summer Intern in August 1979

A. Z. Hussein (Oak Ridge Electron Linear Accelerator) — With Cairo University; completed one-year appointment in January 1981

N. R. Johnson (Nuclear Structure Studies) — Transferred from Chemistry Division to Physics Division in June 1979

S. Kahane (Oak Ridge Electron Linear Accelerator) — With Nuclear Research Centre in Negev, Israel; began one-year appointment in August 1980

M. W. Lucas (Heavy-Ion Atomic Physics) — With University of Sussex in England; completed one-year appointment in August 1979

C. H. Ma (MFE Diagnostic Development) — Formerly with University of Mississippi; completed summer appointment in August 1979; began two-year appointment in June 1980

P. G. McQueen (High-Energy Atomic Physics) — With University of Tennessee; completed appointment as ORNL Summer Intern in August 1979

D. M. Moltz (Nuclear Structure Studies) — Formerly with University of California at Berkeley; began two-year appointment in October 1979

S. Mukhopadhyay (Theoretical Physics) — With Khalsa College in Bombay, India; began temporary appointment in October 1980

R. W. Novotny (Microscopic Reaction Studies) — Formerly with University of Heidelberg in Germany; began two-year appointment in March 1980

V. E. Oberacker (Theoretical Physics) — Formerly with Frankfurt University in Germany; completed temporary appointment in August 1980 (now with Vanderbilt University

M. S. Ortiz (Microscopic Reaction Studies) — With National University of Mexico in Mexico City; completed temporary appointment in September 1980

D. J. Pegg (Heavy-Ion Atomic Physics) — With University of Tennessee; began part-time appointment in April 1979

D. Pelte (Macroscopic Reaction Studies) — With University of Heidelberg in Germany; completed temporary appointment in October 1980

S. Ramavataram (Nuclear Data Project) — Formerly with University of Laval in Quebec, Canada; completed part-time employment in September 1980 (now with Brookhaven National Laboratory)

J. A. Ray (MFE Diagnostic Development) — Transferred from Physics Division to Instrumentation and Controls Division in February 1980

J. F. Reading (Atomic Theory) — With Texas A&M University; completed summer appointment in September 1979

M. J. Rhoades-Brown (Nuclear Theory) — Formerly with Argonne National Laboratory; began two-year appointment in October 1980

L. L. Riedinger (Nuclear Structure Studies) — With University of Tennessee; began part-time appointment in September 1979

D. G. Sarantites (Nuclear Structure Studies) — With Washington University at St. Louis; completed summer appointment in August 1979

J. P. F. Sellschop (Heavy-Ion Atomic Physics) — With University of Witwatersrand in South Africa; completed temporary appointment in January 1980

O. Shahal (Oak Ridge Electron Linear Accelerator) — With Nuclear Research Center in Negev, Israel; completed one-year appointment in August 1980

T. P. Sjoreen (Microscopic Reaction Studies) — Formerly with Indiana University Cyclotron Facility; began two-year appointment in December 1980

M. P. Slusher (Nuclear Structure Studies) — With University of Missouri; completed appointment as ORNL Summer Intern in August 1979

R. G. Stokstad (Microscopic Reaction Studies) — Resigned in February 1980 (now with Lawrence Berkeley Laboratory)

R. S. Thoe (High-Energy Atomic Physics) — Formerly with University of Tennessee; resigned part-time appointment in December 1980 (now with Lawrence Livermore Laboratory)

J. O. Thomson (Electron Spectroscopy) — Transferred from Physics Division to Chemistry Division in March 1979

C. Toepffer (Theoretical Physics) — With University of Witwatersrand in South Africa; completed temporary appointment in March 1979

C. R. Vane (Applications of Heavy-Ion Beams) — Formerly with Lawrence Berkeley Laboratory; began two-year appointment in January 1981

D. C. Weisser (HHIRF) — With National University of Australia in Canberra; completed temporary appointment in January 1980

J. C. Wells (Nuclear Structure Studies) — With Tennessee Technological University; summer appointment (Oak Ridge Linear Accelerator) in 1980; began part-time appointment in September 1980

S. S. Willenbrock (Theoretical Physics) — With Princeton University; completed appointment as ORNL Summer Intern in August 1980

R. R. Winters (Oak Ridge Electron Linear Accelerator) — With Denison University; completed temporary appointment in December 1979

J. R. Wu (Microscopic Reaction Studies) — From University of Maryland; completed temporary appointment in June 1980 (now with Bell Laboratories)

Temporary Assignment of Staff Members Elsewhere

Y. Ellis-Akovali (Nuclear Data Project) — Assigned to Lawrence Berkeley Laboratory, September 1980–August 1981

W. B. Ewbank — On loan to the UCCND Management Information Systems Office, October 1980–March 1981; on loan to the Information Division, beginning in April 1981

E. C. Halbert (Theoretical Physics) — Assigned to the ORNL Energy Division, on loan beginning in April 1980

R. L. Macklin (Oak Ridge Electron Linear Accelerator) — On leave to the French Atomic Energy Commission at Bruyeres-le-Chatel, France, February 1980–May 1980

J. B. McGrory (Theoretical Physics) — Assigned to Gellschaft für Schwerionenforschung (GSI) in Darmstadt, West Germany, June 1979–August 1979

S. Raman (Oak Ridge Electron Linear Accelerator) – Assigned to the Central Bureau for Nuclear Measurements, Geel, Belgium, June 1980–August 1980

T. A. Welton (Theoretical Physics) — On leave to the Institute for Theoretical Physics of the University of Frankfurt in Germany as recipient of Humboldt Senior American Scientist Award, May 1980–October 1980 and also March 1980 – September 1981

Research Participants from Abroad

A. Asadi-Khomami (HHIRF) — With Atomic Energy Organization of Iran in Tehran, Iran

D. R. Bes (Theoretical Physics) — With Comisión Nacional de Energía Atomica in Buenos Aires, Argentina

J. Blachot (Nuclear Data Project) — With Commissariat a l'Energie Atomique in Grenoble, France

A. E. Ceballos (25-MV Tandem Accelerator) — With Comisión Nacional de Energía Atomica in Buenos Aires, Argentina

Y. Chen (Nuclear Structure Studies) — With Institute of Atomic Energy in Peking China and also the University of Tennessee

B. P. Cheynis (Macroscopic Reaction Studies) — With Institút de Physique Nucléaire in Villeurbanne, France

C. Cisneros (Atomic Collisions) — With National University of Mexico in Mexico City, Mexico

N. M. Clarke (Microscopic Reaction Studies) — With Wheatstone Laboratory, King's College in London, England

C. Coceva (Oak Ridge Electron Linear Accelerator) — With Comitato Nazionale per l'Energia Nucleare, Bologna, Italy

A. A. Dacal (HHIRF-Heavy-Ion Research) — With Universiad Nacional Autonoma in Mexico

C. H. Dasso (Theoretical Physics) — With NORDITA in Copenhagen, Denmark

R. J. Donangelo (Theoretical Physics) — With University of Rio de Janeiro in Brazil

T. Dφssing (Theoretical Physics) — With NORDITA in Copenhagen, Denmark

P. L. Ekstrom (Nuclear Data Project) — With University of Liverpool in England

M. El-Azab (Theoretical Physics) — With Faculty of Science at Assiut University in Egypt

N. A. Fazzini (25-MV Tandem Accelerator) — With Argentine Atomic Energy Commission in Buenos Aires, Argentina

D. H. Feng (Theoretical Physics) — With Niels Bohr Institute in Copenhagen, Denmark, and Drexel University

L. Ferreira (Theoretical Physics) — With University of Coimbra in Portugal

B. Fogelberg (Oak Ridge Electron Linear Accelerator) — With Studsvik Science Research Laboratory in Nyköping, Sweden

S. G. Frauendorf (Nuclear Structure Studies) — With Central Institute for Nuclear Research, Academy of Science in Dresden, East Germany, and also the University of Tennessee

M. L. Gaillard (UNISOR) — With Centre National de la Recherche Scientifique in Villeurbanne, France, and also the University of Tennessee

M. Ghanbari (Total Cross Sections and Angular Distributions) — With Atomic Energy Organization of Iran in Tehran, Iran

A. Gobbi (Microscopic Reaction Studies) — With Gesellschaft für Schwerionenforschung in Darmstadt, West Germany

H. Gonzalez (25-MV Tandem Accelerator) — With Comisión Nacional de Energía Atomica in Buenos Aires, Argentina

U. Heinz (Theoretical Physics) — With Frankfurt University in Germany

R. M. Holmes (Heavy-Ion Atomic Physics) — From University of Reading, United Kingdom; with the University of Tennessee

S. Huldt (Heavy-Ion Atomic Physics) — From Lund University, Sweden; with the University of Tennessee

C. Jiang (Macroscopic Reaction Studies) — With Institute of Atomic Energy in Peking, China

F. Kearns (Nuclear Data Project — With University of Liverpool in England

J. Kirsch (Theoretical Physics) — With Frankfurt University in Germany

H. Knudsen (Heavy-Ion Atomic Physics) — With University of Aarhus in Aarhus, Denmark

H. Kröger (Theoretical Physics) — With Justus-Liebig University in Giessen, W. Germany

R. Latz (Heavy-Ion Atomic Physics) — From Goethe University, Frankfurt am Main, W. Germany; with the University of Tennessee

G. A. Leander (UNISOR) — With Lund University in Sweden

R. M. Lieder (Nuclear Structure Studies) — With Institut für Kernphysik Kernforschungsanlage in Jülich, W. Germany

L. I. Liljeby (Heavy-Ion Atomic Physics) — From Royal Institute of Technology, Stockholm, Sweden; with the University of Tennessee

T. Lindblad (Nuclear Structure Studies) — With Research Institute of Physics in Stockholm, Sweden

E. Maglione (Theoretical Physics) — With Niels Bohr Institute in Copenhagen, Denmark

C. C. Mahaux (Oak Ridge Electron Linear Accelerator) — With University of Liege in Belgium

B. Mahdavian (Neutron Capture) — With Atomic Energy Organization of Iran in Tehran, Iran

J. N. Mo (Nuclear Data Project) — With University of Manchester in England

J. A. Nicolai (25-MV Tandem Accelerator) — With Comisión Nacional de Energía Atomica in Buenos Aires, Argentina

F. R. Pougheon (Macroscopic Reaction Studies) — With University of Paris in France

P-G. Reinhard (Theoretical Physics) — With Deutsche Forschungsgemeinschaft in Bonn, Germany

