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PHYSICS Division - Annual PROGRESS REPORT

Period Ending December 31, 1972

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

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PHYSICS DIVISION
ANNUAL PROGRESS REPORT
For Period Ending December 31, 1972

J. L. Fowler, Director
G. R. Satchler, Associate Director
P. H. Stelson, Associate Director
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APRIL 1973

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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Reports previously issued in this section are as follows:

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Foreword

This annual progress report of the Physics Division covers the calendar year 1972. As in previous years the report contains the abstracts of papers published since the last annual report and those prepared for publication. Reprints and preprints of these articles are available upon request. Preliminary results of research work in progress are reported in more detail. Since this work is of a preliminary nature, reference to or inclusion of these results in any other publications should be done with the express consent of the author.

Each month the Division Director submits a report which summarizes some research activity within the Division. These reports follow immediately and will give the reader an overview of the research efforts in progress.

Looking to the future, in June 1972 the Oak Ridge National Laboratory sponsored a summer study on heavy-ion research. A short report of this meeting may be found near the end of Sect. 8, and reports on heavy-ion acceleration are given in Sect. 7.

Monthly Reports of the Physics Division

The Divisional monthly reports, which consist of about 200 words, summarize at least one activity of the Division for each month of the year. These reports for the Division for calendar year 1972, with references to the literature updated as of the time of submission of this annual report, are as follows:

Preliminary Measurements on a Low-Phase-Velocity Superconducting Resonant Cavity – January

Since the Oak Ridge National Laboratory has had for some time now a proposal before the Atomic Energy Commission for a heavy-ion accelerator, it must keep abreast of developments in heavy-ion accelerator technology, such as the superconducting linear accelerator. Consequently, a small experimental group in the Physics Division has investigated one type of superconducting cavity possible for a heavy-ion accelerator. An important problem for the design is the low velocity of the ions being accelerated, which requires cavities of low phase velocities. Since a helically loaded cavity has this property, Jones et al.[1] have constructed such a lead-plated cavity with a lead-plated helix and have measured its electrical characteristics in a superconducting state at relatively low frequencies (~136 MHz). They operated the cavity as a self-excited oscillator effectively at the top of the resonance curve where the rf and mechanical systems are decoupled, so that mechanical vibrations introduced essentially no problems for the measurements. They obtained the following approximate fields at a power consumption of 320 mW/m: maximum magnetic field, 187 G; maximum electric field, 4.75 MV/m; axial accelerating field, 0.7 MV/m. Although formidable problems remain to be solved, C. M. Jones et al., in their preliminary investigation, discovered no insurmountable obstacles to the use of helically loaded structures in an accelerator.

1. C. M. Jones, J. P. Judish, R. F. King, F. K. McGowan, W. T. Milner, and P. Z. Pebbles, Jr., *Particle Accel.* **3**, 103–13 (1972).

The Two-Center Model and Fission Barriers for Light Elements (A = 180–212) – February

For properties of deformed nuclei near their ground states, such as quadrupole moments and collective restoring forces, the Nilsson deformed shell model gives a good theoretical description of the experimental information. For larger deformations, such as those encountered in the fission process, however, the Nilsson model has proven to be inadequate, probably because it does not permit a sufficient parameterization of the nuclear shapes. The two-center model,[1] a model consisting of a two-center oscillator potential, allows a smooth transition from the ground state via the preformation of fragment shells to a system of two completely separated fragment nuclei. In practice, detailed two-center-model calculations for the nuclear potential energy surface as a function of the shape parameters follow the procedure developed by Strutinsky. In this procedure the total potential energy of a nucleus is divided into two parts, a smoothly behaving liquid-drop energy and a strongly deformation-dependent shell correction. For nuclei in the range A = 180 to 212, Mosel and Schmitt[2] have calculated fission barriers on the basis of the two-center model.

Their theoretical work gives an overall satisfactory description of the fission barriers for these relatively light fissionable nuclei within the accuracy of the known experimental values, which is about 1 MeV.

1. P. Holzer, U. Mosel, and W. Greiner, *Nucl. Phys.* **A138**, 24 (1969); U. Mosel and H. W. Schmitt, *Nucl. Phys.* **A165**, 73 (1971).
2. U. Mosel and H. W. Schmitt, *Phys. Lett.* **37B**, 335 (1971).

A Position-Sensitive Proportional Detector for the Enge Magnetic Spectrograph – March

The Enge split-pole magnetic spectrograph associated with the ORNL tandem Van de Graaff has a sufficiently large acceptance angle that it is competitive in efficiency with good-resolution semiconductor detectors. But photographic-plate particle detectors usually used with such magnets have well-known disadvantages. Not only is the reading of the plates tedious and time consuming, but one also loses the ability to monitor and modify an experiment on line. Furthermore, with plates there is a limitation in precision because of the large number of events which must be recorded to obtain statistical accuracy. Ford, Stelson, and Robinson[1] have gotten around these difficulties by using a position-sensitive detector in the focal plane of the Enge magnet. The Borkowski-Kopp type of detector[2] is a single-wire, gas proportional counter, which derives the position information from the rise time of the pulses from the two ends of a high-resistance wire anode. With 15- to 45-MeV alpha particles through the magnet, a 20-cm-long detector and also a 60-cm one gave resolution in position of 0.7 mm. The deviation from spatial linearity was less than 3%, and the detector could handle counting rates up to several tens of thousands of counts per second. Ford et al.[3] have used this detector for a systematic study of alpha-particle scattering from transuranic elements.

1. J. L. C. Ford, Jr., P. H. Stelson, and R. L. Robinson, *Nucl. Instrum. Methods* **98**, 199 (1972).
2. C. J. Borkowski and M. K. Kopp, *Rev. Sci. Instrum.* 39, 1515 (1968).
3. 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).

X-Ray Production by Fast Heavy Ions – April

When an ion passes through matter it can excite inner-shell electrons of the target atoms into the continuum by direct Coulomb excitation, and some of these resulting inner-shell vacancies will decay by emission of x rays. Recently there has been an increased interest in studying the characteristics of x-ray production by fast ions, not only because this could be an attractive way of detecting trace elements, but also because of its intrinsic interest as a new tool in the study of atomic structure. As long as polarization effects can be neglected, the cross section σ_I for the production of vacancies in the K shell for projectiles of the same velocity should be proportional to Z^2, where Z is the projectile charge. The same should hold for the x-ray production cross section σ_X if one assumes that the fluorescence yield, that is, the fraction of inner-shell vacancies that decay by emission of an x ray, does not depend on Z. Using the ORIC, van der Woude et al.[1] have measured σ_X for 5 MeV/amu ^{20}Ne, ^{16}O, ^{12}C, and ^{4}He ions on Ti, Fe, Co, Zr, Sn, and Nd targets. They found large deviations in σ_X from the expected Z^2 dependence and conclude, at least in the case of the K x rays from Zr, Sn, and Nd, that there is very likely a need for a Z^3 term in the expression for the ionization cross section.

1. A. van der Woude, M. J. Saltmarsh, C. A. Ludemann, R. L. Hahn, and E. Eichler, submitted for publication in *Proceedings International Conference on Inner Shell Ionization Phenomena* (Atlanta, Georgia, April 1972).

Improved Upper Limit for the Electric Dipole Moment of the Neutron – May

Dress, Miller, and Ramsey[1] have concluded their experimental search for the electric dipole moment of the neutron at the Oak Ridge Research Reactor. After measuring all known systematic effects, they find no evidence for instability in the spectrometer. In particular, they removed the principal limitation of their previous experiment[2] arising from the nonparallelism of the E and B fields, which gives a spurious effect through a term $B_E = -(v \times E)/c$. They placed the spectrometer and the magnetic shields on a modified, surplus gun mount so that the direction of the neutron beam through the applied fields could be easily reversed, thus reversing the sign of v in B_E. The final result of the experimental search is $\mu/e = 3 \pm 6 \times 10^{-24}$ cm, which Dress et al. interpret as meaning $\mu/e < 1 \times 10^{-23}$ cm with a probability of 75%. They are moving the spectrometer to the High Flux Reactor in Grenoble, where the liquid deuterium secondary moderator and the high flux should provide a factor of 2000 in the intensity of the very slow neutrons required. If the anticipated improved sensitivity of a few times 10^{-25} cm gives no electric dipole moment, the experiment will provide overwhelming evidence for the superweak theory of CP violation; if the result shows an electric dipole moment, then the superweak theory is not responsible and there must be a small CP violation in the weak or strong interactions.

1. W. B. Dress, P. D. Miller, and N. F. Ramsey, submitted for publication in the *Physical Review, D.*
2. J. K. Baird, P. D. Miller, W. B. Dress, and N. F. Ramsey, *Phys. Rev.* 179, 1285 (1969).

Excitation of Giant Quadrupole States in Nuclei – June

Lewis and Bertrand[1] have analyzed data on inelastic scattering of 62-MeV protons from targets of ^{27}Al, ^{54}Fe, ^{120}Sn, and ^{209}Bi, where the protons were accelerated with the Oak Ridge Isochronous Cyclotron. The inelastic proton spectra, which covered the 1.5- to 62.0-MeV range, showed peaks in the continuum structure near the energy region of the giant dipole resonance – that is, the resonance arising from the protons and the neutrons vibrating against each other. But the observed inelastic protons peaked at an excitation energy consistently lower by ~2 MeV than the dipole resonant energy. On the basis of the energy of this proton peak as well as the strength of the resonances, Lewis and Bertrand suggest that they have excited another giant collective state of the quadrupole type, an example of which is a collective motion in which the nucleus vibrates between a prolate and an oblate shape. At 62 MeV the angular distributions of the inelastically scattered protons are consistent with the interpretation of the peaks as quadrupole resonances, although other interpretations are not rigorously ruled out.[1] Data at 182 MeV definitely indicate a quadrupole transition. Satchler[2] has applied the deformed optical potential to calculations of dipole and quadrupole transitions in nuclei. He shows that the strengths of the observed resonances are consistent with the quadrupole interpretation, whereas the giant dipole is insufficient to explain the data. He also points out that virtual excitation of the collective quadrupole resonance would explain the effective charge for quadrupole transitions needed in shell-model calculations.

1. M. B. Lewis and F. E. Bertrand, submitted for publication in *Nuclear Physics;* original data from F. E. Bertrand and R. W. Peelle, ORNL-4455, -4469, -4471, and -4638.
2. G. R. Satchler, *Nucl. Phys.* A195, 1–25 (1972).

Hyperchanneling, an Axial Channeling Phenomenon – July

The channeling of collimated heavy ions of bromine or iodine by adjacent atomic planes of thin crystals of silver or gold has allowed a mapping of interatomic potentials in crystals and has, as well, yielded insights into the electron capture and loss processes in the heavy ions themselves.[1,2] With very tightly collimated 21.6-MeV iodine ions, Appleton et al.[3] have recently studied the channeling of a distinct group of ions in single gold crystals which show, over a very small range of incidence angles with respect to the [011] direction, an unusually low energy loss. They identify this group as ions which remain within a single axial channel throughout the passage through the crystal, and call this type of channeling hyperchanneling. In planar channeling an ion travels in a single channel between adjacent atomic planes, whereas in axial channeling the majority of the channeled ions wander from one axial channel to another. In hyperchanneling, however, the transverse energy of the ions is less than the potential barrier between the rows, and thus the ions are constrained to travel through a single axial channel. The energy spectrum of hyperchanneled 21.6-MeV iodine ions transmitted within ±0.012° of the incident beam direction shows a rate of energy loss of 3.15 MeV/μm, compared with a rate of 3.9 MeV/μm for planar channeled ions. Analysis of the results indicates that hyperchanneled ions provide a new means for studying multiple scattering, radiation damage, and ion-atom potentials in solids.

1. H. O. Lutz, S. Datz, C. D. Moak, and T. S. Noggle, *Phys. Rev. Lett.* 17, 285 (1966).
2. H. O. Lutz, S. Datz, C. D. Moak, and T. S. Noggle, *Phys. Lett.* **33A**, 309 (1970).
3. B. R. Appleton, C. D. Moak, T. S. Noggle, and J. H. Barrett, *Phys. Rev. Lett.* 28, 1307 (1972).

R-Matrix Analysis with a Diffuse Edge Potential for $^{16}O + n$ Data – August

The *R*-matrix analysis, introduced by Wigner and Eisenbud some 25 years ago, is today the most useful and physically significant way of describing resonances in nuclear reactions and scattering. The selection of the boundary radius on which reduced resonance widths depend rather critically, however, has been something of a problem. In an *R*-matrix analysis of $^{16}O(n,n)$ and $^{16}O(n,\alpha)$ cross sections,[1] Johnson[2] has found a self-consistent method of selecting this boundary radius. He fits the off-resonance cross sections by calculated scattering from a real Saxon-Woods potential with a Thomas-type spin orbit term. For s and d waves he chooses the well parameters to bind correctly the $2s_{1/2}$ and the $1d_{3/2}$ states, to give the observed s-wave cross sections at thermal energy, and to place the $1d_{3/2}$ state at the centroid of the five $\frac{3}{2}^+$ states observed as neutron resonances. Placing the *R*-matrix boundary radius inside the tail of the resulting potential at 3.86 fm, so that the $1d_{3/2}$ reduced width is equal to $\hbar^2/\mu r^2$, gives an excellent fit to the total and (n,α) cross section up to 5.8 MeV neutron energy.[1] Besides making the reduced widths of the five $\frac{3}{2}^+$ resonances equal to the single-particle reduced width, this procedure shows that the sum of the reduced widths of the $\frac{1}{2}^+$ and the $\frac{5}{2}^+$ states is very small and that the summed reduced widths of the $p_{3/2}$, $p_{1/2}$, $f_{7/2}$, and $f_{5/2}$ states are, respectively, 12, 5, 14, and 1% of single-particle values as predicted qualitatively by the shell model.

1. C. H. Johnson, J. L. Fowler, and R. M. Feezel, pp. 2–3 in *Contributions – Conference on Nuclear Structure Study with Neutrons* (Budapest, Hungary, July–August 1972), Central Research Institute for Physics, Budapest, 1972.
2. C. H. Johnson, submitted for publication in the *Physical Review*.

New Isotopes of Osmium – ^{171}Os, ^{170}Os, and ^{169}Os – September

The highly ionized neon beams, $^{20}Ne^{6+}$, from the Oak Ridge Isochronous Cyclotron allow sufficient energies (~150 MeV) to produce new isotopes by bombarding targets in the rare-earth region.[1,2] With ^{156}Dy targets, Toth et al.[1] discovered two new isotopes of osmium with alpha energies and half-lives as follows: (1) ^{170}Os, $E_\alpha = 5.40 \pm 0.01$ MeV, $T_{1/2} = 7.1 \pm 0.5$ sec; (2) ^{171}Os, $E_\alpha = 5.24 \pm 0.01$ MeV, $T_{1/2} = 8.2 \pm 0.8$ sec. They made the isotopic assignments on the basis of the alpha energies, half-lives, and the reaction energy systematics. They also observed a weak alpha group with energy consistent with that expected from ^{169}Os decay, but the beam energy limitation at the time prevented an identification from yield vs energy data. More recently, Toth, Hahn, Bingham, Ijaz, and Walker have taken advantage of a 1.7-MeV higher energy ^{20}Ne beam to reinvestigate the possible $^{156}Dy(^{20}Ne,7n)$ reaction which leads to ^{169}Os. They found that the yield of the 5.56 ± 0.02 MeV alpha group of 3.0 ± 0.5 sec half-life increases with energy in the range 146.6 to 153.4 MeV, consistent with the yield expected from the $^{156}Dy(^{20}Ne,7n)^{169}Os$ reaction, which has a threshold at 117 MeV and a predicted maximum yield at 160 MeV. They eliminated other possible reactions on the basis of the yield data. Furthermore, the ^{169}Os assignment is confirmed by the fact that the alpha energy, 5.56 ± 0.02 MeV, falls almost exactly on that expected for ^{169}Os.

1. K. S. Toth, R. L. Hahn, M. A. Ijaz, and R. F. Walker, *Phys. Rev.* C5, 2060 (1972).
2. K. S. Toth, R. L. Hahn, C. R. Bingham, M. A. Ijaz, and R. F. Walker, to be published in the *Physical Review*.

Neutron Capture in ^{86}Sr, ^{87}Sr, and ^{88}Sr and Nucleosynthesis – October

According to cosmologists, nucleosynthesis in the interior of red giant stars takes place by multiple capture of neutrons on a time scale which is slow compared with beta-decay half-lives. Under these conditions the product of the neutron capture cross section for an effective 30-keV temperature and the isotopic abundance is expected to be a slowly varying function of atomic weight. Vanpraet, Macklin, Allen, and Winters[1] have measured the capture cross section of the separated isotopes ^{86}Sr, ^{87}Sr, and ^{88}Sr in the energy range 3 to 100 keV at the 40-m time-of-flight station of the ORELA. Using a pair of total gamma-ray energy detectors with suitable pulse-height weighting so that the detecting efficiency was insensitive to the shape of the capture gamma-ray spectrum, they measured the total capture cross section relative to that of the ^{6}Li(n,α) reaction in a 0.5-mm-thick glass scintillator. Since the 50-neutron shell closure occurs for ^{88}Sr, the 30-keV capture cross section changes abruptly at the nucleus, decreasing from 38 mb for ^{86}Sr and 54 mb for ^{87}Sr to 5.6 mb for ^{88}Sr. Nevertheless, the product of the isotopic abundance, corrected for a small effect arising from fast neutron capture, and the 30-keV capture cross section is remarkably constant, in agreement with the cosmological predictions. This product is 216, 204, and 259 for the isotopes ^{86}Sr, ^{87}Sr, and ^{88}Sr respectively.

1. G. J. Vanpraet, R. L. Macklin, B. J. Allen, and R. R. Winters, pp. 208–9 in *Contributions – Conference on Nuclear Structure Study with Neutrons* (Budapest, Hungary, July–August 1972), Central Research Institute for Physics, Budapest, 1972.

Giant Quadrupole or Giant Monopole Resonances? – November

One of the recent major accomplishments of the Physics Division is the discovery that inelastic proton scattering strongly excites nuclear states just below the giant dipole resonances. Lewis and Bertrand[1] together with Satchler[2] have interpreted these states as being consistent with the excitation of collective giant quadrupole resonances whose strength exhausts the energy-weighted sum rule. Additional measurements[3] of inelastically scattered 67-MeV protons from the Oak Ridge Isochronous Cyclotron with the high-resolution broad-range magnetic spectrograph have confirmed the earlier counter results[1] and have yielded more precise resonant energies. In the meantime, Satchler[4] has shown, using a breathing-mode reaction mechanism, that the available proton inelastic scattering data are consistent with a giant monopole interpretation of the excited states as well as with the quadrupole interpretation which is somewhat favored by the data. Since, as he points out, scattering of polarized protons will distinguish between the giant monopole and the giant quadrupole excitations, experimenters are setting up apparatus to measure the scattering by appropriate nuclei of polarized protons which will be produced by the cyclotron's polarized ion source.

1. M. B. Lewis and F. E. Bertrand, *Bull. Amer. Phys. Soc.* **17**, 462 (1972); *Nucl. Phys.* (in press); M. B. Lewis, *Phys. Rev. Lett.* **29**, 1257 (1972).
2. G. R. Satchler, *Nucl. Phys.* **A195**, 1 (1972).
3. F. E. Bertrand, G. R. Satchler, M. B. Lewis, and D. J. Horen, *Bull. Amer. Phys. Soc.* (New York Meeting, January 29–February 1, 1973).
4. G. R. Satchler, *Particles and Nuclei* (to be published).

The ^{208}Pb(^{12}C,^{13}C)^{207}Pb and ^{208}Pb(^{12}C,^{11}B)^{209}Bi Reactions at High Bombarding Energies – December

Use of the position-sensitive proportional detector in the focal plane of the broad-range magnetic spectrograph of the Oak Ridge Isochronous Cyclotron has allowed precise investigations of heavy-ion reactions produced by bombarding ^{208}Pb with high-energy ^{12}C ions. Larsen et al.[1] have measured the differential cross sections of the neutron pickup reaction, ^{208}Pb(^{12}C,^{13}C)^{207}Pb (Q = –2.42 MeV), and the proton stripping reaction, ^{208}Pb(^{12}C,^{11}B)^{209}Bi (Q = –12.15 MeV), with ^{12}C energies of 77, 98, and 116 MeV. With the detector system resolution of 250 keV, they see groups of ^{13}C and ^{11}B nuclei corresponding to population of five states in each of the ^{207}Pb and ^{209}Bi product nuclei. They find that the angular distributions of the ^{13}C and ^{11}B light-product nuclei are smooth and single peaked and that the peak shifts to forward angles with increasing ^{12}C incident energy. They interpret these observations in terms of semiclassical concepts. Small detector angles correspond to large separation distances; consequently, the probability for nucleon transfer should be low. As the angle increases, the transfer probabilities should increase up to the point where nuclear absorption sets in and compound nuclear reactions begin to predominate. The peak angles in the differential cross sections are thus related to the optimum distance for nucleon transfer to occur. A more detailed analysis allows Larsen et al.[1] to conclude that the proton stripping reaction is compatible with a mechanism which depends on the initial $^{208}Pb + ^{12}C$ system, whereas the neutron pickup case suggests a description dependent on the final $^{207}Pb + ^{13}C$ system.

1. J. S. Larsen, J. L. C. Ford, Jr., R. M. Gaedke, K. S. Toth, J. B. Ball, and R. L. Hahn, submitted to *Physics Letters*.

1. Theory

NUCLEON TRANSFER FORM FACTORS CALCULATED WITH REALISTIC INTERACTIONS[1]

Y. K. So[2] W. T. Pinkston[2] K. T. R. Davies

The microscopic approach to calculating single-nucleon transfer form factors is applied to reactions in the region near Ca, for example, ^{42}Ca$(p,d)^{41}$Ca and ^{40}Ca$(d,p)^{41}$Ca. The interaction of the transferred nucleon with the ^{40}Ca core is taken to be the single-particle Hartree-Fock potential of Tarbutton and Davies, based on a two-body potential developed by Nestor. Realistic effective interactions, including core-polarization renormalization, are used for the interaction of the transferred nucleon with valence nucleons and holes. The results are compared with form factors calculated with Woods-Saxon core interactions and phenomenological residual interactions. It is found that the use of the Hartree-Fock potential yields results that are significantly different from those obtained from Woods-Saxon wells of standard geometry (r_0 = 1.25 fm, a = 0.65 fm). Form factors calculated with the Hartree-Fock potential tend to be larger in the surface and smaller in the interior, compared with those calculated with the Woods-Saxon. A Woods-Saxon well equivalent to Hartree-Fock gives almost identical results in some, but not all, cases, but the parameters of this well are quite different from the standard geometry and are highly state dependent. The form factors are found to be much less sensitive to the effective two-body interaction of the transferred nucleon with the valence particles and holes.

1. Abstract of paper to be published in *Particles and Nuclei.*

2. Department of Physics, Vanderbilt University, Nashville, Tenn.

HIGHER-ORDER CORRECTIONS TO BRUECKNER-HARTREE-FOCK BINDING ENERGIES AND RADII[1]

K. T. R. Davies R. J. McCarthy[2] P. U. Sauer[3]

Some higher-order corrections to renormalized Brueckner-Hartree-Fock calculations are estimated for the nuclei ^{16}O, ^{40}Ca, and ^{208}Pb. The diagrams of interest are the potential insertions in particle lines and the two-body correlation corrections to the rms radii. Studies are made of the sensitivity of these corrections to the shift in the intermediate spectrum used to calculate the G matrix. The correlation corrections to the radii are small and seem to increase somewhat as the intermediate spectrum is lowered, but there is no appreciable change in the overall saturation properties. The errors involved in estimating the corrections are discussed. "Off-diagonal occupation probabilities" are also calculated and found to be small, thereby justifying ignoring such diagrams as is usually done in renormalized Brueckner calculations.

1. Abstract of paper to be published in *Physical Review.*

2. Department of Physics, Indiana University, Bloomington.
3. Physikalisches Institut der Universität, Hermann-Herder-Strasse 3, 7800 Freiburg im Breisgau, Germany.

RENORMALIZED BRUECKNER-HARTREE-FOCK CALCULATIONS USING DIFFERENT PRESCRIPTIONS FOR THE INTERMEDIATE-STATE SPECTRUM[1]

K. T. R. Davies R. J. McCarthy[2] P. U. Sauer[3]

Calculations of the spherical nuclei ^{16}O, ^{40}Ca, and ^{208}Pb are presented for G matrices that differ in the definition of the particle spectrum. Detailed comparisons are made using pure harmonic oscillator, shifted oscillator, and QTQ intermediate-state spectra. Attention is particularly focused on the saturation properties of the various G matrices. The QTQ prescription seems to give somewhat better saturation properties than the oscillator prescriptions. A comparison is made in ^{40}Ca between the QTQ results and some results obtained by Negele. A study is also made of the importance of the relative partial waves not defined in the Reid soft-core potential.

1. Abstract of published paper: *Phys. Rev.* C6, 1461 (1972).
2. Department of Physics, Indiana University, Bloomington.
3. Physikalisches Institut der Universität, Hermann-Herder-Strasse 3, 7800 Freiburg im Breisgau, Germany.

HARTREE-FOCK CALCULATIONS OF BUBBLE NUCLEI[1]

K. T. R. Davies C. Y. Wong S. J. Krieger[2]

Hartree-Fock calculations of ^{36}Ar and of ^{200}Hg in spherical configurations exhibit densities that are very much depleted in the interior region. The depletion agrees well with previous theoretical predictions of bubble nuclei.

1. Abstract of published paper: *Phys. Lett.* 41B, 455 (1972).
2. Department of Physics, University of Illinois at Chicago Circle, Chicago.

THE RENORMALIZED BRUECKNER-HARTREE-FOCK APPROXIMATION[1]

Richard L. Becker

The renormalization of many-body perturbation theory by factorization of insertions in single-particle (SP) lines having the significance of "true" occupation probabilities is reviewed. The renormalized Brueckner-Hartree-Fock (RBHF) approximation is defined, and its analogue of Koopmans' theorem on the near equality of separation energy centroids and SP energies is demonstrated. The plane wave and harmonic oscillator bases of SP states and the energy spectrum of the virtual excited SP states are discussed. Binding energies, charge densities, and SP energies of light spherical nuclei obtained with RBHF calculations in the oscillator basis are presented. Corrections to the RBHF approximation, associated with correlations and rearrangement, are considered. Configuration mixing leads to a distribution of SP strength over many eigenstates. Values are given for the second-order rearrangement energy, the main contribution to the shift away from the centroid of the eigenstate of greatest SP strength. For deep holes the strength function broadens as $2h$-$1p$ states, etc., become quasi-degenerate with $1h$ states; as an example, the $(0s)^{-1}$ strength function in ^{16}O is shown. Correlation corrections to the RBHF charge density are discussed. Results of RBHF calculations for nuclei with a neutron excess are cited, and prospects of future improvements in calculations employing the RBHF approximation are contemplated.

1. Abstract of paper to be published in the proceedings of Symposium on Present Status and Novel Developments in the Many-Body Problem, Rome, Italy, Sept. 19–23, 1972. (Proceedings to be published in *Il Nuovo Cimento.*)

DEFORMED BRUECKNER-HARTREE-FOCK CALCULATIONS[1]

W. F. Ford[2] R. C. Braley[2] R. L. Becker M. R. Patterson[3]

The renormalized Brueckner-Hartree-Fock (RBHF) theory for many-body nuclear systems has been generalized to permit calculations for intrinsic states having permanent deformation. Both Hartree-Fock and

Brueckner self-consistencies are satisfied, and details of the numerical techniques are discussed. The Hamada-Johnston interaction is used in a study of deformations, binding, size, and separation energies for several nuclei. Electromagnetic transition rates, moments, and electron scattering form factors are calculated using nuclear wave functions obtained by angular momentum projection. Comparison is made with experiment as well as with predictions of ordinary and density-dependent Hartree-Fock theory.

1. Abstract of paper to be published in the proceedings of Symposium on Present Status and Novel Developments in the Many-Body Problem, Rome, Italy, Sept. 19–23, 1972. (Proceedings to be published in *Il Nuovo Cimento.*)
2. NASA, Lewis Research Center, Cleveland, Ohio.
3. Mathematics Division.

RENORMALIZED FOLDED DIAGRAM EXPANSION FOR THE NUCLEAR GROUND STATE

Richard L. Becker   Robert W. Jones[1]   Franz Mohling[2]

The Brueckner-Goldstone expansion for the interaction energy in the ground state of a many-fermion system involves effective interactions (Brueckner reaction matrices) that are off the energy shell when they occur in virtual intermediate states. The prime disadvantage of this expansion is that difficulties associated with the off-shell propagation appear in an extreme form. Through a series of investigations culminating in those of Brandow, a rearrangement of the Goldstone expansion by summing terms related by generalized time ordering, which we shall call the Brandow series, has been obtained. Brandow's series involves a very satisfactory definition of the single-particle potential for hole states and for "particle"-hole creation or annihilation but, as with the Brueckner-Goldstone expansion, does not yield a factorized self-energy generalizing the Hartree-Fock potential energy for "particle" states.

By adding and subtracting folded diagrams, those in which normally empty states are included in the sum over states for hole lines and normally occupied states for "particle" lines, one may obtain an extension of generalized time ordering that permits factorization of an on-shell Brueckner-Hartree-Fock potential for "particle" states. This was achieved earlier[3] for an expansion in the bare interaction, v. The expansion with folds is a "global" expansion, meaning that it is a sum of diagrams in which the propagators refer to all the "particles" and holes present in the entire system. The Goldstone and Brandow series are also global expansions. Global expansions are complicated to work with, however. For formal work it is more convenient to use single-particle-propagator formalisms. The folded diagram expansion can be related to expansions obtained by applying "field theoretic" (Feynman propagator) methods. Jones and Mohling[4] had used time-dependent propagators, and Klein[5] had used frequency (energy)-dependent propagators in this way.

For nuclear theory it is essential to convert expansions in v into expansions in a renormalized interaction such as the Brueckner reaction operator. We have found that the energy-dependent single-particle propagator formalism is best suited to this "Bruecknerization" of the "field theoretic" or "folded" expansion, and we have obtained the formal expansion.

If the renormalized propagators are expanded in bare ones and then the corresponding global expansion is worked out, it may be compared with the unrenormalized global expansion obtained from the Brandow series. The lowest two terms in our single-particle potential are compared with Brandow's in Fig. 1. The "cost" of the increased factorizability in our unrenormalized expansion is the presence of new folded skeleton diagrams. For this and other reasons we believe it is far preferable not to expand the renormalized propagators. If one truncates the renormalized propagator at second order and then truncates the sum over irreducible skeletons at first order, one obtains a renormalized Brueckner-Hartree-Fock (RBHF) approximation which is very similar to that of a similar

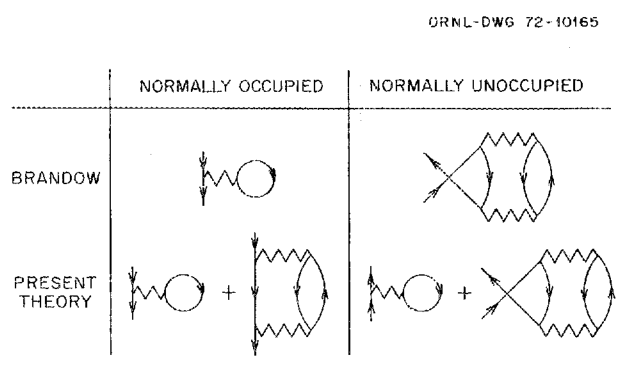

Fig. 1. A comparison of the single-particle potential energies proposed by Brandow and by the present theory.

truncation of the Brandow series,[6] but it contains an RBHF potential energy for "particle" states. We feel the new expansion looks very promising and deserves further investigation.

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PREDICTED INTERMEDIATE STRUCTURE IN HIGH-RESOLUTION DEEP-HOLE SPECTRA

Richard L. Becker

A potentially interesting, but so far relatively unexplored, region of nuclear spectroscopy is that of high excitations ($\gtrsim \hbar\omega$) of a nucleus $A - 1$ produced by nucleon-removal processes such as $(p,2p)$ or $(e,e'p)$ ("knockout") or $(d,{}^3\mathrm{He})$ ("pickup"). With sufficiently high incident energies, hundreds of million electron volts, the dominant reaction mechanism is the relatively simple one of quasi-free scattering, so the experiments can be analyzed in terms of the impulse approximation. The interest in the experiments stems from the presence of gross structures in the cross sections as functions of the momentum and energy given to the target nucleus. These broad resonances have been interpreted in terms of shell structure: the energies of the peaks are assumed to correspond to the separation energies of nucleons in low-lying[1] shells and their widths to the lifetimes of the single-hole states.

Experimental knowledge of separation energies is of great interest to nuclear many-body theorists. A necessary ingredient of calculations of nuclear saturation properties (binding energies and sizes) is the self-consistent determination of the energies and wave functions of single-particle states. The "single-particle energies" $e(k)$ depend on the formulation employed and are not necessarily measurable. They can be defined so as to yield good approximations to various kinds of centroids of experimental distributions. But, in general, single-particle energies differ from theoretical separation energies. This difference is called a rearrangement energy. Thus, a theoretical separation energy is calculated from

$$E_{\mathrm{sep}}(k) = e(k) + E_{\mathrm{rear}}(k) \,. \qquad (1)$$

Depending on whether the experimental separation energy under consideration is that of an eigenstate or a centroid, one needs to calculate an eigenrearrangement energy or a centroid-rearrangement energy.[2] A virtue of the renormalized Brueckner-Hartree-Fock (RBHF) approximation[2,3] is that the centroid rearrangement energy nearly vanishes.[4] Eigenrearrangement energies remain large for deep-lying hole states in the RBHF theory, for example, 13 and 19.5 MeV for 0s holes in ^{16}O and ^{40}Ca, respectively.[2,5] The identification of the eigenstate to which this eigenrearrangement refers will be discussed below. The rearrangement energy calculated is the real part of the diagram shown in Fig. 1.

In analyzing data from quasi-free reactions, a good deal of theoretical attention has been paid to the distortion of the waves of the ingoing and outgoing particles; for $(p,2p)$ some consideration has been given to the off-energy-shell properties of the nucleon-nucleon scattering amplitude. On the other hand, for the "deep-hole" spectra only the simplest model, the single-particle shell model, has been employed for the structure of the target and residual nuclei. The residual

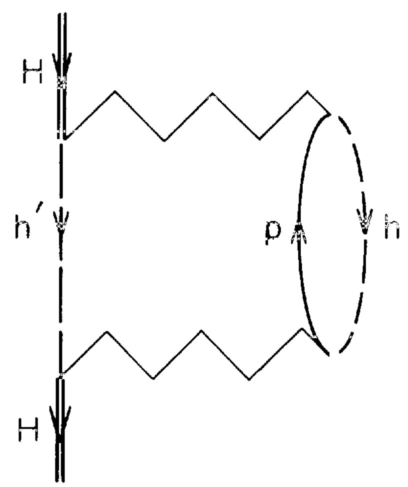

Fig. 1. Renormalized second-order rearrangement energy.

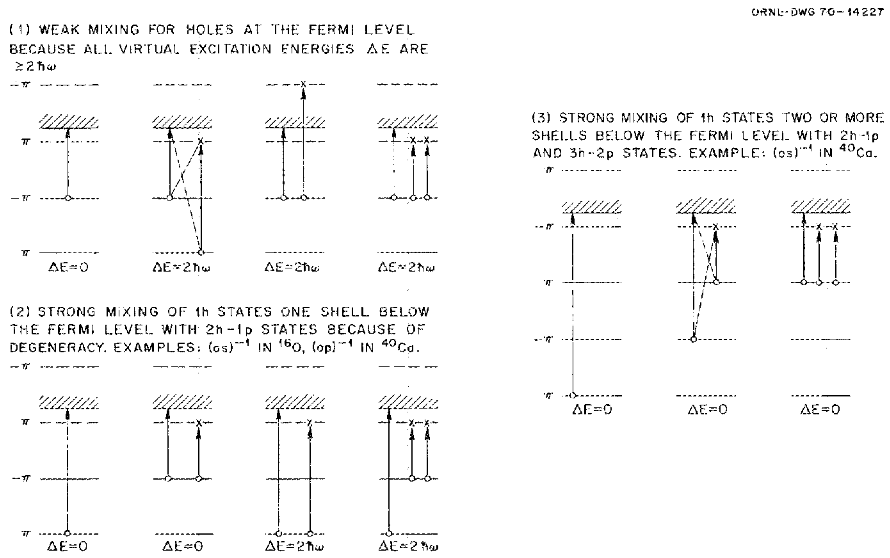

Fig. 2. Mixing of 1h with 2h-1p and 3h-2p states in closed shell nuclei in the harmonic (equal spacing) model.

nucleus is then in a pure single-hole configuration. Köhler's estimate[6] of the width of the hole state goes one step beyond this; he evaluated in lowest order of perturbation theory the imaginary part of the self-energy of virtual transitions to (degenerate) two-hole one-particle states, the imaginary part of Fig. 1 without the renormalization. Widths of 14 and 22 MeV for the 0s holes in ^{16}O and ^{40}Ca were obtained; these are of the same order of magnitude as those seen experimentally. This level of description is about as far as one can go in the context of conventional nuclear matter theory, either with the perturbation theoretic Brueckner-Goldstone expansion or the Landau-Migdal quasi-particle approximation of the Green's function formulation. One may anticipate that such information is crude from the well-known fact that the quasi-particle approximation is accurate only for single-particle states near the Fermi level. In particular, these descriptions do not involve the concept of splitting of single-hole strength[2,5] which has been of great interest for high-lying holes. For this, one needs explicit configuration mixing.

We believe that the increasing width of "hole states" with excitation energy is associated with the availability of more and more configurations which are quasi-degenerate with the hole state. This is shown in Fig. 2. When the hole is in the major shell just below the uppermost one, there are 2h-1p (two holes and one particle) states which in the harmonic oscillator shell model are exactly degenerate with it. If the hole is two major shells down there are, in addition, 3h-2p states degenerate with it. The degeneracies are made approximate by the ℓ and j splittings of the subshells and by residual interactions among the holes and particles.

The role of configuration mixing of the states of the residual nucleus in interpreting the deep-hole spectra can be seen as follows. If $|A\rangle$ is the ground state of the target, then $a(\mathbf{q})|A\rangle$ is the nonstationary state of the $A-1$ nucleon system obtained by removing a nucleon of momentum $\mathbf{q}$. In a good-resolution experiment it is known that energy $W\,(<0)$ as well as momentum q have been removed. The residual nucleus will be in any of the states $\langle W_{A-1}, \alpha|$ of energy $W_{A-1} = W_A^0 - W$ with amplitude $\langle W_{A-1}, \alpha\,|a(\mathbf{q})|A\rangle$. In the plane-wave impulse approximation the cross section for $(p,2p)$ or $(e,e'p)$,

$$\frac{d^6\sigma}{dE_1\, d\Omega_1\, dE_2\, d\Omega_2}\,,$$

where 1 and 2 label the outgoing particles, is proportional to the strength function (structure factor, form factor)

$$S(\mathbf{q};W) = \sum_d |\langle W^b_{A-1},d|a(\mathbf{q})|A\rangle|^2\, \delta(W + W^b_{A-1} - W^0_A) + \sum_d |\langle W^c_{A-1},d\,|a(\mathbf{q})|A\rangle|^2\, \delta_{W^c_{A-1},\, W^0_A - W}\,, \quad (2)$$

where (in the notation of ref. 7) b and c label bound (particle stable) and continuum (particle unstable) states and d distinguishes among degenerate states. The Dirac delta function will be smoothed when one restores the "natural" width from neglected electromagnetic and weak interactions. For the "deep-hole" part of the spectrum under consideration, only the continuum term contributes. In ^{15}N, for example, the states of interest are at an excitation energy of $\geqslant$20 MeV.

The momentum eigenstate $|\mathbf{q}\rangle$ may be decomposed into contributions from the various shell-model states $|k\rangle$, including both those normally occupied in A, h (holes), or normally empty, p ("particles"). Thus,

$$a^\dagger(\mathbf{q})|0\rangle = \sum_{h=1}^{A} \phi_h^*(\mathbf{q})\, a_h^\dagger + \sum\!\!\!\!\!\!\int_p \phi_p^*(\mathbf{q})\, a_p^\dagger\, |0\rangle \qquad (3)$$

and

$$S(\mathbf{q};W) = \sum\!\!\!\!\!\!\int_{kk'} \phi_{k'}^*(\mathbf{q})\, \phi_k(\mathbf{q})\, S(kk';W) \ , \qquad (4)$$

where the expression $S(kk';W)$ involves the amplitudes $\langle W_{A-1},d|a_k|A\rangle$. One sees that the removal process contains interferences between removals from different shells. If one neglects these because the momentum distributions in different shells tend to be different (this may be a poor approximation for certain values of $\mathbf{q}$), one obtains the diagonal approximation

$$S_D(\mathbf{q},W) = \sum_h |\phi_h(\mathbf{q})|^2\, S(h;W) + \sum\!\!\!\!\!\!\int_p |\phi_p(\mathbf{q})|^2\, S(p;W) \ , \qquad (5)$$

with $S(k,W)$ given by Eq. (2) with q replaced by the shell-model-state label k.

If configuration mixing in the target is neglected, then only hole states $k = h$ remain in Eq. (5), and only those states $|W_{A-1}^c,d\rangle$ which have an appreciable single-hole strength $\langle W_{A-1}^c,d|h^{-1}\rangle$ contribute strongly. The states $|W_{A-1}^c,d\rangle$ are mixtures of configurations of type $1h$, $2h$-$1p$, $3h$-$2p$, etc. The states $|W_{A-1}^c,d\rangle$ are particle unstable by virtue of components with one or more "particles" with $e(p) > 0$. The lower part of the continuum of single-particle states may be replaced, to good approximation, by discrete localized states with the energies of single-particle resonances. Alternatively, one may use the discrete virtual "particle" states of an oscillator-basis RBHF calculation; the single-particle energies of these states are calculated off the energy shell and consequently lie somewhat higher than the resonance energies. In either approximation the continuum part of $S(h;W)$ is converted into the form appropriate for particle-stable states $|W_{A-1}^b,d\rangle$, and consequently the spectrum consists of discrete peaks. These would be broadened by inclusion of the widths of the single-particle resonances. One obtains the prediction of an intermediate structure in the single-hole giant resonance. The single-hole strength is split among various approximate eigenstates of the residual nucleus. The subpeaks are weighted according to the single-hole strength in each eigenstate and have widths determined by the single-particle resonance widths of the unbound "particles" in the approximate eigenstates. The shape of the gross "single-hole" resonance may be asymmetrical; it depends on the locations of the unperturbed $2h$-$1p$, etc., states and on the matrix elements of the residual interaction. More generally, one obtains a strength function of the form

$$S_{D,h}(\mathbf{q};W) = |\phi_h(\mathbf{q})|^2 \sum_{W_{A-1},d} |\langle W_{A-1},d\,|h^{-1}\rangle|^2\, \frac{1}{\pi} \times \frac{\frac{1}{2}\Gamma^\uparrow(W_{A-1},d)}{(W-W_{A-1})^2 + \left[\frac{1}{2}\Gamma^\uparrow(W_{A-1},d)\right]^2} \ ,$$

where $\Gamma^\uparrow$ is the decay width of the approximate eigenstate.

We have carried out for ^{16}O Brueckner theoretic calculations in the Bloch-Horowitz formulation of degenerate perturbation theory to obtain eigenstates consisting of mixtures of the $0s_{1/2}$ hole state and the 17 $2h$-$1p$ states quasi-degenerate with it. For simplicity, neutron removal was considered. Figures 3 and 4 show the spectra and the single-hole strengths obtained with two sets of single-particle energies. For virtual particles with e = 8.4, 10.9, and 15.8 MeV for $0d_{5/2}$, $1s_{1/2}$, and $0d_{3/2}$, respectively, the $2h$-$1p$ states lay above the $(0s_{1/2})^{-1}$ state and (Fig. 3) shoved it downward by an amount ~13 MeV in good agreement with that calculated[5] from Fig. 1, when couplings among the $2h$-$1p$ states are neglected. An additional 4.4-MeV rearrangement energy is produced by these couplings in the full 18-state basis. With separation energies of the s-d shell states in ^{17}O used for the $e(p)$'s, the $2h$-$1p$ states lay below the $0s$ hole and shoved the dominant eigenstate upward (Fig. 4). Comparison of Figs. 3 and 4 shows a strong sensitivity to the single-particle energies, the eigenstate of greatest single-hole strength being at 25 MeV in Fig. 3 and at 54 MeV in Fig. 4.

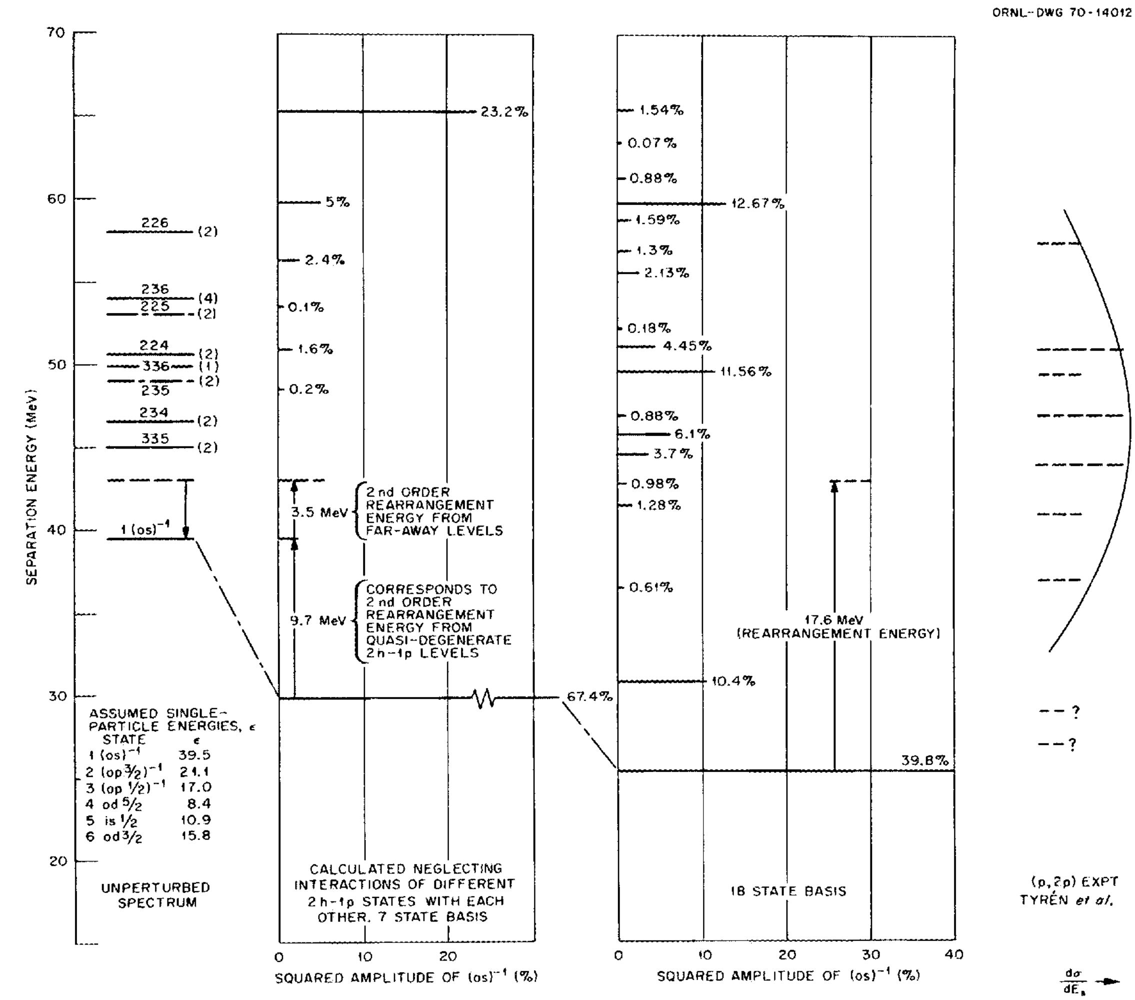

Fig. 3. ^{15}**O; mixing of** $(0s)^{-1}$ **with quasi-degenerate** $(0p)^{-2}$ $(s\text{-}d)^1$. Calculations in which the *s-d* shell energies are those of virtual particles in ^{16}O, for comparison with rearrangement energy calculations. Spuriosities not removed.

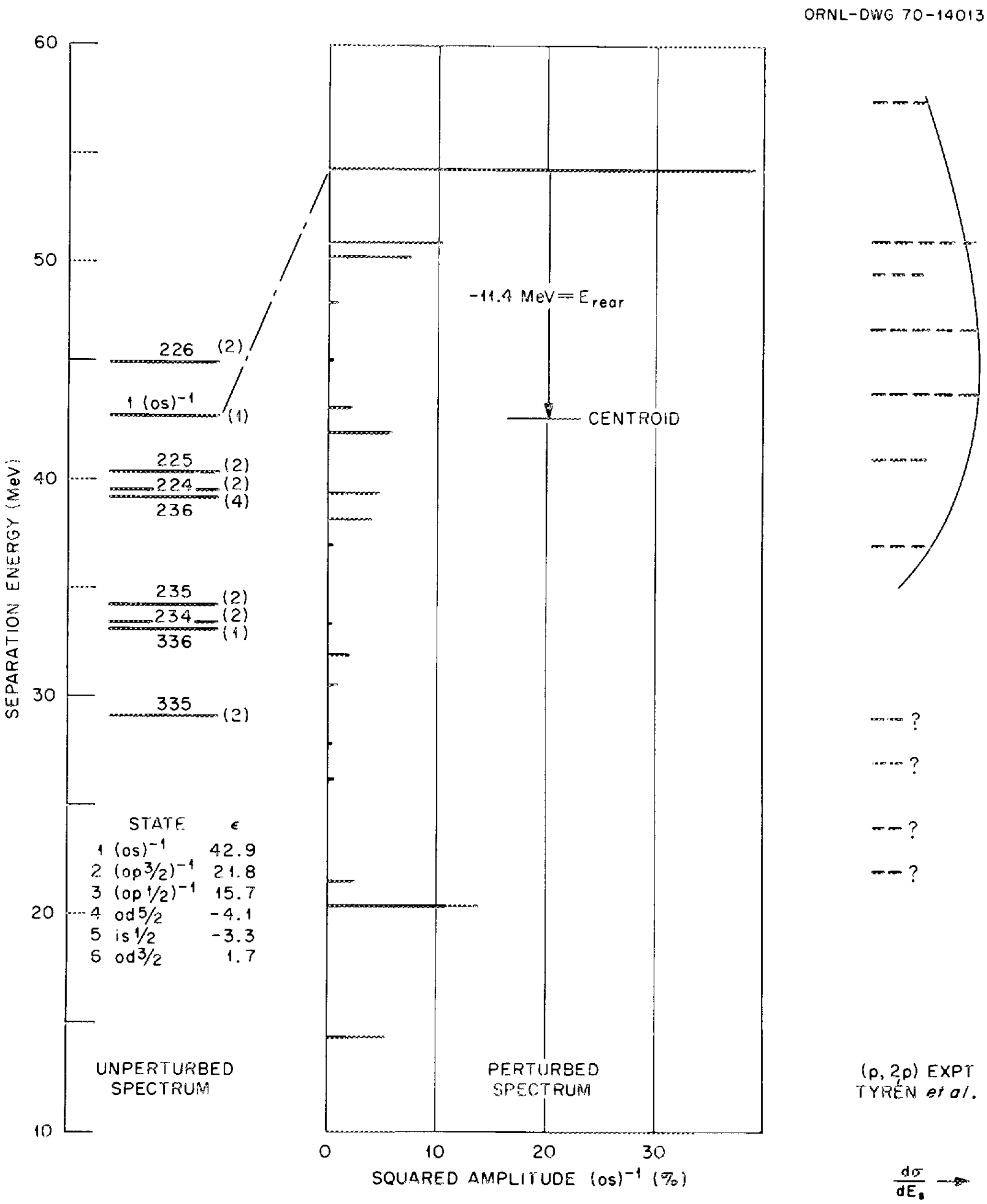

Fig. 4. ^{15}O; mixing of $(0s)^{-1}$ with quasi-degenerate $(0p)^{-2}$ $(s\text{-}d)^{1}$ *s-d* shell single-particle energies are centroids of separation energies of states in ^{17}O. Spuriosities not eliminated.

The calculations of Figs. 3 and 4 ignore a small technical point, namely, that the states of the basis contain "spurious" components corresponding to excitation of the center of mass. For example, the 0*s* hole state is 20% spurious.[8] By repeating the calculations in a 16-dimensional purified basis furnished by J. B. McGrory, we obtained the spectra shown in Figs. 5 and 6. These are shown to differ strikingly from those of Figs. 3 and 4, the strength below 30 MeV being removed. Unlike the earlier results, the centroid is shifted upward from $-e(0s_{1/2})$ to about 49 MeV; the amount of the shift is in agreement with the center-of-mass correction[9] to the analogue of Koopmans' theorem.[4] There is still a striking difference between the two strength functions. The one obtained by using experimental separation energies gives a concentration of strength in a state at 54 MeV (Fig. 5), whereas the virtual "particle" energies lead to a more symmetrical distribution about the centroid. The latter appears to be in good agreement with the best available data of Tyrén

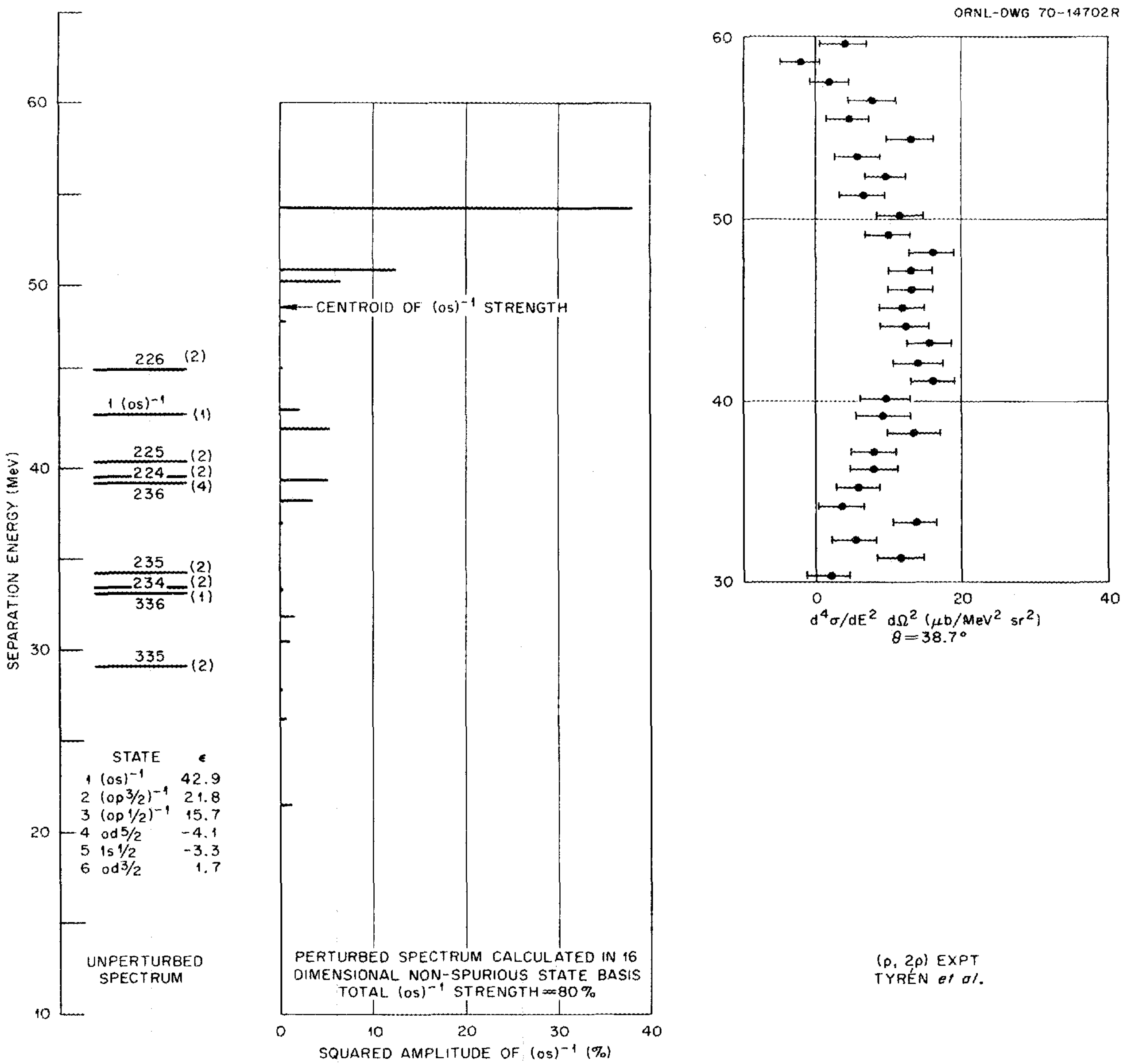

Fig. 5. ^{15}O; **mixing of** $(0s)^{-1}$ **with quasi-degenerate** $(0p)^{-2}$ $(s\text{-}d)^1$ **states.** Spuriosities have been eliminated. *s-d* shell single-particle energies are centroids of separation energies of states in ^{17}O.

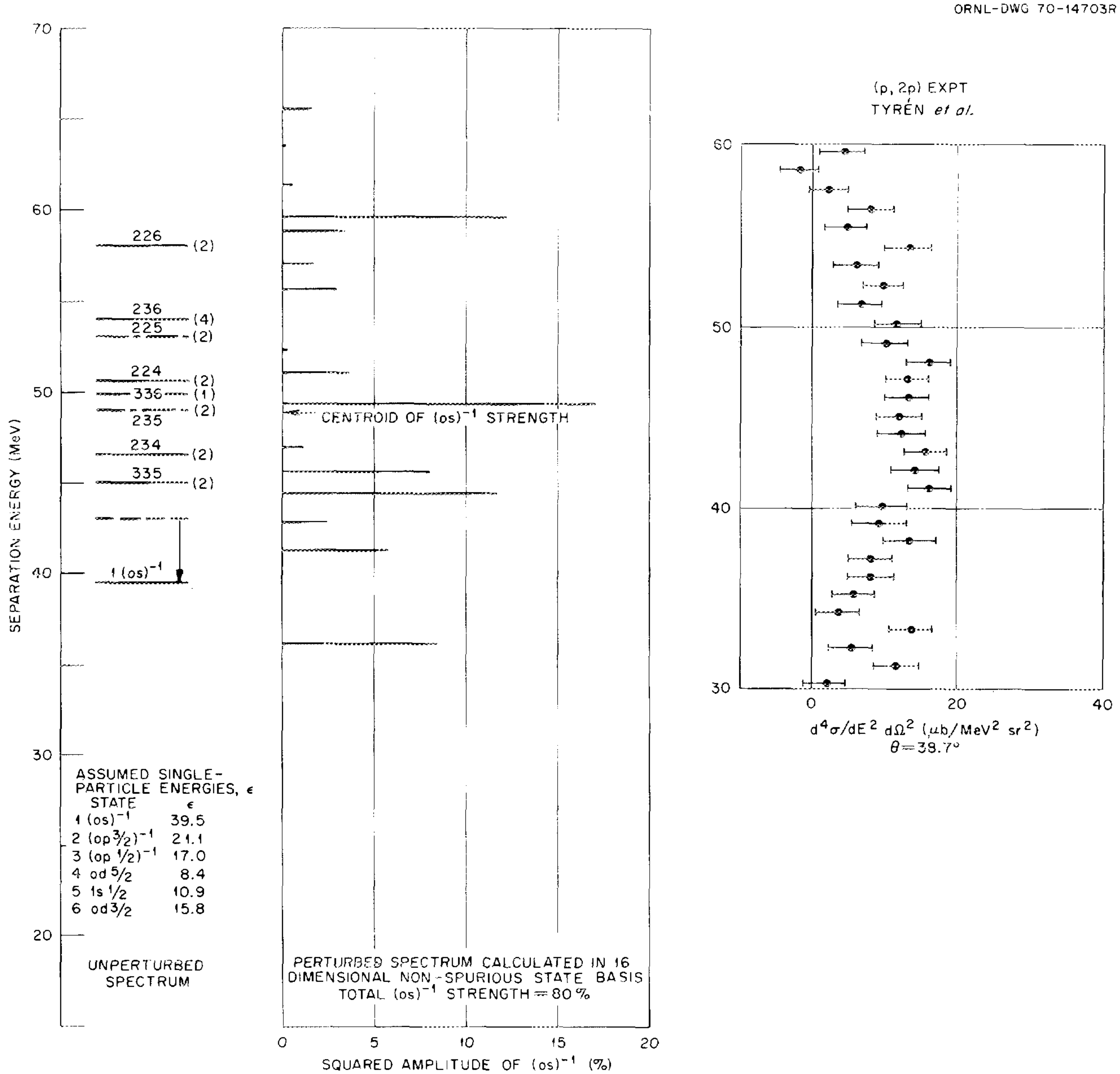

Fig. 6. **^{15}O; mixing of $(0s)^{-1}$ with quasi-degenerate $(0p)^{-2}$ $(s\text{-}d)^1$ states.** The two spurious states have been eliminated. *s-d* shell single-particle energies are those of virtual particles in ^{16}O; $0p_{3/2}$ and $0p_{1/2}$ energies are RBHF (SOC) energies; and the 0s energy is RBHF (SOC) plus the second-order rearrangement energy from faraway configurations.

et al.,[10] for which the energy resolution of the proton detectors is unfortunately not less than several MeV.

In conclusion, we believe that nucleon-removal experiments with energy resolution capable of separating the intermediate structure peaks could provide valuable information regarding deep holes in nuclei.

1. The same reactions have been used also to study nucleon removal from the levels of the uppermost major shell, where the narrower peaks have yielded additional spectroscopic information, namely, occupation probabilities for partially occupied subshells.

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BRUECKNERIZATION OF THE BRANDOW SERIES WITH A NEW PROPAGATOR-RENORMALIZED REACTION MATRIX

Richard L. Becker

Brandow has partially summed Goldstone's linked cluster expansion for the interaction energy in the ground state of many-fermion systems by generalized time ordering.[1] The Brandow series is an improvement because it allows the factorization of certain kinds of insertions in single-particle lines. The factorized insertions are of two kinds, which lead, respectively, to a self-consistent single-particle potential and to renormalization (line-weighting) factors for the lines of the diagrams that represent the terms of the expansion. In this propagator-renormalized expansion the binding energy of an infinite Fermi system is

$$BE = \sum_k N_k e_k + \mathcal{D}\,[\mathrm{v},U,P] - \sum_k P_k U_k \ , \qquad (1)$$

where N_k is the unperturbed occupation probability of the single-particle state k, P_k its "true" occupation probability, U_k and T_k its potential and kinetic energy, $e_k = T_k + U_k$ its single-particle energy, and $\mathcal{D} = \Sigma_i \mathcal{D}_i$, the sum of all irreducible closed Goldstone diagrams with each line renormalized with the weighting factor $(1 - N_k) + (2N_k - 1)P_k$. The expansion satisfies the variational principles

$$U_k = \frac{\partial \mathcal{D}}{\partial P_k} \ , \quad P_k - N_k = \frac{\partial \mathcal{D}}{\partial U_k} \ . \qquad (2)$$

These may be used in defining stationary truncations of the series. One chooses a subset $\mathcal{D}^T$ of $\mathcal{D}$ and then defines U_k and P_k by Eq. (2) with $\mathcal{D}$ replaced by $\mathcal{D}^T$.

For application to nuclei it is essential to convert the expansion to one in a renormalized interaction such as Brueckner's reaction matrix. In all the work done so far the "Bruecknerization" (summation of ladder diagrams) has been done first (giving the Brueckner-Goldstone series), and then for the lowest terms occupation probability line weighting factors have been factorized by generalized time ordering. This has really been discussed in detail only for the lowest-order approximation, the renormalized Brueckner-Hartree-Fock (RBHF) approximation.[2] Unfortunately, this form of Brueckner-Brandow series does not possess the stationary properties of Eq. (2). For example, the dominant term in Brandow's potential U for "particle" states, which is of second order in Brueckner's reaction matrix, does not emerge from Eq. (2) applied to any skeleton $\mathcal{D}_i$.

We have found that the stationary properties are recovered by renormalizing first and then summing ladders. Our renormalized Brueckner reaction matrix[3] $B(\omega)$ contains "true" emptiness factors on the lines for intermediate "particles." The salient properties are exhibited in Fig. 1 for the RBHF approximation to this

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If renormalize then Bruecknerize:

$$\mathcal{D}_B^{(1)} = \frac{1}{2} \sum_{kk'} N_k N_{k'} \langle kk' | B_A(\{N,U,P_p\}; e_{kk'}) | kk' \rangle P_k P_{k'}$$

Renormalized reaction matrix

$$B(\omega) = v + v \frac{Q^R}{\omega - h} B(\omega)$$

$$Q^R = \sum_{k_1 k_2} (1-N_{k_1})(1-N_{k_2})(1-P_{k_1})(1-P_{k_2}) \frac{|k_1 k_2\rangle\langle k_1 k_2|}{\omega - e_{k_1 k_2}}$$

$$U_p^{(1)} = \frac{\partial \mathcal{D}_B^{(1)}}{\partial P_p} = \frac{1}{2} \sum_{hh'}^{occ} \langle hh' | \frac{\partial}{\partial P_p} B_A(e_{hh'}) | hh' \rangle P_h P_{h'}$$

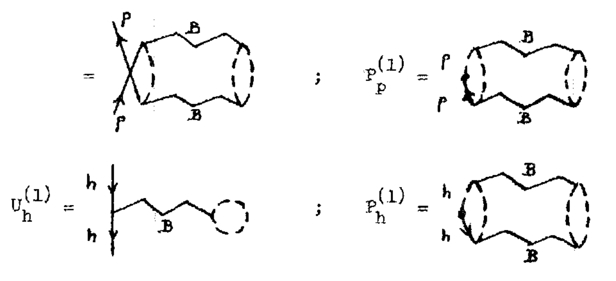

Fig. 1. New RBHF approximation involving the propagator-renormalized reaction matrix B_A. The subscript A denotes antisymmetrization.

new expansion. The on-energy-shell matrix elements of B are shown by dashed jagged interaction lines, and renormalized "particle" and hole lines are also dashed. One sees that Eq. (2) yields the RBHF potential for holes and a renormalized form of Brandow's second-order potential for "particles." The "true" occupation probabilities also are given correctly.

The new renormalized reaction matrix is expected to be of use chiefly for formal work. However, its elements may differ significantly from those of the unrenormalized matrix whenever a "particle" state has a nonnegligible true occupation probability. This will occur only if an unoccupied "particle" state lies close to the Fermi level, as in the case of nuclei with partially open major shells. In ^{12}C, for example, "spherical" calculations based on the $(0s)^4(0p_{3/2})^8$ configuration have yielded $P_{0p_{1/2}}$ = 10%.[4] The inclusion of the emptiness factor, 0.9 in this case, can be handled as a part of the "Pauli correction," which is now routinely made for our reaction matrix elements.

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TARGET EXCITATIONS AND THE OPTICAL POTENTIAL FOR PROTONS SCATTERING FROM NUCLEI[1]

C. L. Rao[2] M. Reeves III[3] G. R. Satchler

We calculate the contributions to the optical potential for 30-MeV protons due to inelastic excitations of the target nucleus. The scattering due to this nonlocal potential is calculated exactly, and some of the results are subjected to conventional optical-model analysis. When only one excited state is included, a resonant dependence on the excitation energy is observed. Even with ten excited states, the position of a single one can strongly influence the scattering. It is possible to account for about three-fourths of the observed absorption in ^{40}Ca and ^{208}Pb, but only by postulating unobserved states which exhaust the remainder of the energy-weighted sum rules at somewhat unreasonably low energies. It was not possible to find simple local potentials that gave the same scattering because of the strong L-dependence of the absorption. The constructed potentials concentrate the absorption at too small radii. It is suggested that rearrangement (pickup) processes contribute a substantial amount of absorption at larger radii, while compound formation will give rise to a volume term in the imaginary potential.

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1. Abstract of paper submitted for publication in *Nuclear Physics*.
2. Formerly consultant and graduate student from the University of Tennessee; present address: Department of Physics, Laval University, Quebec, Canada.
3. Mathematics Division.

EXCHANGE EFFECTS ON THE EXCITATION OF ^{20}Ne BY PROTONS[1]

G. R. Satchler

The importance of knock-on exchange is studied for the microscopic description of the excitation of collective states by inelastic scattering. Much of the discrepancy found earlier between theory and experiment may be removed by the inclusion of exchange. The usefulness of an equivalent zero-range pseudopotential is studied. Results are also presented for the dependence on the shell-model orbits involved and the effects of imaginary, Coulomb, spin-dependent, and odd-state components in the interaction.

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1. Abstract of paper to be published in *Particles and Nuclei*.

INTERFERENCE NEAR THE COULOMB BARRIER AND COMPLEX INTERACTIONS FOR INELASTIC SCATTERING[1]

G. R. Satchler

The interference between nuclear and Coulomb excitation amplitudes for inelastic scattering at energies near the top of the Coulomb barrier is very sensitive to the phase of the nuclear interaction. The $^{114}Cd(h, h')$ reaction is used as an example.

1. Abstract of published paper: *Phys. Lett.* **39B**, 492 (1972).

THE FOLDING AND DEFORMED POTENTIAL MODELS FOR INELASTIC SCATTERING[1]

G. R. Satchler

It is important to include exchange effects when generating transition potentials for inelastic scattering from a folding model. The relation between potential and density deformations is discussed. Transition densities and transition potentials are sensitive to the form of deformation assumed.

1. Abstract of published paper: *Phys. Lett.* **39B**, 495 (1972).

RADIAL MOMENTS OF FOLDING INTEGRALS FOR NONSPHERICAL DISTRIBUTIONS[1]

G. R. Satchler

Simple relations are exhibited between the radial moments of two nonspherical distributions when one is obtained by folding a scalar function into the other. Some applications are mentioned, and the generalization to nonscalar functions is indicated.

1. Abstract of published paper: *J. Math. Phys.* **13**, 1118 (1972).

THE OPTICAL MODEL[1]

G. R. Satchler F. G. Perey[2]

The use of the optical model to describe neutron interactions with nuclei is reviewed.

1. Abstract of paper to be published in the proceedings of Conference on Nuclear Structure Study with Neutrons, Budapest, Hungary, July 31–August 5, 1972.
2. Neutron Physics Division.