J. J. Rossi (25-MV Tandem Accelerator) — With Comisión Nacional de Energía Atomica in Buenos Aires, Argentina

C. P. Roulet (Nuclear Structure Studies) — With Center of Research for Nuclear Physics in Orsay, France

J. P. Rozet (Heavy-Ion Atomic Physics) — From Université P. et M. Curie, Paris; with the University of Tennessee

B. Singh (Nuclear Data Project) — With Kuwait University in Kuwait

U. Smilansky (Microscopic Reaction Studies) — With Weizmann Institute for Science in Rehovot, Israel

H. M. Soffel (Theoretical Physics) — With Frankfurt University in Germany

M. Suter (Heavy-Ion Atomic Physics) — With ETH in Zurich, Switzerland

D. A. Taylor (Heavy-Ion Atomic Physics) — From University of Reading, United Kingdom; with the University of Tennessee

J. W. Tepel (Nuclear Data Project) — With Fachinformationszentrum Energie Physik Mathematik in Karlsruhe, W. Germany

A. van der Woude (Microscopic Reaction Studies) — With Kernfysisch Versneller Instituut in Groningen, The Netherlands

D. A. Viggars (Nuclear Data Project) — With Kuwait University in Kuwait

A. Vitturi (Theoretical Physics) — With Instituto di Fisica Galileo Galilei in Padova, Italy

L. A. Westerberg (Macroscopic Reaction Studies) — With University of Uppsala in Sweden

A. Winther (Theoretical Physics) — With Niels Bohr Institute in Copenhagen, Denmark

R. K. Wolfe (Theoretical Physics) — With Justus Liebig Universitat in Giessen, W. Germany

Research Participants from the United States

P. B. Adams (EN Tandem Operations) — From Corning Glass Works

A. Y. Ahmed (25-MV Tandem Accelerator) — From Vanderbilt University

A. M. D. Amarakoon (UNISOR) — From Louisiana State University

M. C. Andrews (Heavy-Ion Atomic Physics) — From North Texas State University

G. Auchampaugh (Oak Ridge Electron Linear Accelerator) — From Los Alamos National Laboratory

J. H. Barker (Macroscopic Reaction Studies) — From Saint Louis University

P. M. Barlow (High-Energy Physics) — From Florida State University

S. D. Belić (Atomic Collisions) — From JILA, University of Colorado

S. D. Berry (Heavy-Ion Atomic Physics) — From the University of Tennessee

R. P. Bhalla (Heavy-Ion Atomic Physics) — From North Texas State University

M. Blecher (Microscopic Reaction Studies) — From Virginia Polytechnic Institute and State University

G. L. Bomar (Microscopic Reaction Studies) — From Vanderbilt University

M. Breinig (Heavy-Ion Atomic Physics) — From the University of Tennessee

F. J. Breyer (EN Tandem Operations) — From North Texas State University

L. B. Bridwell (Heavy-Ion Atomic Physics) — From Murray State University

M. D. Brown (EN Tandem Operations) — From Naval Surface Weapons

W. S. Burns (Heavy-Ion Atomic Physics) — With Texas A&M University

R. F. Carlton (Oak Ridge Electron Linear Accelerator) — From Middle Tennessee State University

H. K. Carter (UNISOR) — From Oak Ridge Associated Universities

J. L. Carvalho (Nuclear Structure Studies) — From Michigan State University

R. K. Clark (High-Energy Physics) — From Florida State University

J. D. Cole (UNISOR) — From Louisiana State University

R. M. DeVries (Microscopic Reaction Studies) — From Los Alamos National Laboratory

F. A. Dilmanian (Macroscopic Reaction Studies) — From Washington University

G. Dixon (Heavy-Ion Atomic Physics) — From the University of Tennessee

D. M. Drake (Oak Ridge Electron Linear Accelerator) — From Los Alamos National Laboratory

G. H. Dunn (Atomic Collisions) — From JILA, University of Colorado

R. A. Falk (Atomic Collisions) — From JILA, University of Colorado

D. H. Feng (Theoretical Physics) — From Drexel University

J. P. Forester (Heavy-Ion Atomic Physics) — From the University of Tennessee

J. Gaiser (Macroscopic Reaction Studies) — From Auburn University

J. Garg (Oak Ridge Electron Linear Accelerator) — From State University of New York at Albany

A. I. Gavron (Macroscopic Reaction Studies) — From Los Alamos National Laboratory

C. Gelbke (Macroscopic Reaction Studies) — From Michigan State University

K. A. Geoffroy (Macroscopic Reaction Studies) — From Washington University

G. A. Glass (Heavy-Ion Atomic Physics) — From the University of Tennessee

M. S. Goodman (High-Energy Physics) — From Harvard University

K. Gotow (Microscopic Reaction Studies) — From Virginia Polytechnic Institute and State University

D. C. Griffin (Theoretical Physics) — From Rollins College

A. H. Hamdi (Heavy-Ion Atomic Physics) — From North Texas State University

J. H. Hamilton (25-MV Tandem Accelerator and UNISOR) — From Vanderbilt University

T. Handler (High-Energy Physics) — From the University of Tennessee

H. J. Hargis (High-Energy Physics) — From the University of Tennessee

H. C. Hayden (Heavy-Ion Atomic Physics) — From the University of Tennessee

R. H. Hughes (Atomic Collisions) — From the University of Arkansas

M. E. Jääskeläinen (Macroscopic Reaction Studies) — From Washington University

M. G. Justice (EN Tandem Operations) — From Pennsylvania State University

J. Kasagi (Nuclear Structure Studies) — From Michigan State University

G. Lapicki (Oak Ridge Electron Linear Accelerator) — From Northwestern Louisiana State University

R. Laubert (Heavy-Ion Atomic Physics) — From the University of Tennessee and New York University, and then East Carolina University, now deceased

P. W. Lisowski (Oak Ridge Electron Linear Accelerator) — From Los Alamos National Laboratory

W. K. Luk (Nuclear Structure Studies) — From the University of Tennessee

F. D. McDaniel (Heavy-Ion Atomic Physics) — From North Texas State University

R. Mehta (EN Tandem Operations) — From North Texas State University

R. L. Mlekodaj (UNISOR) — From Oak Ridge Associated Universities

J. D. Moses (Oak Ridge Electron Linear Accelerator) — From Los Alamos National Laboratory

R. E. Neese (Nuclear Structure Studies) — From the University of Tennessee

C. W. Ng (Microscopic Reaction Studies) — From Virginia Polytechnic Institute and State University

T. L. Nichols (UNISOR) — From the University of Tennessee

H. Noma (UNISOR) — From the University of South Carolina

H. Ower (Nuclear Structure Studies) — From the University of Tennessee

R. L. Parks (Microscopic Reaction Studies) — From the University of Virginia

R. Peterson (Heavy-Ion Atomic Physics) — From the University of Connecticut

G. A. Petitt (Macroscopic Reaction Studies) — From Georgia State University

M. S. Pindzola (Atomic Collisions) — From Auburn University, ORAU Research Participant

B. M. Preedeom (Microscopic Reaction Studies) — From the University of South Carolina

P. V. Rao (UNISOR) — From Emory University

B. G. Ritchie (UNISOR) — From the University of South Carolina

C. R. Ross (EN Tandem Operations) — From Pennsylvania State University

Y. Sangsingkeow (EN Tandem Operations) — From North Texas State University

D. G. Sarantites (Macroscopic Reaction Studies) — From Washington University

G. A. Smith (EN Tandem Operations) — From Pennsylvania State University

R. Soundranayagam (UNISOR) — From Vanderbilt University

D. C. Sousa (UNISOR) — From the University of Tennessee

E. H. Spejewski (UNISOR) — From Oak Ridge Associated Universities

Y. S. Su (EN Tandem Operations) — From Corning Glass Works

H. Tang (Theoretical Physics) — From Yale University

C. N. Thomas (HHIRF Experimental Facilities) — From Oak Ridge Associated Universities

T. M. Thomas (Electron Spectroscopy) — From the University of Tennessee

S. T. Thornton (EN Tandem Operations) — From the University of Virginia

S. Tong (EN Tandem Operations) — From Corning Glass Works

J. van der Plicht (Macroscopic Reaction Studies) — From Los Alamos National Laboratory

R. Vane (Heavy-Ion Atomic Physics) — From the University of Tennessee

S. L. Varghese (Oak Ridge Electron Linear Accelerator) — From the University of South Alabama

J. A. Vrba (Microscopic Reaction Studies) — From the University of Tennessee

K. E. Wikstrom (Macroscopic Reaction Studies) — From Washington University

L. E. Williams (EN Tandem Operations) — From the University of Tennessee

R. Wilson (EN Tandem Operations) — From Harvard University)

R. R. Winters (Oak Ridge Electron Linear Accelerator) — From Denison University

J. L. Wood (UNISOR) — From Georgia Institute of Technology

R. F. Woodward (Macroscopic Reaction Studies) — From Washington University

H. Yamada (Nuclear Structure Studies) — From Vanderbilt University

S. W. Yates (Nuclear Structure Studies) — From the University of Kentucky

Undergraduate Students

J. D. Blizzard (Holifield Heavy-Ion Research Facility, Accelerator Development — From Millsaps College; Southern Colleges and Universities Union (SCUU) Science Semester at ORNL, January–April 1981

E. D. Blodgett (Microscopic Reaction Studies) — From the University of Wisconsin; 1979 ORAU Student Research Participant at ORNL.

R. Doerner (EN Tandem Operations) — From Texas A&M University

S. P. Ducharme (Macroscopic Reaction Studies) — From the University of Lowell; 1980 ORAU Student Research Participant at ORNL

B. A. Ely (Atomic Collisions) — From Stetson University; 1979 ORAU Student Research Participant at ORNL

B. D. Ewbank (Nuclear Data Project) — From Washington University

S. M. Fetzer (Macroscopic Reaction Studies) — From North Texas State University; 1980 ORAU Student Research Participant at ORNL

S. V. Greene (EN Tandem Operations) — From the University of Tennessee; ORNL Co-op Program

D. A. Hileman (High-Energy Physics) — From the University of Tennessee

J. A. Katz (MFE Diagnostic Development) — From Earlham College; 1980 ORAU Student Research Participant at ORNL

M. Lacerna (Oak Ridge Electron Linear Accelerator) — From Denison University

R. Megson (High-Energy Physics) — From the University of Tennessee

P. L. Melvin (Heavy-Ion Atomic Physics) — From Murray State University; 1979 ORAU Student Research Participant at ORNL

S. T. Milner (Theoretical Physics) — From Vanderbilt University

C. L. Moore (Oak Ridge Electron Linear Accelerator) — From Roberts Wesleyan College; 1979 ORAU Student Research Participant

J. K. Moyle (Negative-Ion Source Development) — From the University of Lowell; 1980 ORAU Student Research Participant at ORNL

C. D. Myre (Macroscopic Reaction Studies) — From Vanderbilt University; 1979 ORAU Student Research Participant at ORNL

T. Narten (Heavy-Ion Atomic Physics) — From the University of Tennessee

A. L. Paige (Heavy-Ion Atomic Physics) — From the University of Tennessee

N. L. Rodning (Negative-Ion Source Development) — From Concordia College; 1979 ORAU Student Research Participant at ORNL

M. Schauer (Heavy-Ion Atomic Physics) — From the University of Tennessee

J. F. Stiefel (Nuclear Physics Research) — From the University of Tennessee

E. Watson (High-Energy Physics) — From the University of Tennessee

A. L. Wintenberg (EN Tandem Operations) — From the University of Tennessee; ORNL Co-op Program

R. A. Wykoff (High-Energy Physics) — From the University of Tennessee

ORNL Consultants

G. F. Bertsch (Theoretical Physics) — From Michigan State University

D. M. Brink (Theoretical Physics) — From the University of Oxford in Oxford, England

D. A. Bromley (Nuclear Physics Research) — From Yale University

B. Castel (Oak Ridge Electron Linear Accelerator) — From Queen's University in Kingston, Ontario, Canada

T. P. Cleary (Oak Ridge Isochronous Cyclotron) — From World Information and Technology Systems Corporation

R. Y. Cusson (Theoretical Physics) — From Duke University

C. H. Dasso (Theoretical Physics) — From Niels Bohr Institute in Copenhagen, Denmark

R. A. Dayras (Nuclear Physics Research) — From Centre de'Etudes Nucleaires in Saclay, France

L. S. Ferreira (Theoretical Physics) — From Universidade de Coimbra in Coimbra, Portugal

C. Feuillade (Theoretical Physics) — From Manchester University in Manchester, England

J. L. Fowler (Oak Ridge Electron Linear Accelerator) — ORNL retiree; also, part-time Professor with the University of Tennessee

S. L. A. Huldt (Heavy-Ion Atomic Physics) — From the University of Tennessee

B. Gilbody (Atomic Collisions) — From Queen's University in Belfast, Ireland

W. Greiner (Theoretical Physics) — From the University of Frankfurt in Frankfurt, Germany

F. Iachello (Theoretical Physics) — From Yale University

A. K. Kerman (Theoretical Physics) — From the Massachusetts Institute of Technology

S. E. Koonin (Theoretical Physics) — From the California Institute of Technology

W. G. Love (Theoretical Physics) — From the University of Georgia

C. F. Maguire (Macroscopic Reaction Studies) — From Vanderbilt University

J. A. Maruhn (Theoretical Physics) — From Frankfurt University in Frankfurt, Germany

E. McDaniels (Atomic Collisions) — From the Georgia Institute of Technology

R. H. McKnight (Atomic Cross-Sections Compilations) — From the University of Virginia

T. J. Morgan (Atomic Cross-Sections Compilations) — From Wesleyan University

V. E. Oberacker (Theoretical Physics) — From Vanderbilt University

M. S. Pindzola (Atomic Collisions) — From Auburn University

W. T. Pinkston (Theoretical Physics) — From Vanderbilt University

G. Poilarolo (Theoretical Physics) — From the University of Torino in Torino, Italy

J. F. Reading (Theoretical Physics) — From Texas A&M University

A. B. Ritchie (Electron Spectroscopy) — From the University of Alabama

A. Russek (Atomic Collisions) — From the University of Connecticut

V. Sidis (Theoretical Physics) — From the University of Paris-Sud in Orsay, France

A. J. Sierk (Theoretical Physics) — From Los Alamos National Laboratory

A. H. Snell (Nuclear Physics Research) — ORNL retiree

M. R. Strayer (Theoretical Physics) — From Yale University

D. M. Thomas (MFE Diagnostic Development) — From the University of Texas

E. W. Thomas (Atomic Collisions) — From the Georgia Institute of Technology

A. Vitturi (Theoretical Physics) — From the University of Padova in Padova, Italy

ORAU Consultants

Many university and college faculty members and graduate students visited the Physics Division for consultation and collaboration during 1979–April 1981 through arrangements with Oak Ridge Associated Universities. These individuals and their affiliations are listed below.

Albridge, R. G., Vanderbilt University

Amarakoon, M. D., Louisiana State University

Andrews, M. C., North Texas State University

Antar, A. A., University of Connecticut

Avignone, F. T., III, University of South Carolina

Azziz, N. J., University of Puerto Rico at Mayaguez

Baker, F. T., University of Georgia

Barclay, M. E., Vanderbilt University

Barker, J. H., Saint Louis University

Blankenbecler, R., Stanford University

Braga, R. A., Georgia Institute of Technology

Brantley, W. H., Furman University

Bridwell, L. B., Murray State University

Burns, W. S., Texas A&M University

Chaturvedi, R. P., State University of New York at Cortland

Church, D., Texas A&M University

Cipolla, S. J., Creighton University

Duggan, J. L., North Texas State University

Edge, R. D., University of South Carolina

Feng, D. H., Drexel University

Fink, R. W., Georgia Institute of Technology

Ford, A. L., Texas A&M University

Forester, J. P., University of Tennessee at Chattanooga

Furia, J., Washington University

Gnade, B. E., Georgia Institute of Technology

Greenfield, M. B., Florida A&M University

Griffin, J. J., University of Maryland

Hamilton, J. H., Vanderbilt University
Heil, T. G., University of Georgia
Hughes, R. H., University of Arkansas
Hungerford, E. V., University of Houston
Ijaz, M. A., Virginia Polytechnic Institute & State University
Kenefick, R. A., Texas A&M University
Kern, B. D., University of Kentucky
Kessel, Q. C., University of Connecticut
Krieger, S. J., University of Illinois at Chicago Circle
Kuenhold, K. A., University of Tulsa
Kumar, K., Tennessee Technological University
Laubert, R., East Carolina University (deceased)
Lin, J., Tennessee Technological University
MacDonald, W. M., University of Maryland
MacKellar, A., University of Kentucky
Maguire, C. F., Vanderbilt University
McDaniel, F. D., North Texas State University
Merzbacher, E., University of North Carolina
Natowitz, J. B., Texas A&M University
Nettles, W. G., Vanderbilt University
Parks, R. L., University of Virginia
Peterson, R. S., University of Connecticut
Petitt, G. A., Georgia State University
Piercey, R. B., Vanderbilt University
Pullen, B. P., Southeastern Louisiana University
Ramayya, A. V., Vanderbilt University
Rao, P. V., Emory University
Rayburn, L. A., University of Texas at Arlington
Reading, J. F., Texas A&M University
Ritchie, B. G., University of South Carolina
Robinson, E. L., University of Alabama at Birmingham
Salaita, G. N., Southern Methodist University
Sarantites, D. G., Washington University
Schwaiger, G. P., Georgia Institute of Technology
Semmes, P. B., Georgia Institute of Technology
Silberman, E., Fisk University
Sousa, D. C., Eastern Kentucky University
Strayer, M. R., Texas A&M University
Thornton, S. T., University of Virginia
Varghese, S. L., University of South Alabama
Walkiewicz, T. A., Edinboro State College
Wheeler, R. M., State University of New York at Cortland
Wildenthal, B. H., Michigan State University
Winters. R., Denison University
Wood, J. L., Georgia Institute of Technology
Woodward, R. F., Washington University
Yamada, H., Vanderbilt University
Yates, S. W., University of Kentucky
Zander, A. R., East Texas State University
Zganjar, E. F., Louisiana State University

GRADUATE THESIS RESEARCH

Physics Division staff and associates have served as advisors for graduate students engaged in thesis research with facilities operated at least in part by the Division. In addition to thesis research mentioned in the previous progress report, which extended into the present reporting period, a number of new thesis projects were begun. These are listed below.