EXCITATION OF GIANT MONOPOLE RESONANCES BY PROTON SCATTERING[1]

G. R. Satchler

Data from proton inelastic scattering to the giant resonance region are examined for evidence of the excitation of an isoscalar monopole breathing mode. Two slightly different models for the interaction are constructed and studied. The currently available data are compatible with such a monopole excitation whose strength exhausts the energy-weighted sum rule, although the quadrupole interpretation is somewhat to be preferred. Asymmetry measurements on the excitation by polarized protons could easily distinguish between these two possibilities. The asymmetries predicted for monopole excitation are sensitive to the deformation of the spin-orbit coupling.

1. Abstract of paper to be published in *Particles and Nuclei.*

NUCLEAR GIANT RESONANCES, SUM RULES, EFFECTIVE CHARGES, AND SUCH-LIKE[1]

G. R. Satchler

Recent results on the excitation of giant multipole resonances are reviewed.

1. Abstract of paper submitted for publication in *Comments on Nuclear and Particle Physics.*

EXCITATION OF GIANT DIPOLE AND GIANT QUADRUPOLE STATES IN NUCLEI[1]

G. R. Satchler

Calculations are presented for the excitation by protons of giant dipole ($T = 1$) and quadrupole ($T = 0$) states in nuclei. Two simple models are used for the transition densities and potentials in the dipole excitation. The usual deformed optical potential is applied to the quadrupole transitions. The strengths are determined by exhausting the linear energy-weighted sum rules. The relationship to the effective charges needed for transitions between low excited states is discussed. The isovector coupling potential is determined by analysis of (p, n) transitions to analog states. Comparison with data for 61- and 182-MeV protons shows that the dipole excitation is too weak, but inclusion of the quadrupole state gives good agreement with the measurements.

1. Abstract of published paper: *Nucl. Phys.* **A195**, 1 (1972).

EFFECTIVE HAMILTONIANS FOR TRUNCATED SHELL MODELS

B. R. Barrett[1] E. C. Halbert J. B. McGrory

We continue our study[2] of the construction and properties of renormalized Hamiltonians. In this project we concentrate on the nuclei $A = 17$–20, and we try to construct some $(d_{5/2}, s_{1/2})^{A-16}$ models that will simulate the results of a given $(d_{5/2}, s_{1/2}, d_{3/2})^{A-16}$ model. Hereafter we refer to the larger vector space as *dsd*, and the truncated space as *ds*.

In all our work we assume for the *dsd* model a Hermitian (1 + 2)-body Hamiltonian H. We investigate three distinct methods to find renormalized *ds* Hamiltonians H_{eff}. One method is a simple second-order perturbation scheme. The second method is least-squares search to fit selected *dsd* eigenvalues. The third is a "projection method," by which we construct a *ds* Hamiltonian whose eigenvalues exactly match selected *dsd* eigenvalues, and whose eigenvectors exactly match the corresponding projections of *dsd* eigenvectors on the *ds* space.

Several variations of each method are examined. In the study of perturbation and projection methods, our recent efforts are to extend these methods so as to take account of three-body-operator terms induced in the effective Hamiltonian, as well as the (1 + 2)-body terms. For the least-squares method, our recent efforts are to refine our criteria for selecting the *dsd* levels to be fitted by least squares.

For the simple truncation *dsd* → *ds*, a complete second-order perturbation scheme gives an effective Hamiltonian having (1 + 2 + 3)-body terms (but no terms of higher particle rank). In our previous work[2] we found that the (1 + 2)-body terms of second-order H_{eff} were surprisingly successful in reproducing the *dsd* results for A = 18, 19, and 20. Given this moderate success, we guessed that we would only improve things by adding in the missing term of second-order H_{eff}. However, we now find that this addition does *not* yield general improvement. Instead, we find very serious deterioration for ^{19}F, ^{20}F, and ^{20}Ne. Thus, the simple second-order scheme seems to be qualitatively correct for the two-body part of the effective Hamiltonian but misleading for the three-body part.

In our study of the projection method, the three-body-operator part of H_{eff} has been used so far only for A = 19. In this case we are interested in the importance of non-Hermiticity. (Non-Hermiticity arises in H_{eff} because the *ds* projections of the *dsd* eigenvectors are not mutually orthogonal.) In our previous work we learned that the non-Hermiticity of the projection-method H_{eff} is unimportant for A = 18. Now we find that for A = 19, non-Hermiticity is slightly more important, but still almost inconsequential for most levels. One exception is the lowest $7/2^+$ in ^{19}F, where symmetrization of the non-Hermitian H_{eff} leads to a 2-MeV error in the energy eigenvalue.

The aim of our least-squares-search study is to determine whether there exists a Hermitian (1 + 2)-body operator H_{eff} which somehow incorporates the advantages gained in the other methods by resorting to *ds* Hamiltonians which are non-Hermitian (1 + 2 + 3)-body operators. It is advisable to take considerable care in selecting the set of *dsd* levels to be fitted by least squares, because the emergent least-squares Hamiltonian will be unnecessarily distorted if the least-squares-fitted subset includes too many states with considerable "intruder" character. Two separate least-squares searches are studied. Case A concentrates on fitting low-lying *dsd* levels and also any others that seem to be members of ground-state bands. Case B concentrates on fitting *dsd* levels that we hopefully identify as "nonintruders," because their wave functions have large projections on the *ds* space and because these projections are almost orthogonal to each other. Unfortunately, our results from these searches are not so clear-cut. In particular, we find no clear confirmation of the hope that our criteria in case B are useful for defining and identifying "nonintruder" states. The optimized fits from cases A and B each include some disappointingly large deviations from *dsd* eigenvalues — even for levels that were explicitly fitted by least squares. Still, each of A and B yields fits which are, overall, obviously better than those produced by the (1 + 2)-body parts of H_{eff} (second order) and H_{eff} (projection). This superiority does not extend to the eigenvectors of H_{eff}. For low-lying states, all our renormalized Hamiltonians H_{eff} have *ds* eigenvectors that look very much like *ds* projections of the *dsd* eigenvectors; the exceptions are no fewer or milder for H_{eff} (least squares) than for the (1 + 2)-body parts of H_{eff} (second order) and H_{eff} (projection).

1. Department of Physics, University of Arizona, Tucson.
2. *Phys. Div. Annu. Progr. Rep. Dec. 31, 1971*, ORNL-4743.

A PROGRAM FOR EXTENDED WEAK-COUPLING CALCULATIONS

L. B. Hubbard[1] J. B. McGrory

It is now established that large shell-model calculations are extremely useful in the study of nuclear structure. It is also well known that the region of applicability of such calculations is severely limited by the dimension explosion problem; that is, as the number of active particles or the number of single-particle orbits in the model space is increased, the dimensions of the matrices to be diagonalized rapidly increase until the problem is intractable in practice. It is thus very desirable to find a truncation scheme that leads to results in a small-dimensional space that are in good agreement with calculations in a larger more complete space. We have developed a program that should be useful in investigations of some types of truncation schemes. We assume that the model space is divided into two completely inequivalent spaces (so that antisymmetrization between the two spaces can be ignored). The model interaction can be written in the form

$$H = H_I + H_{II} + H_{I-II} ,$$

where I and II label the two inequivalent spaces. One can always work in a basis of states of the form

$$|\psi\rangle = |\phi_I\rangle \times |\phi_{II}\rangle ,$$

where $|\phi_I\rangle$ and $|\phi_{II}\rangle$ are eigenstates of H_I and H_{II}. If there is some reason that the interaction between states in the two inequivalent spaces is weak, then one approach would be to diagonalize H_I and H_{II} in the large inequivalent spaces, choose only a small set of low-lying eigenstates of H_I and H_{II} to form a truncated coupled basis, and diagonalize H_{I-II} in this truncated space. We have developed a program to carry out this procedure. One type of calculation that might be carried out with the program is for nuclei where there is a significant neutron excess, so that the valence neutron orbits are quite different from the valence proton orbits. One might then expect the neutron-proton interaction to be relatively weak. The prescription is then to diagonalize the proton-proton and the neutron-neutron interaction separately, use a truncated set of neutron states and a truncated set of proton states, and diagonalize the neutron-proton interaction in the space generated by coupling these inequivalent states.

The program has been checked out by repeating complete *s-d* shell-model calculations in a neutron-proton formalism, that is, treat ^{20}Ne as ^{18}O states coupled to ^{18}Ne states, and making no truncation in the two spaces. These results have then been compared with calculations made of the same nuclei with the Oak Ridge–Rochester shell-model program.

Applications of the program will include studies of transitions from spherical to deformed structure in nuclei with neutron excesses and studies of the coupling of multiparticle multihole states in nuclei near closed shells.

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SHELL-MODEL CALCULATIONS OF NUCLEI IN THE ^{208}Pb REGION

J. B. McGrory C. M. Ko[1] T. T. S. Kuo[1]

The properties of the following nuclei have been calculated in terms of a conventional shell model: ^{204,205,206,210,211,212}Pb, ^{210}Po, ^{211}At, and ^{212}Rn. The lead isotopes ^{204,205,206}Pb were treated as nuclei with four, three, and two neutron holes in ^{208}Pb. The isotopes ^{210,211,212}Pb were treated as nuclei with two, three, and four neutron particles outside ^{208}Pb. The remaining three nuclei were treated as two, three, and four protons outside ^{208}Pb. The model space for the neutron-hole states calculations included the lowest six single-neutron-hole orbits in ^{208}Pb. The model space for the proton-particle nuclei included the lowest six single-proton particle orbits outside ^{208}Pb. The model space for the neutron particle states included the lowest five single-neutron particle orbits outside ^{208}Pb. Experimental single-particle energies were used, and for the two-body part of the model Hamiltonian, we used the "realistic" interaction of Kuo and Herling.[2] The properties calculated include binding energies, excitation energies, magnetic dipole and electric quadrupole moments, $B(M1)$'s and $B(E2)$'s, and strengths for one- and two-particle transfer reactions. With a few exceptions, the calculated values for these observables are in good agreement with measured values. The main discrepancies involve the two-nucleon transfer strengths. For the lead particle states, the $d_{3/2}$ and $g_{7/2}$ orbits were omitted from the model space. For the case of ^{210}Pb, these orbits can be included in the model space, and it is found that although they comprise only 4% of the ^{210}Pb ground-state wave function, this 4% accounts for almost 50% of the ground-state transition strength for the ^{208}Pb$(t, p)^{210}$Pb reaction. The observed relative strengths for transitions to states of the same J value in the ^{208}Pb$(p, t)^{206}$Pb and ^{206}Pb$(p, t)^{204}$Pb reactions are accurately reproduced by the calculations.

A "pairing-vibration" phonon model for ^{212}Pb and ^{204}Pb has been investigated. The phonons consist of the lowest few eigenstates in ^{210}Pb and ^{206}Pb. The spectrum of low-lying states is found to be very accurately reproduced in a space formed by coupling the five lowest "phonons" of ^{210}Pb, that is,

$$\psi(^{212}\mathrm{Pb}) = \sum_{ij} c_{ij}\, \psi_i(^{210}\mathrm{Pb}) \times \psi_j(^{210}\mathrm{Pb}) ,$$

where ψ_i is an eigenstate in ^{210}Pb. Similar results are found for ^{204}Pb, when treated as the coupling of low-lying "phonons" of ^{206}Pb.

1. Department of Physics, State University of New York at Stony Brook, Stony Brook, Long Island, N.Y.
2. T. T. S. Kuo and G. H. Herling, N.R.L. memorandum report 2258 (1971).

COULOMB ENERGY DIFFERENCES IN *s-d*-SHELL NUCLEI IN THE CONVENTIONAL SHELL MODEL

J. B. McGrory

A subject of long interest in nuclear physics is the Coulomb energy difference between members of isobaric multiplets. I have calculated these Coulomb energy differences in nuclei with masses $A = 19$, 20, and 21 in terms of a conventional shell model. An inert ^{16}O core is assumed, and particles are distributed in the $d_{5/2}$, $s_{1/2}$, and $p_{3/2}$ orbits. All possible states of all Pauli-allowed configurations of active particles distributed among these orbits are included in the model space. The calculations are done in a neutron-proton (n, p) formalism. For neutron states, the single-particle energies are taken from the experimental spectrum of ^{17}O; for proton states, the single-particle energies are taken from the experimental spectrum of ^{17}F. The same single-particle energies are used for all the calculations. For the two-body part of the effective nuclear Hamiltonian, I used the "realistic" interaction of Kuo. For the two-body Coulomb interaction, the bare Coulomb interaction and harmonic oscillator wave functions were used, with the oscillator parameter evaluated from the relationship $\hbar\omega = 41A^{-1/3}$ MeV. In Table 1, I have tabulated the difference in binding energies, measured with respect to ^{16}O, of the ground state and its isobaric multiplet partner for 11 different nuclei. For the 11 cases shown, the typical energy difference is about 4.00 MeV, and the average absolute deviation between theory and observation is 0.05 keV. The calculations have been repeated with only the one-body Coulomb interaction included, and with only the two-body Coulomb interaction included. The preponderance of the Coulomb energy difference comes from the one-body part, which probably accounts for the good agreement. In the calculation of both the nuclear and Coulomb two-body matrix elements, the single-particle wave functions are approximated by charge-independent harmonic-oscillator wave functions. This should be especially bad for the case of the relatively long-ranged Coulomb interaction. The isospin mixed wave functions generated with the full 1-body + 2-body charge-dependent interaction have been analyzed for the degree of isospin impurity. In a majority of cases, the mixing is very small, less than 2%, but in several isolated cases, the mixing is as much as 20%. This is due to accidental degeneracy of states with the same J and different T values in the calculated spectrum, and not because of any strong Coulomb matrix elements. This type of shell-model calculation is not nearly accurate enough to predict when such mixing will occur, but it clearly points to the possibility of such strong mixing due to similar degeneracies in nature.

Table 1. Energy differences of lowest member of isobaric multiplets in light *s-d*-shell nuclei

Nuclei	T	Experiment[a]	Calculation
^{19}F-^{19}Ne	½	4.02	3.94
^{19}O-^{19}F	3/2	3.53	3.50
^{19}F-^{19}Ne	3/2	3.98	3.93
^{20}Ne-^{20}F	1	4.03	3.93
^{20}Na-^{20}F	1	4.42	4.40
^{20}F-^{20}O	2	3.48	3.47
^{20}Ne-^{20}F	2	3.97	3.91
^{21}Ne-^{21}Na	½	4.33	4.36
^{21}Ne-^{21}F	3/2	3.95	3.95
^{21}Na-^{21}Ne	3/2	4.44	4.36
^{21}Mg-^{21}Na	3/2	4.95	4.78

[a] J. Janecke, *Isospin in Nuclear Physics*, p. 376, ed. by D. H. Wilkinson, North-Holland, 1969.

ALPHA-PARTICLE SPECTROSCOPIC AMPLITUDES AND THE SU(3) MODEL[1]

Munetake Ichimura[2] Akito Arima[3] E. C. Halbert Tokuo Terasawa[4]

Formulas for calculating spectroscopic amplitudes for emission or transfer of alpha particles are developed in the framework of the harmonic-oscillator shell model with SU(3) classification. These formulas are applied to some interesting states of ^{20}Ne, for example, low-lying $(sd)^4$ shell-model states, members of the lowest $K = 0^-$ band with SU(3) label (90), and $2\hbar\omega$-excited states with SU(3) label (10,0). Spurious center-of-mass motion is removed. The formulas are also applied to the ground and some excited states of ^{16}O. The ^{16}O wave functions of Brown and Green are used in an investigation of how the mixing among $0p$-$0h$, $2p$-$2h$, and $4p$-$4h$ states affects the wave function for relative motion between the alpha cluster and the mass 12 nucleus. These calculations indicate much larger alpha reduced widths for states which are mainly $4p$-$4h$ than for states which are mainly $0p$-$0h$ or $2p$-$2h$. Spectroscopic amplitudes are also calculated for some ^{16}O and ^{12}C states described as linear chains of alpha particles.

1. Abstract of paper submitted for publication in *Nuclear Physics*.

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AN ANALYSIS OF SHELL-MODEL WAVE FUNCTIONS FOR *s-d* AND *f-p* SHELL NUCLEI IN TERMS OF SU(3) REPRESENTATIONS

J. B. McGrory

It was suggested[1] by J. P. Elliott that states which carry representations of the group SU(3) would make up a "good" representation for nuclei in the light *s-d* shell nuclei. Shell-model wave functions for *s-d* shell nuclei with A = 18–22 and A = 34–38 have been determined by diagonalizing so-called "realistic" interactions in the complete space of *s-d* shell wave functions in a *j-j* coupled representation. States which carry representations of the group SU(3) have been determined by diagonalizing the one-body plus two-body Casimir operator for this group in the complete space of *j-j* coupled *s-d* shell states for $A = 18-22$ and $A = 34-38$ nuclei. It is then possible to express the "realistic" eigenstates for these nuclei in terms of SU(3)-labeled states by computing overlaps between the "realistic" eigenstates and the SU(3) eigenstates as expressed in the *j-j* representation. The members of the ground-state bands of ^{19}F, ^{20}F, ^{20}Ne, ^{21}Ne, ^{22}Ne, and ^{22}Na are all dominated by one SU(3) state, as expected. In Table 1 we list the dominant component for each band and the average value of the probability that this component exists in each member of the ground-state band for these nuclei. Some members of excited bands in these nuclei also have large admixtures of one or two SU(3) states. Arguments have been made to show that the spectroscopic factor for use in the calculation of alpha-transfer cross sections and alpha-decay widths is proportional to how "good" the SU(3) is for the involved states, so that the type of analysis made here might be useful in the calculation of alpha-transfer processes. For $A = 34-38$ nuclei the SU(3) representation is no longer "good." For these nuclei the largest SU(3) component typically is 15–20% of the total wave function. Similar calculations for *f-p* shell nuclei with $A = 44$ also show that SU(3) is no longer a "good" representation in these nuclei. This breakdown can be traced to strong spin-orbit effects.

Table 1. Average probability amplitude for indicated SU(3) representation in the member of the ground-state potential band in some light *s-d* shell nuclei

Nucleus	SU(3) label (λ, μ)	Average probability (%)
^{19}F	(6,0)	75
^{20}F	(6,1)	70
^{20}Ne	(8,0)	78
^{21}Ne	(8,1)	74
^{22}Ne	(8,2)	57
^{22}Na	(8,2)	71

1. J. P. Elliott, *Proc. Roy. Soc.* **A245**, 128 and 562 (1958).

SHELL-MODEL CALCULATION FOR MASSES 27, 28, AND 29: GENERAL METHODS AND SPECIFIC APPLICATIONS TO ^{27}Al, ^{28}Si, AND ^{29}Si[1]

B. H. Wildenthal[2] J. B. McGrory

A shell-model calculation for $A = 27$, 28, and 29 nuclei has been carried out in a truncated $0d_{5/2}$-$1s_{1/2}$-$0d_{3/2}$ basis space with an MSDI Hamiltonian. A comparison of the calculated results for level energies, single-nucleon spectroscopic factors, and $E2$ and $M1$ transition strengths in ^{27}Al; ^{28}Si, and ^{29}Si with the corresponding experimental values indicates that a unified and quantitative explanation of nuclear structure around $A = 28$ can be obtained via shell-model techniques.

1. Abstract of paper to be published in *Physical Review*.
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SHELL-MODEL CALCULATIONS FOR $A = 18$, 19, AND 20 NUCLEI WITH CORE EXCITATION INCLUDED EXPLICITLY[1]

J. B. McGrory B. H. Wildenthal[2]

Eigenvalues and eigenvectors for all low-lying positive and negative parity nuclear states of $A = 18$, 19, and 20 are calculated in a shell-model basis of all Pauli-allowed $0p_{1/2}$-$0d_{5/2}$-$1s_{1/2}$ configurations outside an inert ^{12}C core. Two different effective Hamiltonians are used. One is based on a reaction matrix treatment of the Hamada-Johnston potential. The second one is obtained by varying the 33 effective Hamiltonian matrix elements to reach a least-squares fit between 153 experimental level energies in nuclei in the $A = 13-22$ region and the corresponding shell-model eigenvalues. The energy-level spectra and single-nucleon spectroscopic factors from these calculations are compared with the available experimental data in this region. The calculations are also examined for the existence and characteristics of sequences of levels which might be called "rotational bands."

1. Abstract of paper to be published in *Physical Review*.
2. Cyclotron Laboratory, Department of Physics, Michigan State University, East Lansing.

ANALOG AND CONFIGURATION STATES IN ^{49}Sc ($J^\pi = 3/2^-$ AND $1/2^-$) AND THE LOW-LYING LEVEL STRUCTURE IN ^{48}Sc[1]

S. D. Bloom[2] J. B. McGrory S. A. Moszkowski[3]

$J^\pi = 3/2^-$ and $1/2^-$ states in ^{49}Sc generated by the configurations $[(1f_{7/2})^8\ (2p_{3/2,1/2})]$ are discussed. Excitation energies, $M1$ transitions, and $E2$ transitions among the seven $3/2^-$ and five $1/2^-$ levels, including the $3/2^-$ analog state at E_x = 11.56 MeV and putative excited analog $1/2^-$ state at ≈13.6 MeV, were calculated and compared with experiment where possible. The beta decay of ^{49}Ca to the $3/2^-$ level at 3.08 MeV and to the (presumably) $1/2^-$ level at 4.49 MeV (the lowest-lying $3/2^-$ and $1/2^-$ levels) were also calculated. Two interactions were used, the well-known Kuo-Brown (KB) force and a new interaction that we call the PMM force, the latter being derived mainly from direct-reaction cross sections of nucleons on various nuclei. Both KB and PMM interactions lead to cancellations which cut down both the beta decay of ^{49}Ca and the $M1$ decay of the A state to the lowest-lying $3/2^-$ and $1/2^-$ states, as observed experimentally. In addition, strong $M1$ decays to several $3/2^-$ and $1/2^-$ levels with excitations of 7 to 11 MeV are predicted, as is observed experimentally. The $E2$ decays of all the predicted $3/2^-$ states to the $7/2^-$ ground state were also calculated. In the case of the $E2$ decay of the $A(3/2^-)$ state, comparison with experiment is hampered by the role of fine structure; experiment is weaker than theory by a factor of ≈50X.

The $(1f_{7/2})^8$ group of levels in ^{48}Sc were also calculated ($J^\pi = 0^+ \rightarrow 7^+$). The PMM force gave excellent agreement with recent experimental results, while the KB force gave relatively poor agreement, as might be expected from the severe truncation of the shell-model basis. The suggestion is that the phenomenological basis of the PMM force corresponds physically to the $(1f_{7/2})^8$ space of ^{48}Sc as well as the $(1f_{7/2})^8(2p_{3/2}$ or $2p_{1/2})$ space of ^{49}Sc.

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1. Abstract of paper to be published in *Nuclear Physics*.
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ON THE TRANSITION FROM SHELL STRUCTURE TO COLLECTIVE BEHAVIOR: A SIMPLIFIED SHELL-MODEL STUDY[1]

K. T. Hecht[2] J. B. McGrory J. P. Draayer[2]

To study the feasibility of carrying out shell-model calculations in nuclei with active protons and neutrons in different major shells, the following simple idealized model has been studied: (1) Proton and neutron configurations are chosen to be $(f_{5/2}p_{3/2}p_{1/2})^{n_p}$ and $(g_{7/2}d_{5/2}d_{3/2}s_{1/2})^{n_n}$, so that results for the separate proton and neutron basis states to be used in any approximation scheme can be compared with the results for exact shell-model calculations. (2) The proton and neutron single-particle energies for these active shells are separately taken to be degenerate. (3) The two-body interaction is approximated by the simple surface delta interaction (SDI).

To effect the severe truncation of the full shell-model space needed to make such a shell-model study possible, the separate proton and neutron parts of the shell-model basis are built from a superposition of the favored pair states of the SDI (with $J \neq 0$, as well as $J = 0$). In the neutron configuration

$$(g_{7/2}d_{5/2}d_{3/2}s_{1/2})^{n_n=4}\ ,$$

for example, only three of the 94 shell-model states with $J_n = 2$ are retained in the truncation scheme. In this highly truncated basis both the energies and the strong BEk values for the transitions from these states to similar favored states with other J values are within a few percent (or better) of the results of exact shell-model calculations. A truncation of the shell-model space based on such superpositions of favored pair states leads to a manageable shell-model basis (dimensions ⩽200). (1) The number of states in the separate proton and neutron parts of the basis are small enough (8 to 13 for the proton space, 15 to 30 for the neutron space). They are also the key states in the following sense. (2) They include the low-lying energy eigenstates of the separate *p-p* and *n-n* parts of the interaction. (3) They contain most of the collective coherence of the separate proton and neutron configurations. (4) The matrix elements of the *n-p* part of the interaction between the favored states is in general very large compared with the matrix elements between a favored and an excluded state. The latter effect is studied from several aspects, in particular in terms of sum rules for the matrix elements of the surface multipole operators from which the *n-p* part of the SDI is built. For most of the low-lying favored states the sum over *all* favored states gives more than 90% of the total sum rule for the squares of matrix elements of the surface multipole operators. The results of shell-model calculations in this truncation scheme, with $n_p = 4$ or 6 and $n_n = 4$, show many of the features of a quadrupole vibrational spectrum. The presence and exact nature of a 0^+ member of the 0^+, 2^+, 4^+ "two-phonon triplet" is dependent on the inclusion of the key favored states with seniorities of 6.

1. Abstract of published paper: *Nucl. Phys.* **A197**, 369 (1972).
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WHERE LIES THE INTERACTION BARRIER?[1]

C. Y. Wong

Simple expressions are obtained for the total reaction cross section in terms of the interaction barrier for the *s* wave. These expressions allow the interaction barrier to be determined experimentally.

1. Abstract of paper submitted for publication in *Physical Review Letters.*

ON SUPERHEAVY NUCLEI SYNTHESIS BY THERMONUCLEAR EXPLOSIONS[1]

C. Y. Wong

Simple estimate shows that with presently available technology the yield of superheavy nuclei obtained in thermonuclear explosions is very small. A recent claim of a possible production of macroscopic quantities of superheavy atoms with thermonuclear explosions is not well substantiated.

1. Abstract of paper submitted for publication in *Physical Review "Comments and Addenda."*

STABILITY OF A ROTATING TOROIDAL MASS[1]

C. Y. Wong

Idealizing a rotating toroidal star as uniform and incompressible, Kowalewsky, Poincaré, and Dyson in the last century showed that a toroidal mass has a minimum in its energy vs breathing deformations and therefore can be stable against expansion and contraction of the major radius because of the balance between the gravitational and the centripetal forces. Dyson also investigated other distortions and found that such a breathing deformation minimum is stable against all distortions except "sausage" deformations, in which the torus is thicker in some sections but thinner in others. Sausage deformations are therefore the only large-scale distortions leading to instability. It should be realized that Dyson's proofs made use of approximate expressions for the gravitational potential and the moment of inertia appropriate for large aspect ratios of major to minor radius R/d. The conclusion on instability of the toroidal mass against sausage deformations should be considered proved for such a case only. The case of small and moderate aspect ratios, for which a high degree of accuracy is required, was never discussed. Attention is therefore fixed on a toroidal mass with an arbitrary aspect ratio which need not be large. The mass is likewise idealized for simplicity to be a uniform and incompressible mass distribution rotating about the central symmetry axis with a uniform angular velocity. A high degree of accuracy in the evaluation of the gravitational potential is achieved by expanding the potential as an infinite series of functions of toroidal harmonics. Our result indicates that for a given angular momentum, one obtains a definite breathing deformation minimum characterized by an aspect ratio of major to minor axis. The aspect ratio increases monotonically as a function of the angular momentum, being nearly unity for no rotation. However, not all the toroidal masses at their respective breathing deformation minima are unstable against sausage deformations. Although a toroidal mass with a large aspect ratio ($R/d \gtrsim 6.7$) is indeed unstable against sausage deformation — as was already pointed out by Dyson — a toroidal mass with an aspect ratio R/d in the range $1.05 \lesssim R/d \lesssim 6.7$ is *stable against sausage deformations of all orders.* Some of these stable toroidal masses may conceivably be stable also against all other large-scale deformations. Thus, the possibility is opened up for a rotating toroidal mass to have its independent existence, and it need not necessarily be the companion of a central nucleus, as a ring structure has, up to now, always been held to be.

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1. Abstract of paper submitted for publication in *Astrophysical Journal.*

FUSION THRESHOLD ENERGY IN HEAVY-ION REACTIONS[1]

C. Y. Wong

We examine the dependence of the fusion threshold energy for various combinations of projectile and target nuclei. It is found that when the threshold energy is parameterized in the form $Z_1 Z_2 e^2 / [r_e(A_1{}^{1/3} + A_2{}^{1/3})]$ the effective radius parameter r_e decreases as the charge of either the projectile or the target nucleus increases. The value of r_e is larger when either the projectile or the target nucleus is endowed with a permanent positive quadrupole moment.

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1. Abstract of published paper: *Phys. Lett.* **42B,** 197 (1972).

TOROIDAL NUCLEI[1]

C. Y. Wong

There are shells in the single-particle spectrum of a toroidal nucleus. The shell-corrected deformation energies, calculated with Strutinsky's theory of renormalization, show breathing deformation minima for $40 \lesssim A \lesssim 70$ and $A \lesssim 250$ along the beta-stability line.

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1. Abstract of published paper: *Phys. Lett.* **41B,** 446 (1972).

BUBBLE NUCLEI[1]

C. Y. Wong

There are shells in the single-particle spectrum of a bubble nucleus. The shell-corrected deformation energies, calculated with Strutinsky's theory of renormalization, show that ^{36}Ar, ^{84}Se, ^{138}Ce, and ^{200}Hg in their ground or low-lying excited states are bubble nuclei with a small hole in the interior, while ^{174}Yb and ^{250}104 have secondary minima in the bubble degree of freedom.

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1. Abstract of published paper: *Phys. Lett.* **41B,** 451 (1972).

TOROIDAL LIQUID STARS[1]

C. Y. Wong

The toroidal liquid stars of Poincaré, Dyson, and Kowalewsky are found to be stable against sausage deformations if the aspect ratio is not too large. It is conceivable that these stars may also be stable against other perturbations and render themselves observable in nature.

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1. Abstract of paper submitted for publication in *Nature.*

A PEDESTRIAN APPROACH TO THE INTERMEDIATE STRUCTURE IN PHOTONUCLEAR REACTIONS IN LIGHT NUCLEI[1]

F. B. Malik[2] M. G. Mustafa[3]

The intermediate structure in photonuclear reactions is discussed within the context of a general theory based on a many-body Hamiltonian. The results are shown for ^{12}C, ^{16}O, and ^{28}Si. The comparison with experiment indicates two competing processes for photonucleon emission in light nuclei: a direct emission and a transition via a series of closely lying intermediate states.

1. Abstract of paper to be published in *Proceedings of the V Symposium on the Structure of Low-Medium Mass Nuclei.*
2. Department of Physics, Indiana University, Bloomington.
3. On leave from Atomic Energy Centre, Dacca, Bangladesh.

A THEORY OF INTERMEDIATE STRUCTURE, OVERLAPPING RESONANCES, AND PHOTONUCLEAR REACTIONS IN LIGHT NUCLEI[1]

M. G. Mustafa[2] F. Bary Malik[3]

Starting from a many-body Hamiltonian, a general theory involving intermediate structures and overlapping resonances in nuclear reactions has been worked out. This treatment, based on Trefftz's work on dielectronic recombination in atomic physics, avoids explicit use of projection operators, and all relevant quantities like decay widths and energy shifts are explicitly expressed in terms of two-body matrix elements. In particular, attention has been focused on the interaction of bound states among themselves and then on the coupling of the continuum with these interacting bound states. For the case of overlapping resonances, it is shown that in general one cannot take a simple energy average of the resonant amplitudes, and explicit equations for this case have been obtained. This microscopic theory also provides a justification of the model of Duke, Malik, and Firk in explaining the intermediate structure in giant dipole resonance region of ^{16}O and ^{28}Si. However, the formalism is a general one and is suitable for the study of intermediate structure involving isolated and overlapping resonances for many types of reactions.

1. Abstract of paper submitted for publication in *Helvetica Physica Acta.*
2. On leave from Atomic Energy Centre, Dacca, Bangladesh.
3. Department of Physics, Indiana University, Bloomington.

THE GAMMA-RAY ABSORBED FRACTION FOR SMALL OBJECTS

Lincoln B. Hubbard[1]

At the limit of extremely small size the absorbed fraction for internal gamma emitters varies as the cube root of the mass. As the mass increases, the effects of attenuation and multiple scatter become proportionately larger and larger; eventually this causes significant deviation from this simple dependence. These effects become significant at relatively small sizes; with a 1-MeV source in a mass of about 10 g the attenuation correction is 10% of the absorbed fraction. However, the attenuation and multiple scatter effects enter with algebraically opposite signs and approximately equal magnitudes. For example, if multiple scatter is neglected (i.e., only the first collision of each gamma ray is included) in a uniform sphere of radius R containing a central point source, the absorbed fraction is:

$$1 \approx \frac{\mu_{en}}{\mu}(1 - e^{-\mu R}) ,$$

where μ_{en} is the energy absorption coefficient and μ is the attenuation coefficient. If this is expanded in powers of R, the absorbed fraction appears as

$$1 \approx \mu_{en}R - \frac{1}{2}\mu\mu_{en}R^2 + \dots .$$

The first term, proportional to the cube root of the mass, is the no-attenuation, no-scatter-buildup approximation.

If the multiple scatter contribution is also expressed in powers of R, the lead term can be calculated[2] for $R < 1/\mu$ as

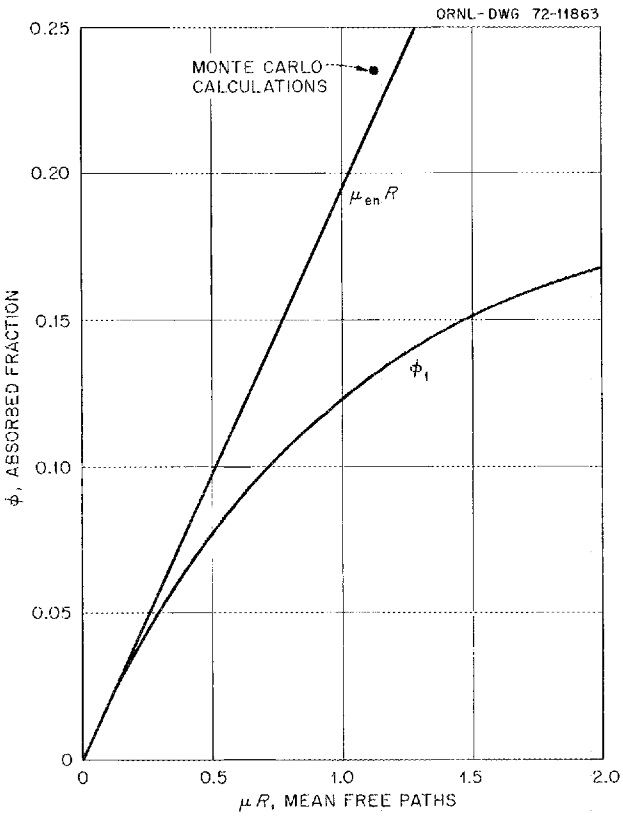

Fig. 1. The absorbed fraction as a function of size for a muscle sphere containing a central 0.16-MeV point source. The line labeled $\mu_{en}R$ is the small mass (no-attenuation, no-scatter-buildup) approximation. ϕ_1 is the result assuming no scatter buildup but assuming attenuation. The Monte Carlo result is from Brownell et al., *J. Nucl. Med. MIRD Suppl.* 1, 27 (1968).

$$+0.77(\mu + \mu_{en})\mu_{en}{}^{*}R^2 \ ,$$

where $\mu_{en}{}^{*}$ is the energy absorption coefficient for gamma rays having the average scattered energy. If we take the ratio of these correction terms we find:

$$\frac{1/2\mu\mu_{en}R^2}{[0.77(\mu - \mu_{en})\mu_{en}{}^{*}R^2]}$$

$$\sim 0.7 \text{ at } 0.1 \text{ MeV}, 1.4 \text{ at } 3.0 \text{ MeV} .$$

Thus, there is an approximate cancellation of the leading attenuation correction term and the leading multiple scatter term. The approximation

$$\approx \mu_{en}R$$

is fairly good to radii of the order of a mean free path.

An example for an 0.16-MeV source is shown in Fig. 1. The Monte Carlo result is from the results of Brownell et al.[3]

1. Consultant from Furman University, Greenville, S.C.
2. L. B. Hubbard and F. S. Williamson, *Phys. Med. Biol.* **16**, 35 (1971).
3. G. L. Brownell, W. H. Ellet, and A. R. Reddy, *J. Nucl. Med. MIRD Suppl.* **1**, 27 (1968).

2. High-Energy Physics

EVIDENCE FOR A NEUTRON HALO IN HEAVY NUCLEI FROM ANTIPROTON ABSORPTIONS

W. M. Bugg[1] H. O. Cohn G. T. Condo[1] E. L. Hart[1] R. D. McCulloch[2]

In recent years, considerable interest has been attached to the question of whether heavy nuclei have a neutron excess in their periphery. The most recent experimental results[3] utilizing high-energy scattering imply near equality for the neutron and proton radii in the heavy nuclei. The strongest evidence supporting the existence of a neutron halo has been presented by Davis et al.[4] from a study of K^- absorptions in the heavy and light nuclei of nuclear emulsion. They observed that K^- capture by a neutron in (Ag,Br) was $5.0^{+1.2}_{-0.8}$ times as likely as was K^- absorption by a neutron in (C,N,O). A subsequent analysis of these data by Burhop[5] has reduced this number to 4.2 ± 0.8. Since the nuclear absorption of slow, heavy, strongly interacting particles is expected to occur from atomic states of large angular momentum ($l \sim 6$ in Ag), this implies that the capture occurs in the nuclear surface where the nucleon density is $\lesssim 20\%$ of its central density.[6] The obvious conclusion, therefore, is that a considerable neutron halo exists in heavy nuclei; however, a precise analysis of the extent of this halo is difficult[5] because of the Σ conversion process and the presence of the Y_0^* (1405), which drastically alters the K^-p and K^-n absorption amplitudes. In the present paper we will report on an experiment utilizing $\bar{p}$ absorptions that confirms the existence of a neutron halo in heavy nuclei.

The data were obtained from an exposure of the 30-in. BNL hydrogen bubble chamber to a beam of slow antiprotons. The chamber contained four rectangular plates of carbon, titanium, tantalum, and lead that were mounted so that the optic axis of two of the stereo cameras was approximately parallel to the faces of the plates. The thicknesses of the plates were: C, 0.85 cm; Ti, 0.56 cm; Ta, 0.22 cm; Pb, 0.35 cm. These were selected so that about 25% of the low-momentum $\bar{p}$ beam at BNL would stop in the plates. The physics of the experiment derives from the fact that $\bar{p}p$ and $\bar{p}n$ annihilations produce events with a net charge of 0 and -1 respectively. It is presumed that the nuclear capture process, as in the K^- case, occurs in the nuclear periphery.[7]

A summary of our data is presented in Table 1, in which we give the numbers of events with the observed net charges in the mesonic prongs. Strict scanning criteria were imposed to exclude from our sample all events for which the exact origin of each mesonic prong could not be determined. This is clearly desirable, since the annihilation star was not visible when it occurred in one of the plates. The data in Table 1 have not been corrected for hydrogen events that occurred in the darkened regions about the plates and that were indistinguishable from events occurring in the plates. This hydrogen contamination amounts to 12.3% for C, 9.1% for Ti, 13.3% for Ta, and 11.7% for Pb. Thus, for example, for each 1000 events which appear to stop in tantalum, 133 are actually hydrogen captures occurring in darkened regions about the plates.

Although few antiproton annihilation experiments in media other than hydrogen or deuterium have been reported, it is clear from the early experiment of Agnew

Table 1. Net observed charge distribution of $\bar{p}$ annihilations after geometric correction

Bosonic charge	C	Ti	Ta	Pb
+3	10	6	5	1
+2	141	54	75	45
+1	1166	391	400	265
0	3491	927	940	767
−1	2246	784	856	659
−2	512	209	236	215
−3	43	23	33	30
−4	2	2	0	0

Table 2. Summary of results

Element	N/Z	Total[a] No. of events	No. of events	$M = n(\pi^+) + n(\pi^-)$	Observed charged multiplicity	π^- excess, $n(\pi^-) - n(\pi^+)$	Number of neutron captures	Proton captures	$\bar{p}n/\bar{p}p$	$(\bar{p}n/\bar{p}p)_c$	"Halo factor"
C	1.00	7611	6675	19,023	2.500	1929	2469	4206	0.587	1.00	1.00
Ti	1.18	2396	2178	5,600	2.337	762	1043	1135	0.919	1.57	1.33 ± 0.22
Ta	1.48	2545	2207	5,772	2.268	862	1216	991	1.227	2.09	1.41 ± 0.24
Pb	1.54	1982	1750	4,431	2.236	821	1175	575	2.043	3.48	2.26 ± 0.50

[a]Including events in hydrogen.

et al.[8] that secondary interactions of the annihilation products are an important facet of any annihilation experiment in nuclear matter. The data in Table 1 also support this conclusion. Rather than attempt to predict the charge distributions in Table 1 from a theoretical model, we resort to a purely empirical interpretation, which is outlined in Table 2. This analysis relies on the fact that each neutron annihilation will produce a mesonic system with a net charge of -1. Thus, to determine the number of neutron annihilations in any particular plate, we must find the total excess of negative charge in the mesonic prongs. This is not difficult to effect, since we need only multiply the observed π^- excess by the ratio of the multiplicity of charged pions at the annihilation to the observed charged pion and multiplicity:

Number of $\bar{p}n$ annihilations

$$= \text{No. of excess } \pi^- \left(\frac{\text{true multiplicity}}{\text{observed multiplicity}} \right) .$$

This assumes that secondary interactions and our geometric limitations affect the number of π^+ and π^- losses equally. The charged pion multiplicity has been measured in deuterium[9] to be 3.11 for $\bar{p}p$ annihilations and 3.15 for $\bar{p}n$ captures. The extant data for carbon[8] and the light nuclei of emulsion[10] are consistent with those figures if there is a pion absorption probability in the parent nucleus of about 8%. Therefore, we take the true multiplicity of charged pions to be 3.13. Once the number of neutron annihilations is known, the number of proton annihilations is just the difference between the total number of captures in the element and $N(\bar{p}n)$. The last three columns of Table 2 list the ratio $\bar{p}n/\bar{p}p$ for each element, $\bar{p}n/\bar{p}p$ normalized to the carbon result, and the "halo factor," which we define as the normalized $(\bar{p}n/\bar{p}p)_c$ ratio divided by N/Z.

The most striking feature of Table 2 is that the neutron-to-proton annihilation ratio for the various elements normalized to the carbon data always exceeds the ratio of neutrons to protons in the capturing nucleus. Thus an antiproton is about 3½ times as likely to be absorbed by a neutron in lead as it is in carbon. One would expect this ratio to be 1.54 merely because of the neutron excess of heavy nuclei. Over and above this expected neutron enhancement, neutron captures are 2.26 times as likely as proton captures in Pb. The corresponding enhancements in Ti and Ta are 1.33 and 1.41 respectively. It is interesting that tantalum appears to be more like titanium than lead, even though it is much nearer lead in the periodic table. While this must remain a mystery, it is interesting to observe that nearby elements exhibit anomalous behavior in the K^- mesic x-ray studies of Wiegand et al.[11] In these x-ray experiments, the x-ray intensities observed near the termination of the atomic cascade are far less for elements similar to Ta than to those observed for most other elements. It is also possible that the large quadrupole moment of Ta could affect either the atomic cascade or the subsequent nuclear annihilation process.

It is to be noted that $\bar{p}n/\bar{p}p$ for carbon is 0.587, whereas it has been reported to be 0.69 and 0.75 in two prior deuterium experiments.[9,12] Since N/Z is the same for both elements and since there exist no known bosonic resonances with a mass near $\bar{p}p$ threshold, it might be expected that the carbon and deuterium results would be similar. The differences in this result could have several origins. First, Agnew et al.[8] present evidence which suggests that, in carbon, about 15% of the $\bar{p}p$ absorptions charge-exchange to an $\bar{n}n$ final state. The resulting annihilation is that of an $\bar{n}$ in carbon, which will lead to a substantial number of mesonic final states with a net positive charge $[q(\bar{n}p) = +1]$. If $\bar{p}$ charge exchange also occurs in deuterium, $\bar{p}(pn) \rightarrow \bar{n}(nn)$, only neutral mesonic systems can result. This would cause our reported $\bar{p}n/\bar{p}p$ ratio for carbon to be smaller than the deuterium determination. Second, any observation of ambiguity between protons and positive pions in our experimental procedure which resulted in the inclusion of protons in our π^+ sample would also distort our $\bar{p}n/\bar{p}p$ ratio toward a smaller value. We observe, however, that both of these effects would be applicable to all four of our plates, and while they affect the absolute $\bar{p}n/\bar{p}p$ ratio for any individual plate, comparisons between plates are relatively independent of these effects. Thus a 2% pion-proton ambiguity and a 10% $pp \to nn$ rate results in the normalized $\bar{p}n/\bar{p}p$ ratios of 1.48 for Ti, 1.97 for Ta, and 3.17 for Pb, and an absolute ratio for carbon, $\bar{p}n/\bar{p}p = 0.74$.

Our conclusion is that for nuclei with a neutron excess, the neutron-to-proton ratio in the nuclear periphery is enhanced to a value greater than expected from N/Z. On the basis of the available evidence, it would appear that the conclusion voiced by several authors[13,14] is valid; namely, that while the mean square radii of neutrons and protons in heavier nuclei are quite similar, nevertheless, there exists in their tenuous outer reaches an ethereal neutron halo.

We are grateful to the many people at Brookhaven National Laboratory, especially A. G. Prodell, who gave us their complete cooperation during the course of this experiment. We also wish to thank our scanners, Mrs. I. S. Han and Mrs. M. K. Burton, for their painstaking efforts on our behalf.

1. University of Tennessee, Knoxville.
2. Mathematics Division.

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14. E. H. S. Burhop, D. H. Davis, J. Sacton, and G. Schorochoff, *Nucl. Phys.* **A132**, 625 (1969).

THE FOUR-PION DECAY OF THE f^0 MESON[1]

W. M. Bugg[2] G. T. Condo[2] E. L. Hart[2] H. O. Cohn R. D. McCulloch[3]
R. J. Endorf[4] C. P. Horne[4,5] M. M. Nussbaum[4]

A search for the $\pi^+\pi^+\pi^-\pi^-$ decay of the f^0 (1260) has been made in 7.87-GeV/c π^+d interactions. We find no evidence for this decay. The ratio of this decay mode relative to the dipion decay mode of the f^0 is consistent with zero and less than 3.1% with 90% confidence.

1. Abstract of paper submitted for publication in the *Physical Review*.

2. University of Tennessee, Knoxville.
3. Mathematics Division.
4. University of Cincinnati, Cincinnati, Ohio.
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MULTIPION DATA ON THE T REGION[1]

W. M. Bugg[2] G. T. Condo[2] E. L. Hart[2] H. O. Cohn R. D. McCulloch[3]
M. M. Nussbaum[4] C. P. Horne[4,5] R. J. Endorf[4]

From 8-GeV/c π^+D interactions we have found that one of the two resonances reported in the T region has a dominant decay into other than the reported decay modes or that there is a third resonance on this region.

1. Abstract of paper submitted for publication in *Physics Letters*.

2. University of Tennessee, Knoxville.
3. Mathematics Division.
4. University of Cincinnati, Cincinnati, Ohio.
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HIGHER-MASS BOSONS FROM 7.87-GeV/c π^+d INTERACTIONS[1]

W. M. Bugg[2] G. T. Condo[2] E. L. Hart[2] H. O. Cohn R. D. McCulloch[3]
M. M. Nussbaum[4] R. Endorf[4] C. P. Horne[4,5]

By employing the 80-in. BNL deuterium bubble chamber as a missing mass spectrometer, evidence for an odd G parity state with a mass in the T region (2.1 to 2.4 GeV/c^2) is presented. Indications from the individual channels suggest that it has at most a marginal amplitude for decay into $\rho p \pi$.

1. Abstract of published paper: *Phys. Rev.* **6D**, 3047–50 (1972).

2. University of Tennessee, Knoxville.
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4. University of Cincinnati, Cincinnati, Ohio.
5. Present address: Department of Physics, Florida State University, Tallahassee.

3. Nuclear Structure, Reactions, and Radioactivity

3*a*. Systematics

ORELA NEUTRON CAPTURE AND STELLAR NUCLEOSYNTHESIS[1]

B. J. Allen[2] R. L. Macklin

NUCLEAR REACTIONS: $^{A}X(n,\gamma)$, E = 2.5–1000 keV; measured $\sigma_{n,\gamma}$. Deduced parameters, averages. Enriched targets.

The Electron Linear Accelerator (ORELA) at Oak Ridge, Tennessee, is an outstanding facility for neutron physics research. Well planned and equipped, this accelerator is making a strong impact on the neutron data situation, particularly in the important kilovolt energy region. This article reviews briefly the ORELA research program, and considers in detail the measurement of fast-neutron capture cross sections and the application of these data to reactor physics and nucleosynthesis, the creation of elements in stars.

1. Abstract of paper submitted for publication in Australian journal *Atomic Energy*.
2. Present address: Australian Atomic Energy Commission, Lucas Heights, Australia.

STATUS REPORT OF THE NUCLEAR DATA PROJECT

D. J. Horen R. L. Auble F. E. Bertrand Y. A. Ellis W. B. Ewbank B. Harmatz
M. B. Lewis M. J. Martin S. Raman M. R. Schmorak D. C. West

During the calendar year 1972, the Nuclear Data Project continued its efforts to update the A-chain compilations, improve communications between the Project and researchers in the field as well as other compilers of nuclear data, pursue the utilization of computer aids in the compilation process, and pursue interactions with applied users of nuclear data. These topics are more thoroughly discussed in the following.

Nuclear Data Sheets

Revised A chains

A = 70, K. R. Alvar[1] and S. Raman
A = 91, H. Verheul[2] and W. B. Ewbank
A = 92, D. C. Kocher[1] and D. J. Horen
A = 93, D. C. Kocher[1]
A = 95, L. R. Medsker[1] and D. J. Horen
A = 96, L. R. Medsker[1]
A = 107, F. E. Bertrand and D. J. Horen
A = 108, F. E. Bertrand
A = 112, S. Raman and H. J. Kim
A = 122, F. E. Bertrand
A = 123, R. L. Auble
A = 125, R. L. Auble
A = 127, R. L. Auble
A = 129, D. J. Horen
A = 163, A. Buyrn[1]
A = 193, M. B. Lewis
A = 194, R. L. Auble
A = 195, M. J. Martin
A = 196, M. R. Schmorak
A = 197, M. B. Lewis
A = 206, K. K. Seth[2]
A = 212, S. C. Pancholi[2] and M. J. Martin

Survey of Nuclear Structure Systematics for $A \geqslant 229$, Y. A. Ellis and M. R. Schmorak.

1. Nuclear Information Research Associate (NIRA).
2. Consultant.

Recent References

The response to a questionnaire indicated excellent reception of "Recent References" by the basic nuclear structure community. In view of this, publication three times per year as issues of *Nuclear Data Sheets* will be continued. The first issue for 1973 will include a listing of nuclear reaction papers tabulated according to specific reactions to demonstrate more clearly the potentialities of the key-word system.

During 1972, the Council of the Division of Nuclear Physics of the American Physical Society, based upon the results of a poll of the membership, recommended that nuclear key words be included in *Physical Review C*. This has been accepted by the editors of the journal and will commence in 1973. We have sent letters requesting similar action to the editors of the other major nuclear physics journals.

"Recent References (September 1971–December 1971)," D. C. West, F. W. Hurley, S. H. Dockery, and S. J. Ball

"Recent References (January 1972–April 1972)," D.C. West, F. W. Hurley, S. H. Dockery, and S. J. Ball

"Recent References (May 1972–August 1972)," D. C. West, W. B. Ewbank, F. W. Hurley, and M. R. McGinnis

Research Papers, Verbal Presentations, Etc.

Most members of the Project are actively engaged in experimental or theoretical research, and writeups of the works are included in this annual report. These amount to 12 published papers and 16 abstracts presented at American Physical Society meetings.

Computerization

Efforts are proceeding to improve the utilization of computer techniques in three areas: (*a*) reference systems, (*b*) calculational and analysis programs used by compilers, and (*c*) establishment of a data file. A basic data format has been adopted. Work is progressing to develop and modify operational programs which can utilize data prepared in the basic format to perform routine calculations, etc., as well as produce new data cards for graphics and use for a data file.

Non-Project Mass Chain Compilers

S. C. Pancholi (India) spent three months at ORNL to begin work on compilation of $A = 138$.

A. Artna-Cohen (U.S.A.) is presently compiling $A = 183$.

H. Verheul (Netherlands) is presently compiling $A = 62$.

L. K. Peker and B. S. Dzhelepov (U.S.S.R.) are presently compiling $A = 140$.

National Science Foundation–Nuclear Information Research Associate (NIRA) Program

The NIRA Program entered its second year in October 1972 with the addition of 11 postdoctoral appointments. This makes a total of 22 NIRA's presently engaged in mass-chain compilations. The Data Project is participating in this program in four ways:

1. Providing reference lists to all NIRA's (and magnetic tapes containing tables and programs useful in preparing compilations),
2. consultation and/or coauthorship,
3. review,
4. publication.

As of January 1, 1973, the status was:

Mass chains published – $A = 70, 92, 93, 95, 96, 163$.

Mass chains received and at various stages of review – $A = 71, 77, 101, 153, 157, 159, 165, 174, 225$.

Services Provided

The Data Project routinely provides reference lists to the following:

Table of Isotopes (J. M. Hollander and C. M. Lederer, U.S.A.), magnetic tapes

Atomic Mass Adjustment (A. H. Wapstra, Netherlands; N. B. Gove, U.S.A.)

Nuclear Moments (G. H. Fuller and V. Shirley, U.S.A.)

Photonuclear Cross Section Center (E. G. Fuller, U.S.A.)

National Neutron Cross Section Center (BNL, U.S.A.)

NIRA's (22 compilers)

Non-Project Compilers (4)

In addition, more than 30 recorded requests for information from a variety of establishments, including other divisions at ORNL, private industry, U.S. government laboratories and agencies, university researchers, foreign scientists, etc., were answered in 1972. Information requested included selected reference lists as well as specific data.

In late 1972, the Data Project offered to provide on magnetic tape the Atomic Mass Adjustment by Wapstra and Gove to those persons supplying a tape. Fourteen such mass tapes have been sent to requesters, including both U.S. and foreign scientists, This is being done with the assistance of N. B. Gove of the Mathematics Division.

EVIDENCE FROM INELASTIC PROTON SCATTERING FOR A GIANT QUADRUPOLE VIBRATION IN SPHERICAL NUCLEI[1]

M. B. Lewis F. E. Bertrand

NUCLEAR REACTIONS: ^{27}Al, ^{54}Fe, ^{120}Sn, ^{209}Bi (p,p'), E_x = 6–40 MeV, E_p = 61.7 MeV; deduced giant quadrupole excitation from systematics of $\sigma(E_x, \theta)$.

A systematic study of inelastic proton continuum spectra produced at small angles by bombardment of ^{27}Al, ^{54}Fe, ^{120}Sn, and ^{209}Bi with 62-MeV protons suggests the existence of a collective region in the continuum with properties of a giant quadrupole vibration.

1. Abstract of published paper: *Nucl. Phys.* **A196**, 337 (1972).

REACTION LIST FOR CHARGED-PARTICLE-INDUCED NUCLEAR REACTIONS. Z = 1 TO Z = 99 (H TO Es), JULY 1971–JUNE 1972[1]

F. K. McGowan W. T. Milner

This reaction list for charged-particle-induced nuclear reactions has been prepared from the journal literature for the period July 1971 through June 1972. Each published experimental paper is listed under the target nucleus in the nuclear reaction with a brief statement of the type of data in the paper. The nuclear reaction is denoted by $A(a,b)B$, where $M_a \geqslant$ (one nucleon mass). There is no restriction on energy. Nuclear reactions involving mesons in the outgoing channel are not included. Theoretical papers which treat directly with the analysis of nuclear reaction data and results are included in the reaction list.

1. Abstract of published paper: *Nucl. Data Tables* **A11**, 1–126 (1972).

REACTION LIST FOR CHARGED-PARTICLE-INDUCED NUCLEAR REACTIONS.[1] Z = 1 AND 2 (H AND He), MAY 1969–JUNE 1971; Z = 3 TO 99 (Li TO Es), 1948–JUNE 1971; COULOMB EXCITATION, 1956–JUNE 1971

F. K. McGowan W. T. Milner

This reaction list for charged-particle-induced nuclear reactions has been prepared from the journal literature for the period 1948 through June 1971. Each published experimental paper is listed under the target nucleus in the nuclear reaction with a brief statement of the type of data in the paper. The nuclear reaction is denoted by $A(a,b)B$, where $M_a \geqslant$ (one nucleon mass). There is no restriction on energy. Nuclear reactions involving mesons in the outgoing channel are not included. Beginning with July 1970, theoretical papers which treat directly with the analysis of nuclear reaction data and results are included in the reaction list.

1. Abstract of paper to be published in *Atomic and Nuclear Data Reprints*, vol. I (Academic Press).

3b. $A \leqslant 22$

IMPROVED UPPER LIMIT FOR THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON[1]

W. B. Dress P. D. Miller N. F. Ramsey[2]

The previously described neutron resonance spectrometer has been modified to improve the determination of the effect of $E \times v/c$. An improved upper limit has been obtained for the neutron electric dipole moment $|\mu_e/e| < 1.0 \times 10^{-23}$ cm with 80% confidence.

1. Abstract of paper submitted for publication in the *Physical Review*.
2. Harvard University, Cambridge, Mass.

PROGRESS REPORT ON THE EXPERIMENT TO DETECT AN ELECTRICAL DIPOLE MOMENT OF THE NEUTRON

P. D. Miller[1] W. B. Dress[1] P. Perrin[2] R. Bouchez[2] N. F. Ramsey[3] R. Mössbauer[4]

During the last half of 1972, most of the apparatus for the experiment to detect an electrical dipole moment of the neutron has been assembled. The mechanical assembly of the magnetic resonance spectrometer on its turntable and the assembly of those on the platform furnished by the Institut Laue-Langevin has been completed.

The intensity has been measured to be 6×10^6 neutrons/sec. The detector uses a ^{6}Li-loaded glass scintillator with fairly standard photomultiplier and fast electronic equipment.

A PDP-11 computer furnished by the ILL has been interfaced to a CAMAC crate containing the necessary standard and special modules for the data acquisition system, the latter being furnished by CENG. The programming of the system is commencing with the new year.

The measurement of the neutron intensity confirms our earlier estimates that about 60 days of data acquisition should produce a sensitivity of a small number times 10^{-25} cm. This compares with the present upper limit of 1.0×10^{-23} cm. This estimate assumes that the apparatus is mechanically and magnetically stable enough to take full advantage of the intensity available.

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THE *p-p* FINAL-STATE INTERACTION IN THE ^{3}He(*d,t*)2*p* REACTION[1]

R. W. Rutkowski[2] E. E. Gross

The final-state interaction peak for the reaction ^{3}He$(d,t)2p$ at 5° lab, 23.5 MeV c.m. is analyzed with the Born approximation. Using an effective-range wave function for the diproton system, we extract $\gamma = 0.360 \pm 0.015$ fm^{-1} for the Gaussian range parameter describing the charge distribution in ^{3}He.

1. Abstract of published paper: *Phys. Lett.* **35B**, 151 (1971).
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CHARGE-ASYMMETRY EFFECTS IN THE REACTION ^{2}H(^{4}He,^{3}He)^{3}H[1]

E. E. Gross E. Newman M. B. Greenfield[2] R. W. Rutkowski[3] W. J. Roberts[4] A. Zucker

Differential cross sections for the process ^{2}H(^{4}He,^{3}He)^{3}H are presented for ^{4}He beam energies of 82.1, 64.3, and 49.9 MeV. The measurements were made to test the Barshay-Temmer theorem, which requires ^3H and ^3He yields to be independently symmetric about 90° c.m. We find a pronounced deviation from 90° c.m. symmetry which is angle- and energy-dependent. A distorted-wave Born-approximation analysis assuming the reaction mechanism to be a simple $l = 0$ nucleon-pickup process can qualitatively account for the observed deviations.

1. Abstract of published paper: *Phys. Rev.* C5, 602 (1972).
2. Florida State University, Tallahassee.
3. USAEC, Oak Ridge, Tenn.
4. Tennecomp, Oak Ridge, Tenn.

SEARCH FOR A $^3He + ^3He$ RESONANCE IN ^6Be; ASTROPHYSICAL IMPLICATIONS

M. L. Halbert D. C. Hensley H. G. Bingham

NUCLEAR REACTIONS: $^6Li(^3He,t)$, $E = 46.3$ MeV; measured $\sigma(E_t, \theta = 5°)$. Deduced: no $^3He-^3He$ resonance in ^6Be.

Recent measurements of the terrestrial flux of high-energy neutrinos[1] give an upper limit approximately nine times smaller than the flux expected from the proton-proton cycle in the sun.[2] One explanation, proposed independently by two groups,[3,4] postulates that in the solar interior the reaction $^3He(^3He,^4He)2p$ removes most of the ^3He and thereby reduces the amount of ^7Be formed from the capture of ^3He by ^4He. This in turn decreases the production of high-energy neutrinos, since such neutrinos are produced mainly in the β^+ decay of ^8B formed from the radiative capture of protons by ^7Be.

For this explanation to be quantitatively successful, the $^3He + ^3He$ reaction must be resonant very near threshold, with a width of no more than about 20 keV. If the resonance were further above threshold or were broader, its effects would have been already observed in two experiments[5] that measured the reaction down to within 80 keV of threshold. Moreover, because of the strong energy dependence of both the cross section (due to the Coulomb barrier) and the Maxwellian velocity distribution of the solar ^3He, there would be a negligible reduction in the amount of ^7Be formed unless the supposed resonance were about 20 keV above threshold and had a width $\leqslant$10 keV.[3,4]

Such a resonance would correspond to an excited state in ^6Be at about 11.5 MeV. The reaction $^6Li(^3He,t)\ ^6Be^*$ was selected to search for a state in this region of excitation. A beam energy of 46.3 MeV was chosen to avoid possible interference from deuteron groups originating in target impurities. The beam was produced by the ORIC. The tritons were observed with the Elbek broad-range spectrograph[6] at a laboratory angle of 5° in order to obtain adequate energy resolution. A silicon position-sensitive detector was used in the focal plane to distinguish tritons from deuterons.

The focal-plane position expected for tritons corresponding to the resonance was determined by increasing the magnetic field slightly to record the ground-state and first-excited-state deuterons from the $^6Li(^3He,d)^7Be$ reaction. The resolution of these two peaks was about 30 to 35 keV FWHM for a target of about 60 μg/cm^2 ^6Li(98.7% enrichment) on a backing of ~3 μg/cm^2 Formvar. With a target having about ten times as much Li, the observed resolution was about 42 keV; the resolution for tritons should have been similar. An additional position check was obtained by substituting a carbon target, reducing the magnetic field, and recording ground-state tritons from the $^{12}C(^3He,t)^{12}N$ reaction.

Figure 1 shows the measured triton spectrum from the $^6Li(^3He,t)^6Be^*$ reaction for 5.1×10^{-4} C of $^3He^{2+}$ on the thicker target. The solid angle of the spectrograph-detector combination was 0.93×10^{-4} sr. The range of ^6Be excitation energies covered here is about 0.89 MeV. Tritons from $^{12}C(^2He,t)^{12}N$ are off scale at this field setting.

The expected position of the resonance, near channel 2800, is shown by the arrow, and the horizontal bar indicates the expected FWHM. No peak is evident in this vicinity. By means of a least-squares peak-fitting program, the peak area was found to be consistent with zero, with a standard deviation of about 40 counts. This result did not change if the centroid was allowed to lie anywhere in the range 2500 to 3250. The corresponding limit on the cross section is

$$\left(\frac{d\sigma}{d\Omega}\right)_{c.m.} \leqslant 1.7\ \mu b/\text{sr} \quad \text{for } \theta_{c.m.} = 8.4° .$$

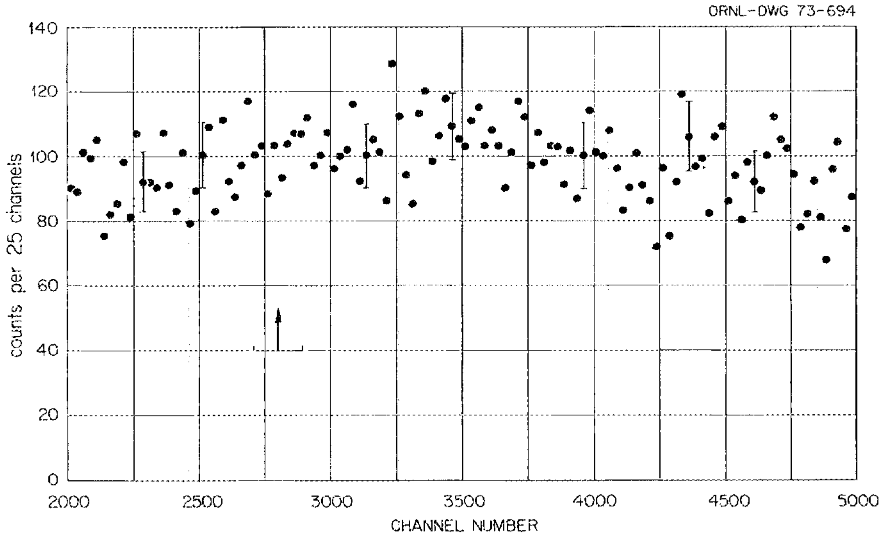

Fig. 1. Spectrum of tritons at 5° from bombardment of ^{6}Li with 46.3-MeV ^{3}He.

To express this limit in terms of the structure of ^{6}Be, we have carried out simplified DWBA calculations very similar to those described by Parker et al.,[7] who studied the same reaction at 25.5 MeV. Parker's calculations are based on the zero-range approximation reported by Oh et al.[8] for (^{3}He,^{6}Li) reactions on a number of light nuclei. In our calculations it was assumed that 75% of the time the ^{6}Li consists of ^{3}He + t clusters.[9,10] The resulting spectroscopic factor for the ^{6}Be* being composed of two ^{3}He particles is

$$S(^6\text{Be}^*) \leqslant 0.00036\ ,$$

which is 17 times smaller than the result from ref. 7.

A ^{3}He + ^{3}He resonance this weak is inadequate to account for the apparent absence of high-energy neutrinos from the sun.[4,7]

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2. J. N. Bahcall and R. K. Ulrich, *Astrophys. J.* **170**, 593 (1971); Z. Abraham and I. Iben, Jr., *Astrophys. J.* **170**, 157 (1971).
3. W. A. Fowler, *Nature* **238**, 24 (1972).
4. V. N. Fetisov and Yu. S. Kopysov, *Phys. Lett.* **40B**, 602 (1972).
5. M. R. Dwarakanath and H. Winkler, *Phys. Rev.* **C4**, 1532 (1971); A. D. Bacher and T. A. Tombrello, unpublished work quoted in the same reference.
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ISOSPIN CONSERVATION IN COMPLICATED REACTIONS

C. D. Goodman D. C. Hensley A. van der Woude S. Raman

NUCLEAR REACTIONS: ^{11}B(d,^{6}He)^{7}Be, ^{11}B(d,^{6}Li*)^{7}Li, ^{11}B(d,^{7}Li)^{6}Li*, ^{11}B(d,^{7}Be)^{6}He, measured $\sigma(\theta)$, $\sigma_1(\theta)/\sigma_2(\theta)$ compared with isospin prediction.

As a continuation of our study of the excitation of isospin multiplets in nuclear reactions, we turned our attention to reactions that appeared to have reasonable cross sections, in contrast to the reactions that we reported last year, for which the cross sections were so small that we were unable to make useful measurements.

We have studied the reactions ^{11}B(d,^{6}He)^{7}Be and ^{11}B(d,^{6}Li*)^{7}Li (where ^{6}Li* stands for the 3.59-MeV T = 1 state in ^{6}Li). We have also studied the complementary pair of reactions: $^{11}B(d,^{7}Li)^{6}Li^{*}$ and $^{11}B(d,^{7}Be)^{6}He$. The ground states of ^{6}He and $^{6}Li^{*}$ are two members of a mass 6 isospin triplet, and the ground states of ^{7}Be and ^{7}Li are isospin mirrors of each other. If isospin is conserved in the above reactions, then at any angle of observation the number of observed ^{6}He particles should be twice the number of $^{6}Li^{*}$ particles, and the number of ^{7}Be particles should be twice the number of ^{7}Li particles. This follows simply from the coefficients necessary to construct a $T = 1/2$ wave function for the mass 6–7 combination specified.

This is, however, a case of a broken symmetry; the Q values are different because of different Coulomb energies in the two final states, and it is of interest to see if the symmetry breaking shows up in the actual reaction measurements. Adair[1] in his 1952 article implicitly expected that the effect could be accounted for simply with a phase-space correction for the difference in final energies. This correction would alter the ratios of the cross sections but would preserve the shapes of the angular distributions. Our experiment is reasonably sensitive to the possible presence of a $T = 3/2$ component in the final state. If the final state is assumed to contain a small $T = 3/2$ component, say 5% in amplitude, then the ratio might depart by as much as 10% from its predicted value.

In our experiment we bombarded ^{11}B targets, about 100 $\mu g/cm^2$ thick, with 40-MeV deuterons from the ORIC. We observed the product particles with a pair of ΔE-E telescopes consisting of 10- or 25-μ ΔE detectors and 400-μ E detectors. Figure 1 shows the electronics arrangement. The data acquisition was done with the ORIC ADC system using a 400 × 550 channel array for the ΔE-E storage. Singles events were recorded in the sorted array. Figure 2 shows a sample of such an array.