Ph.D. Thesis Research

Candidate	Advisor(s)	Thesis title or field of research
A. Y. Ahmed, Vanderbilt University	R. L. Robinson	In-beam gamma-ray spectroscopy of $A \approx 70$ nuclei
A. M. D. Amarakoon, Louisiana State University	E. H. Spejewski	Properties of nuclei in the mass region around $A = 180$

S. D. Berry, University of Tennessee	I. A. Sellin	Accelerator-based atomic collisions experiments
B. Cheynis, University of Tennessee	F. Plasil F. E. Obenshain	Heavy-ion-induced fission
J. L. Carvalho, Michigan State University	N. R. Johnson L. L. Riedinger	Studies of band crossings in high angular momentum states in deformed nuclei
D. E. DiGregorio, National Technical University Buenos Aires, Argentina	F. E. Bertrand J. Gomez del Campo	Heavy-ion fusion reactions
G. A. Glass, University of Tennessee	I. A. Sellin	Accelerator-based atomic collisions experiments
R. E. Neese, University of Tennessee	N. R. Johnson M. W. Guidry	Heavy-ion inelastic scattering from deformed nuclei
T. L. Nichols, University of Tennessee	N. R. Johnson M. W. Guidry	Transfer reactions with very heavy ions populating strongly collective states
R. L. Parks, University of Virginia	J. L. C. Ford, Jr.	Installation and testing and initial experiments with the supersonic gas jet target
B. G. Ritchie, University of South Carolina	E. H. Spejewski	Experimental and theoretical investigations of the decays of ^{206}Fr and ^{208}Fr
D. M. Thomas, University of Texas	D. H. Crandall	Low-energy neutral particle spectrometer for use on Tokamaks

M. S. Thesis Research

W. K. Luk, University of Tennessee	N. R. Johnson L. L. Riedinger	A testing of cranking model predictions for high angular momentum states

MISCELLANEOUS PROFESSIONAL ACTIVITIES OF DIVISIONAL PERSONNEL

The research personnel frequently are involved in professional work incidental to their primary laboratory responsibilities. For example, a majority act as referees for over two dozen scientific journals, principally *The Physical Review*, *Physical Review Letters*, and *Nuclear Physics*. Other activities include those mentioned below.

G. D. Alton — member, Organizational Committee for the 1980 Conference on the Application of Accelerators in Research and Industry

J. B. Ball — member, DOE/NSF Nuclear Sciences Advisory Committee (NUSAC); member, Organizing Committee and chairman for the Third International Conference on Electrostatic Accelerator Technology, April 1981; member, Organizing Committee for 1979 Symposium on Heavy-Ion Physics (BNL); member, ORNL Landscape and Architecture Committee

C. F. Barnett — committee member, American Physical Society Topical Conference on Plasma Diagnostics in High-Temperature Plasmas; committee member, American Physical Society Topical Conference on Atomic Physics in High-Temperature Plasmas; member, National Academy of Science —

National Research Council Committee Atomic and Molecular Physics; member, DOE Personnel Security Review Board

R. L. Becker — part-time faculty member, Department of Physics, University of Tennessee; reviewer of research proposals for the U.S. Department of Energy, Division of Physical Research, and for the National Science Foundation

C. E. Bemis, Jr. — member, users groups of LBL Super HILAC, LAMPF, Indiana University Cyclotron Facility, and BNL Tandem Facility; reviewer, National Science Foundation and Department of Energy contract proposals

F. E. Bertrand — member, APS Division of Nuclear Physics Committee on Nuclear Science Resources; member, Users Groups at the Indiana University Cyclotron, LAMPF and TRIUMF

J. A. Biggerstaff — member, National Instrumentation Methods Committee and three of its subcommittees: the Executive Committee for CAMAC (Computer Automated Management and Control), the Dataway Working Group, and the Fastbus Design Group

C. Bottcher — adjunct professor of physics, Georgia Institute of Technology

C. H. Crandall — member, Seed Money Committee ORNL, March 1978–March 1981; member, General Committee for the International Conference on Electron and Atomic Collisions, July 1977–July 1981; member, Local Committee for the XII ICPEAC, Gatlinburg, June 1980–July 1981; member, Program Committee of the Division of Electron and Atomic Physics of the American Physical Society, December 1978–December 1979; member, Data Center Consultants Network of IAEA Atomic and Molecular Data Unit, May 1979–present

J. W. T. Dabbs — registered Professional Engineer (Tenn. No. 11475); University Relations Coordinator for ORNL and ORAU summer student trainee, graduate student, and faculty research programs, 1979–80, and for the Great Lakes Colleges Association program, 1976–80; member, Editorial Board of Nuclear Instruments and Methods since 1978; member, 1979–80, of the ORNL Selection Committee for Industrial Research Magazine's IR-100 Award entries

S. Datz — member, Organizational Committee for the 1980 Conference on the Application of Accelerators in Research and Industry; member, Executive and General Committees and chairman of the Local Committee of the XII International Conference on the Physics of Electronic and Atomic Collisions

J. L. C. Ford — member, Program Advisory Committee, Brookhaven National Laboratory Tandem Accelerator Facility; member, users groups of LBL Super HILAC, Facility, and Indiana University Cyclotron Facility

J. L. Fowler — organizer, conference chairman, and editor of the Proceedings of the International Conference on Nuclear Cross Sections for Technology (Knoxville, Tenn., Oct. 22–26, 1979); part-time faculty member, Physics Department, University of Tennessee

J. A. Harvey — member, ORNL Accelerators and Radiation Sources Review Committee; labor coordinator, Physics Division; Physics Division coordinator for ORNL Awards Committee; secretary-treasurer, Division of Nuclear Physics of the American Physical Society (1967–81); member, editorial board of the Atomic and Nuclear Data Tables

D. J. Horen — member, Organizing and Program Committees for the Giant Multipole Resonance Topical Conference, Oak Ridge, Tenn. (October 1979); organizer, Workshop on the (p,n) Interaction at Intermediate Energies (ORNL, Mar. 18–20, 1981); Quality Assurance Coordinator, Physics Division (1980–present)

C. H. Johnson — organizer, conference secretary, and editor of the Proceedings of the International Conference on Nuclear Cross Sections for Technology, Knoxville, Tenn. Oct. 22–26, 1979

N. R. Johnson — member, Super-HILAC Users' Executive Committee, 1978–80 (chairman, 1980); chairman, 1979 Gordon Research Conference on Nuclear Chemistry; mentor, HHIRF Gamma-Ray Facilities; member, Program Committee, Division of Nuclear

Chemistry and Technology, American Chemistry Society, 1981; member, Super-HILAC Users' Group, Lawrence Berkeley Laboratory

C. M. Jones — chairman, Scientific Committee of the Third International Conference on Electrostatic Accelerator Technology, April 13–16, 1981

J. A. Martin — member, Administrative Committee, IEEE Nuclear and Plasma Sciences Society; member, Board of Directors, Mid-Continent Electronics Conference (MIDCON); member, Editorial Advisory Board of *Particle Accelerators*; member, Organizing Committee 1981 Particle Accelerator Conference; member, International Organizing Committee, 9th International Conference of Cyclotron and Their Applications, Caen, France, 1981; IEEE liaison, 1981 Conference on Applications of Accelerators in Research and Industry; General Chairman, 1980 Nuclear Science Symposium; Proceedings editor, Third International Conference on Electrostatic Accelerator Technology

F. K. McGowan — associate editor, Atomic Data and Nuclear Data Tables

J. B. McGrory — member, ORIC Program Committee; member, ORNL Technical Seminar; member, ORNL, Computer Advisory Committee; chairman, Fellowship Committee, Division of Nuclear Physics, American Physical Society, 1980–91; member, Fellowship Committee, Division of Nuclear Physics, American Physical Society, 1981–82; member, Department of Energy Nuclear Theory Review Committee

P. D. Miller — member, Organizational Committee for the 1980 Conference on the Application of Accelerators in Research and Industry, Nov. 3–5, 1980; treasurer, Local Committee, and member of Program Committee of the XII International Conference on the Physics of Electronic and Atomic Collisions, July 1981

C. D. Moak — mentor, HHIRF Atomic Physics Beam Line; member, Local Committee for the XII International Conference on the Physics of Electronic and Atomic Collisions, July 1981

S. W. Mosko — member, Electrical Safety Committee; Physics Division Energy Conservation Coordinator

S. Raman — member, APS Division of Nuclear Physics Program Committee 1979–81; member, International Advisory Committee, International Conference on the Theory and Applications of Moment Methods in Many-Fermion Systems, Ames Laboratory, Iowa State University, Sept. 10–14, 1979, Traveling Lecturer, Oak Ridge Associated Universities, 1979–81; member, Program Committee, Fourth International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Institute Max von Laue-Langevin, Grenoble, France, Sept. 7–11, 1981; member, APS Division of Nuclear Physics Publications Committee, 1981–82; Editor, Actinide Newsletter, since 1977

L. L. Riedinger — visiting scientist, Niels Bohr Institute, Copenhagen, Denmark, July, 1978–August, 1979; chairman, Executive Committee of the User's Group, Holifield Heavy-Ion Accelerator Facility; chairman, UNISOR Executive Committee, 1981; member, Program Advisory Committee for the Tandem Accelerator, Brookhaven National Laboratory, since January 1981

R. L. Robinson — liaison officer, User's Group of the Holifield Heavy-Ion Research Facility; member, Organizing Committee for Fall 1979 APS Nuclear Physics Meeting

G. R. Satchler — member, editorial board for Atomic Data and Nuclear Data Tables; member, Organizing Committee and co-editor for the Proceedings (Plenum Publishing Co., 1980) of the conference on "The (p,n) Reaction and the Nucleon-Nucleon Force," Telluride, Colo. March 29–31, 1979; author, "Introduction to Nuclear Reactions" [Macmillan, London (1980)]; reviewer, Department of Energy and National Science Foundation proposals; member, Organizing Committee for the Topical Conference on Giant Multipole Resonances, Oak Ridge, Oct. 15–17, 1979; member, International Advisory Committee for the Fifth Polarization Conference, Santa Fe, N. M., Aug. 11–15, 1980; member, International Advisory Committee for the Topical Research Institute of Theoretical Physics, University

of Washington, Seattle, July 23–August 24, 1979

P. H. Stelson — part-time faculty member, Department of Physics, University of Tennessee; associate editor, *Nuclear Physics*; member, Executive Committee, Division of Nuclear Physics of the American Physical Society; member, Visiting Committee for Nuclear Science Division, Lawrence Berkeley Laboratory; member, International Advisory Committee of the International Conference on Nuclear Physics, Berkeley, August 1980

K. S. Toth — member, Organizing Committee for the International Symposium on "Future Directions in Studies of Nuclei Far from Stability," Vanderbilt University, Sept. 10–13, 1979; chairman, UNISOR Scheduling Committee; member, UNISOR Salary Committee; member, UNISOR Technical Committee; guest scientist, Super-HILAC and 88-inch Cyclotron, LBL, and the Cyclotron Institute, Texas A&M University; mentor, Physics Division Library

T. A. Welton — part-time faculty member and colloquium chairman, Department of Physics, University of Tennessee; reviewer of research proposals for the Department of Energy and National Science Foundation

C. -Y. Wong — member, Editoral Board of *Chinese Physics*

PHYSICS DIVISION SEMINARS: JANUARY 1979—APRIL 1, 1981

Those seminars arranged by the Physics Division and announced in the ORNL Technical Calendar are listed below. In addition, there were more specialized meetings (not listed), which fell primarily into three categories: nuclear research coffees, atomic physics seminars, and theoretical "circuses." During the period of this report M. Halbert served as seminar chairman until July 1980 and then E. H. Spejewski through April 1981.