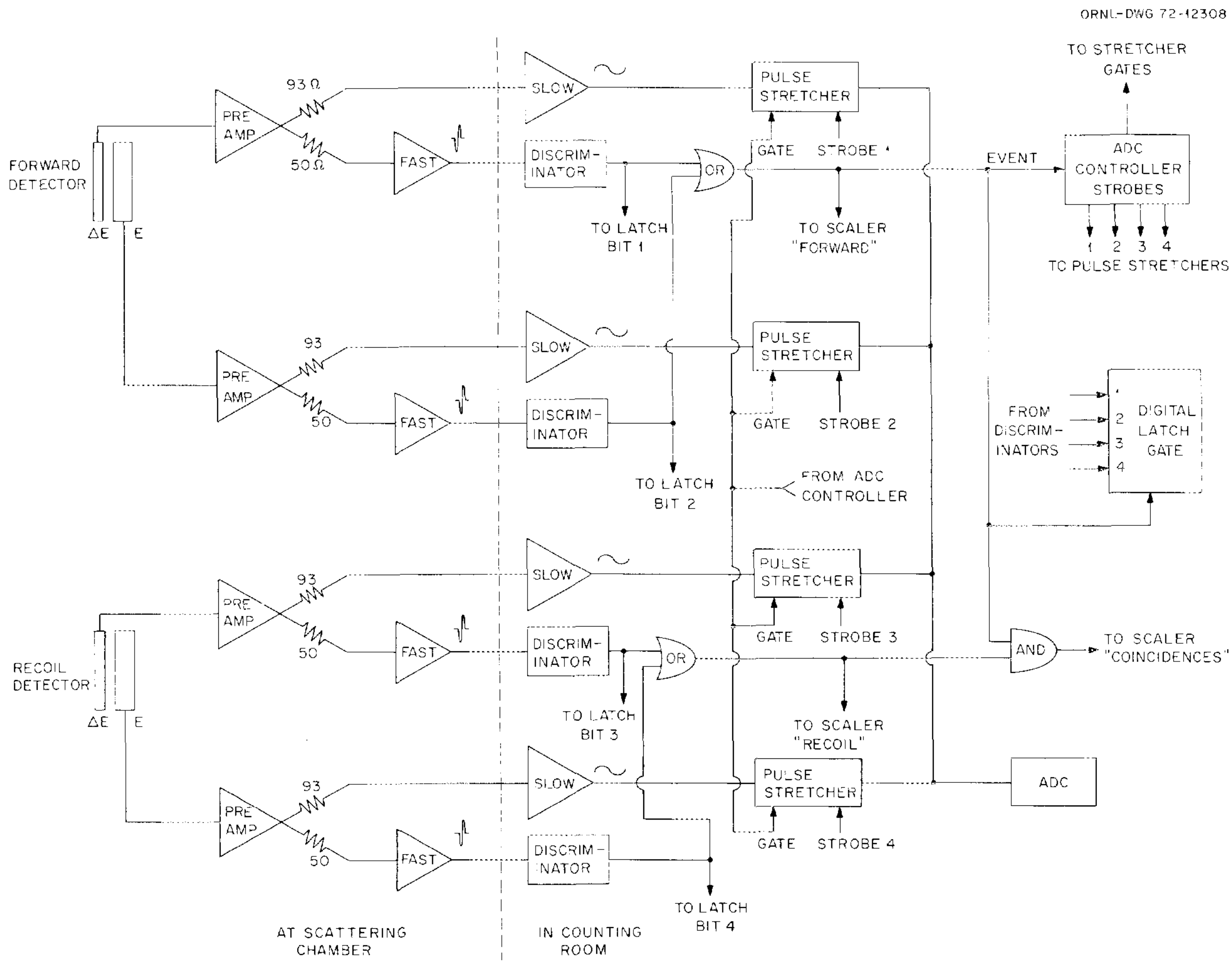

Fig. 1. Electronics arrangement for data acquisition in the $^{11}B(d,^{6}He)^{7}Be$ and $^{11}B(d,^{6}Li^{*})^{7}Li$ study.

ORNL DWG. 73-1585

Fig. 2. Display of the ΔE-E data showing the identification of ^{6}He, ^{6}Li, ^{7}Li, ^{8}Li, ^{7}Be, ^{9}Be, and ^{10}Be.

For each coincidence we recorded E and ΔE for both counters in a list mode.

The $^{11}B(d,^6He)^7Be$ and $^{11}B(d,^7Be)^6He$ reactions could be identified in the singles array, but the $^{11}B(d,^7Li)^6Li^*$ and, to some extent, the $^{11}B(d,^6Li^*)^7Li$ reactions could not be observed clearly in singles due to a continuum background from particle breakup of unbound ^6Li and ^7Li states. Thus we studied both singles and coincidence data.

For each angle of the forward counter, it was necessary to collect data for several settings of the recoil angle because the reactions do not have identical kinematics; in particular the recoil angle for mass 7 forward differs significantly from the recoil angle for mass 6 forward. To save time, it was necessary to run at compromise recoil angles for some runs, at one setting to pick up the mass 6 recoils and at another to pick up the mass 7 recoils. We measured the coincidence efficiency curve for making corrections to the runs for which the recoil angle was set at a compromise value. An additional complication occurs because the $^6Li^*$ deexcites by gamma emission in flight. This produces a very small uncertainty in the forward angle cone and produces a significant spread in the recoil angle cone. In our case the maximum spread in angle was smaller than the angular acceptance of the recoil counter, so no correction was required within the accuracy of the experiment.

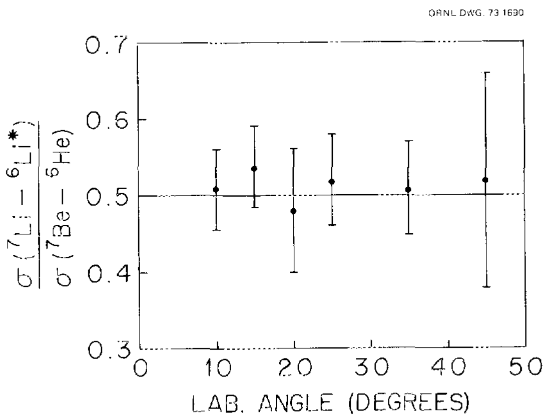

Fig. 3. The observed ratio of cross sections corrected for coincidence efficiency.

The measured ratios are shown in Fig. 3. They are in good agreement with the predicted ratio.

1. Robert K. Adair, *Phys. Rev.* 87, 1041 (1952).

ABSOLUTE NEUTRON YIELDS FROM THICK-TARGET $^{NAT}C(\alpha,n)$[1]

J. K. Bair

Recent measurements of the neutron yield resulting from the alpha-particle bombardment of carbon have disclosed an error in the data reported in the literature. New values are given for the thick-target yield of neutrons for alpha-particle energies between 2 and 9 MeV.

1. Abstract of paper submitted for publication in *Nuclear Science and Engineering*, Technical Note.

TOTAL NEUTRON YIELD FROM THE REACTIONS $^{13}C(\alpha,n)^{16}O$ AND $^{17,18}O(\alpha,n)^{20,21}Ne$[1]

J. K. Bair F. X. Haas[2]

Compound states of high excitation in ^{17}O and $^{21,22}Ne$ have been observed, with good resolution, in the total neutron yield from the reactions $^{13}C(\alpha,n)^{16}O$ and $^{17,18}O(\alpha,n)^{20,21}Ne$. Bombarding alpha-particle energies were approximately from 1 to 5 MeV. Analysis of the area under the excitation curves gives alpha-particle strength functions of S_α = 0.029 ± 0.030 for $^{13}C + \alpha$, 0.030 ± 0.023 for $^{17}O + \alpha$, and 0.022 ± 0.010 for $^{18}O + \alpha$. For astrophysical purposes these strength functions are used to extrapolate the average cross sections to lower energies.

1. Abstract of paper submitted for publication in the *Physical Review*.
2. Mound Laboratory, Miamisburg, Ohio.

THE LEVEL STRUCTURE OF ^{17}O FROM NEUTRON TOTAL CROSS SECTIONS[1]

J. L. Fowler C. H. Johnson R. M. Feezel[2]

The neutron total cross section of oxygen is measured in the energy regions from 0.6 to 0.9, 1.12 to 1.16, and 1.39 to 4.33 MeV. More than half of this region is surveyed with energy resolution and energy steps of about 2.5 keV. On the basis of these data and supplementary published data on the (n,n) angular distributions and the $^{13}C(\alpha,n)$ reaction, the ^{17}O level energies in million electron volts and, in parentheses, J^π values and center-of-mass total widths, $\Gamma_T = \Gamma_n + \Gamma_\alpha$ in thousand electron volts, are 5.696 ($7/2^-$, 3.4), 5.731 (not $1/2^+$, <1.0), 5.867 ($3/2^+$, 6.6), 5.937 ($1/2^-$, 32), 6.354 ($1/2^+$, 124), 6.860 (not $1/2^+$, <1.0), 6.970 (not $1/2^+$, <1.0), 7.163 ($5/2^-$, 1.4), 7.20 ($3/2^+$, 280), 7.377 ($5/2^+$, 0.5), 7.380 ($7/2^-$, 1.2), 7.56 ($3/2^-$, 500), 7.685 ($7/2^-$, 18), 7.955 ($1/2^+$, 90), 7.99 ($1/2^-$, 260), 8.058 ($3/2^+$, 86), 8.18 ($1/2^-$, 69), and 8.20 ($3/2^-$, 52). Resonances are not observed for known ^{17}O levels at 5.215 and 7.573 MeV; these levels have $\Gamma_T < 0.1$ keV. The previously reported narrow $3/2^+$ level at 7.694 MeV does not exist. Many of the results are based on a multilevel R-matrix analysis; this is also extended to the published $^{16}O(n,n)$ and $^{13}C(\alpha,n)$ cross sections for energies corresponding to ^{17}O excitation up to 9.5 MeV. This extension shows that there are two levels rather than only one near 8.47 MeV and that the 9.42-MeV level has $J^\pi = 3/2^-$. Other assignments are confirmed. The most accurate excitation energies below 9.5 MeV are reviewed from the literature, and the ^{17}O-^{17}F mirror structure is reviewed.

1. Abstract of paper submitted for publication in the *Physical Review*.
2. Undergraduate student from Auburn University in ORNL Cooperative Educational Program.

R-MATRIX ANALYSIS WITH A DIFFUSE-EDGE POTENTIAL FOR ^{16}O + n DATA[1]

C. H. Johnson J. L. Fowler R. M. Feezel[2]

An R-matrix analysis of the $^{16}O(n,n)$ and $^{16}O(n,\alpha)$ cross sections below 5.8 MeV shows that the off-resonance cross sections are described by scattering in a potential, that the boundary radius must be inside the tail of this potential, that the total of the spectroscopic factors for five observed $d_{3/2}$ fragments is unity, and that the spectroscopic factors for other partial waves are about as expected from the shell model.

1. Abstract of published paper: pp. 2–3 in *Contributions – Conference on Nuclear Structure Study with Neutrons* (Budapest, Hungary, July–August 1972), Central Research Institute for Physics, Budapest, 1972.
2. Undergraduate student from Auburn University in ORNL Cooperative Educational Program.

A UNIFIED R-MATRIX-PLUS-POTENTIAL ANALYSIS FOR ^{16}O + n CROSS SECTIONS[1]

C. H. Johnson

A multilevel two-channel R-matrix analysis is made for both the neutron total and angle-integrated (n,α) cross sections of ^{16}O for 0- to 5.8-MeV neutrons. Off-resonant phase shifts are described by scattering in a real Saxon-Woods local potential with a spin-orbit term and a parity dependence for the well depths. The well parameters are chosen to bind the $1d_{5/2}$ and $2s_{1/2}$ levels at the energies of the lowest two states in ^{17}O and the quasi-bound $1d_{3/2}$ level at the centroid of five observed $3/2^+$ resonances. The $1d_{3/2}$ level is replaced by these five fragments, which contain nearly 100% of the $1d_{3/2}$ strength and have their eigenenergy centroid at 5.74 MeV in ^{17}O. The 5.08-MeV level in ^{17}O has 69% of the strength. The R-matrix boundary radius must be chosen carefully inside the tail of the potential in order to subtract the $1d_{3/2}$ state and in order to place the unbound $2p$ and $1f$ states at energies consistent with the observed p- and f-wave fragments. Spectroscopic factors are deduced for 26 levels in ^{17}O between 4.5 and 9.5 MeV, and the sums of these factors are 1% for $J^\pi = 1/2^+$; 5% for $1/2^-$; 12% for $3/2^-$; 99% for $3/2^+$; 0.1% for $5/2^+$; 1% for $5/2^-$; and 14% for $7/2^-$. Thus, the observed single-particle structure of ^{17}O in both the bound and unbound region is described by an R-matrix-plus-potential analysis.

1. Abstract of paper to be published in the *Physical Review*.

NEUTRON CAPTURE IN FLUORINE BELOW 1500 keV[1]

R. L. Macklin R. R. Winters[2]

NUCLEAR REACTION: $^{19}F(n,\gamma)$, $E = 2.5$–5000 keV; measured $\sigma_{n\gamma}$. Deduced levels, Γ, $g\Gamma_\gamma$.

Neutron time-of-flight radiative capture data taken at the Oak Ridge Electron Linear Accelerator have been analyzed for single-level resonance parameters. Ten resonances were found, with parameters as indicated, listing E_0 (keV), J value assumed, and Γ_γ (ev) in order. 27.07 (2) 1.4 ± 0.3, 48.7 (1) 1.7 ± 0.4, 97.0 (1) ≤6.0 ± 1.8, 269 (2) 3.5 ± 0.8, 270 (1) ≤4.4, 386 (1) ≥7 ± 2, 490.5 (0) ≥10 ± 3, 595 (2) ≥7 ± 2, 1460 (1) ≥11 ± 3. Values of total width were also found for these resonances. Two resonances are very narrow, and their capture yields estimates of $g\Gamma_n$. At 43.5 keV, $g\Gamma_n = 0.086 \pm 0.02$ eV if $J > 1$ or $\Gamma_n = 0.42 \pm 0.1$ eV if $J = 0$; and at 173.5 keV, $g\Gamma_n = 0.35 \pm 0.10$ eV. The increase of nearly an order of magnitude in radiative width with increasing energy up to 600 keV is notable. Twelve large resonances between 1600 and 5000 keV were not analyzed for capture because of detector sensitivity to the inelastic scattering channels which open in that energy region.

1. Abstract of paper submitted for publication in *Physical Review C.*
2. Present address: Denison University, Granville, Ohio.

TOTAL NEUTRON YIELDS FROM THE PROTON BOMBARDMENT OF $^{17,18}O$[1]

J. K. Bair

The $^{17}O(p,n)^{17}F$ reaction has been observed for the first time in the energy region from threshold to 5 MeV. Total neutron production cross sections measured with good resolution are given. The reaction threshold is determined to be 3743 ± 6 keV. High-resolution total neutron cross sections are also given for the reaction $^{18}O(p,n)^{18}F$ from threshold to 4 MeV.

1. Abstract of paper submitted for publication in the *Physical Review.*

THE ENERGY LEVELS OF ^{21}Na[1]

F. X. Haas[2] C. H. Johnson J. K. Bair

NUCLEAR REACTIONS: $^{20}Ne(p,\gamma)^{21}Na$, $E = 0.98$ to 2.2 MeV; measured E_γ, I_γ, Γ, enriched targets; deduced ^{21}Na levels, Q value. $^{20}Ne(d,n)^{21}Na$, $E = 3.6$ to 6 MeV. Measured absolute differential cross sections, enriched targets; deduced levels and spectroscopic factors.

The energy levels of ^{21}Na are investigated with the $^{20}Ne(p,\gamma)^{21}Na$ and $^{20}Ne(d,n)^{21}Na$ reactions. From the gamma-ray energy measurements the excitation energies in ^{21}Na are found to be 331 ± 3, 1717 ± 3, 2426 ± 2, 2800 ± 4, 3545 ± 3, 3679 ± 4, 3867 ± 4, 4117 ± 11, and 4297 ± 4 keV. A $^{20}Ne(p,\gamma)^{21}Na$ Q value of 2434 ± 2 keV is deduced. Branching ratios are determined for the upper five levels. Direct nonresonant capture is observed to the 0.33- and 2.43-MeV states. Angular distributions for the $^{20}Ne(d,n)^{21}Na$ reaction are presented for all of these levels and for levels at 4453 ± 12 keV and 5009 ± 12 keV for incident deuteron energies of 3.60, 4.88, 5.57, and 5.94 MeV. The unbound 4.12-MeV state has a stripping pattern consistent with $l = 1$. Its laboratory width from the gamma-ray work is 125 keV. The combined evidence of the branching ratios, reduced widths, and stripping patterns shows that the 4.12-keV level is the mirror of the 4.73-MeV level in ^{21}Ne.

1. Abstract of published paper: *Nucl. Phys.* **A193**, 65 (1972).
2. Mound Laboratory, Miamisburg, Ohio.

HEAVY-ION NEUTRON YIELDS

J. K. Bair W. B. Dress C. H. Johnson P. H. Stelson

NUCLEAR REACTIONS: $^{NAT}C(^{16,18}O,xn)$, $^{16,18}O(^{16,18}O,xn)$: E = 15 to 55 Mev; $^{63,65}Cu(^{16,18}O,xn)$, $^{58,60,61,62,64}Ni(^{16,18}O,xn)$, $^{64,66,67,68,70}Zn)^{16,18}O,xn)$, E = 35 to 55 MeV. Measured total neutron yields.

Previously reported [1] total neutron yields resulting from the $^{16,18}O$ bombardment of thin targets have been completed. Final results are now available for ^{NAT}C, $^{16,18}O$, and $^{63,65}Cu$. Figures 1–4 show these data. Since at sufficiently high energies more than one neutron can be produced per neutron-producing event, the yield is plotted as $\sigma \cdot \nu$, where σ is the usual cross section and ν is the average number of neutrons produced per neutron-producing event. Energies are the

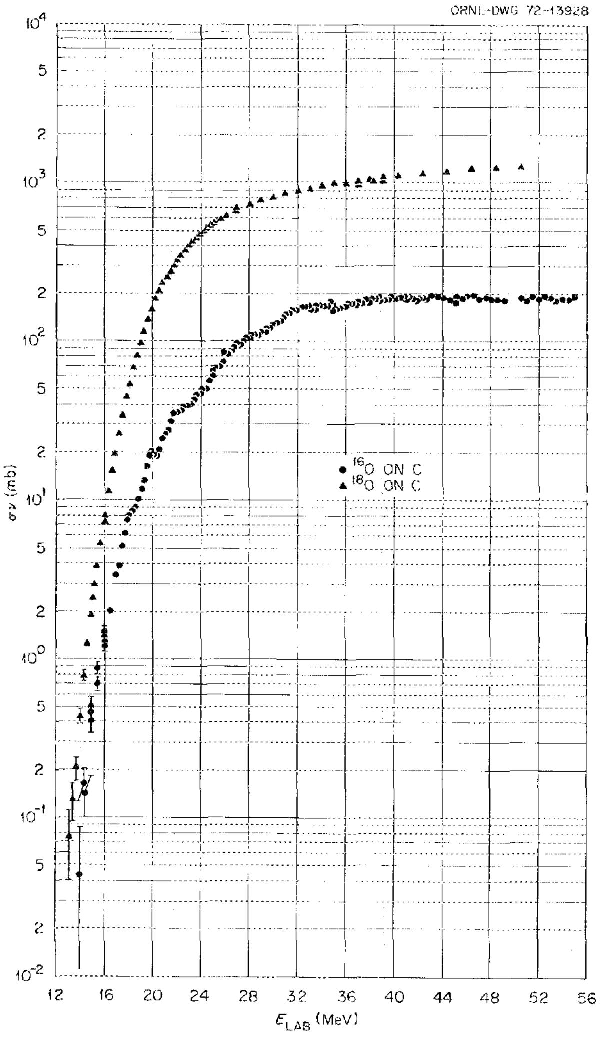

Fig. 1. These data were obtained by bombarding a layer of carbon evaporated onto a platinum blank. Target thickness was approximately 160 keV at 30 MeV.

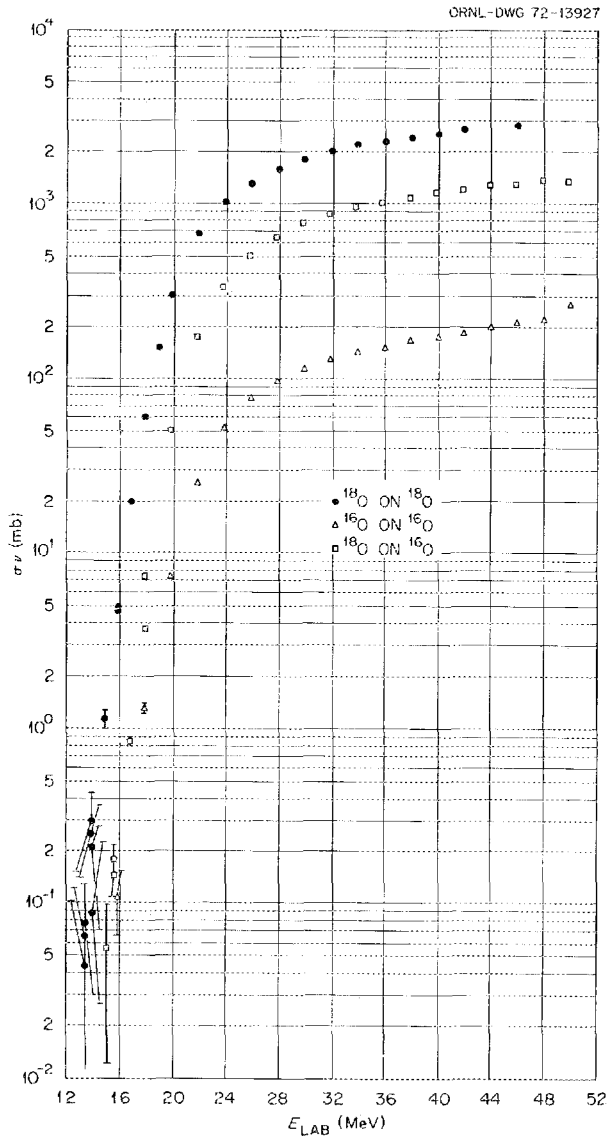

Fig. 2. These data were obtained by bombarding tantalum blanks which had been anodized in either natural water or water enriched to 97.2% ^{18}O. Target thickness was approximately 180 keV at 50 MeV.

bombarding laboratory energies corrected for target thickness effects.

In addition to the error bars shown, we estimate an uncertainty of ±4, ±7, and ±4% (one standard deviation) for the carbon, oxygen, and copper targets respectively.

Final corrections have yet to be made to the ^{58,60,61,62,64}Ni(^{16,18}O,xn) data and to the ^{64,66,67,68,70}Zn(^{16,18}O,xn) data.

1. W. B. Dress, J. K. Bair, C. H. Johnson, and P. H. Stelson, *Bull. Amer. Phys. Soc.* **17**, 530 (1972). Also J. K. Bair, W. B. Dress, C. H. Johnson, C. M. Jones, and P. H. Stelson, *Program and Abstracts, Physics Division Information Meeting* (1971), abstract 16(*c*).

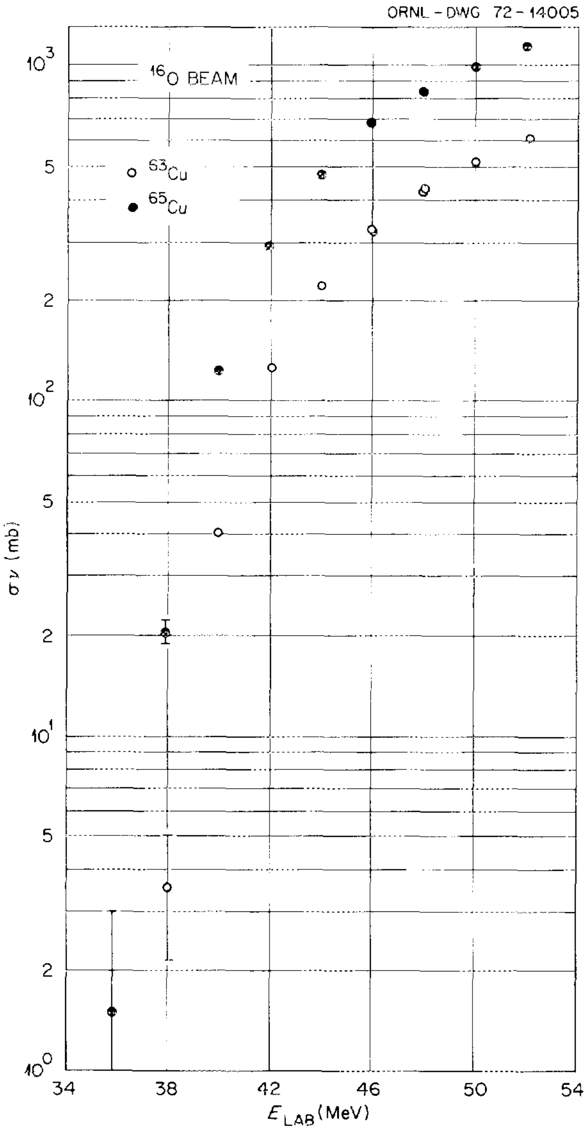

Fig. 3. These data were obtained by bombarding a thin layer of enriched metallic copper evaporated on platinum blanks. Target thickness was approximately 350 keV at 50 MeV.

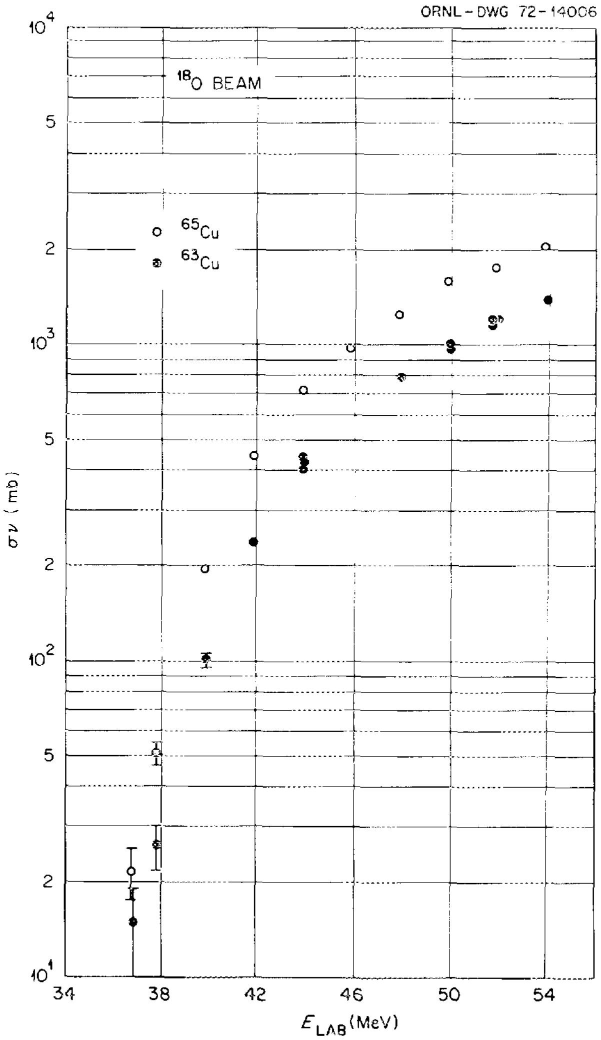

Fig. 4. These data were taken using the same targets as used to obtain the data of Fig. 3.

TOTAL NEUTRON YIELD FROM THE (α,n) REACTION ON ^{21,22}Ne[1]

F. X. Haas[2] J. K. Bair

Compound states of high excitation in ^{25,26}Mg have been observed, with good resolution, in the total neutron yield from alpha-particle bombardment of ^{21,22}Ne. Bombarding energies were from 1 to 5 MeV. Analysis of the areas under the yield curves gives alpha-particle strength functions of $\bar{S}_\alpha = 0.031 \pm 0.021$ for ^{21}Ne + α and $\bar{S}_\alpha = 0.026 \pm 0.012$ for ^{22}Ne + α. For astrophysical purposes, these strength functions are used to extrapolate the averaged cross sections to lower energies.

1. Abstract of paper submitted for publication in the *Physical Review*.
2. Mound Laboratory, Miamisburg, Ohio.

$(^3He,n)$ REACTION AT 25 MeV[1]

M. B. Greenfield[2] C. R. Bingham[3] E. Newman M. J. Saltmarsh

The $(^3He,n)$ reaction has been studied on targets of ^{12}C, ^{27}Al, ^{28}Si, and ^{58,60,62}Ni at an incident energy of 25 MeV. The observed resolution of the neutron time-of-flight spectrometer used in this work was about 1%. Differential cross sections were obtained for the resolvable final states over the angular range of 0 to 40° (L). The angular distributions were compared with the predictions of a simple one-step two-nucleon-transfer model. In this formalism the diproton stripped from ^{3}He is transferred to the target, retaining its $^1S_0$ relative motion. The shapes of the angular distributions were unique for a given l transfer and were, in most cases, generally reproduced by the calculations. For 0^+ targets the J^π of many final states could be assigned. Comparison of experimental with theoretical relative magnitudes permitted assignment of dominant shell-model configurations. To first approximation the relative transition strengths to final states in ^{14}O, ^{30}S, and ^{60}Zn were consistent with the assumption of two particles coupled to an effectively "closed core."

1. Abstract of published paper: *Phys. Rev.* **C6**, 1756 (1972).
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3*c*. $22 < A \leqslant 100$

NEUTRON TOTAL CROSS SECTIONS FOR KILOVOLT NEUTRON ENERGIES

W. M. Good J. A. Harvey

NUCLEAR REACTIONS: 21 nuclides; measured σ_{nT}, $E_n = 10^3$–10^6 eV; enriched targets.

Neutron transmission studies have continued of nuclides whose neutron resonant spacings are of the order of a kilovolt. The energy range of study generally is about 1 to 400 keV, and separated isotopes are employed.

Continuing as of one year ago, ^{29,30}Si, ^{40,42,43,44}Ca, ^{47,49}Ti, ^{54,57}Fe, and ^{204,206,207,208}Pb are in various stages of study, and to these have been added ^{90,91,92,94,96}Zr, ^{33,34}S.

Very little information is generally available on total cross sections ^{29,30}Si, ^{33,34}S.[1] Hence the resonant energies observed for these nuclides in the present measurements are listed in Table 1. An explicit representation of the results as obtained for ^{34}S is given in Fig. 1.

On account of ORELA's high resolution, many levels are expected to be observed in present transmission measurements which were unobservable before, except

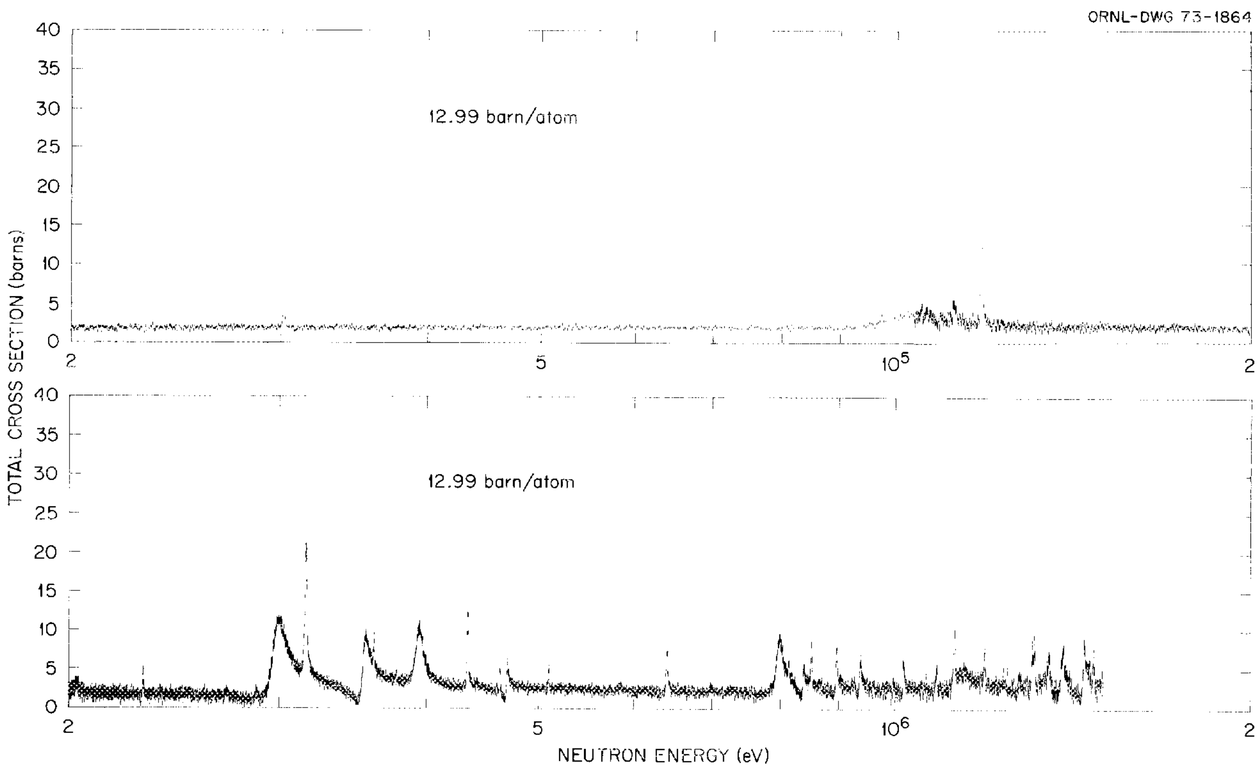

Fig. 1. The total cross section of ^{34}S.

Table 1. Listing of resonances observed in the target nuclides $^{29,30}Si$, $^{33,34}S$, $^{54,57}Fe$

In $^{54,57}Fe$, * indicates new, ** in kiloelectron volts previously observed but different energy assignments

^{29}Si	^{30}Si	^{33}S	^{34}S	^{54}Fe	^{57}Fe
15.29	2.235	13.44	30.37	7.813	1.628
38.79	4.98	17.63	118.5	9.476	3.973
159.6	63.43	23.93	231.3	11.169*	4.746
184.5	185.8	30.37	301.3	14.455	6.276
336.7	235.1	52.17	317.6	30.628*	7.215
385.4	302.7	53.54	357.2	39.053*	7.934
553.2	413.5	59.06	362.5	51.533*	12.847
650.3	644.4	77.84	396.6	52.1	13.286*
	747.6	81.46	435.7	55.341*	13.966
	849.9	87.50	464.0	72.089	18.224
		101.2	470.8	98.820	21.049*
		151.6	510.2		21.284
		168.7	642.5		28.624
		178.3	800.6		29.680
		197.3	814.5		37.078*
		221.7	839.5		39.361*
		228.8	851.0		41.643
		238.4	893.7		41.958*
			935.8		47.164
			1019		49.917*
			1089		52.644*
			1125		56.539
			1193		61.786
			1313		65.416*
			1352		74.331*
			1391		77.528
			1450		83.812*
					88.089*
					89.816*
					91.672*
					93.912*
					101.695**
					109.866**
					118.832**

possibly for the earlier capture measurements (capture can be a bit more sensitive to narrow resonances than transmission). In Table 1 are listed the resonances observed in $^{54,57}Fe$ in the present measurements. The most recent data for comparison are Hockenbury et al.[2] and Rohr and Müller.[3]

No listing is provided of the resonance levels observed in $^{90,91}Zr$.[4] However, a scan of the raw ^{90}Zr transmission data indicates many small resonances not resolved in the previous measurements.[5] In the energy interval from 3 to 70 keV, on which only 13 resonances were then reported, there now appear at least 35.

Study and analysis of these nuclides are continuing.

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3. G. Rohr and K. N. Müller, *Z. Phys.* **227**, 1 (1969).

4. Measurements on $^{90,91}Zr$ were made in collaboration with Mr. Richard E. Toohey, Physics Division, Argonne National Laboratory. Samples were courtesy of Dr. A. H. Smith, Argonne National Laboratory.

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keV NEUTRON TOTAL CROSS SECTION MEASUREMENTS AT ORELA[1]

J. A. Harvey

NUCLEAR REACTIONS: Fe, ^{54}Fe, ^{57}Fe σ_{nT}; E_n = 10–1000 keV; Fe filters for minima. Enriched targets.