Date	Speaker	Title
1/4/79	A. van der Woude, Kernfysisch Versneller Instituut, Groningen, The Netherlands	Excitation of Giant Resonances
1/11/79	Cheuk-Yin Wong, Division Staff	The Origin of the Low-ℓ Fusion Window in Heavy-Ion Collisions
1/18/79	R. E. Warner, Oberlin College	Double Spectator Poles in ^{6}Li + ^{6}Li Double Breakup
1/25/79	M. W. Guidry, University of Tennessee	Semiclassical Localization in Heavy-Ion Scattering
2/8/79	C. H. Johnson, Division Staff	S and Ca Neutron Total Cross Sections: Single-level, Multi-level, and Picket Fences
2/8/79	D. E. Murnick, Bell Laboratories	Laser-Induced Nuclear Orientation
2/15/79	Dennis Moltz, Lawrence Berkeley Laboratory	Study of T_z = -2 Nuclei with RAMA: A Recoil Atom Mass Analyzer
2/22/79	Stephen Lundeen, Harvard University	Precision Subnatural Line Width Spectroscopy: A New Measurement of the Lamb Shift in Atomic Hydrogen
2/28/79	R. A. Broglia, Niels Bohr Institute, Denmark, and SUNY at Stony Brook	^{208}Pb(α, α') Inclusive Reactions and the Giant Resonance Background

3/1/79	T. Heiles, Harvard University	Charge Transfer at Low Velocities
3/8/79	H. Miller, State University of New York, Stony Brook	Configuration-Mixing Calculations with Basis States Generated from Variational Methods
3/14/79	C. Toepffer, University of the Witwatersrand, South Africa, and ORNL	Quadrupole Giant Resonances as Doorways in the $^{12}C + ^{12}C$ System
3/22/79	Y. D. Chan, University of Washington	A Comparison of 180° Elastic Scattering of $^{12,13}C$ by ^{28}Si and ^{32}S
4/5/79	M. W. Guidry, University of Tennessee and ORNL	A Taste of Corona: The February 1979 Total Solar Eclipse
4/12/79	C. M. Jachcinski, State University of New York, Stony Brook	Angular Correlation Studies of Intermediate-Width Structure in $^{16}O + ^{12}C$
4/17/79	D. Habs, Max-Planck Institut für Kernphysik, Heidelberg and Lawrence Berkeley Laboratory	Spectroscopy in the Second Minimum of the Fission Barrier
4/19/79	C. D. Goodman, Physics Division	The (p,n) Reaction at Intermediate Energies
4/30/79	H. H. Bolotin, University of Melbourne and Rutgers University	Measured Lifetimes of States in ^{197}Au and a Critical Comparison with the Weak-Coupling Core-Excitation Model
5/1/79	S. Polikanov, Niels Bohr Institute, Denmark	Muon-Induced Fission
5/1/79	M. W. Johnson, University of Rochester	The Nuclear and Atomic Physics of Actinide Muonic Atoms
5/8/79	D. Robson, Florida State University	Quarks in Nuclei
5/15/79	F. Iachello, Yale University	Recent Developments in the Interacting-Boson Model
5/17/79	W. Bertozzi, Massachusetts Institute of Technology	Recent Electron Scattering Results from MIT-Bates
5/22/79	Jorge Flores, University of Mexico	Research at the Institute of Physics of the University of Mexico
5/23/79	P. J. Daly, Purdue University	Particle + Octupole $M2$-$E3$ Isomers in ^{147}Tb and ^{148}Tb
5/24/79	Jorge Flores, University of Mexico	Properties of Small Thermodynamic Systems
5/31/79	Thomas Kuhl, Massachusetts Institute of Technology and University of Mainz, West Germany	Optical Spectroscopy of Radioactive Nuclei
5/31/79	R. S. Raghavan, Bell Laboratories	Neutrinos from the Sun: New Techniques for Neutrino Spectroscopy
6/7/79	D. Kleppner, Massachusetts Institute of Technology	Atoms in Very Strong Fields
6/12/79	P. Kleinheinz, Institute for Nuclear Physics, KFA Julich, West Germany	Shell-Model Yrast States in the $A = 150$ Region

6/14/79	A. Arima, University of Tokyo, Japan	Why is α-Decay Enhanced?
6/21/79	J. Callaway, Louisiana State University	Electron Scattering by Hydrogen Atoms
6/26/79	D. R. Haenni, Institute for Nuclear Physics, KFA Julich, West Germany	Recent Experiments with Gamma-Ray Spectroscopy at Julich
6/27/79	C. Roulet, Institute of Nuclear Physics, Orsay, France	Very High Angular Momentum Selection Using Total Gamma-Ray Energy Measurements
6/28/79	P. A. Butler, University of Liverpool, England	Measurements of Coulomb Fission Cross Section of ^{238}U and ^{184}W Projectiles
7/20/79	M. C. Mermaz, CEN Saclay, France	Success and Failure of the Distorted-Wave Methods Applied to Transfer Reactions Induced by Heavy Ions
7/23/79	J. S. Williams, Queens University, Belfast, Northern Ireland	Electron-Photon Coincidence Measurements in e + H or He Collisions and $e + 2e$ Experiments
7/23/79	D. Guerreau, Institute of Nuclear Physics, Orsay, France	The Relaxation of the Neutron-Excess Degree of Freedom in Deeply Inelastic Collisions and the Production of New Neutron-Rich Nuclides
7/24/79	M. Algard, Stanford University	Radiation from Channeled Leptons
7/24/79	U. Lynen, University of Heidelberg, West Germany	Is There Fast Breakup following Deeply Inelastic Collisions?
7/30/79	J. M. Irvine, Manchester University, England	Neutron Stars
8/2/79	H. Weigmann, Central Bureau for Nuclear Measurements, Geel, Belgium	Exploring the Deformation Potential of Actinide Nuclei by Neutron-Induced Fission
8/8/79	G. Fricke, Institute for Nuclear Physics, University of Mainz, West Germany	Systematics of Nuclear Charge Distributions from Ca to Mo by Elastic Electron Scattering and Muonic Atoms
8/16/79	J. Reading, Texas A&M University	Ion-Atom Collisions
8/21/79	B. Martin, Max Planck Institut fur Kernphysik, Heidelberg, West Germany	Delta Electrons from Heavy-Ion Collisions
8/23/79	C. Y. Wong, Division Staff	Central Collisions in Intermediate-Energy Heavy-Ion Reactions
8/30/79	R. L. Robinson, Division Staff	Band Structure in Even-Mass Nuclei around $A = 70$
9/4/79	R. Novotny, University of Heidelberg, West Germany	Multiparticle Exit Channels of the Reactions $^{32}S + {}^{27}Al$ and $^{32}S + {}^{28}Si$
9/6/79	G. C. Morrison, University of Birmingham, England	Heavy-Ion Reactions at 10 MeV/Nucleon

9/11/79	R. H. Hughes, University of Arkansas	A Laser-Generated Heavy-Ion Source
9/13/79	H. Stocker, GSI, Darmstadt, West Germany	Compressed Nuclear Matter in Relativistic Heavy-Ion Collisions
9/14/79	A. H. Wapstra, IKO, Amsterdam, The Netherlands	Recent Work at the IKO Electron Accelerator
9/17/79	S. Frauendorf, Central Institute of Nuclear Research in Rossendorf, East Germany, and Niels Bohr Institute, Denmark	Quasiparticle Band Structures above the Yrast Line
9/18/79	D. M. Brink, University of Oxford, England	Transfer Reactions with Polarized Heavy Ions
9/20/79	S. C. Pancholi, University of Delhi, India	Status of Timing with Plastic Scintillation Detectors
9/25/79	A. Rytz, International Bureau of Weights and Measures, Sevres, France	Absolute Determination of Alph-Particle Energies
9/27/79	R. P. Sharma, Tata Institute of Fundamental Research, Bombay, India	Interactions of Nuclei with Their Surroundings in a Solid
10/4/79	L. L. Riedinger, University of Tennessee	Multiple Band Crossings in the Light Yb Nuclei
10/13/79	M. F. Pindzola, Auburn University	Electron Impact Ionization of Positive Ions
10/22/79	M. S. Hussein, University of Wisconsin and University of Sao Paulo, Brazil	Heavy-Ion Coulomb Polarization Potential
10/29/79	L. P. Somerville, Lawrence Berkeley Laboratory	New Spontaneous Fission Activities Produced in Bombardments of ^{248}Cm and ^{249}Bk by ^{13}C, ^{15}N, ^{16}O, and ^{18}O Ions
11/1/79	S. Hjorth, Research Institute for Physics, Stockholm, Sweden	Selected Aspects of Nuclear Structure Physics at High Spin
11/8/79	V. Sidis, Laboratoire des Collisions Atomiques et Molecularies, Universite de Paris-Sud, France	The Theory and Practice of Diabatic States
11/12/79	J. A. Maruhn, University of Frankfurt, West Germany	Systematic Study of Potential-Energy Surfaces
11/15/79	I. Hamamoto, Massachusetts Institute of Technology and the Niels Bohr Institute, Denmark	Some Recent Developments in the Field of Rotating Nuclei
11/26/79	Moshe Gai, State University of New York at Stony Brook	On the Systematics of Heavy-Ion Scattering Resonances
11/29/79	A. Gobbi, GSI, Darmstadt, West Germany	Structure Effects in Dissipative Collisions
11/30/79	H. Machner, KFA Julich, West Germany	How Can We Describe the Continuous Background in Hadron Scattering and Reactions?
12/6/80	H. Freiesleben, University of Bochum, West Germany	Energy Dependence of γ-Ray-Multiplicity Distributions in the System ^{86}Kr + ^{154}Sm
12/7/79	W. Nörenberg, GSI, Darmstadt, West Germany	Transport Theory and Doorway Configuration in Dissipative Heavy-Ion Collisions

12/10/79	R. Bass, University of Frankfurt am Main, West Germany	Fusion Reactions: Successes and Limitations of a One-Dimensional Description
12/12/79	U. Smilansky, Weizmann Institute, Israel	Semiclassical Theory of Dissipative Processes
1/10/80	K. Erb, Yale University	Resonances and Diffraction in Heavy-Ion Interactions
1/17/80	J. P. Delaroche, Bruyeres-le-Chatel, France	Neutron Scattering from Tungsten Isotopes and Comparison with Structure Calculations
1/22/80	M. Rhoades-Brown, Argonne National Laboratory	Coupled-Channels Approach to Peripheral Heavy-Ion Collisions
1/24/80	M. V. Hynes, Massachusetts Institute of Technology	Comparison of Electron and Proton Scattering Data from the Oxygen Isotopes
2/1/80	G. A. Victor, Center for Astrophysics, Harvard University	Radiative and Collisional Processes in Long-Pulse-Length Laser-Gas Interactions
2/7/80	C. Y. Wong, Division Staff	The Determination of Nuclear Momentum Distributions from Heavy-Ion Reactions
2/14/80	R. N. Compton, Health and Safety Research Division	Compound States of He
2/21/80	P. Huray, University of Tennessee	A SQUID-based Micromagnetic Susceptometer: Recent Results for Actinide Metals
2/28/80	J. C. Glowienka, Fusion Energy Division	What Is an EBT?
3/3/80	J. F. W. Jansen, Kernversneller Institut, Groningen, The Netherlands	In-Beam Spectroscopy of the Actinide Nuclei with $(\alpha,xn\gamma)$ Reactions
3/5/80	J. Delaunay, SPNBE, CEN Saclay, France	Interplay between Spectroscopy and Mechanism Studies for Ti Isotopes + ^{12}C and ^{13}C at Tandem Van de Graaff Energies
3/6/80	R. E. Marshak, Virginia Polytechnic Institute	Majorana Neutrinos and Neutron Oscillations and Tests of Unified Theory of Electro-weak and Strong Interactions
3/6/80	R. M. Lieder, KFA Julich, West Germany	Study of the Mechanism of the ^{209}Bi $(\alpha,xn\gamma)$ Reaction
3/17/80	B. Müller, University of Frankfurt, West Germany, and Vanderbilt University	An Atomic Clock for Deep Inelastic Heavy-Ion Collisions
3/25/80	D. Dehnhard, University of Minnesota	Isospin Structure of Transitions in ^{13}C from π^+, π^-, t, ^3He Inelastic Scattering
4/8/80	M.-F. Rivet, State University of New York at Stony Brook	Light Charged Particle Emission in Argon-40 Induced Reactions
4/17/80	D. J. Horen, Division Staff	Giant Gamow-Teller and $\Delta \ell = 1$, Spin-Flip Resonances Observed in the (p,n) Reaction: Energy Systematics
4/21/80	R. Blankenbecler, Stanford Linear Accelerator Center	Games with Φ^4 Theory

4/24/80	F. E. Bertrand, Division Staff	Ten Years of Giant Multipole Resonances
5/6/80	C. Dasso, Niels Bohr Institute, Denmark	Stability of a Di-Nuclear System at High Angular Momentum
5/8/80	V. Shkolnik, University of Minnesota	A Close Look at the Elastic Scattering of ^{16}O from ^{28}Si
5/9/80	Y. Alhassid, California Institute of Technology	Time-Dependent Mean-Field Approximation for the Many-Body *S*-Matrix
5/15/80	E. L. Hart, University of Tennessee	Recent Advances in Elementary Particle Physics and Related Research at ORNL/UT
5/19/80	R. Spohr, GSI Darmstadt, West Germany	Nuclear Tracks—An Emerging Technology
5/20/80	A. T. G. Ferguson, AERE Harwell, England	Application of Nuclear Techniques at Harwell
5/27/80	Th. Lindblad, Research Institute for Physics, Stockholm, Sweden	Recent Stockholm Results from Energy Correlations in the Gamma-Ray Continuum
5/29/80	T. D. Anderson, Engineering Technology Division	A Perspective on the Energy Crisis
6/5/80	H. Flocard, IPN Orsay, France	Microscopic Calculation of the Effective Mass for Heavy-Ion Collisions
6/12/80	N. Frascaria, IPN Orsay, France	A Status Report on High-Energy Structures in Heavy-Ion Collisions
6/16/80	T. Åberg, Helsinki Institute of Technology, Finland	Electronic Raman Resonance Scattering by Oriented Atoms
6/19/80	S. Plattard, Bruyeres-le-Chatel, France	Is There Any Experimental Evidence for a New Metastable Shape of Light-Actinide Nuclei?
6/23/80	G. Rosner, Max-Planck Institut fur Kernphysik, Heidelberg, West Germany	Deep Inelastic Processes in the Reaction $^{32}S + {}^{27}Al$
6/24/80	H. Nifenecker, CEN Grenoble, France	Experiments with 1-GeV C Ions: Transparency, Explosion, Fragmentation
6/26/80	T. Lund, Phillips University of Marburg, Germany	Reactions Induced in Cu, Ag, and Pb by 86-MeV/Nucleon ^{12}C Ions
7/7/80	Rand L. Watson, Texas A&M University	X-Ray Excitation by Heavy-Ion Bombardment
7/8/80	Jerry Garrett, Niels Bohr Institute, Denmark	Nuclear Spectroscopy at Very High and Very Low Rotational Frequencies
7/10/80	F. H. Froehner, Kernforschungszentrum Karlsruhe	Efficient Estimation of Strength Functions and Average Level Spacings from Resonance Parameters
7/22/80	Ashok, Dhar, Daresbury Laboratories, United Kingdom	TDHF Calculations of Heavy-Ion Reactions
7/24/80	Z. Fraenkel, Weizmann Institute of Science, Israel	Internuclear Cascade Calculations of High-Energy Heavy-Ion Reactions