Neutron total cross sections are measured at ORELA using samples as small as a few square millimeters and flight paths from 18 to 200 m, with energy resolutions ($\Delta E/E$) from 1/300 for measurements below ~10 keV to ~1/2500 up to 200 keV and $\sqrt{E}$ (in MeV)/1000 above 1 MeV. A new efficient neutron detector using NE 110 has been developed for keV measurements whose efficiency is ~30% for 10-keV neutrons, rising to 90% for 50-keV neutrons. Transmission measurements using iron-filtered neutron beams have been made upon samples of iron 4, 6, 12, and 20 in. thick to obtain accurate values of the cross-section minima. Enriched ^{54}Fe and ^{57}Fe samples have been measured to determine their contributions to the windows in natural iron.

1. Abstract of invited paper published in *Proceedings of ANS Topical Meeting on New Developments in Reactor Physics and Shielding Calculations, Kiamesha Lake, New York, September 12–15, 1972,* USAEC CONF-720901, Book 2, pp. 1075–86 (1972).

THE $^{10}B(^{16}O,d)$, $^{10}B(^{16}O,\alpha)$, AND $^{12}C(^{16}O,\alpha)$ REACTIONS

J. L. C. Ford, Jr. J. Gomez del Campo[1] S. T. Thornton[2] R. L. Robinson P. H. Stelson

NUCLEAR REACTIONS: $^{10}B(^{16}O,d)$, $^{10}B(^{16}O,\alpha)$, $^{12}C(^{16}O,\alpha)$; E = 40–46 MeV, measured $\sigma(E)$ at 7°. ^{22}Na, ^{24}Mg deduced levels. Enriched target.

The observation of sharp states at high excitation energies in ^{24}Mg by means of the $^{12}C(^{16}O,\alpha)$ reaction[3] has created a great deal of interest in such reactions. The use of position-sensitive proportional detectors on the focal plane of the Enge split-pole spectrograph which is located at the tandem accelerator provides a technique for observing states over a wide energy range with good resolution and is, therefore, well suited for such studies. Our counter is a 60-cm-long single-wire gas proportional detector of the Borkowski-Kopp design[4–6] which derives the position information from the rise time of the pulses from the two ends of a high-resistance wire anode. The construction of the detector is shown in Fig. 1.

The alpha-particle spectrum measured with this counter from the $^{12}C(^{16}O,\alpha)$ reaction at an incident energy of 46 MeV and a laboratory angle of 7° is displayed in Fig. 2. The target was an approximately 7-μg/cm^2-thick ^{12}C foil. The states observed at 14.14, 16.3, 16.55, and 16.8 MeV are those which were most strongly excited in the work of Middleton et al.[3] Those states at 4.12, 8.12, and 13.2 MeV are the 4^+, 6^+, and 8^+ members of the ground-state rotational band.[7] The selectivity of this heavy-ion reaction can be noted by the fact that light-ion work has indicated that there are at least 50 states between 13 and 14 MeV in excitation energy. At this energy and angle the most prominent features of the spectrum are the very strong states near 12 MeV. The extensive excitation functions of the MIT-Brookhaven group show that there is a strong maximum in the yield curve near this energy for these states.[8]

The energy resolution for this spectrum is about 50 keV, and the doublet at 16.55 and 16.59 MeV is not separated. However, if the magnetic field is changed in order to shift the spectrum along the focal plane so that the radii of curvature of the particles within the field are increased, then the resolution improves sufficiently to separate these states, as is shown in Fig. 3. In addition, other peaks, such as that corresponding to the 15.15-MeV state, also appear to have a complex structure.

Most of the strong states observed in the $^{12}C(^{16}O,\alpha)$ reaction were also seen by means of the $^{10}B(^{16}O,d)$ reaction, which also leads to ^{24}Mg as the final nucleus. However, the yield for the majority of the levels was down by a factor of about 100.

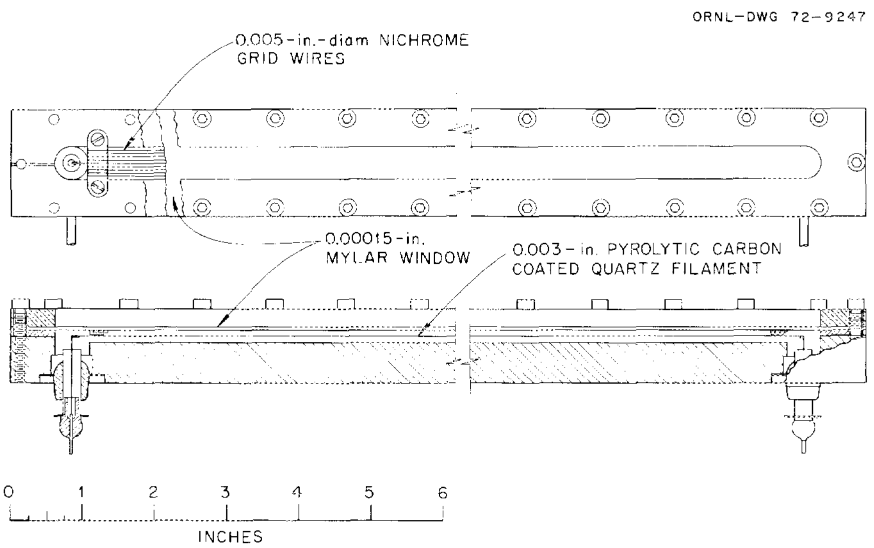

Fig. 1. Assembly drawings of the 60-cm-long proportional detector.

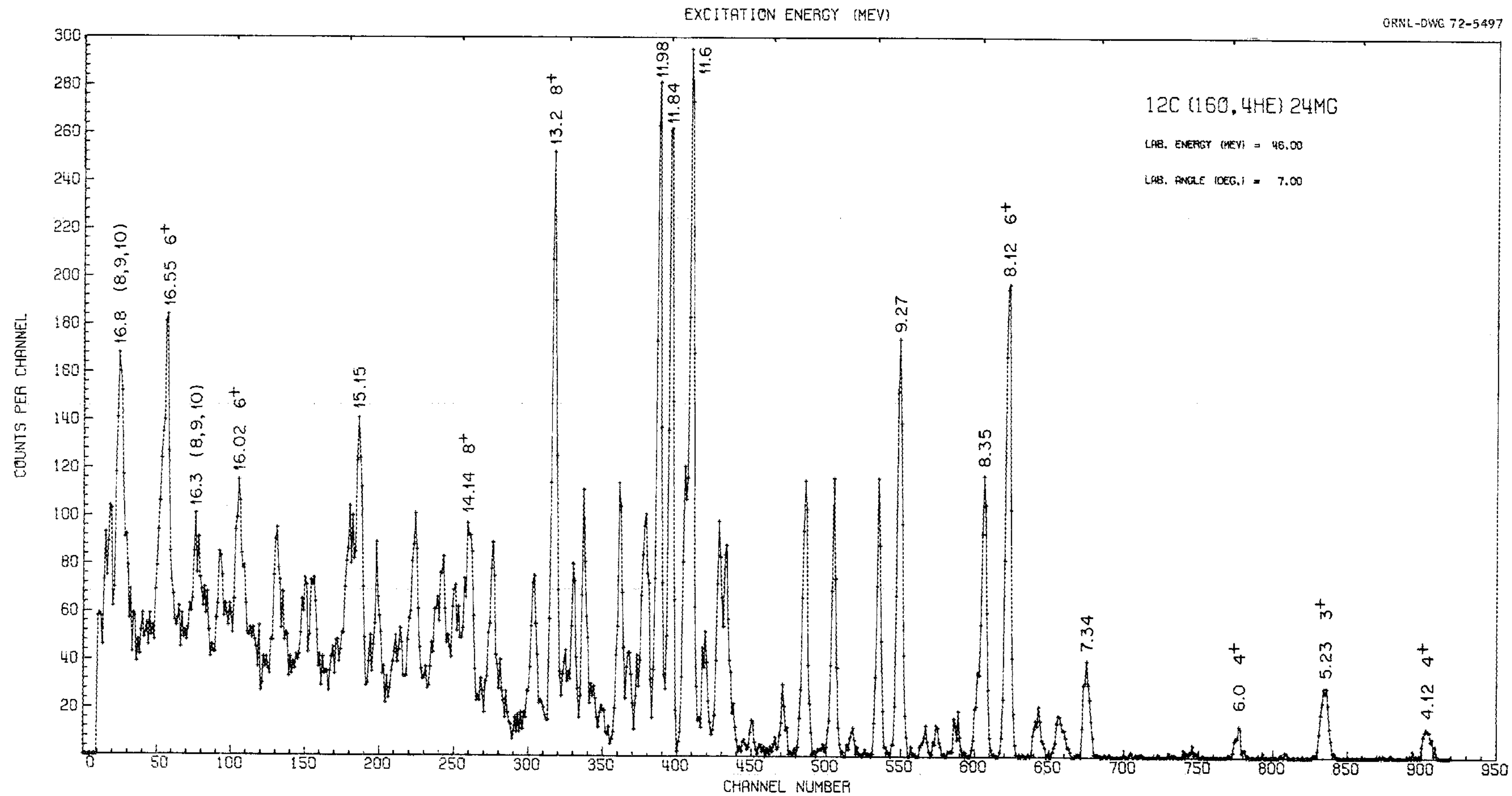

Fig. 2. The alpha-particle spectrum from the $^{12}C(^{16}O,\alpha)$ reaction with the magnetic field set to cover the energy region from the doublet at 4.12 to 4.23 MeV up to 17 MeV in excitation energy in ^{24}Mg. The laboratory angle and bombarding energy were 7° and 46 MeV respectively.

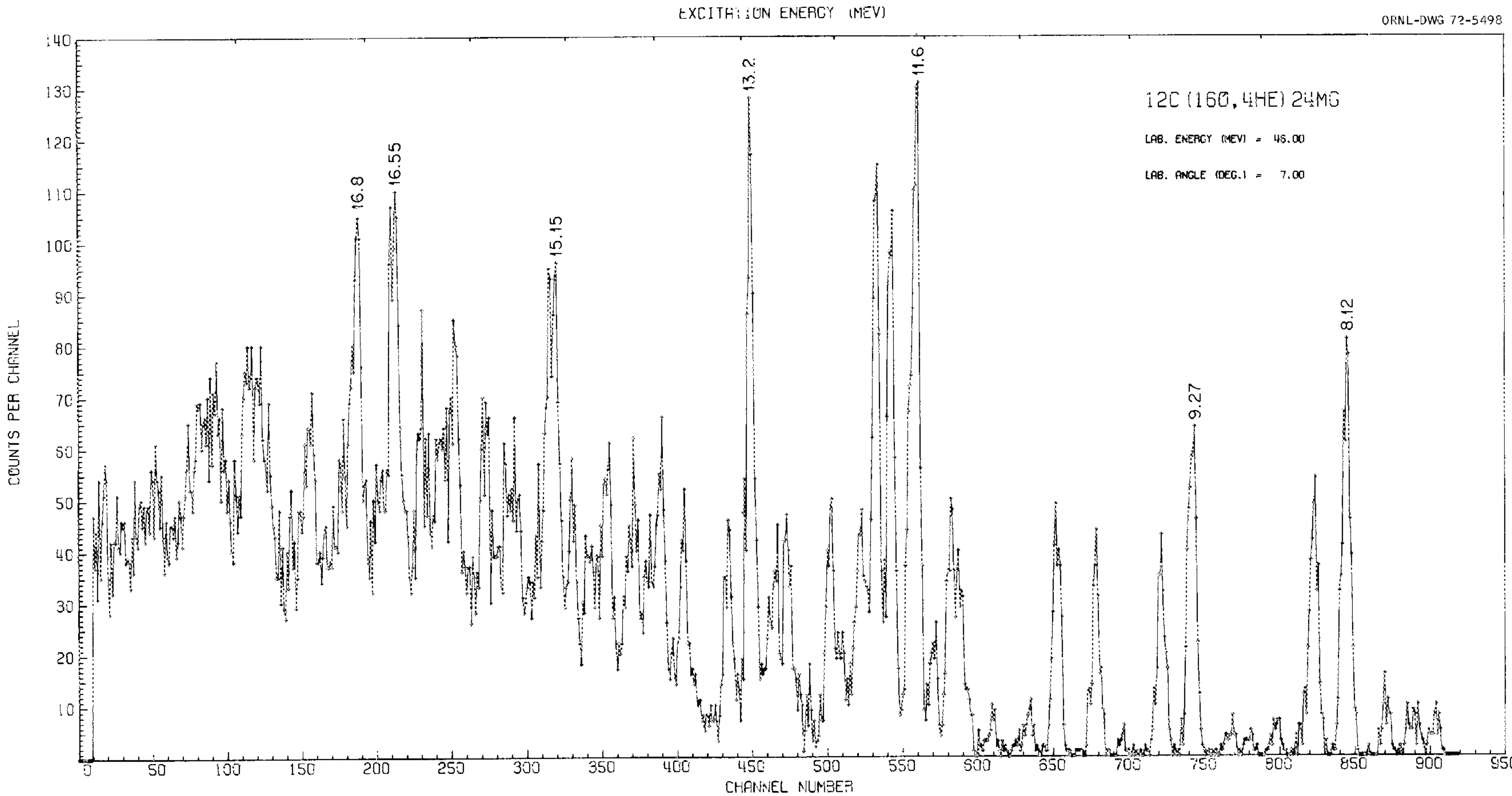

Fig. 3. The $^{12}C(^{16}O,\alpha)$ spectrum observed at a higher magnetic field setting showing the splitting of the peaks near 15.15 and 16.55 MeV in excitation energy.

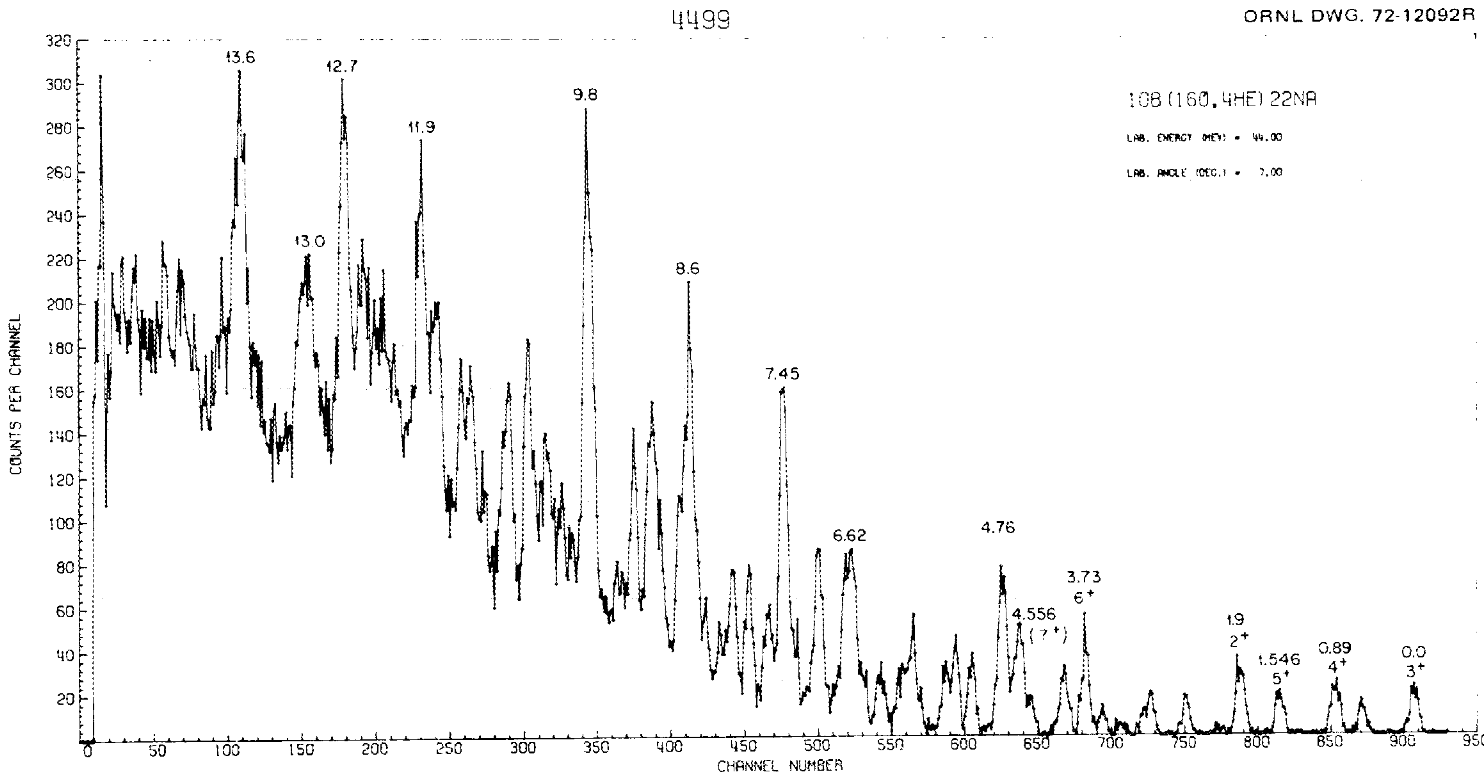

Fig. 4. The alpha-particle spectrum from the $^{10}B(^{16}O,\alpha)$ reaction. The laboratory angle and bombarding energy were 7° and 44 MeV respectively.

The competing $^{10}B(^{16}O,\alpha)$ reaction has a larger yield and leads to ^{22}Na, an odd-odd nucleus with a rotational-like level structure. The levels observed in this nucleus at an incident energy of 44 MeV and an angle of 7° are shown in Fig. 4. The target was a self-supporting enriched ^{10}B foil with a thickness of approximately 17 $\mu g/cm^2$, resulting in an energy resolution of about 120 keV. Among the states populated are the 3^+, 4^+, 5^+, and 6^+ members of the ground-state rotational band at 0, 0.89, 1.54, and 3.72 MeV respectively. An investigation of ^{22}Na by means of the $^{12}C(^{14}N,\alpha)$ reaction has suggested that the 7^+ member of the band may be the state at 4.520 MeV.[9] If the 7^+ state is the one observed here near 4.5 MeV, then the intensities of the first five members of the band are in reasonable agreement with the $2J + 1$ intensity rule. The members of the lowest lying $T = 1$ band have been identified at 0.66, 1.95, and 4.07 MeV. These peaks should occur at approximately channels 865, 785, and 670 respectively. The possible appearance of the 1.95- and 4.07-MeV states in the $^{10}B(^{16}O,\alpha)$ reaction is in contrast to the $^{12}C(^{14}N,\alpha)$ reaction, in which these states were not populated. States in ^{22}Na have been reported in the literature up to about 10 MeV in excitation energy. However, in the present reaction we continue to see strong structure in the energy spectrum that corresponds to excited states up to at least 18 MeV and that tracks with angle as it should to be in ^{22}Na.

The excitation functions for members of the ground-state rotational band, as well as the strong states at 7.45 and 9.9 MeV, are plotted in Fig. 5. In the energy interval from 40 to 46 MeV there appear to be no dramatic changes in the cross sections. In contrast, the excitation functions for the $^{12}C(^{16}O,\alpha)$ reaction fluctuate rapidly with energy.[8,10,11] The smoother $^{10}B(^{16}O,\alpha)$ excitation functions may be due to the nonzero spin of ^{10}B, which results in about seven times as many effective open channels. The data appear to be consistent with a statistical compound-nuclear process as the dominant reaction mechanism. A detailed analysis of the measurements will be made with Hauser-Feshbach theory, which has proved successful in interpreting similar heavy-ion reactions.[12]

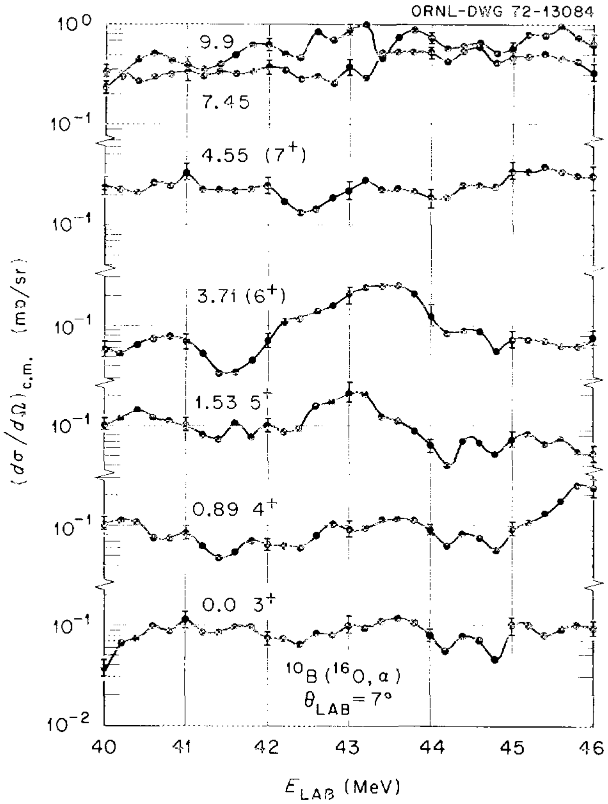

Fig. 5. Excitation functions measured at 7° for the members of the ground-state rotational band, and the strongly populated levels at 7.45 and 9.9 MeV.

1. University of Mexico, Mexico City, Mexico.
2. University of Virginia, Charlottesville.

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OPTICAL-MODEL FAMILY AMBIGUITY RESOLVED FOR HELION ELASTIC SCATTERING FROM ^{60}Ni[1]

C. B. Fulmer J. C. Hafele[2]

NUCLEAR REACTIONS: $^{60}Ni(h,h)$, E = 29.6, 35.1, 49.7, 59.8, 71.1 MeV; optical-model analysis, deduced potentials. Enriched target.

Optical-model fits with successive fixed values of real well depth V to five angular distributions for $^{60}Ni(h,h)^{60}Ni$ which include data to angles >110° for projectile energies between 29.6 and 71.1 MeV yield χ^2 vs V plots with a deep minimum at $V \sim$ 130 MeV for each data set. For the lower energy data sets, other minima (parameter families) are observed at intervals above and below this value, but the higher energy data sets (59.8 and 71.1 MeV) show only one unique family near V = 130 MeV. The absence of the family ambiguity for the higher energy data sets demonstrates the importance of both large-angle and high-energy data for the removal of optical-potential ambiguities. The normalized volume integral of the real potential at $V \sim$ 130 MeV is $J_R \sim$ 330 MeV fm^3 for each data set, and J_R changes by ~100 MeV fm^3 for successive families. The unambiguous value of $J_R \sim$ 330 MeV fm^3 for the higher energy data sets and the near independence of J_R on energy implies a similar unique value and corresponding unique family for the lower energy data sets. This value of 330 MeV fm^3 is somewhat lower than values of J_R > 400 MeV fm^3 suggested by earlier studies.

1. Abstract of paper to be published in *Physical Review C.*
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ENERGY DEPENDENCE OF THE OPTICAL MODEL FOR HELION SCATTERING FROM ^{60}Ni[1]

C. B. Fulmer J. C. Hafele[2] C. C. Foster[3]

NUCLEAR REACTIONS: $^{60}Ni(h,h)$, E = 29.6, 35.1, 49.7, 59.8, 71.1 MeV; optical-model analysis, deduced potentials and energy dependence. Enriched target.

An optical-model analysis of measured angular distributions for $^{60}Ni(h,h)^{60}Ni$ with five different helion energies (29.6, 35.1, 49.7, 59.8, and 71.1 MeV) produced satisfactory fits to all five of the data sets with an optical potential having all parameters common. This energy-independent potential gave a χ^2 minimum with V = 126 MeV, $r_R = r_s$ = 1.12 fm, $a_R = a_s$ = 0.84 fm, W_D = 20.4 MeV, r_I = 1.26 fm, a_I = 0.84 fm, and V_s = 2.85 MeV. Another parameter family with V = 170 MeV also gave an equally good minimum in χ^2. These two parameter families were used to predict scattering cross sections at 180° over the helion energy range from 21 to 32 MeV, and corresponding laboratory data were found to be in better agreement with the predictions of the above-listed family with V = 126 MeV. Slightly improved fits to the five data sets were obtained in a search with the real and imaginary well depths dependent on helion energy and with the rest of the parameters common. In this case, V and W_D were found to have a weak but approximately linear dependence on helion energy E, with $V = 133.9 - 0.14E$ MeV and $W_D = 22.4 - 0.04E$ MeV.

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SPIN-ORBIT AND TARGET-SPIN EFFECTS IN HELION ELASTIC SCATTERING[1]

C. B. Fulmer J. C. Hafele[2]

The well depth of the spin-orbit term for the helion-nucleus optical-model potential was determined by performing parameter searches for elastic scattering data at successive fixed values of V_s. Resulting plots of

χ^2/N vs V_s show consistent minima for the 13 data sets used. Elastic angular distributions studied were for ^{60}Ni at four energies between 35 and 71 MeV and for three groups of neighboring even- and odd-mass targets at energies between 60 and 71 MeV. The χ^2/N vs V_s plots for all the even-mass ($I = 0$) targets have minima at values of V_s between 2.0 and 3.0 MeV, while the plots for all the odd-mass ($I \neq 0$) targets have minima about 1 MeV greater (3.0 to 4.0 MeV). This difference in the best-fit values of V_s is consistent over a wide range of target mass and of scattering energy and suggests the presence of a detectable target-spin interaction in helion elastic scattering.

1. Abstract of a paper to be published in *Physical Review C.*
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$^{63,65}Cu(n,n'\gamma)$ REACTIONS

G. G. Slaughter G. L. Morgan[1] J. K. Dickens[1]

NUCLEAR REACTIONS: $^{63,65}Cu(n,n'\gamma)$; E = 0.5 MeV–10 MeV; measured E_n, E_γ, I_γ; $^{63,65}Cu$ deduced energy levels. Enriched and natural samples.

Gamma-ray spectra have been obtained due to neutron interactions with natural copper at the 10-m station of the ORELA for $0.5 \leqslant E_n \leqslant 10$ MeV using a Ge(Li) detector system.[2] Spectra were also obtained for small enriched isotopic samples of ^{63}Cu and ^{65}Cu; however, the small sample sizes (~50 g each) precluded obtaining definite data in a reasonable period of machine time. However, for both of these small isotopic samples, gamma-ray spectra were obtained using a Ge(Li) detector and 4.9-MeV neutrons produced using a Van de Graaff accelerator system.[3] These two sets of data are being studied to obtain spectroscopic information for the two copper isotopes. Figure 1 shows the level structure and gamma decay scheme determined thus far for ^{65}Cu.

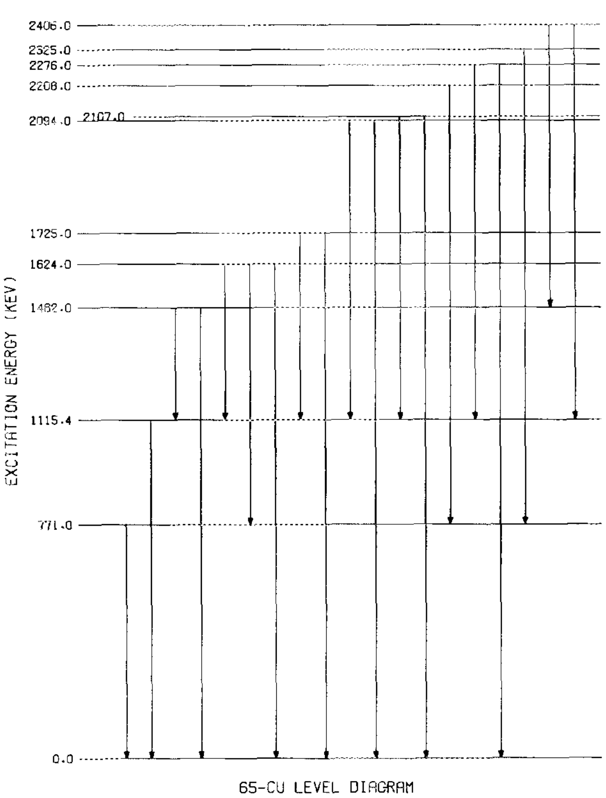

Fig. 1. ^{65}**Cu level structure determined from this experiment.** These data represent new information on the decay modes for levels having $E_x > 2$ MeV.

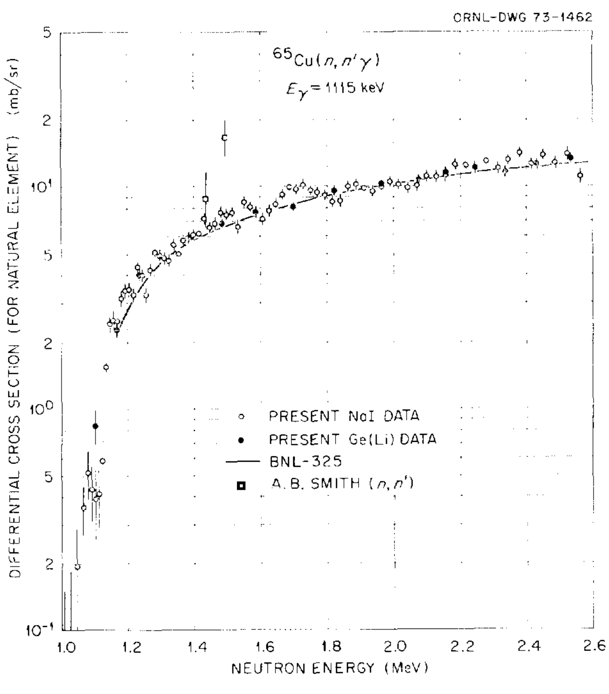

Fig. 2. Excitation function for the 1115-keV transition in ^{65}**Cu.** The differential cross sections are in millibarns per steradian with respect to the natural sample and not corrected for isotopic abundance.

The Ge(Li) data are also being supplemented by gamma-ray production cross-section data obtained with the natural copper sample at the 50-m station of the ORELA.[4] We have begun to extract excitation functions from these data for individual transitions; that for the E_γ = 1115 keV transition in ^{65}Cu is shown in Fig. 2. In this figure the data are shown for the natural element and not corrected for isotopic abundance. The NaI data are determined absolutely; the Ge(Li) data are determined relatively and normalized to the NaI data. The solid curve and the dashed extrapolation were taken from BNL-325 (ref. 5). Neutron scattering measurements by Smith et al.[6] are also shown. These data should be amenable to theoretical interpretation which should aid in spin-parity assignments.

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3. J. K. Dickens and F. G. Perey, *Nucl. Sci. Eng.* **36**, 280 (1969).
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6. A. B. Smith, C. A. Engelbrecht, and D. Reitmann, *Phys. Rev.* **135**, B76 (1964).

NEUTRON CAPTURE CROSS-SECTION MEASUREMENTS FOR ^{86}Sr, ^{87}Sr, AND ^{88}Sr[1]

G. J. Vanpraet[2] R. L. Macklin B. J. Allen[3] R. R. Winters[4]

NUCLEAR REACTIONS: ^{86}Sr(n,γ), ^{87}Sr(n,γ), ^{88}Sr(n,γ), E = 3–600 keV; measured $\sigma_{n\gamma}$. Deduced Maxwellian average vs stellar temperatures. Enriched targets.

Neutron capture cross sections for ^{86}Sr, ^{87}Sr, and ^{88}Sr have been measured from 3 keV up to 600 keV with total-energy detectors. Maxwellian averaged cross sections are calculated as a function of energy. The correlation between these values and the solar system isotopic abundances is discussed in terms of stellar nucleosynthesis by slow capture.

1. Abstract of paper to be published in proceedings of IAEA Conference on Nuclear Structure Study with Neutrons, July 29–August 4, 1972, Budapest, Hungary.
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NEUTRON RESONANCE PARAMETERS OF ^{92}Mo[1]

O. A. Wasson[2] B. J. Allen[3] R. R. Winters[4] R. L. Macklin J. A. Harvey

NUCLEAR REACTIONS: ^{92}Mo(n,γ), E < 32 keV; measured σ_{nT}, $\sigma_{n\gamma}$. Deduced 42 levels, Γ_n, Γ_γ, J, π, l, S^0, S^1. Enriched target.

Neutron transmission and total neutron capture yields were measured using the time-of-flight technique at the Oak Ridge Electron Linear Accelerator facility using enriched samples of ^{92}Mo. A total of 42 resonances were observed for neutron energies less than 32 keV. Twelve are assigned to s-wave interactions, while 23 are assigned to p-wave interactions. The resonant energies, neutron widths, radiation widths, and spins are deduced. The average s- and p-wave radiation widths are equal to 0.178 ± 0.015 eV and 0.24 ± 0.03 eV respectively. The s-wave neutron strength function is $(0.65 \pm 0.26) \times 10^{-4}$, while the p-wave strength function is $(3.3 \pm 1.1) \times 10^{-4}$.

1. Abstract of paper submitted for publication in *Physical Review C*.
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VALENCY NEUTRON CAPTURE IN $^{92}Mo(n,\gamma)^{93}Mo$[1]

O. A. Wasson[2] G. G. Slaughter

NUCLEAR REACTIONS: $^{92}Mo(n,\gamma)$; E = 5 eV–100 keV; measured E_n, E_γ, I_γ, $\sigma_{n\gamma}$; ^{93}Mo measured binding energy, deduced J, π, l. Enriched target.

Capture gamma-ray spectra from the $^{92}Mo(n,\gamma)^{93}Mo$ reaction were measured for neutron energies below 100 keV using the 10-m flight path at the Oak Ridge Electron Linear Accelerator. For neutron energies less than 25 keV a total of 23 different s- and p-wave resonances were resolved. The neutron binding energy is 8067.4 ± 1.5 keV. The partial radiation widths for the 12 highest energy gamma rays which populate positive parity states below 2.5 MeV excitation were deduced and compared with the valency model predictions of Lane and Lynn. For gamma-ray energies less than 6.5 MeV, the average $M1$ partial radiation width is approximately equal to the average $E1$ partial radiation width. The reduced transition strengths as defined by Bartholomew for these transitions are $\bar{k}(E1) = (1.2 \pm 0.2) \times 10^{-3}$ and $\bar{k}(M1) = (11.5 \pm 2.3) \times 10^{-3}$. For the 7129-keV transition to the s = 1/2 first excited state the average reduced strength is enhanced by a factor of 5 and 2 for the $E1$ and $M1$ transitions respectively. Nearly 30% of this enhancement for the $E1$ multipoles is attributed to the valency-model contribution, while the remainder is assigned to other processes, such as the giant dipole resonance and doorway state components. The average $E2$ width for the 8067-keV ground-state gamma rays is approximately 10% of the average $E1$ ground-state width.

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VALIDITY OF THE VALENCE-NEUTRON MODEL FOR ^{98}Mo

G. W. Cole[1] R. E. Chrien[1] R. C. Byrd[1] S. F. Mughabghab[1] J. A. Harvey G. G. Slaughter

NUCLEAR REACTIONS: $^{98}Mo(n,\gamma)$; E = 5 eV–6 keV; measured E_n, E_γ, I_γ; ^{99}Mo deduced levels. Enriched sample.

Recent resonance neutron capture measurements near the $3p$ maximum in the p-wave strength function have shown a considerable degree of validity for the valence-neutron model. The model describes radiative capture in terms of a transition of a valence neutron outside the core to a low-lying state of the final nucleus; the core does not participate in the transition. This leads to the prediction that $\Gamma_{\gamma i}$, the partial radiative width to state i, is proportional both to the reduced neutron width of the resonance and to the spectroscopic factor of the final state. Such valence contributions should be most important where the neutron widths are large, since they compete with the random compound-nucleus contributions.

In the case of ^{98}Mo, the success of the model for several large p-wave resonances below 1 keV prompted further study at ORELA in order to extend the energy range over which the model could be tested. Both capture gamma-ray measurements and total cross-section measurements were made on separated ^{98}Mo samples in order to obtain partial radiative widths and resonance parameters at higher neutron energies. The radiative capture measurements were made at a nominal time-of-flight resolution of 2.5 nsec/m. Twenty-three resolved resonances, up to 5600 keV, have been analyzed. The resonance parameters were obtained from total cross-section measurements on a thick sample of 0.0434 atom/b, taken with a nominal resolution of 0.06 nsec/m.

The success of the model for resonances below 1 keV is related to the large reduced widths of these resonances. Spectra obtained for these resonances are in substantial agreement with the earlier work. Above 1 keV, the reduced neutron widths are significantly smaller, and statistical processes can be expected to dominate the valence capture process. This expectation is confirmed by the present results, in which measured partial radiative widths do not in general agree with those calculated using the valence model and the measured resonance parameters. It is of interest, however, to note that the ground-state transition is the strongest in 11 out of 18 *p*-wave resonances up to 5600 keV; the ground state of ^{99}Mo has the largest spectroscopic factor of the six low-lying *s* and *d* states of interest [$S(d,p) = 0.67$].

1. Brookhaven National Laboratory.

THE ^{91}Zr(p,t) REACTION AND THE LEVEL STRUCTURE OF ^{89}Zr[1]

J. B. Ball

NUCLEAR REACTIONS: ^{91}Zr(p,t), E = 31 MeV; measured $\sigma(E_t, \theta)$. ^{89}Zr deduced levels, L_{2n}, J, π, enhancement factors.

The ^{91}Zr(p,t) reaction has been studied at a proton energy of 31 MeV. Tritons were detected in a magnetic spectrograph yielding a resolution of 18 keV. Angular distributions for levels up to 2.75 MeV of excitation in ^{89}Zr are compared with two-nucleon-transfer DWBA calculations and analyzed in terms of the mixed L transfers allowed from a nonzero-spin target. Two types of neutron configurations are observed to be populated in ^{89}Zr by this reaction: single-hole states and one-particle, two-hole states.

1. Abstract of published paper: *Phys. Rev. C* **6**, 2139 (1972).

SYSTEMATICS OF L = 0 TRANSITIONS OBSERVED IN THE (p,t) REACTION OF NUCLEI NEAR N = 50[1]

J. B. Ball J. S. Larsen[2]

NUCLEAR REACTIONS: ^{88}Sr, ^{90,92}Zr, ^{92,94}Mo, ^{96}Ru (p,t), E = 31 MeV; measured $\sigma(E_t, \theta)$. ^{86}Sr, ^{88,90}Zr, ^{90,92}Mo, ^{94}Ru deduced 0^+ levels, enhancement factors.

We present excitation energies and transition intensities observed for 0^+ states populated by the (p,t) reaction on nuclei near N = 50. Comparison of results on selected isotopes of Sr, Zr, Mo, and Ru shows an unexpected loss of neutron L = 0 transfer strength with increasing proton number.

1. Abstract of published paper: *Phys. Rev. Lett.* **29**, 1014 (1972).
2. Visiting scientist from Niels Bohr Institute, Copenhagen, Denmark.

A REMARK ON THE LEVEL STRUCTURE OF ^{93}Mo AND THE FAILURE OF j DETERMINATION BY SPECTROSCOPIC FACTOR RATIOS NEAR CLOSED SHELLS[1]

J. B. Ball

NUCLEAR REACTIONS: ^{95}Mo(p,t), E = 31 MeV; measured $\sigma(E_t, \theta)$. ^{93}Mo deduced levels, L_{2n}, J, π, j for 1.495- and 1.695-MeV levels.

The ^{95}Mo(p,t)^{93}Mo reaction is used to establish the 1.69-MeV level in ^{93}Mo as $5/2^+$ rather than $3/2^+$ as assigned in recent (d,p) and (d,t) studies. An explanation for this failure of j-value determination by comparison of spectroscopic factor ratios is presented.

1. Abstract of published paper: *Phys. Lett.* **41B**, 55 (1972).

ENERGY LEVELS OF ^{94}Ru OBSERVED WITH THE ^{96}Ru(p,t) REACTION[1]

J. B. Ball C. B. Fulmer J. S. Larsen[2] G. Sletten[2]

NUCLEAR REACTIONS: ^{96}Ru(p,t), E = 31.1 MeV; measured $\sigma(E_t, \theta)$. ^{94}Ru deduced levels, L_{2n}, J, π. Enriched target.

The level structure of the neutron-magic nucleus ^{94}Ru, up to an excitation energy of 4 MeV, has been studied by means of the (p,t) reaction. Particular emphasis was placed on a search for excited 0^+ levels, none of which have been reported previously. Among new levels observed in this study are 0^+ levels at 2.995, 3.615, and 3.770 MeV and the 3^- octopole vibration at 2.965 MeV.

1. Abstract of paper submitted for publication to *Nuclear Physics*.
2. The Niels Bohr Institute, University of Copenhagen, Denmark.

THE LEVEL STRUCTURE OF ^{92}Mo AND ^{94}Mo STUDIED WITH THE (p,t) REACTION[1]

J. S. Larsen[2] J. B. Ball C. B. Fulmer

NUCLEAR REACTIONS: ^{94,96}Mo(p,t), E = 31 MeV; measured $\sigma(E_t, \theta)$. ^{92,94}Mo deduced levels, σ, π. Enriched targets.

The ^{94}Mo(p,t)^{92}Mo and ^{96}Mo(p,t)^{94}Mo reactions have been studied at an incident proton energy of 31 MeV. The triton spectra were obtained with a magnetic spectrograph with overall resolution of about 20 keV. Experimental angular distributions are compared with two-nucleon-transfer distorted-wave Born-approximation calculations to extract spin-parity assignments and enhancement factors. Particular emphasis is placed on the study of the L = 0 transitions near the closed shell at 50 neutrons.

1. Abstract of paper to be published in *Physical Review C*.
2. Visiting scientist from Niels Bohr Institute, Copenhagen, Denmark.

CALCULATED ENERGY LEVELS FOR ^{89}Y, ^{90}Zr, ^{91}Nb, ^{92}Mo, ^{93}Tc, AND ^{94}Ru[1]

J. B. Ball J. B. McGrory J. S. Larsen[2]

Recent experimental data for the heavier N = 50 nuclei are examined in terms of a model based on an inert ^{88}Sr core. The 11 interaction parameters required to define the shell-model space are determined by fitting 44 experimental level energies.

1. Abstract of published paper: *Phys. Lett.* **41B**, 581 (1972).
2. Visiting scientist from Niels Bohr Institute, Copenhagen, Denmark.

EXCITATION FUNCTIONS FOR HELION-INDUCED REACTIONS IN IRON[1]

C. B. Fulmer I. R. Williams[2] W. C. Palmer[3] G. Kindred[4]

NUCLEAR REACTIONS: Fe(h,x)^{56,57}Ni, ^{55,56,57,58}Co, ^{52,53}Fe, ^{52,54,56}Mn, and ^{51}Cr, $E \leq 70$ MeV; measured $\sigma(E)$; deduced reaction mechanism. Natural targets.

Target foil stacks of iron were bombarded with beams of helions at incident energies ≤70 MeV. Gamma spectra of individual foils were measured and analyzed to obtain excitation functions for production of ^{56,57}Ni, ^{55,56,57,58}Co, ^{52,53}Fe, ^{52,54,56}Mn, and ^{51}Cr; for ^{53}Fe and ^{52}Mn, data were obtained for both ground and isomeric states. The yields of ^{56}Co and ^{57}Co are much larger than those of the respective Ni isobars. Recoil measurements (to determine momentum transfer to the target nucleus) were made at E_h = 41 and 51 MeV. These data show ^{57}Co to result principally from direct reactions. There is also evidence of a large contribution by direct reactions to the ^{56}Co yield. The excitation function data are compared with predictions of compound-nucleus evaporation theory; these indicate compound-nucleus reactions to be the dominant contributor to the yields of ^{51}Cr, ^{52,54}Mn, ^{52,53}Fe, ^{55}Co, and ^{56,57}Ni.

1. Abstract of published paper: *Phys. Rev. C* 6, 1720–30 (1972).
2. Consultant from Knoxville College, Knoxville, Tenn. 37921.
3. Great Lakes Colleges Association–ORNL trainee from Earlham College, Richmond, Ind. 47374.
4. Undergraduate Summer Science and Engineering Program trainee from Knoxville College, Knoxville, Tenn. 37921.

ELASTIC SCATTERING OF HELIONS AND ALPHA PARTICLES AT AND NEAR 180°

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Recently reported analyses[4,5] have demonstrated the importance of large-angle helion and alpha elastic scattering for removal of ambiguities in the optical-model potentials involved. Measurements[6–8] of alpha scattering at angles approaching 180° show apparently anomalous behavior, suggesting that a careful theoretical analysis could yield important nuclear reaction information. Such data, which have usually been obtained for targets with $A < 50$ and at energies below 30 MeV, indicate pronounced maxima at 180°. These maxima have been analyzed in terms of nuclear glory scattering,[9] angular momentum mismatch between the elastic channel and the reaction channels,[10] and alpha cluster structure in the target nuclei.[8] Data from a wider range of target nuclei and at higher energy are obviously needed for a better understanding of extreme back-angle scattering of composite particles. We report here preliminary results of such a systematic study.

A magnetic deflection system for obtaining large-angle (including 180°) measurements was developed by Hafele at Washington University. This system was used at the Washington University cyclotron to obtain helion and alpha scattering data from a number of targets at energies extending up to ~30 MeV, the maximum energy available at that accelerator. The magnet facility is capable, however, of being used for alpha particles with energies up to ~45 MeV and helions up to ~60 MeV. During 1972, with the support of a National Science Foundation grant to the University of Missouri at St. Louis, the apparatus was moved to Oak Ridge and installed on a beam line at ORIC. Calibration runs have been made, and preliminary data have been obtained with the system in the new installation.

In the system the incident beam of particles passes through a magnetic field, into a target chamber at the exit side of the magnet, through the target foil at the center of the chamber, and thence into a Faraday cup. Particles scattered through large angles traverse the magnetic field again and are deflected away from the incident beam into a detector. The detector is mounted on a movable arm which pivots about an axis through the target position and can be moved into position to detect particles scattered in the angular range 155 to 188°.

For alpha particles a silicon surface-barrier detector is used; for helions, where particle identification is necessary, a ΔE-E detector telescope is used. When the apparatus was moved to ORIC, we decided to use a position-sensitive detector to permit simultaneous data accumulation over a range of angles. This increased efficiency is needed because the particles are scattered in a reflection mode from the target, which necessitates the use of thin ($\gtrsim 1$ mg/cm^2) target foils, and because the cross sections being measured are small, especially for helions. The position-sensitive detector is a transmission detector and can serve as a ΔE counter when particle identification is required. The detector pulses are processed by the Tennelec ADC system at ORIC to yield energy spectra for seven angles at intervals of 1°.

A collimator is used to ensure that only scattered particles with the proper rays in the magnetic field enter the detector, but since proper rays are a function of both incident particle energy and target mass, there is an angle adjustment for the skew of the collimator. Calibration of the angle adjustment of the collimator for the position-sensitive detector was a time-consuming but necessary part of the early data runs at ORIC.

Angular distributions taken with this system are shown in Figs. 1–4 for a range of incident particle energies for both helions and alpha particles elastically scattered from ^{27}Al and ^{28}Si. Excitation functions for 180° scattering are plotted in Fig. 5. Figure 6 shows angular distributions of 28.3-MeV alpha particles elastically scattered from targets of a wide range of mass.

The data shown in Figs. 1–5 were obtained at Washington University, and the data shown in Fig. 6 were obtained at ORIC. Some preliminary 40-MeV alpha scattering data have also been obtained at ORIC. At 40 MeV the 180° alpha scattering cross section for ^{27}Al is ~50% larger than at 28.3 MeV.

Although analysis and interpretation of the data shown in Figs. 1–6 are incomplete, a few observations can be made at this time. At all of the energies studied, large-angle alpha elastic scattering cross sections are orders of magnitude larger than helion elastic scattering cross sections. There are large differences between neighboring targets for elastic scattering of either particle type. All of the alpha elastic angular distributions exhibit a maximum at 180°, whereas the helion angular distributions at 180° may vary from a maximum to a minimum within a few MeV range of incident particle energy.

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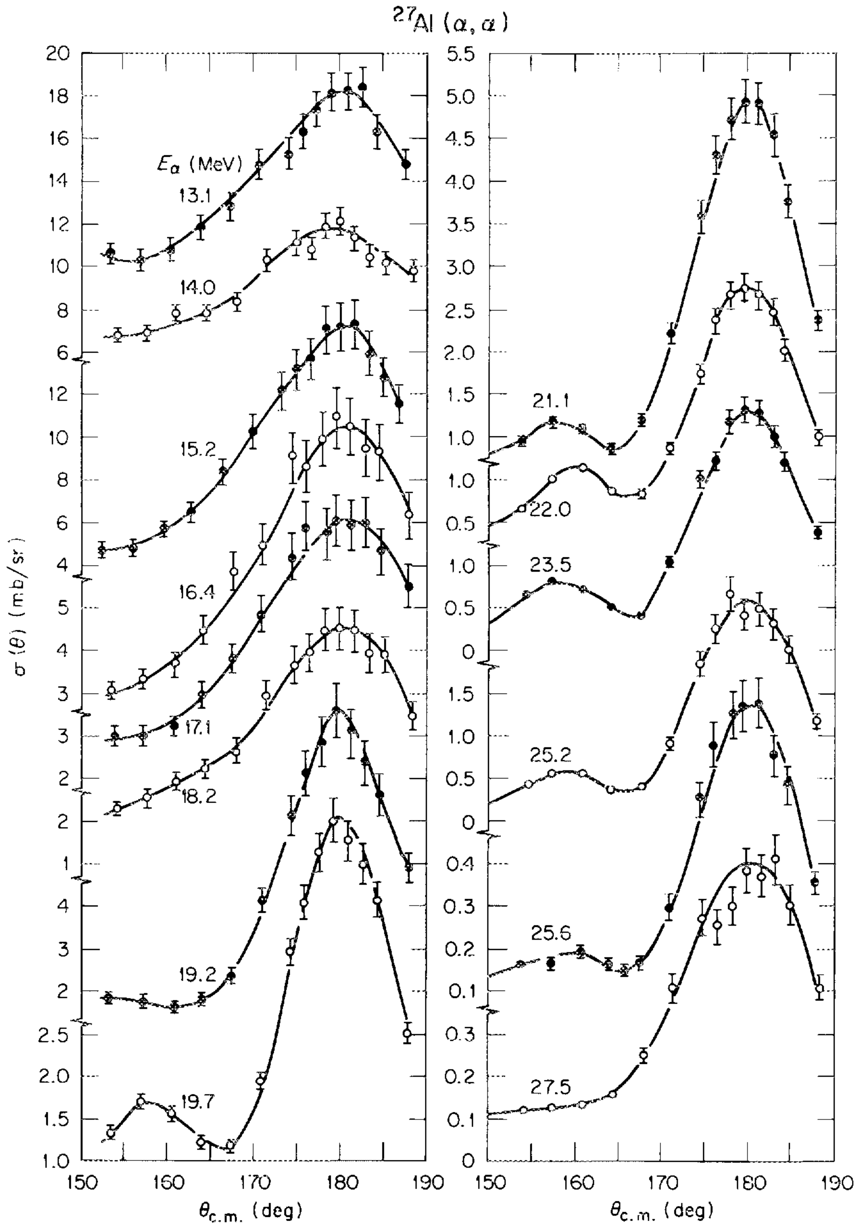

Fig. 1. Large-angle alpha elastic scattering angular distributions for ^{27}Al.

When optical-model potentials obtained from analysis of angular distribution data that do not include extreme back-angle data are used, the optical model predicts 180° helion elastic scattering cross sections that are in reasonable agreement with measured values.[11] Using potentials that correspond to alpha scattering data of a similar range, however, the optical model predicts 180° cross sections that are too small by an order of magnitude or more.[12]

The angular distributions in Fig. 6 show a maximum between 160 and 170° in addition to the larger maximum at 180°. We have performed preliminary optical-model calculations that show a strong dependence of r_0, the radius parameter of the real well depth, on the extreme back-angle alpha elastic cross section, both the magnitude of the 180° maximum and the relative size of the two observed maxima. The calculated cross sections, however, are more than an order of

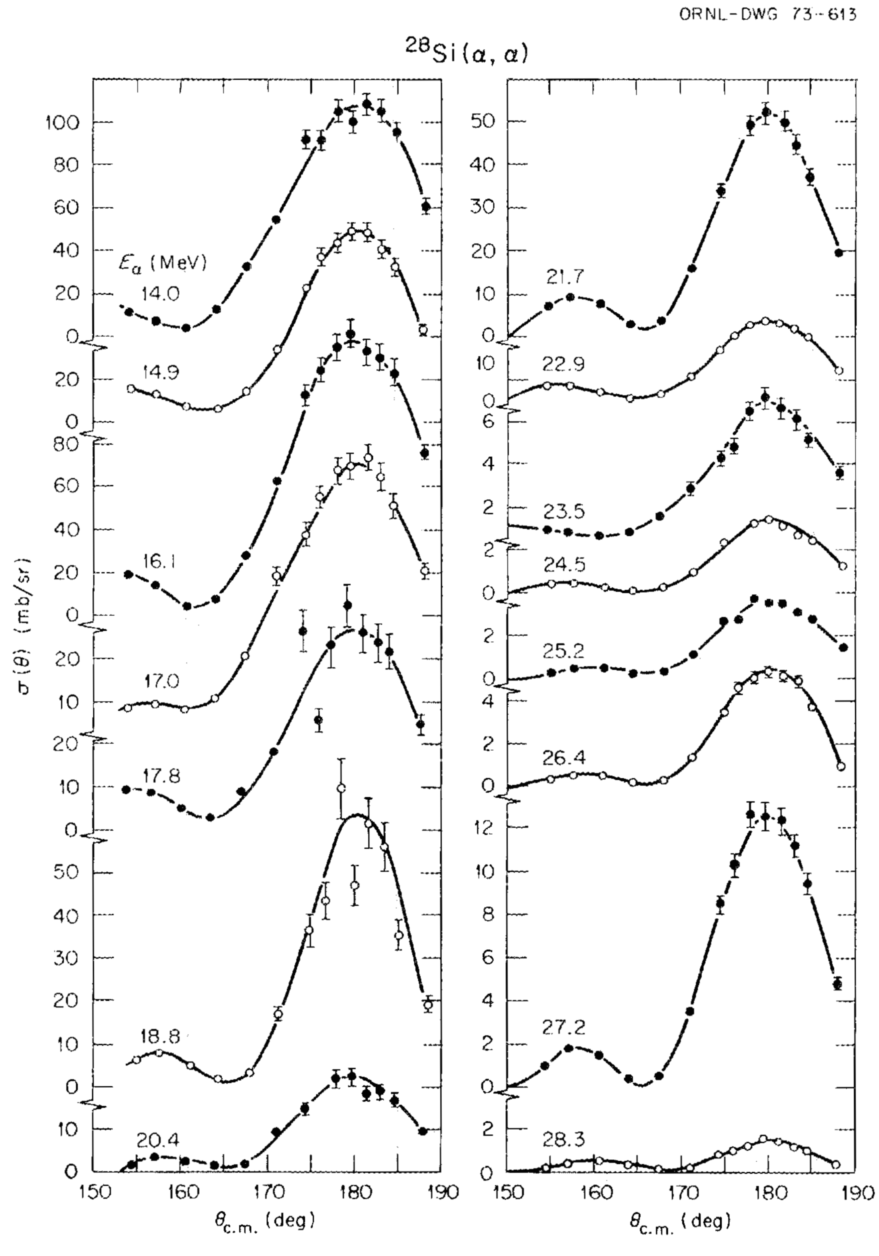

Fig. 2. Large-angle alpha elastic scattering angular distributions for ^{28}Si.

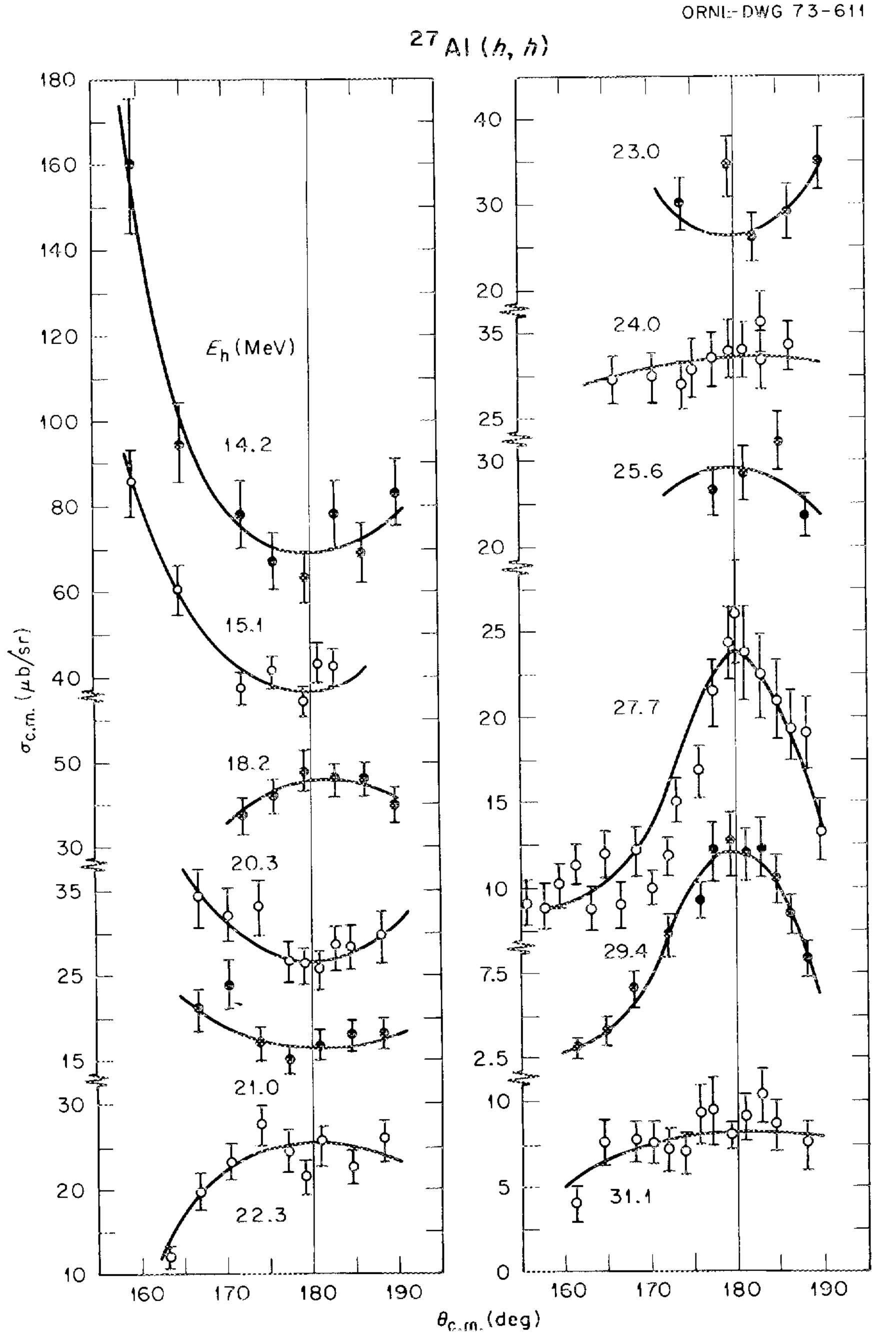

Fig. 3. Large-angle helion elastic scattering angular distributions for ^{27}Al.

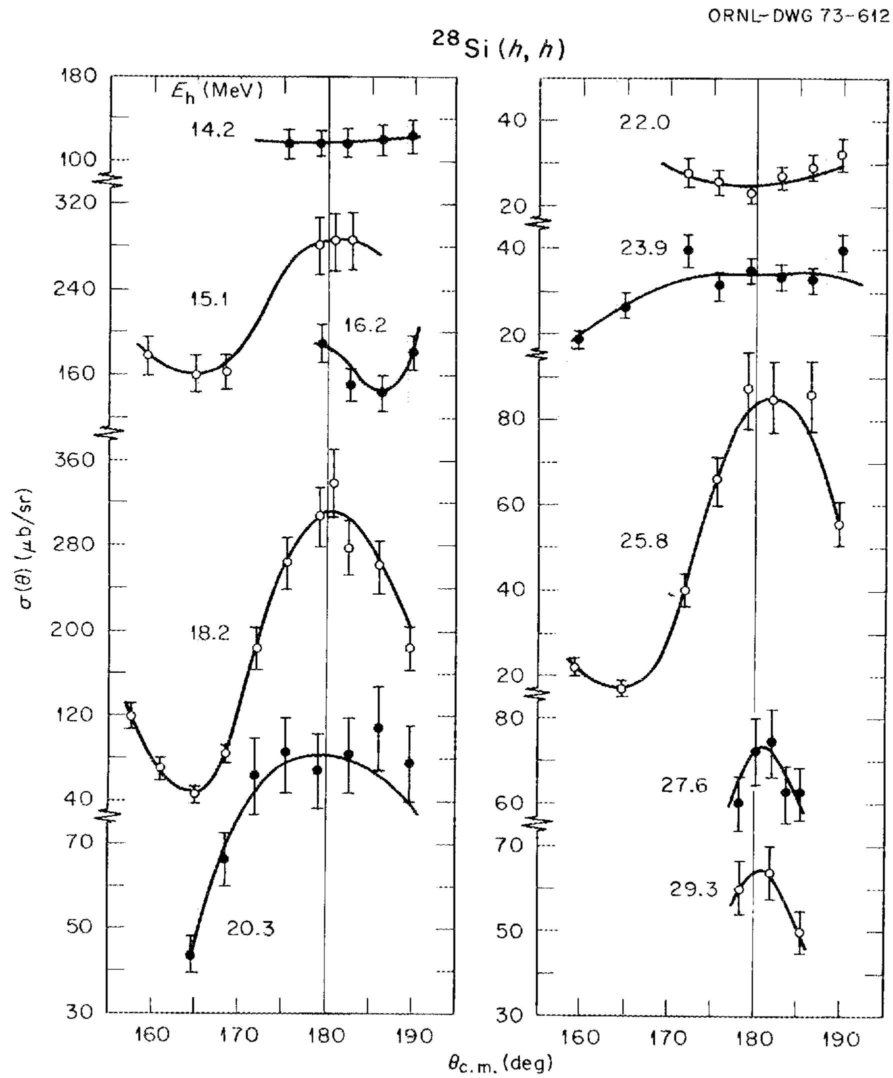

Fig. 4. Large-angle helion elastic scattering angular distributions for ^{28}Si.

magnitude smaller than the measured ones. The shapes of these large-angle alpha elastic angular distributions are in good qualitative agreement also with the nuclear glory scattering model presented in ref. 9, especially for the $I = 0$ targets. This model, however, does not attempt to explain the absolute magnitude of the scattering.

The model of alpha-particle clustering in the target nucleus[8,13] suggests that the consistent difference between the ^{27}Al and ^{28}Si angular distributions could be attributable to alpha-particle clustering in ^{28}Si, but it gives little insight into the observed difference between the ^{58}Ni and ^{60}Ni angular distributions. In addition, it would appear that the magnitude of the ^{27}Al angular distribution measured at 40 MeV is inconsistent with the predictions of this theory, but more data at 40 MeV on alpha-cluster-like nuclei will be needed before any definite conclusion can be drawn.

Eberhard[10] has used a model suggested by Robson to explain the "anomalous" backward enhancement of 24-MeV elastic alpha scattering from targets near A = 40. The model treats the angular momentum "mismatch" between the elastic channel and the reaction channels, principally the (α,n) reaction channels. Since the neutrons generally can carry off less angular momentum than alpha particles, there are many high-angular-momentum partial waves in the incoming channel that the (α,n) reaction channels cannot match, and

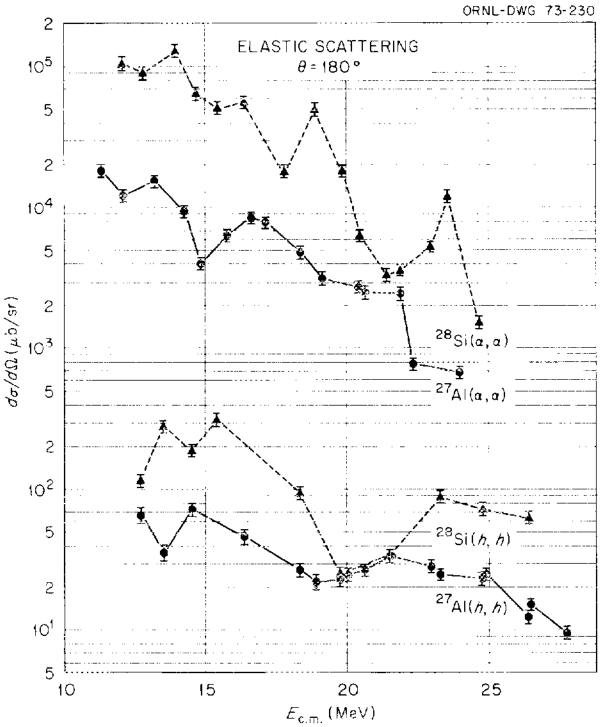

Fig. 5. Excitation functions for 180° elastic scattering of alpha particles and helions from ^{27}Al and ^{28}Si.

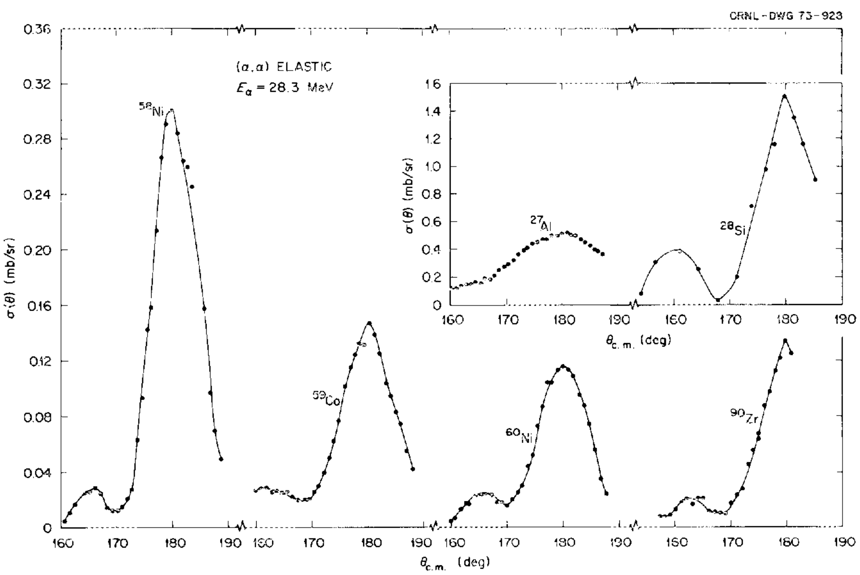

Fig. 6. Large-angle 28.3-MeV alpha elastic scattering angular distributions for several targets.

there is, hence, an l-value cutoff for the effect of the (α,n) channels. It turns out that these higher partial waves most strongly contribute to the cross section near 0 and 180° and may account for the enhancement of alpha-particle elastic scattering at back angles. The order of enhancement involved appears, qualitatively, to be sufficient to bring the predictions of the optical model into agreement with our data, but detailed calculations have not yet been attempted. Furthermore, this "mismatch" model predicts that the ^{58}Ni elastic alpha cross section should be bigger than that for ^{60}Ni, since ^{60}Ni has a lower (α,n) threshold, which, because of the additional energy and number of channels available, implies a high l-value cutoff and, consequently, less enhancement for the elastic scattering on ^{60}Ni — this is in good agreement with our data.

The 180° excitation functions shown in Fig. 5 indicate that the magnitude of the elastic scattering of ^{28}Si relative to ^{27}Al is roughly the same for helions as for alpha particles. Consequently, the target-alpha-cluster model does not seem either necessary or adequate to explain this feature of our data. On the other hand, the greater binding of ^{28}Si with respect to ^{27}Al suggests that the angular momentum mismatch theory would predict greater back-angle enhancement for the scattering from ^{28}Si. We plan to examine this possibility in the near future.

We are especially interested in testing the angular momentum mismatch theory because of its obvious relevance to heavy-ion-induced reactions, in which large amounts of angular momentum are present in the incoming channel. To this end, we are extending our systematic study of large-angle scattering to neighboring targets over a wide range of target masses and to higher energies for both helions and alpha particles.

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1. Drexel University.
2. University of Missouri, St. Louis.
3. Washington University, St. Louis, Mo.; present address: Research Department, Caterpillar Tractor Co., Peoria, Ill.

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INTERFERENCE BETWEEN COULOMB AND NUCLEAR EXCITATION IN INELASTIC SCATTERING OF ^{16}O IONS[1]

F. Videbaek[2] I. Chernov[3] P. R. Christensen[2] E. E. Gross

The excitation function for the process ^{58}Ni(^{16}O, ^{16}O')^{58}Ni* has been measured at 60, 75, and 90° lab over the energy range 34 to 58 MeV. At low energy the cross section rises as expected from Coulomb excitation of an electric quadrupole with a $B(E2)$ value of (0.066 ± 0.004) $e^2 b^2$. As the energy is increased further, the 2^+ excitation function exhibits a deep valley, due to an interference between Coulomb and nuclear excitations, which is localized over a distance of ~1 F and appears to be correlated with a rise in elastic scattering (relative to Rutherford scattering).

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1. Abstract of published paper: *Phys. Rev. Lett.* **28**, 1072 (1972).
2. Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark.
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TOTAL CROSS SECTION OF CALCIUM

C. H. Johnson J. L. Fowler N. W. Hill[1]

NUCLEAR REACTION: Ca; E_n = 60 to 1000 keV, measured $\sigma_{n,T}(E)$.

We have made a preliminary measurement of the total cross section of calcium from 60 to 1000 keV with energy resolution ranging from 0.1 to 1.0 keV. We used the plastic scintillator NE 110[2] for the neutron detector at the 200-m time-of-flight station of the Oak Ridge Electron Linear Accelerator. Figures 1 and 2 show the total cross section of calcium (96.96% ^{40}Ca) in the range 200 to 600 keV. From the widths of narrow unresolved resonances, we determined the neutron energy resolution as a function of neutron energy as follows:

$$\Delta E/E = 0.0004[1 + 3.5E\,(\text{MeV})]^{1/2} ,$$

which gives $\Delta E = 0.1$ keV at 200 keV.