7/25/80	I. Tserruya, Weizmann Institute of Science	Pre-Equilibrium Neutron Emission in $^{86}Kr + ^{166}Er$ at 12 MeV/μ
7/31/80	F. R. Pougheon, Institute de Physique Nucleaire	Experiments Performed with a ^{14}C Beam at the Orsay MP Tandem
8/5/80	H. K. Kroger, Justus Liebig University, Giessen, West Germany	Local Density Increase Effects in the Lee-Wick Model
8/6/80	W. Hammer and G. Schleussner University of Stuttgart	Measurement of Analyzing Power of ^{238}U and La for 7.6-MeV Neutrons
8/7/80	Richard Ward, Max-Planck Institute, Munich, West Germany	The ^{176}Lu-^{176}Hf Pair: Cosmic Clock or Stellar Thermometer?
8/11/80	C. R. Vane, Lawrence Berkeley Laboratory	Ion Trapping of Target Recoils
8/13/80	S. Veprek, University of Zurich, Switzerland	Current Status of Plasma Chemistry
8/14/80	R. Babinet, CEN, Saclay, France	Secondary Light Charged Particle Emission and Angular Momentum Transfer in DIC: ^{40}Ar (280 MeV) + ^{58}Ni
8/15/80	D. C. Gregory, Brookhaven	Beam Foil Spectroscopy of Heavy Ions
8/21/80	K. Eskola, University of Helsinki	Studies of Beta-delayed Charged-Particle Emission with a Compact Cyclotron
9/2/80	S. Liberman, Laboratorie Aime Cotton, Orsay, France	Optical Spectroscopy of Atoms Far from Nuclear Stability
9/3/80	C. Gregorie, Saclay, France	Dynamic Model for Isospin Transfer in Heavy-Ion Collisions
9/5/80	W. D. Hamilton, University of Sussex, England	Nuclear Orientation Gamma-Ray Spectroscopy
9/8/80	A. Wolf, Reactor Center, Negev, Israel	Photoneutron Experiments on Lead Isotopes
9/9/80	J. Galin, Institute de Physique Nucleaire, Orsay, France	Mass Asymmetry Effects in Heavy-Ion Reactions, and New Neutron-Rich Isotopes Produced in Deeply Inelastic Collisions
9/10/80	C. Coceva, ENEN, Bologna, Italy	Gamma-Ray Transitions from and to Neutron Resonances
9/11/80	G. M. Gowdy, Brookhaven National Laboratory, Upton, N. Y.	Decays of Very Neutron Deficient Nuclei in the Lead Region
9/16/80	M. Fewell, Yale University	Quadrupole Moments and Nuclear Shape
9/18/80	T. L. Khoo, Argonne National Laboratory	Very High Spin Yrast States and the Link to the Continuum
9/23/80	U. Lynen, GSI, Darmstadt, Germany	Collective Effects in Heavy-Ion Reactions at 86 MeV/u
9/25/80	T. P. Sjoreen, University of Indiana	Pion Production by Protons in Nuclei

9/30/80	R. Brandt, Philips University, Marburg, Germany	Search for Unknown Spontaneous Fission Activities in Hot Brines
10/2/80	UNISOR Colloquium	
10/13/80	D. Cline, University of Rochester, New York	Electromagnetic Properties of Shape transitional Nuclei
10/15/80	B. E. Fischer, GSI, Darmstadt	Heavy-Ion Lithography
10/16/80	F. T. Avignone III, University of South Carolina	Neutrino Oscillations: What Evidence Do We Have That We Really See Them?
10/17/80	R. Hasse, University of Munich, Germany	Description of Nuclear Giant Resonance by Long Mean Path Fluid Dynamics
10/23/80	F. Stancu, University of Liege, Belgium	Fusion Cross Section of Light Ions at Subcoulomb Energies
10/27/80	W. Cooke, University of Southern California	Laser Spectroscopy of Autoionizing States
10/30/80	S. Levit, Massachusetts Institute of Technology	Time-Dependent Mean-Field Description of Tunneling, Spontaneous Fission, and Induced Fission
10/31/80	C. M. Lederer, Lawrence Berkeley Laboratory	*E*1 Transition Rates from Octupole-Vibration States in Actinide Nuclei
11/13/80	S. P. Rosen, Purdue University	Proton Decay
11/20/80	K. Sistemich, Iowa State University and KFA, Julich, West Germany	Microsecond Isomers around ^{132}Sn
11/25/80	E. A. Knapp, Los Alamos National Laboratory	Linacs and Storage Rings at Los Alamos
12/1/80	Wu Cheng Li, Jilin University	Nuclear Field Theory
12/3/80	Wu Cheng Li, Jilin University	Nuclear Field Theory
12/4/80	Wu Cheng Li, Jilin University	Nuclear Field Theory
12/18/80	F. Perey, Engineering Physics Division	Logical Inference and Bayesian Statistics
1/13/81	Gregory Lapicki, Northwestern Louisiana State University	Energy Loss in Ion-Atom Collisions
1/15/81	Michel Buenerd, Institute des Sciences Nucleaires, Grenoble	Giant Resonance Research at Grenoble
1/22/81	Heinz Ower, University of Tennessee	Coulomb Excitation with ^{208}Pb on Actinide Nuclei
1/29/81	David Elmore, University of Rochester	Ultrasensitive Mass Spectrometry Research with 8–25 MV Tandems
2/5/81	M. S. Hussein, University of Wisconsin	Low-ℓ Cutoff Effects in Heavy-Ion Fusion
2/20/81	Wick Haxton, Purdue University	Double β Decay
2/26/81	Yong-Shou Chen, University of Tennessee and the Institute of Atomic Energy, Peking	A Solvable Gamma-Ray Side Feeding Problem
3/19/81	J. Speth, KFA, Julich, Federal Republic of Germany	Dynamical Theory of Collective States

3/26/81	Steve Younger, National Bureau of Standards	Electron Impact Ionization Theory
4/2/81	Margaret McMahan, Columbia University	Laser Studies of the Cross-Beam Reaction: $HgI_2 \rightarrow HgI$
4/7/81	H. B. Gilbody, Queens University, Belfast, Northern Ireland	Atomic Collisions with Crossed Ion Beams
4/28/81	Cyrus Baktash, Brookhaven National Laboratory	High-Spin Yrast Structure in the $N = 86$ Region
5/5/81	Carlos Dasso, Niels Bohr Institute, Copenhagen, Denmark	Stability of Nuclear Systems at High Angular Momentum
5/7/81	T. C. Awes, Cyclotron Laboratory Michigan State University	Light-Particle Emission in ^{16}O-Induced Reactions at Incident Energies between 8 and 20 MeV/Nucleon
5/13/81	Ugo Fano, University of Chicago	Hyperspherical Coordinate Description of Two-Electron States
5/19/81	M. Paul, Racah Institute of Physics, Jerusalem	Selective Population of States in ^{36}Ar by the $^{12}C(^{28}Si, \alpha)$ Reaction
5/28/81	John Newton, Australian National University	Gamma Rays from Giant Dipole States Based on States of High Excitation and Spin
5/28/81	H. A. Schuessler, Texas A&M University	Laser Spectroscopy On-line with Nuclear Accelerators

COLLOQUIA AND SEMINARS PRESENTED BY PHYSICS DIVISION MEMBERS AT OTHER INSTITUTIONS

J. B. Ball — Vanderbilt University, April 11, 1980, "Holifield Heavy-Ion Research Facility — Present Status and Future Plans"

R. L. Becker — University of Tennessee, March 1979, "Four-Body Classical Trajectory Monte-Carlo Theory of $^4He^+ + H$ and $H + H$ Collisions"; Kansas State University (DOE Meeting on High-Energy Atomic Physics), April 6, 1979, "Thoery of Electron Transfer and Ionization"; Texas A&M University, June 26, 1980, "Nonstatistical Theory of Multiple Vacancy Production"

J. R. Beene — Chalk River Nuclear Laboratory, Canada, December 7, 1979, University of Mainz, W. Germany, July 28, 1980, and State University of New York at Stony Brook, July 30, 1980, "Study of the Fission Isomer ^{240m}AM Using Laser-Induced Nuclear Polarization"; Texas A&M University, September 9, 1980, "In-Beam Nuclear Physics Using Laser-Induced Nuclear Polarization"; Washington University, St. Louis, October 24, 1980, "Laser-Induced Nuclear Polarization"; Michigan State University, December 10, 1980, "Laser-Induced Nuclear Polarization: Applications to In-Beam Experiments"; Los Alamos National Laboratory, February 23, 1981, and Texas A&M University, March 11, 1981, "Angular Momentum Effects in Fusion-like Reactions"

C. E. Bemis — University of Tennessee, November 13, 1979, "Laser-Induced Nuclear Polarization"; Massachusetts Institute of Technology, March 17, 1980, "Studies of Spontaneous Fission Isomerism Using Laser Technique"; Tulane University, October 17, 1980, University of Arkansas, January 16, 1981, and University of North Carolina, January 21, 1981, "Laser-Induced Nuclear Polarization (LINUP): A Technique for the Study of Short-Lived Nuclides"; Duke University, January 22, 1981, "Laser-Induced Nuclear Polarization (LINUP): Applications

in the Heavy-Ion Nuclear Sciences" (TLP); Georgia State University, January 26, 1981, Yale University, March 6, 1981, and University of Rochester, March 19, 1981, "Laser-Induced Nuclear Polarization (LINUP): A Technique for the Study of Short-Lived Nuclides" (TLP)

F. E. Bertrand — Massachusetts Institute of Technology, May 8, 1979, "Giant Multipole Resonances"; University of Neuchatel, Switzerland, July 17, 1979, "Excitation of Giant Multipole Resonances via Inelastic Hadron Scattering", Massachusetts Institute of Technology, March 12, 1980, "Giant Multipole Resonances — An Experimental View"

A Bottcher — Georgia Institute of Technology, February 8, 1979, and Auburn University, May 25, 1979, "New Phenomena in Heavy-Ion Atom Collisions"; Lawrence Berkeley Laboratory, May 30, 1979, "Collision Processes in the Region of Very Strong Coupling" and "Maser Theory with Collisions;" University of Southern California, December 4, 1979, "Ion-Polar Molecule Scattering"; Clarkson College of Technology, November 6, 1980, Yale University, November 14, 1980, and University of Georgia, February 5, 1981, "Numerical Calculations of Ionization"; Harvard University, April 15, 1981, "Autoionizing Contributions to Electron Impact Ionization"

H. K. Carter — Emory University, February 15, 1980, and University of Texas at Arlington, March 26, 1980, "Lasers: A New Tool for Nuclear Spectroscopy in Measurement of the Atomic Hyperfine Structure"

D. H. Crandall — Princeton Plasma Physics Laboratory, Princeton University, March 14, 1979, "Review of Collisions between Impurity Ions and Atomic Hydrogen"; Colorado School of Mines, April 3, 1979, "Atomic Physics in Fusion"; JILA, University of Colorado, February 20, 1980, "Atomic Collisions, Fusion, and Astrophysics"; Austin Peay State University, February 28, 1980, "Fusion Energy Prospects"; University of Georgia, March 12, 1981, "Atomic Physics in Fusion Research"

K. T. R. Davies — Yale University, August 18, 1980, "Time-Dependent Hartree-Fock Calculations"; Rutgers University, March 30, 1981, and University of Maryland, April 2, 1981, "Time-Dependent Hartree-Fock Comes of Age"

K. A. Erb — University of Tennessee, November 1980, "Rotations and Vibrations of the ^{12}C-^{12}C Nuclear Molecule"; University of Georgia, March 5, 1981, "Nuclear Molecules"

C. B. Fulmer — Valdosta State University, April 10, 1979, "Heavy-Ion Research at ORNL"

A. I. Gavron — Massachusetts Institute of Technology, April 15, 1980, "Neutron Emission in Heavy-Ion Reactions"

J. Gomez del Campo — Centre d'Etudes Nucleaires, Saclay, France, March 25, 1980, "Modeling the Equilibrium Decay, Applications of Monte Carlo Calculations to Fusion, and Deep Inelastic Collisions"; Texas A&M University, April 22, 1980, "Monte Carlo Calculations of Evaporation Residues"; Instituto Nactional de Investigaciones Nucleares, Zalazar, Mexico, January 20, 1981, "Experimental Heavy-Ion Physics with EN Tandem Accelerators"

D. R. Haenni — Texas A&M University, June 3, 1980, "Gamma-Ray Spectroscopy in the Ge-Gd Region below the 82-Neutron Closed Shell"

J. A. Harvey — University of Kentucky, March 30, 1979, "The Need for High-Resolution Neutron Measurements for Basic and Applied Physics"

D. C. Hensley — The Citadel, January 10, 1979, Identification of Elements 102–105 with an X-Ray Technique" (TLP); Georgia State University, January 14, 1980, and Southern Illinois University, May 8, 1980, "Gamma-Ray Multiplicity Measurements in Heavy-Ion Reactions" (TLP); University of Alabama in Birmingham, February 6, 1980, Principia College, May 7, 1980, and West Virginia Wesleyan College, March 11, 1981, "Unequivocal Identification of Elements 102 through 105" (TLP)

S. A. Hjorth — Vanderbilt University, May 5, 1980, "Studies of High-Spin States Using Discrete and Continuous Gamma Radiation"

D. J. Horen — Yale University, April 20, 1979, "Neutron Scattering by Lead Isotopes: Doorway States, Particle-Core Excitation, *M*1 Radiative Strength, and Nuclear Level Densities"; Institut des Sciences Nucleaires, Grenoble, France, May, 1979, "Excitation of Giant Resonances by Hadrons"; Kernforschungszentrum Karlsruhe, W. Germany, June 11, 1979, "Investigation of Giant Resonances with Proton and Neutrons"; Centre d'Etudes de Bruyeres-le-Chatel, Montrouge, France, June 18, 1979, "Particle-Core Excitations in ^{207,208}Pb and Nuclear-Level Densities in ^{207}Pb"; Institute Laue-Langevin, Grenoble, France, May, 1979, and Atomic Energy Research Establishment, Harwell, England, June 25, 1979, "Doorway States in the *s*-, *p*-, and *d*-Wave Neutron Channels in ^{206,207}Pb + *n* Reactions and Nuclear-Level Densities in ^{207}Pa"; Institute fur Kernphysik, Julich, W. Germany, June 12, 1979, and Institut de Physique Nucleaire, Orsay, France, June 19, 1979, "Giant Resonances Investigated by Inelastic Hadron Scattering"; Japan Atomic Energy Research Institute, Tokai-mura, May 1980, "Neutron Doorway States and Level Densities in ^{207}Pb" and "Search for Giant Spin-Flip Resonances in Heavy Nuclei"; University of Tsukaba, Japan, May 1980, "Giant Gamow-Teller and $\Delta\varphi = 1$ Spin-Flip Resonances Observed in the (*p*,*n*) Reaction" and "Fission Decay of the Giant Quadrupole Resonance in ^{238}U"; University of Connecticut, March 6, 1981, and Yale University, March 9, 1981, "Isovector Resonances Observed in the (*p*,*n*) Reaction: Possible Connection between Low, Intermediate, and High-Energy Nuclear Physics"

D. P. Hutchinson — North Carolina Central University, May 3, 1979, "Plasma Diagnostics Using Submillimeter Lasers" (TLP)

N. R. Johnson — University of Tennessee, April 22, 1980, "Behavior of Nuclei when Excited into States of High Angular Momentum"; Michigan State University, June 6, 1980, "Gamma-Ray Experiments and Plans for New Devices at the Holifield Heavy-Ion Facility"

C. M. Jones — University of Tsukuba, Japan, February 12, 1981, "Large Pelletron Accelerators"

H. J. Kim — Tsukuba University, Japan, September 10, 1979, "Ionization of Highly Excited Hydrogen Atoms"; Tokyo University, Japan, September 13, 1979, "High-Spin States of $A \sim 70$ Region"; Institute of Physical and Chemical Research, Wako-Shi, Japan, September 15, 1979, "Ionization of Highly Excited Hydrogen Atoms"; Tokyo Institute of Technology, Japan, September 17, 1979, "In-Beam Gamma-Ray Study of $A \sim 70$"; University of Kentucky, October 10, 1980, "Electron Loss from Highly Excited Hydrogen Atoms in Fast Collision with Heavy Ions"

I. Y. Lee — University of Pittsburgh, November 16, 1979, "Study of Nuclear High-Spin States by Observing Continuum Gamma Rays"; University of Notre Dame, August 4, 1980, and Argonne National Laboratory, November 18, 1980, "Study of Nuclear High-Spin Properties from Continuum Gamma Rays"; Rutgers University, January 19, 1981, "High-Spin Properties from Continuum Gamma-Ray Studies"

M. W. Lucas — University of Connecticut, June 22, 1979, "Charge Exchange to Continuum in Gases and Solids"

R. L. Macklin — Centre d'Etudes de Bruyeres-le-Chatel, France, March 3, 1980, "Neutron Capture Cross Sections at ORELA"; Institut fur Angewandte Kernphysik, Karlsruhe, W. Germany, March 7, 1980, "Re/Os and the Age of the Milky Way"

J. A. Martin — Technical University, Munich, W. Germany, June 27, 1979, "The Holifield Heavy-Ion Research Facility — Status and Future Plans"; Texas A&M University, February 20, 1980, "Plans for Phase II of the Holifield Heavy-Ion Research Facility" (TLP); Auburn University, May 20, 1980, and University of Alabama, Birmingham, May 21, 1980, "Heavy-Ion Accelerators at Oak Ridge" (TLP); University of Tennessee, Knoxville, May 27, 1980, "The Holifield Heavy-Ion Research Facility"

J. B. McGrory — University of Cincinnati, January 11, 1979, Georgia State University, January 30, 1979, Tulane University, March

16, 1979, and Duke University, April 5, 1979, "Shell Model to Bosons to Rotations" (TLP); Yale University, April 23, 1980, "Role of *n-p* Interactions in Shell-Model Calculations"

F. W. Meyer — Southwestern University, Memphis, January 29, 1981, Auburn University, February 13, 1981, and Clemson University, March 12, 1981, "Atomic Physics in Magnetically Confined (Tokamak) Fusion Plasmas" (TLP); Justus Liebig University, Giessen, W. Germany, April 16, 1981, "Multicharged Ion Collision Experiments at ORNL"

C. D. Moak — Argonne National Laboratory, Illinois, March 1981, "Resonant Coherent Excitation of One- and Two-Electron Ions in Crystal Channels"

D. M. Moltz — University of Jyvaskyla, Finland, September 11, 1980, and Institut des Sciences Nucleaires, Grenoble, France, September 11, 1980, "Nuclear Physics Directions with On-Line Mass Separators"; Universite Lyon, France, September 18, 1980, "Studies of $Z_2 = -2$ Nuclei with a Helium-Jet-Fed On-Line Mass Separator"

R. Novotny — University of Rochester, February 3, 1981, "Multiparticle Production in Heavy-Ion Reactions of Medium-Heavy Systems"

V. E. Oberacker — Yale University, November 29, 1979, "Recent Developments in Coulomb Fission and Muon-Induced Fission"; Vanderbilt University, April 16, 1980, "Muon-Induced Fission: A Possible Probe for Fission Dynamics"

R. A. Phaneuf — Dickinson College, March 13, 1979, Tennessee Technological University, April 17, 1979, "Atomic Physics in Thermonuclear Fusion Research" (TLP); Kansas State University, November 29, 1979, "Laser-Produced Plasma Ion Source of Low-Energy Multiply Charged Ions for Electron Capture Cross-Section Measurements"; University of Tennessee, Knoxville, January 22, 1980, "Charge Transfer Measurements Using a Laser-Produced-Plasma Ion Source"; University of Arkansas, October 24, 1980, "Charge Transfer Measurements with a Pulsed-Laser Ion Source"

F. Plasil — Fudan University, Shanghai, China, April 10, 1979, Lanchow University, China, April 13, 1979, and Institute of Atomic Energy, Peking, China, April 16, 1979, "Heavy-Ion-Induced Fission and Fusion", Niels Bohr Institute, Denmark, September 24, 1979, "Heavy-Ion-Induced Fission"; Institut de Physique Nucleaire, Orsay, France, April 24, 1980, "Particle Emission in Heavy-Ion-Induced Reaction", University of Munich, W. Germany, January 16, 1981, "Neutron and Charged-Particle Emission in Reactions with Carbon and Oxygen Ions"; Texas A&M University, May 5, 1981, and Lawrence Livermore Laboratory, May 15, 1981, "Neutron Emission in Reactions with ^{12}C, ^{16}O, and ^{20}Ne Ions"

S. Raman — University of Maryland, March 15, 1979, Catholic University, March 21, 1979, Central Bureau for Nuclear Measurements, Geel, Belgium, June 12, 1979, University of Utrecht, The Netherlands, June 15, 1979, Reactor Centrum Nederland, Petten, June 18, 1979, Kernfysisch Versneller Instituut, Groningen, The Netherlands, June 19, 1979, Centre d'Etudes Nucleaires de Saclay, France, June 27, 1979, Comitato Nazionale per Energie Nucleare, Bologna, Italy, June 27, 1979, Institut Max von Laue-Paul Langevin, Grenoble, France, August 3, 1979, Tulane University (TLP), February 15, 1980, Auburn University (TLP), February 18, 1980, University of Massachusetts, October 1, 1980, Rutgers University, March 23, 1981, Ohio State University, April 30, 1981, "Basic and Applied Research with Neutrons at ORELA"; United States Geological Survey, Reston, Virginia, March 16, 1979, California Institute of Technology, May 2, 1979, Studiecentrum voor Kernenergie, Mol Belgium, June 21, 1979, Slovak Academy of Sciences, Bratislava, Czechoslovakia, June 28, 1979, Atomic Energy Research Establishment, Harwell, United Kingdom, July 13, 1979, Max-Planck Institut fur Kernphysik, Heidelberg, W. Germany, July 20, 1979, Indiana University (TLP), February 20, 1980, University of Marburg, Germany, September 26, 1980, Technische Universitat, Munchen, Germany, September 26, 1980, "Search for Superheavy Elements and Trace-Element Analyses with Synchrotron Radiation"

L. L. Riedinger — Spring Meeting of the Germany Nuclear Physics Society, Gent, Belgium,

March 30, 1979, "Aligned Rotational Bands in Light Yb Nuclei"; University of Bergen, Norway, May 11, 1979, "Status of the New Accelerator at Oak Ridge and Experiments on Light TI Nuclei"; Opening Symposium of the Oslo Cyclotron, Oslo, Norway, May 15, 1979, "The Five Backbends of ^{160}Yb: A Detailed Test of Rotation Alignment Models"; Gordon Research Conference on Nuclear Chemistry, June 18, 1979, "Observation of Multiple Band Crossings in Light Yb Nuclei"; Nordic Symposium on Nuclear Physics, Lysekil, Sweden, August 21, 1979, "Multiple Band Crossings in Light Yb Nuclei"; Nobel Symposium on Nuclei at Very High Spins, Oresnas, Sweden, June 1980, "The Limits of Studying High-Spin States by Discrete-Line Gamma-Ray Spectroscopy"; Oak Ridge Associated Universities, UNISOR Users Meeting, October 2, 1980, "Future UNISOR Experiments with HHIRF"; Brookhaven National Laboratory, November 14, 1980, "High-Spin States in the Light Yb and Hf Nuclei"; University of Tennessee, February 3, 1981, "Nuclear Spectroscopy by Radioactive Decay, Laser Excitation, or Heavy-Ion-Induced Reactions", Yale University, February 18, 1981, "High-Spin States in the Light Yb and Hf Nuclei"; Washington University, March 19, 1981, "High-Spin States and the Cranked Shell Model"

R. L. Robinson — University of Mexico, January 8, 1979, "The Holifield Heavy-Ion Research Facility"

G. R. Satchler — University of Washington, July 25, 1979, "Microscopic Description of Heavy-Ion Scattering Using Semi-Realistic Interactions"

V. Sidis — North Carolina State University, October 19, 1979, "Formation of Metastable Atoms in Charge Exchange Collisions between H^+, He^+, and Alkali Atoms"

R. G. Stokstad — Lawrence Berkeley Laboratory, October 8, 1979, "Angular Momentum Transfer in Deep Inelastic Reaction"

C. Toepffer — Lawrence Berkeley Laboratory, January 3, 1979, and University of Washington, January 8, 1979, "Isoscalar Quadrupole Giant Resonances in ^{24}Mg"; Vanderbilt University, February 1, 1979, "Resonance and Interference Phenomena in Light Heavy-Ion Reactions"; Argonne National Laboratory, February 27, 1979, Michigan State University, February 28, 1979, and University of Arizona, March 2, 1979, "Quadrupole Giant Resonances in the ^{12}C-^{12}C System"

K. S. Toth — University of Tennessee, March 2, 1979, "Nuclear Structure Studies near $N = 82$ and $Z = 64$"; Oak Ridge Associated Universities, UNISOR Users Meeting, October, 2, 1980, "Anomalous Alpha-Decay Rates of Pb Isotopes"

R. R. Winters — Middle Tennessee State University, December 6, 1979, "Neutron Cross Sections and the Age of the Elements"

C.-Y. Wong — University of Tennessee, February 13, 1979, "Nucleon Dynamics in Heavy-Ion Collisions"; Florida State University, April 12, 1979, "Nuclear Hydrodynamics in Heavy-Ion Collisions"; University of Manchester, England, June 4, 1979, and Niels Bohr Institute, Denmark, June 7, 1979, "TDHF Approximation from a Classical Viewpoint"; Tulane University, November 19, 1979, and Louisiana State University, November 20, 1979, "Extended Time-Dependent Hartree-Fock" (TLP); Stanford University, March 28, 1980, "Scaling Phenomena in Heavy-Ion Reactions"; University of Maryland, June 12, 1980, "Nuclear Momentum Distribution and Heavy-Ion Reactions"; Rutgers University, December 15, 1980, "Nuclear Giant Resonances as Elastic Vibrations"

SCIENTIFIC MEETINGS SPONSORED BY THE PHYSICS DIVISION AND HELD DURING THE REPORTING PERIOD

Giant Multipole Resonance Topical Conference
Oak Ridge, Tenn., October 15–17, 1979
F. Bertrand, E. Gross, D. Horen, R. Satchler, organizers

International Conference on Nuclear Cross Sections for Technology
Knoxville, Tenn., October 22–26, 1979
(co-organized by the University of Tennessee)
J. L. Fowler and C. H. Johnson, ORNL organizers

Workshop on the (p,n) Interaction at Intermediate Energies
ORNL, March 18–20, 1981
D. J. Horen, organizer

Third International Conference on Electrostatic Accelerator Technology
Oak Ridge, Tenn., April 13–16, 1981
J. B. Ball, C. M. Jones, J. A. Martin, organizers

1981 Topical Conference on Computerized Data Acquisition in Particle and Nuclear Physics
Oak Ridge, Tenn., May 28–30, 1981
D. C. Hensley, organizer

Information Meeting, November 1979

The most recent Physics Division Information Meeting was held on November 5 and 6, 1979. The members of the Advisory Committee were:

C. K. Bockelman, Yale University
A. Dalgarno, Harvard University
H. A. Enge, Massachusetts Institute of Technology
S. E. Koonin, California Institute of Technology
D. K. Scott, Michigan State University
H. E. Wegner, Brookhaven National Laboratory

PHYSICS DIVISION

SEPTEMBER 1981

P. H. STELSON, DIRECTOR
W. L. STAIR, SEC.

ENGINEERING COORDINATION AND PROCUREMENT
J. W. JOHNSON[1]
J. C. COPELAND
R. K. GOOSIE[14]
A. D. HIGGINS[13]
T. C. MINTON[13]
R. H. WARD[13]

FINANCE AND PROPERTY OFFICER
C. M. GALLAHER

SPECIAL STAFF ASSIGNMENTS
R. L. AUBLE, RADIATION AND SAFETY OFFICER
D. J. HOREN, QUALITY ASSURANCE OFFICER
M. J. MARTIN, AFFIRMATIVE ACTION OFFICER
S. W. MOSKO, ENERGY CONSERVATION OFFICER
D. J. HOREN, SEMINAR CHAIRMAN

HOLIFIELD HEAVY ION RESEARCH FACILITY
J. B. BALL
J. A. MARTIN
A. B. LIVINGSTON, SEC.
J. K. THACKER, SEC.

EXPERIMENTAL FACILITIES
R. L. ROBINSON[1]
J. W. JOHNSON[1]
R. P. CUMBY[3]
R. W. MILES
C. A. REED[8]
C. N. THOMAS[8]

COMPUTER SYSTEMS
J. A. BIGGERSTAFF
W. H. ATKINS[10]
D. C. HENSLEY[1]
R. C. JURAS[1,3]
W. T. MILNER
R. O. SAYER[10]

25 MV TANDEM ACCELERATOR
C. M. JONES

TANDEM OPERATIONS AND ENGINEERING
N. F. ZIEGLER
J. A. BENJAMIN
R. C. JURAS[1,3]
J. E. MANN
E. G. RICHARDSON
D. M. GALBRAITH[1]

NEGATIVE ION SOURCE DEVELOPMENT
G. D. ALTON[1]

ORIC ACCELERATOR
R. S. LORD
E. D. HUDSON
G. S. McNEILLY[10]
F. IRWIN

ORIC OPERATIONS AND ENGINEERING
S. W. MOSKO
C. A. LUDEMANN
C. L. VIAR[1]
B. J. CASSTEVENS[10]

OPERATIONS STAFF
C. L. VIAR[1]
H. D. HACKLER
C. L. HALEY
N. L. JONES
S. N. LANE
C. T. LeCROY
C. A. MAPLES
S. N. MURRAY

NUCLEAR PHYSICS RESEARCH
E. E. GROSS
S. J. BALL, SEC.
V. K. HILL, SEC.
C. R. WALLACE, SEC.

MICROSCOPIC REACTION STUDIES
F. E. BERTRAND
R. L. AUBLE
O. E. DIGREGORIO
K. A. ERB
R. W. FEARICK
J. L. C. FORD, JR.[9]
C. R. FULMER
J. GOMEZ DEL CAMPO
D. J. HOREN[1]
R. W. HOVOTNY
D. A. H. SCHULL
D. SHAPIRA
B. SHIVAKUMAR
F. P. SADIEEN

MACROSCOPIC REACTION STUDIES
F. PLASIL
T. C. AWES
J. R. BEENE
C. E. BEMIS, JR.
R. L. FERGUSON
M. L. HALBERT[3]
F. E. OBENSHAIN[8]
R. L. ROBINSON[1]
G. R. YOUNG

NUCLEAR STRUCTURE
N. R. JOHNSON[8]
C. R. BINGHAM[4]
M. P. FEWELL
M. W. GUIDRY
I. Y. LEE
M. J. MARTIN[1]
F. K. McGOWAN
D. M. MOLTZ
L. L. RIEDINGER[4]
K. S. TOTH
J. C. WELLS[5]
D. M. GALBRAITH[1]

EQUIPMENT DEVELOPMENT
D. C. HENSLEY[1]
J. L. BLANKENSHIP[3]

UNISOR PROJECT
E. H. SPEJEWSKI[8,9]
H. K. CARTER[8]
G. A. LEANDER[3]
R. L. MLEKODAJ[8]
J. HELTON, SEC.[8]

ATOMIC PHYSICS RESEARCH
S. DATZ
K. P. HAMILTON, SEC.
L. J. HAWKINS, SEC.

HIGH ENERGY ATOMIC PHYSICS
P. D. MILLER
G. D. ALTON[1]
P. F. DITTNER
S. B. ELSTON[2]
C. D. MOAK
D. J. PEGG[1]
I. A. SELLIN[4]
G. E. WELLS

MFE EXPERIMENTAL PHYSICS RESEARCH
D. H. CRANDALL[1]

ATOMIC COLLISIONS
D. H. CRANDALL[1]
D. C. GREGORY
P. M. GRIFFIN
J. W. HALE
H. J. KIM
F. W. MEYER
R. A. PHANEUF

MFE DIAGNOSTIC DEVELOPMENT
D. P. HUTCHINSON
C. H. MA
P. A. STAATS
K. L. VANDER SLUIS

ATOMIC CROSS SECTION COMPILATIONS
C. F. BARNETT
B. J. FARMER
P. M. HARFORD[7]
M. I. KIRKPATRICK

NEUTRON PHYSICS RESEARCH
J. A. HARVEY
S. F. McHARGUE, SEC.

NEUTRON CAPTURE
R. L. MACKLIN
S. RAMAN[1]
G. G. SLAUGHTER

TOTAL CROSS SECTIONS AND ANGULAR DISTRIBUTIONS
D. J. HOREN[1]
C. R. JOHNSON
N. M. LARSON[10]

ACTINIDE CROSS SECTIONS
J. W. T. DABBS
L. W. WESTON[6]

INSTRUMENTATION
N. W. HILL[3]

THEORETICAL PHYSICS
J. B. McGRORY
A. S. TATE, SEC.

NUCLEAR THEORY
K. T. R. DAVIES
E. C. HALBERT[11]
M. J. RHOADES-BROWN
G. R. SATCHLER
A. J. SIERK[15]
T. A. WELTON
C. Y. WONG

ATOMIC THEORY
R. L. BECKER
C. BOTTCHER

NUCLEAR DATA NETWORK
M. J. MARTIN[1]
Y. A. ELLIS-AKOVALI
W. B. EWBANK[12]
S. HARMATZ
M. R. McGINNIS
J. T. MILLER[7]
M. B. SCHMORAK

APPLICATIONS OF HEAVY ION BEAMS
S. RAMAN
C. R. VANE

HIGH ENERGY PHYSICS
H. O. COHN
W. M. BUGG[4]
G. T. CONDO[4]
E. L. HART[4]
J. T. MARTIN
J. C. SHARP

[1] DUAL CAPACITY
[2] FINANCE AND MATERIALS DIVISION
[3] INSTRUMENTATION AND CONTROLS DIVISION
[4] UNIVERSITY OF TENNESSEE
[5] TENNESSEE TECHNICAL UNIVERSITY
[6] ENGINEERING PHYSICS DIVISION
[7] INFORMATION DIVISION
[8] OAK RIDGE ASSOCIATE UNIVERSITIES
[9] HOLIFIELD MENTOR
[10] COMPUTER SCIENCES DIVISION
[11] ON ASSIGNMENT TO ENERGY DIVISION
[12] ON ASSIGNMENT TO INFORMATION DIVISION
[13] PLANT AND EQUIPMENT DIVISION
[14] GENERAL ENGINEERING DIVISION
[15] ON ASSIGNMENT FROM LANL

ORNL-5787
Dist. Category UC-34

INTERNAL DISTRIBUTION

1. G. D Alton
2. R. L. Auble
3. J. A. Auxier
4. J. B. Ball
5. C. F. Barnett
6. R. L. Becker
7. J. R. Beene
8. C. E. Bemis
9. J. A. Benjamin
10. F. E. Bertrand
11. J. A. Biggerstaff
12. C. R. Bingham
13. Biology Library
14. C. Bottcher
15. D. N. Braski
16. W. M. Bugg
17. H. P. Carter
18–19. Central Research Library
20. H. O. Cohn
21. G. T. Condo
22. D. H. Grandall
23. J. W. T. Dabbs
24. S. Datz
25. K. T. R. Davies
26. G. DeSaussure
27. P. F. Dittner
28. W. B. Dress
29. Y. A. Ellis-Akovali
30. S. B. Elston
31. K. A. Erb
32. W. B. Ewbank
33. R. L. Ferguson
34. M. P. Fewell
35. J. L. C. Ford, Jr.
36. J. L. Fowler
37. C. B. Fulmer
38. J. Gomez del Campo
39. D. C. Gregory
40. J. D. Griffin
41. P. M. Griffin
42. E. E. Gross
43. M. W. Guidry
44. R. L. Hahn
45. E. C. Halbert
46. M. L. Halbert
47. B. Harmatz
48. E. L. Hart
49. J. A. Harvey
50. D. C. Hensley
51. R. F. Hibbs
52. C. C. Hopkins
53. D. J. Horen
54. E. D. Hudson
55. D. P. Hutchinson
56. C. H. Johnson
57. J. W. Johnson
58. N. R. Johnson
59. C. M. Jones
60. S. V. Kaye
61. O. L. Keller
62. H. J. Kim
63–64. Laboratory Records Department
65. Laboratory Records, ORNL R.C.
66. G. A. Leander
67. I. Y. Lee
68. R. S. Lord
69. C. A. Ludemann
70. Barbara Lyon
71. C. H. Ma
72. R. L. Macklin
73. F. C. Maienschein
74. J. E. Mann
75. J. A. Martin
76. M. J. Martin
77. F. K. McGowan
78. J. B. McGrory
79. C. J. McHargue
80. F. W. Meyer
81. P. D. Miller
82. W. T. Milner
83. R. L. Mlekodaj
84. C. D. Moak
85. D. M. Moltz
86. O. B. Morgan
87. S. W. Mosko
88. F. W. Mynatt
89. R. W. Novotny
90. F. E. Obenshain
91. D. K. Olson
92. G. W. Oliphant

93. ORNL—Y-12 Technical Library Document Reference Section
94. R. W. Peele
95. D. J. Pegg
96. F. G. Perey
97. R. A. Phaneuf
98. F. Plasil
99. H. Postma
100. S. Raman
101. M. J. Rhoades-Brown
102. E. G. Richardson, Jr.
103. C. R. Richmond
104. L. L. Riedinger
105. R. L. Robinson
106. M. W. Rosenthal
107. G. R. Satchler
108. R. O. Sayer
109. M. R. Schmorak
110. I. A. Sellin
111. D. Shapira
112. W. D. Schults
113. T. P. Sjoreen
114. G. G. Slaughter
115. A. H. Snell
116–119. E. H. Spejewski
120–319. P. H. Stelson
320. K. S. Toth
321. D. B. Trauger
322. K. L. Vander Sluis
323. C. R. Vane
324. C. L. Viar
325. G. F. Wells
326. J. C. Wells
327. T. A. Welton
328. M. K. Wilkinson
329. Cheuk-Yin Wong
330. G. R. Young
331. N. R. Ziegler
332. A. Zucker

EXTERNAL DISTRIBUTION

333. Fay Ajzenberg-Selove, Department of Physics, University of Pennsylvania, Philadelphia, PA 19104
334. B. J. Allen, Physics Division, Australian Atomic Energy Commission, Sutherland, N.S.W., Australia
335. C. H. Annett, The Physics Group, 117B, University of Kansas, 4417 Minnie St., Kansas City, KS 66103
336. M. Baranger, 6-308-A, Massachusetts Institute of Technology, Cambridge, MA 02139
337. C. A. Barnes, Physics Division, California Institute of Technology, Pasadena, CA 91109
338. H. Behrens, Zentralstelle für Atomkernenergie-Dokumentation, Kernforschungszentrum Karlsruhe 7514, Eggenstein-Leopoldshafen-2, West Germany
339. Ingmar Bergstrom, Nobel Institute of Physics, Stockholm 50, Sweden
340. Biblioteca do Depto. de Fisica Nuclear, Instituto de Fisica da USP, Caixa Postal 20516, 0100—Sao Paulo, SP, Brazil
341. Bibliotheque—Madame Belle, Universite' de Grenoble, Institut des Sciences Nucleaires, 53, rue des Martyrs, B.P. 21, 38 Grenoble, France
342. M. Blann, University of California, Lawrence Radiation Laboratory, P.O. Box 808, Livermore, CA 94550
343. S. D. Bloom, University of California, Lawrence Radiation Laboratory, P.O. Box 808, Livermore, CA 94550
344. H. G. Blosser, Cyclotron Laboratory, Michigan State University, East Lansing, MI 48823
345. H. Bohr, Physik-Department E12, Technische Universität, 8046 Garching bei München, West Germany
346. A. Bohr, Copenhagen University, Niels, Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark
347. R. O. Bondelid, Cyclotron Branch, U.S. Naval Research Laboratory, Washington, DC 20390
348. J. S. Briggs, Theoretical Physics Division, Atomic Energy Research Establishment, Harwell, Didcot, Oxfordshire Ox 11 ORA, England
349. J. A. Brink, Library Division, The Merensky Institute of Physics, University of Stellenbosch, Stellenbosch, Republic of South Africa
350. D. A. Bromley, Nuclear Structure Laboratory, Yale University, New Haven, CN 06520

351. John C. Browne, P Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544
352. H. T. Burn, Technical Librarian, ORAU/MERT, P.O. Box 117, Oak Ridge, TN 37830
353. H. Camarda, P.O. Box 808, Lawrence Livermore National Laboratory, Livermore, CA 94550
354. Jose' L. S. Carvalho, Instituto de Radioprotecão e Dosimetria, C.N.E.N. Av. das Americas km 11,5 Barra da Tijuca—R.J., 22700—Rio de Janeiro, R.J. Brazil
355. R. E. Chrien, Brookhaven National Laboratory, Upton, NY 11973
356. David Clark, Lawrence Radiation Laboratory, University of California, Berkeley, CA 94720
357. B. L. Cohen, Department of Physics, University of Pittsburgh, Pittsburgh, PA 15213
358. M. D. Cohler, Postgraduate School of Studies in Physics, University of Bradford, Bradford Yorkshire BDP7 1DP, West Yorkshire
359. H. E. Conzett, Lawrence Radiation Laboratory, University of California, Berkeley, CA 94720
360. F. L. Culler, Office of the President, Electric Power Research Institute, P.O. Box 10412, 3412 Hillview Avenue, Palo Alto, CA 94303
361. T. J. Curtin, Director, Office of Research and Grants Administration, Texas Women's University, Box 22939, TWU Station, Denton, TX 76204
362. R. Y. Cusson, Physics Department, Duke University, Durham, NC 27706
363. Cary Davids, Argonne National Laboratory, Building 203, Argonne, Il 60439
364. Ding Dazaho, P.O. Box 275, Beijing, China
365. Solange de Barros, Head, Department of Nuclear Physics, Universidade Federal do Rio de Janeiro, Instituto de Fisica—Department Fisica Nuclear, Centro de Technologia—Bloco A, Ilha do Fundao—Rio de Janeiro, Brazil
366. Adriano de Lima, Physics Laboratory, University of Coimbra, Coimbra, Portugal
367. R. M. Diamond, Chemistry Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720
368. R. M. Drisko, Physics Department, University of Pittsburgh, Pittsburgh, PA 15213
369. U. Facchini, Physics Department, University of Milan, Via Saldini 50, Milan, Italy
370. H. Faraggi-Mathieu, Centre d'Etudes Nucleaires de Saclay, B.P. No. 2, Gif-Sur-Yvette (S. and O.), France
371. G. N. Flerov, Laboratory for Nulcear Reactions, Dubna Joint Institute for Nuclear Research, Dubna, Moscow Oblast, U.S.S.R.
372. W. A. Fowler, California Institute of Technology, Pasadena, CA 91109
373. J. D. Fox, Department of Physics, Florida State University, Tallahassee, FL 32306
374. A. I. Galonsky, Cyclotron Laboratory, Michigan State University, East Lansing, MI 48823
375. J. B. Garg, Department of Physics, State University of New York at Albany, 1400 Washington Avenue, Albany NY 12222
376. W. Gentner, Max Planck Institute für Kernphysik, Saupfercheckweg, 69 Heidelberg, West Germany

377–386. GLCA-ORS, Attention: R. R. Winters, Denison University, Granville, OH 43023

387. M. Gouttefangeas, Ganil, B. P. 6115, 14004 Caen Cedex, France
388. G. W. Greenless, Physics Department, University of Minnesota, Minneapolis MN 55455
389. R. J. Griffiths, Physics Department, Kings College, Strand, London, W.C. 2, England
390. H. Grunder, Lawrence Berkeley Laboratory, Berkeley, CA 94720
391. M. Micheline Guichard, Institut de Physique Nucleaire, B.P. No. 1, 91 Orsay, France
392. F. Haas, Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824
393. J. H. Hamilton, Department of Physics, Vanderbilt University, Nashville, TN 37203
394. S. S. Hanna, Physics Department, Stanford University, Stanford, CA 94305
395. B. G. Harvey, Lawrence Radiation Laboratory, University of California, Berkeley, CA 94720
396. R. L. Heath, Idaho National Engineering Laboratory, EG&G Idaho, Inc., P.O. Box 1625, Idaho Falls, ID 83401
397. D. L. Hendrie, Department of Physics, University of Maryland, College Park, MD 20742
398. G. Holzwarth, Gesamthochschule Siegen, Fachbereich 7—Physik, Adolf Reichwein Str., 5900 Sigen 21, West Germany
399. Cheng Hsiao-Wu, Institute of Nuclear Research, P.O. Box 8204, Shanghai, The Peoples Republic of China

400. Institute for Energy Analysis, P.O. Box 117, Oak Ridge, TN 37830
401. Institute of Physics, High Energy and Nuclear Physics Library, Caixa Postal 20516, 0100—Sao Paulo—SP, Brazil
402. Hu Jimin, Department of Technical Physics, Beijing University, Beijing, China
403. Arne Johansson, Tandem Accelerator Laboratory, Box 533, S-751, 21 Uppsala, Sweden
404. C. Johnson, Triumf, University of British Columbia, Vancouver 8, BC, Canada
405. H. H. Jung, 2057 Geesthacht, Reaktorstation, Insitut für Reine and Angewandte Kernphysik der Christian-Albrechts-Universitat, Keil, Germany
406. R. Kamermans, Robert van de Graafflaboratorium, Sorbonnelann 4, 3508 TA, Utrecht, The Netherlands
407. H. Kamitsubo, Head, Cyclotron Laboratory, Institute of Physical and Chemical Research, Wako-Shi, Saitama, 351 Japan
408. D. G. Kambe, Ruhr-Universität Bochum, Dynamitron Tandem Laboratory, Universitattstr, 150, Gibaunde NT, Postfach 1021 48, 4360 Bochum 1, Germany
409. H. Kawakami, Institute for Nuclear Study, University of Tokyo, Midori-cho, Tokyo, Japan
410. K. W. Kemper, Physics Department, Florida State University, Tallahassee, FL 32306
411. V. N. Kononov, Institute of Physics and Energetics, Obninsk, U.S.S.R.
412. Christa Kroh, Gesellschaft für Schwerionenforschung MBH, 61 Dearmstadt 1, Postfach 541, Darmstadt, West Germany
413. L. L. Lee, Physics Department, State University of New York, Stony Brook, NY 11790
414. J. A. Lenhard, DOE-ORO, Federal Office Building, Oak Ridge, TN 37830
415. Librarian, Atomic Energy Centre, P.O. Box 164, Ramna, Dacca, Bangladesh
416. Librarian, Cyclotron Laboratory, Michigan State University, East Lansing, MI 48823
417. Librarian, Department of Physics, Georgia State University, Atlanta, GA 30303
418. Library of the Institute of Atomic Energy, Beijing, China
419. Librarian, MERT Division Library, Oak Ridge Associated Universities, P.O. Box 117, Oak Ridge, TN 37830
420. Librarian, Physics Division 374 Bausch and Lomb Building, University of Rochester, Rochester, NY 14627
421. Librarian, Institut des Sciences Nucleaires, BP No. 257—Centre de Tri, 38044 Grenoble Cedex, France
422. T. Lindblad, Research Insitute of Physics, S-104 OT Stockholm 50, Sweden
423. R. S. Mackintosh, SRC Daresbury Laboratory, Warrington WA4 4AD, England
424. G. Madurga, Departameto de Fisica Atomica y Nuclear, Facultad de Ciencias, Universidad de Sevilla, Sevilla, Spain
425. Sven Malmskog, AB Atomenergi, Studsvik, Nykoping, Sweden
426. Niels Marquardt, Institut für Expermentalphysik III, Der Ruhr-Univeersität Bochum, Postfach 1021, 48, 4630 Bochum 1, West Germany
427. J. V. Martinez, Department of Energy, Washington, DC 20545
428. W. R. McMurray, Deputy Chief Scientist, Kerninstituut Van Die Suidelike Universiteite, Southern Universities Nuclear Institute, Republic of South Africa
429. A. Michaudon, Chef du Service de Physique Nucleaire, Commissariat a l'Engerie Atomique, Centre d'Etudes de Bruyeres, le Chatel, P.P. No. 61, Montrouge 92120, France
430. J. C. D. Milton, Physics Division, Atomic Energy of Canada Ltd., Chalk River, Canada
431. J. N. Mo, Department of Physics, University of Manchester, Manchester, England
432. L. Moretto, Lawrence Berkeley Laboratory, University of California Nuclear Science Division, Berkeley, CA 94720
433. S. A. Moszkowski, Physics Department, University of California at Los Angeles, Los Angeles, CA 90024
434. S. C. Mukherjee, Librarian, Saha Institute of Nuclear Physics, 92, Acharya Prafulla Chandra Road, Calcutta—9, India
435. Y. Nakamura, JPL, Systems Analysis Section, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91103

436. Max Peisach, Southern Universities Nuclear Insitute, P.O. Box 17, Faure, 7131, Republic of South Africa
437. Elliott S. Pierce, Assistant Director, Molecular Sciences, Department of Energy, Washington, DC 20545
438. A. A. Pilt, Tandem Accelerator Laboratory, McMaster University, Hamilton, Ontario, Canada L8S 4K1
439. Tom Pinkston, Arts and Sciences, Vanderbilt University, Nashville, TN 37312
440. W. D. Ploughe, Van de Graaff Accelerator Laboratory, Department of Physics, 1302 Kinnear Road, Columbus, OH 43212
441. B. Povh, Max Planck Institut für Kernphysik, 69 Heidelberg, Saupfercheckweg, Postfach 124B, West Germany
442. Jacobo Rapaport, Department of Physics, Ohio University, Athens, OH 45701
443. John Rasmussen, Lawrence Berkeley Laboratory, Building 70A, Berkeley, CA 94720
444. Patrick Richard, Physics Department, Kansas State University, Manhattan, KS 66506
445. E. T. Ritter, Department of Energy, Washington, DC 20545
446. L. D. Roberts, Physics Department, University of North Carolina, Chapel Hill, NC 27514
447. L. Rosen, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544
448. Rainer Santo, Sektion Physik der Universität München, 8046 Garching, Beschleuigerlaboratorium (Forschungsgelande), West Germany
449. D. G. Sarantites, Department of Chemistry, Washington University, St. Louis, MO 63130
450. J. P. Schiffer, Physics Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439
451. Christoph Schmelzer, Gesellschaft für Schwerionenforschung MBH, 6100 Darmstadt 1, West Germany
452. F. H. Schmidt, Physics Department, University of Washington, Seattle, WA 98105
453. A. Schwarzchild, Brookhaven National Laboratory, Upton, NY 11973
454. Li Shou-nan, The Institute of Atomic Energy, Beijing, China
455. R. H. Siemssen, Kernfysisch Versneller Institut der Rijksuniversiteit Zernikelaan 25, 9747 AA Groningen, The Netherlands
456. Hsu Leke Soo, Department of Physics, Nanyang University, Singapore 22, Republic of Singapore
457. T. Springer, Institut Max von Laue—Paul Langevin, 156 X Centre de Tri, 38402 Grenoble Cendex, France
458. T. T. Sugihara, Cyclotron Institute, Texas A&M University, College Station, TX 77843
459. Kazusuke Sugiyama, Department of Nuclear Engineering, Faculty of Engineering, Tohoku University, Sendai, Japan
460. Taro Tamura, Department of Physics, University of Texas, Austin, TX 78712
461. Shigyea Tanaka, Japan Atomic Energy Research Insitute, Tokai-Mura, Ibaraki-Ken, Japan
462. J. Teillac, Laboratoire de Physique Nucleaire d'Orsay, Facultes des Sciences, B.P. No. 1, Orsay (S. and O.), France
463. G. M. Temmer, Physics Department, Rutgers State University, New Brunswick, NJ 08903
464. Jacques Thirion, CEN—Saclay SPNME, BP No. 2, Gif-Sur-Yvette 91, France
465. S. T. Thornton, Physics Department, University of Virginia, Charlottesville, VA 22901
466. P. J. Twin, Oliver Lodge Laboratory, University of Liverpool, Oxford Street, P.O. Box 147, Liverpool 1 69 3BX, England
467. J. P. Unik, Building 200, Argonne National Laboratory, Argonne, IL 60439
468. Robert Vandenbosch, Department of Chemistry, University of Washington, Seattle, WA 98105
469. A. van der Woude, Kernfysisch Versneller Institut der Rijksuniversiteit, Universiteitscomplex Paddepoel, Groningen, The Netherlands
470. H. Verheul, Natuurkundig Laboratorium der Vrije Universiteit de Boelelaan 1081, Amsterdam, The Netherlands
471. J. Vervier, Laboratoire du Cyclotron Louvain-La-Neuve, Rue de Namur, 1340 Ottingnies, Belgique
472. R. G. P. Voss, Daresbury Nuclear Physics Laboratory, Daresbury, Nr. Warrington, Lancashire, England
473. A. H. Wapstra, Institute Voor Kernphysisch Onderzoek, Ooster Ringdijk 18, Amsterdam, The Netherlands

474. Katharine Way, Department of Physics-TUNL, Duke University, Durham, NC 27706
475. Horst H. F. Wegener, Tandemlabor des Physikalischen Instituts der Universität Erlangen-Nurnberg, 8520 Erlangen, Erwin-Rommel-Strasse 1, West Germany
476. F. Weller, Institute for Neutron Physics and Reactor Technology, Kernforschungszentrum Karlsruhe, Postfach 3640, West Germany
477. Joseph Wenesser, Department of Physics, Brookhaven National Laboratory, Upton, NY 11973
478. Lars Westerberg, Institute of Physics, University of Uppsala, Box 530, S-75121 Uppsala, Sweden
479. Ward Whaling, Division of Physics and Astronomy, California Institute of Technology, Pasadena, CA 91109
480. E. P. Wigner, Department of Physics, Princeton University, Princeton, NJ 08540
481. L. Wilets, Department of Physics, University of Washington, Seattle, WA 98105
482. D. H. Wilkison, Department of Physics, University of Sussex, Sussex England
483. H. B. Willard, Program Director for Intermediate Energy Physics, National Science Foundation, 1800 G Street, NW, Washington, D.C. 20550
484. D. Youngblood, Cyclotron Institute, Texas A&M University, College Station, TX 77940
485. Alexander Xenoulis, Van de Graaff Laboratory, Nuclear Research Center, Demokridos, Aghia Paraskevi Attikis, Athens, Greece
486. E. F. Zganjar, Louisiana State University, Department of Physics and Astronomy, Baton Rouge, LA 70803
487. J. C. C. Sharp, Information Officer, Daresbury Laboratory, Science Research Council, Daresbury, Warrington WA4 4AD, England
488. Gerhard Schleussner, Institut für Strahlenphysik der Universität Stuttgart, D-7000 Stuttgart 80, Allmandring 3, West Germany

489–601. Given distribution as shown in TID-4500 under Physics category (25 copies—NTIS)

* U.S. GOVERNMENT PRINTING OFFICE: 1981-740 052/288