In the range of our measurements up to 1000 keV we see approximately 100 resonances, about one-sixth of which we identify as *s*-wave resonances from their

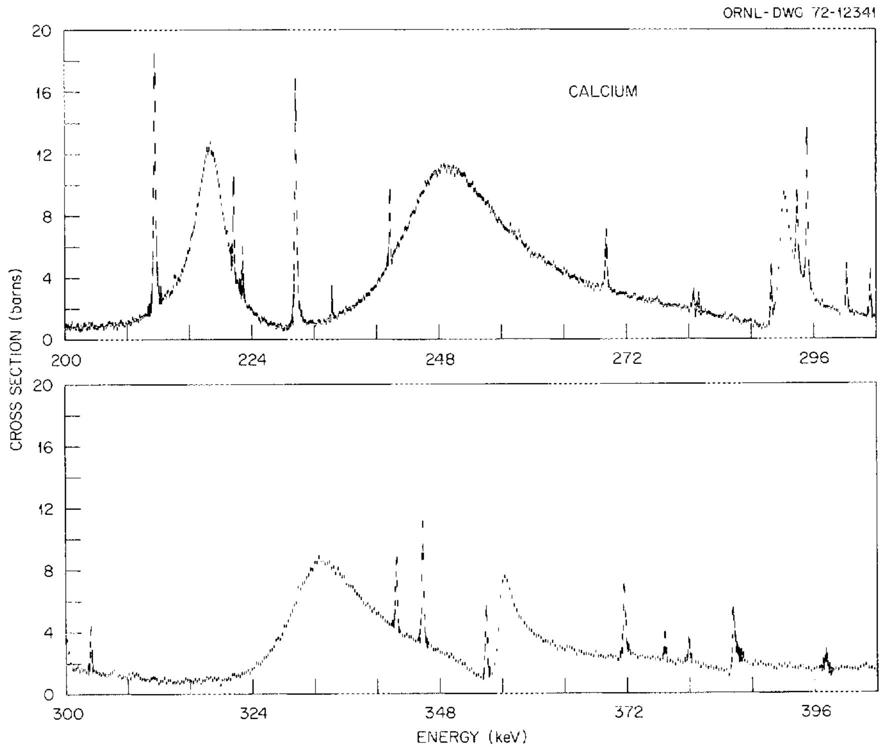

Fig. 1. Total cross section of calcium from 200 to 400 keV. Vertical lines give counting statistics.

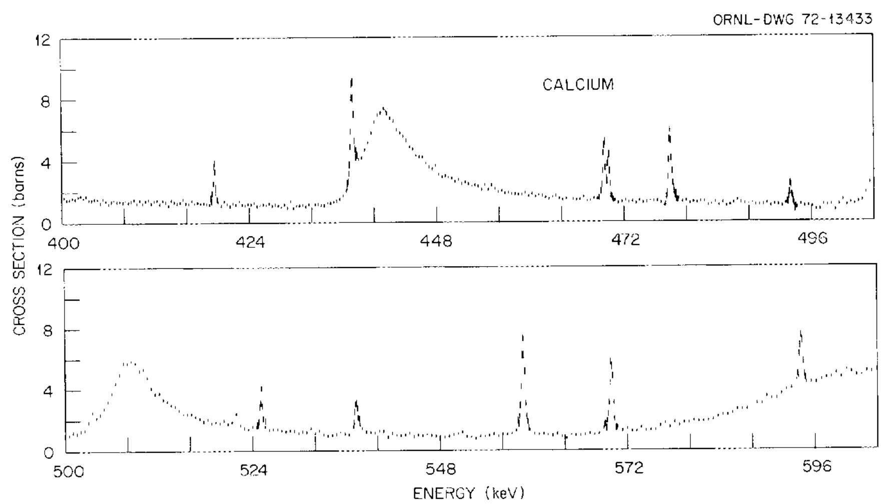

Fig. 2. Total cross section of calcium from 400 to 600 keV.

heights and shapes. The cross sections at the interference dips before the s resonances seem to be unexpectedly large. We are investigating background effects, particularly background arising from gamma rays, which could have an appreciable effect on total cross-section measurements in the energy range below 1000 keV.

1. Instrumentation and Controls Division.
2. J. A. Harvey, N. W Hill, and W. E. Kinney, *Bull. Amer. Phys. Soc.* 17, 901 (1972).

NEUTRON SHELL STRUCTURE IN ^{93}Zr, ^{95}Zr, AND ^{97}Zr BY (d,p) AND $(\alpha,{}^3\text{He})$ REACTIONS[1]

C. R. Bingham[2] G. T. Fabian[3]

NUCLEAR REACTIONS: ^{92,94,96}Zr(d,p), ^{92,94,96}Zr$(\alpha,{}^3\text{He})$, E_d = 33.3 MeV, E_α = 65.7 MeV; measured $\sigma(\theta)$; deduced levels, l, j, sj. Enriched targets.

Differential cross sections for ^{92,94,96}Zr(d,p) at 33.3 MeV were measured in 5° increments from 12.5 to 42.5° lab. The resolution was about 25 keV full width at half maximum. Many levels were characterized which were not reported or were improperly identified in previous neutron-transfer studies. $(\alpha,{}^3\text{He})$ spectra with 55 keV resolution were obtained at 15 and 20° for each target with 65.7-MeV alpha particles. The data were compared with distorted-wave calculations. With a few exceptions, consistent spectroscopic factors were obtained from the (d,p) and $(\alpha,{}^3\text{He})$ reactions. Sums of spectroscopic factors and centers of gravity are presented for levels assigned to $d_{5/2}, s_{1/2}, d_{3/2}, g_{7/2}$, and $h_{11/2}$ configurations in ^{93}Zr and ^{95}Zr. Except for the $h_{11/2}$ states, these sums are in good agreement with sum-rule predictions. Only ~50% of the expected $h_{11/2}$ strength was observed; the remainder appears to be highly fragmented and at excitation energies above 5 MeV.

1. Abstract of paper accepted for publication in *Physical Review C.*
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3. Graduate student from U.T.; present address: Kirtland AFB, Albuquerque, N.M. 87117.

GIANT RESONANCES IN THE HIGH-ENERGY INELASTIC SCATTERING CONTINUUM[1]

M. B. Lewis

The details of the structure previously observed in the high-energy proton scattering continuum are inspected for collective multipole contributions. Evidence is shown that in the $E^* \approx 10$–25 MeV excitation region of the ^{40}Ca continuum, at least dipole, quadrupole, and octopole excitations contribute to the structure of the cross section $[\sigma(\theta, E^*)]$. While the dipole and quadrupole strengths exhaust most of their corresponding sum rules, the octopole component does not. The possible nature of the less structured component at this continuum region is discussed.

1. Abstract of published paper: *Phys. Rev. Lett.* 29, 1257 (1972).

RULES FOR SPIN AND PARITY ASSIGNMENTS BASED ON LOG ft VALUES[1]

S. Raman N. B. Gove[2]

RADIOACTIVITY: ^{65}Ni [from ^{64}Ni(n,γ)]; ^{90m}Y [from ^{89}Y(n,γ)]; ^{144}Pm [from ^{145}Nd$(p,2n)$]; measured E_γ, I_γ; deduced log ft. ^{65}Cu, ^{90}Zr, ^{144}Nd deduced levels.

A survey was made of log ft values for forbidden beta transitions. Three cases, ^{90m}Y, ^{65}Ni, and ^{144}Pm decays, were examined experimentally. A number of low log ft values reported in the literature were superseded by more recent larger values. Empirical rules for making spin and parity assignments from log ft values are proposed.

1. Abstract of paper to be published in the *Physical Review.*
2. Mathematics Division.

LOG ft VALUES FOR SECOND-FORBIDDEN BETA TRANSITIONS AND THE DECAY OF ^{24}Na[1]

S. Raman N. B. Gove[2] J. K. Dickens[3] T. A. Walkiewicz[4]

RADIOACTIVITY: ^{24}Na [from $^{23}Na(n,\gamma)$]; measured E_γ, I_γ; deduced log ft. ^{24}Mg deduced levels.

The $4^+ \rightarrow 2_2^+$ beta transition in ^{24}Na decay is important because it has been considered to have the lowest log ft (10.7) for a second-forbidden beta transition. We find that this beta transition is possible, but only a lower limit on the log ft (>11.2) is really established. Therefore, a revision of J^π assignment rules based on log ft is appropriate.

1. Abstract of published paper: *Phys. Lett.* 40B, 89 (1972).
2. Mathematics Division.
3. Neutron Physics Division.
4. Summer research participant from Edinboro State College, Edinboro, Pa., supported by Oak Ridge Associated Universities.

CROSS SECTIONS FOR THE ^{61}Ni, ^{63}Cu (^{16}O,X) REACTIONS

R. L. Robinson J. C. Wells, Jr.[1] H. J. Kim J. L. C. Ford, Jr.

NUCLEAR REACTIONS: ^{61}Ni, ^{63}Cu (^{16}O,X), E = 38.5–48.5 MeV; measured $\sigma(E)$. Enriched targets.

This is a continuation of a program to ascertain quantitatively what nuclei can be produced via heavy-ion-induced reactions. Here we present the cross sections for some of the exit channels from the reactions ^{61}Ni, ^{63}Cu (^{16}O,X) for $E_{^{16}O}$ = 38.5, 41, 43.5, 46, and 48.5 MeV.

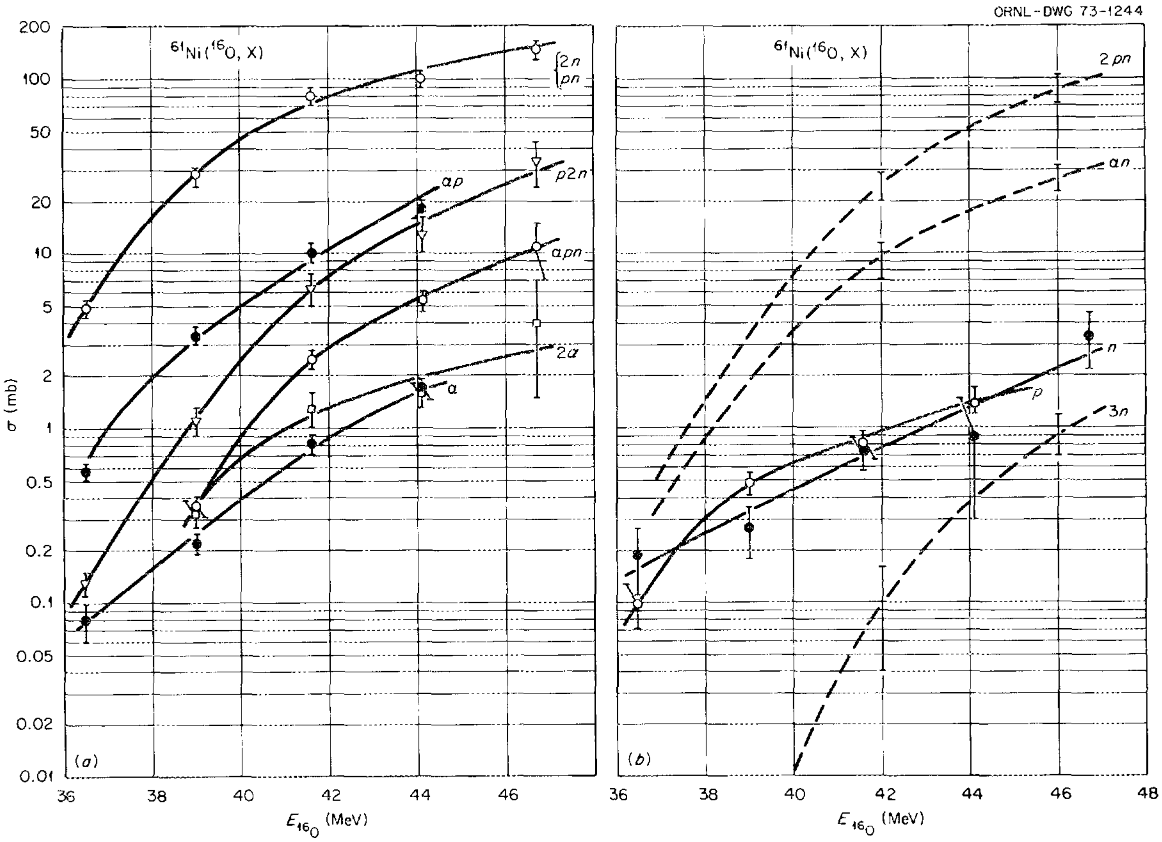

Fig. 1. Cross sections for the $^{61}Ni(^{16}O,X)$ reactions where the emitted particles X are denoted in the figure. ^{16}O energies are given in the laboratory system.

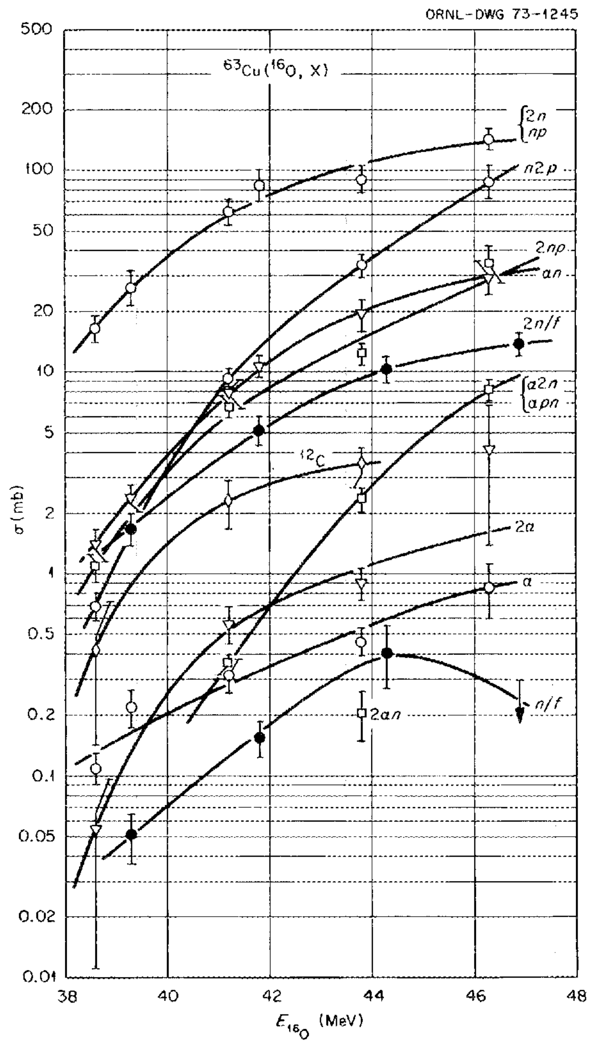

Fig. 2. Cross sections for the ^{63}Cu(^{16}O,X) reactions.

The gamma rays from the resulting radioactivities and in-beam gamma rays were measured. Cross sections were extracted from the resulting yields. Some discussion of the details is given in ref. 2.

The present results are summarized in Figs. 1 and 2. For the radioactivity studies, the ^{61}Ni target was 0.99 mg/cm^2 thick, and the two ^{63}Cu targets were 0.895 and 1.20 mg/cm^2 thick. An approximate correction of the target thickness is obtained by plotting the experimental points in Figs. 1 and 2 at the average ^{16}O energy in the targets.

In the case of the 1n and 2n emission in Fig. 2, the actual cross sections will be those shown divided by the unknown quantity f, where f is the ratio of the intensity of the gamma ray used in obtaining the cross section to the total decay rate. For 1n emission the 455.2-keV gamma ray in ^{78}Kr and for 2n emission the 69.3-keV gamma ray in ^{77}Kr was used for the cross-section determination.

For the in-beam studies of ^{61}Ni, the target was thick enough to stop the beam. Cross sections obtained from the thick-target yields are given as dashed curves in Fig. 1, and errors are illustrated by the flags. The in-beam data for ^{63}Cu have not yet been analyzed.

1. Tennessee Technological University, Cookeville.
2. R. L. Robinson, H. J. Kim, and J. L. C. Ford, Jr., *J. Phys.*, suppl. to No. 11–12, **32**, 265 (1971).

INTERPRETATION OF THE ^{58,60}Ni(^{16}O,X) REACTIONS

R. L. Robinson H. J. Kim

One of the most promising uses of heavy-ion projectiles is in inducing reactions which produce nuclei far from stability. However, there is still very limited knowledge about the degree to which this process is successful. More specifically, there is little detailed experimental information about the competition between pure neutron emission, which is the mechanism required to produce nuclei farthest from stability, and charged-particle emission. There has been an excellent effort by Blann[1] to predict what products will result in such reactions. By assuming statistical decay of a compound-nuclear system, he calculated exceedingly small cross sections for production of nuclei far from stability. But again because of lack of experimental data, there has been little testing of these calculations.

To provide quantitative information, we initiated a program for determining absolute cross sections for the various exit channels resulting from heavy-ion-induced reactions. Thus far, we have obtained the cross sections for products due to bombardment of ^{58,60}Ni with 38-, 42-, and 46-MeV ^{16}O ions. The technique is discussed in ref. 2; the results are summarized by Figs. 1 and 2. The flags indicate the size of the relative errors. These curves were derived from gamma-ray yield curves after correcting for the thickness of the target (1.00 mg/cm^2 for ^{58}Ni and 1.64 mg/cm^2 for ^{60}Ni). There has been

ORNL-DWG 72-3707R

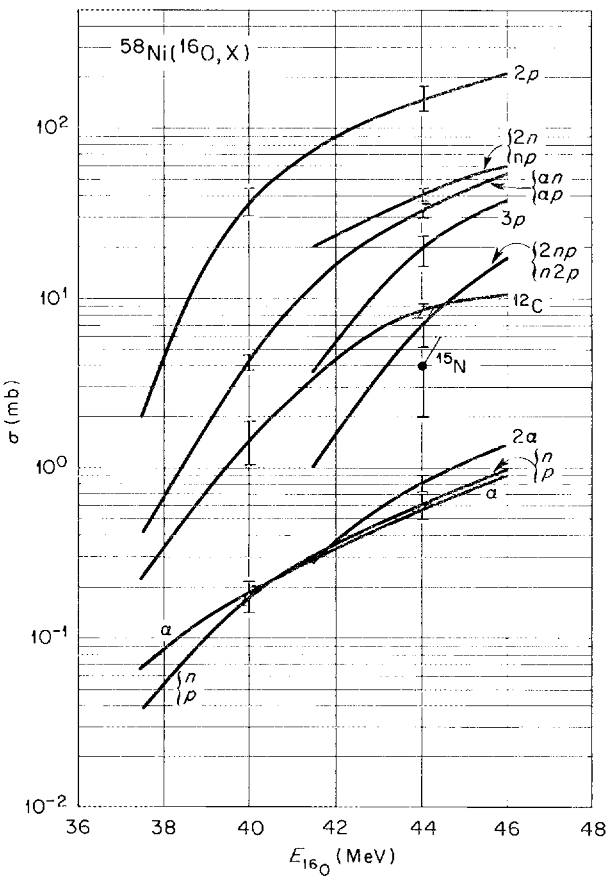

Fig. 1. Experimental cross sections for reaction products from ^{16}O ions incident on ^{58}Ni. The ^{16}O energies are in the laboratory system.

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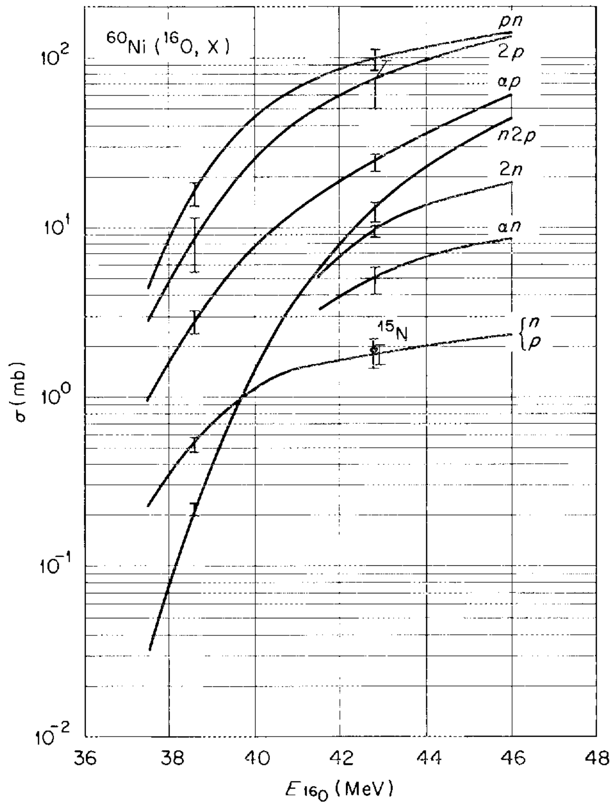

Fig. 2. Experimental cross sections for reaction products from ^{16}O ions incident on ^{60}Ni.

another measurement of some of these cross sections by Bair et al.[3] which provides an independent check of our absolute cross sections. They measured with high precision the total number of neutrons emitted in these reactions as a function of projectile energy by means of a large graphite sphere with embedded BF_3 counters. Their results are given in Figs. 3 and 4. Then by taking our cross sections in which neutrons are emitted, with appropriate weight for the number of neutrons, we obtain the solid curves given in Figs. 3 and 4. The error bars give representative uncertainties in our data.

In this report, we compare the total experimental cross section with the total reaction cross section calculated with an optical model and compare the relative population of the exit channels with those given for statistical decay of a compound nucleus in which angular momentum is ignored. Initial values for the optical-model parameters were taken from those obtained by Obst et al.[4] for the ^{56}Fe(^{16}O,^{16}O)^{56}Fe reaction. The real and imaginary potentials have a Woods-Saxon form with r_0 = 1.25 fm [$R = r_0(A_T{}^{1/3} + A_P{}^{1/3})$] and a = 0.6 fm. For V = 27 MeV and W = 11.4 MeV, the parameters of Obst et al. for energies well above the Coulomb barrier, the predicted total reaction cross sections for ^{58,60}Ni at 46 MeV are 415 and 457 mb, as compared with the experimental values of 390 ± 40 and 405 ± 40 mb. We examined the dependence of the magnitude of the cross section on the various optical-model parameters and found it insensitive to V and W (a 5% change in V or W gives ~1% change in σ) but very sensitive to r_0 (a 1% change in r_0 gives ~7% change in σ).

To explain the shape of the cross section at the Coulomb barrier requires a drastic change in one or more parameters. Obst et al. in their fit of the ^{56}Fe(^{16}O,^{16}O)^{56}Fe data varied W, the imaginary potential, as a function of the projectile energy. We have done a similar thing after first forcing the calculations at 46 MeV to equal our data by varying only r_0; r_0 was somewhat arbitrarily adjusted because this required the smallest percentage change of any

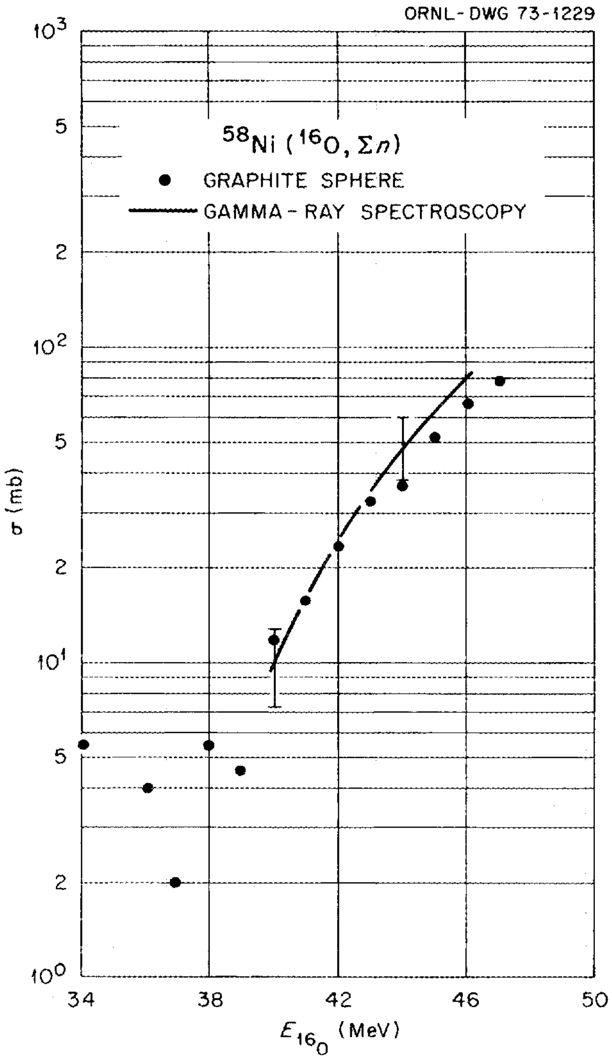

Fig. 3. Comparison of experimental cross sections for neutron emission. Points give the values obtained by means of the graphite sphere. The solid curve is a fit to the cross sections deduced from the gamma-ray studies.

parameter. The values r_0 = 1.24 and 1.23 fm were obtained for ^{58,60}Ni. We then forced the calculated values to fit our experimental curves below 46 MeV by varying only W. The resulting curves of W for ^{58,60}Ni with error bars representing the experimental uncertainties are given in Fig. 5. Values derived by Obst et al. from their elastic scattering of ^{16}O from ^{56}Fe are given by the points in this figure. Note that W as obtained by the two types of measurement goes to zero at about the same projectile energy.

For the decay we have used a modified version of a program developed by Blann.[1] Briefly, it considers the statistical probability for decay of the compound

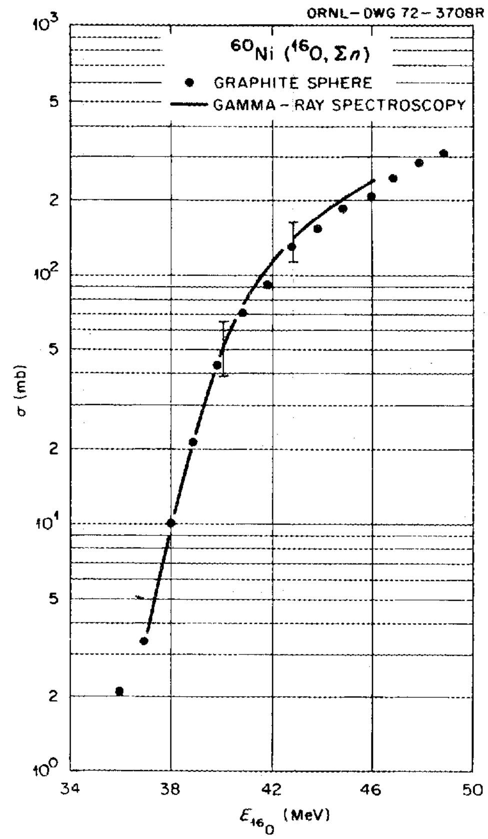

Fig. 4. Comparison of experimental cross sections for neutron emission. Points give the values obtained by means of the graphite sphere. The solid curve is a fit to the cross sections deduced from the gamma-ray studies.

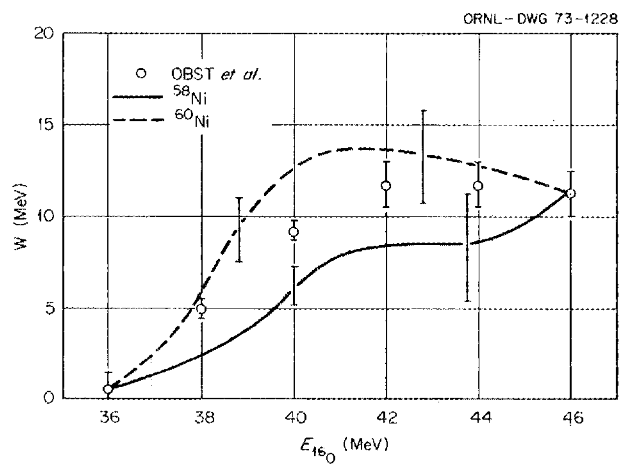

Fig. 5. Values of the imaginary potential required for the optical-model predictions to fit the experimental results. The points are obtained by Obst et al. [*Phys. Rev. C* **6**, 1814 (1972)] for fitting the elastic scattering of ^{16}O from ^{56}Fe. The curves are from fitting the reaction cross-section results of ^{58,60}Ni.

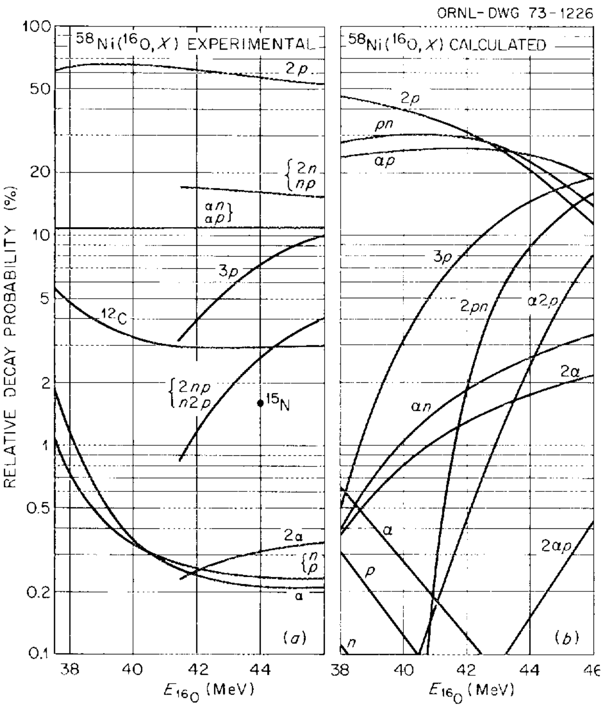

Fig. 6. Comparison of the experimental relative decay probabilities into the various exit channels with those predicted by the statistical decay of a compound nucleus.

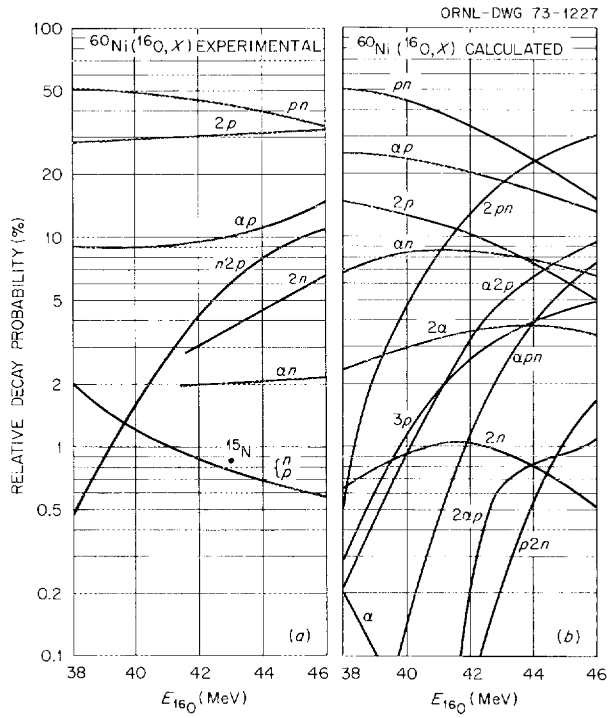

Fig. 7. Comparison of the experimental relative decay probabilities into the various exit channels with those predicted by the statistical decay of a compound nucleus.

system and for decay from each resulting nucleus by proton, neutron, and alpha-particle emission. The probability was taken as proportional to the inverse reaction cross section times the level density of the residual nucleus. The inverse reaction cross section was calculated from an optical-model program which was a modified version of that developed by Smith.[5] The level density has the form

$$\rho(E) \propto \frac{1}{(E-\delta)^2} e^{2\sqrt{a(E-\delta)}} ,$$

where δ is an adjustment to account for the difference in level density between odd-odd, even-odd, and even-even nuclei. In our calculations we used, respectively, $\delta = 0.0$, 1.4, and 2.8 for these classes of nuclei. (Other values of δ were tried without any overall improvement in agreement with the experimental data.) The value of the parameter a was $A/8$. As long as there is sufficient energy available to emit any nucleon, gamma emission is assumed to be zero. The predictions are illustrated in Figs. 6*b* and 7*b*, where the population of each channel is given as a percent of the total decay. The experimental results are plotted in a similar manner in Figs. 6*a* and 7*a*.

A comparison of Figs. 6*a* and 7*a* with 6*b* and 7*b* shows that the general features but not the details of the experimental data are given by the theory. Predictions that the 2*p*, *pn*, and α*p* cross sections are the largest are consistent with the experimental results. But the experimental values for the one-nucleon emission are significantly larger than that given by the calculations. The experimental three-nucleon emissions are smaller than predicted. It is possible that these differences are attributable to angular momentum, which would favor fewer nucleon emission.

The reaction listed as ^{12}C for the ^{58}Ni reaction would give the same product as emission of three alpha particles. However, the predicted relative (^{16}O,3α) cross section is <0.1%. Presumably both the (^{16}O,^{12}C) reaction and the (^{16}O,^{15}N) reaction are direct.

In several cases, our experimental results cannot decide between one of several reactions. If we take the theory as being a reasonable approximation, then cross sections for 2*n*-*np*, 2*np*-*n*2*p*, and α*p*-α*n* emission from the $^{16}O + ^{58}Ni$ system (see Fig. 6*a*) are, respectively, predominantly due to *np*, *n*2*p*, and α*p*. For both ^{58}Ni and ^{60}Ni, the calculations favor the (^{16}O,*p*) reaction over the (^{16}O,*n*) reaction.

The reaction consistent with the available energy that would produce the nuclei farthest from stability would be ^{58}Ni(^{16}O,2n). The calculated ^{58}Ni(^{16}O,2n) decay is ~0.07% of the total decay for $E_{^{16}O}$ = 46 MeV, or 0.3 mb. However, based on the results for the ^{60}Ni(^{16}O,2n) reaction, the actual cross section is an order of magnitude larger than predicted.

In summary, we find here that the competition with charged-particle emission greatly reduces the available cross section for producing nuclei far from stability. The total reaction cross section is adequately predicted by the optical model using reasonable parameters. The theory for the statistical decay of a compound nucleus in which angular momentum is neglected gives the general characteristics found for the cross sections of the exit channels but needs refinement or introduction of other features to explain the details.

1. M. Blann, *Phys. Rev.* **157**, 869 (1967), and private communication.
2. R. L. Robinson, H. J. Kim, and J. L. C. Ford, Jr., *J. Phys.*, suppl. to Nos. 11–12, **32**, 265 (1971).
3. J. K. Bair, P. H. Stelson, C. H. Johnson, and W. B. Dress, private communication.
4. A. W. Obst, D. L. McShan, and R. H. Davis, *Phys. Rev. C* **6**, 1814 (1972).
5. W. R. Smith, *Comput. Phys. Commun.* **1**, 106 (1969).

IN-BEAM GAMMA RAYS FROM THE ^{16}O AND ^{12}C BOMBARDMENT OF SILICON ISOTOPES

H. J. Kim R. L. Robinson W. T. Milner J. C. Wells, Jr.[1]

NUCLEAR REACTION: ^{28,29,30}Si(^{16}O,$xn\gamma$), ^{28,29,30}Si(^{16}O,$xp\gamma$), ^{28,29,30}Si(^{16}O,$xpyn\gamma$), and ^{28}Si(^{12}C,2$p\gamma$)^{38}Ar, E = 25–43 MeV. Measured E_γ, $T_{1/2}$, γ-γ, n-γ, $\sigma(E;\gamma)$, $\sigma(\theta)$. Enriched targets.

In-beam gamma rays from the E = 25 to 43 MeV ^{16}O and E = 25 MeV ^{12}C bombardment of ^{28,29,30}Si targets were investigated. The bombarding energy dependence of the gamma-ray yields and angular distributions is under investigation. The properties of those states which are prominently populated by these reactions are further investigated via particle-gamma and gamma-gamma coincidence studies. Figures 1 and 2 show the gamma-ray transitions in ^{42}Ca and ^{38}Ar induced by the 41-MeV (^{16}O,2p) and 25-MeV (^{12}C,2p) reactions on the ^{28}Si target which have been identified. The known levels of ^{42}Ca and ^{38}Ar are also shown for comparison. From these figures it is apparent the ^{16}O and ^{12}C bombardment of ^{28}Si selectively populates certain high-spin states. The results for the other targets are being analyzed.

1. Permanent address: Tennessee Technological University, Cookeville.

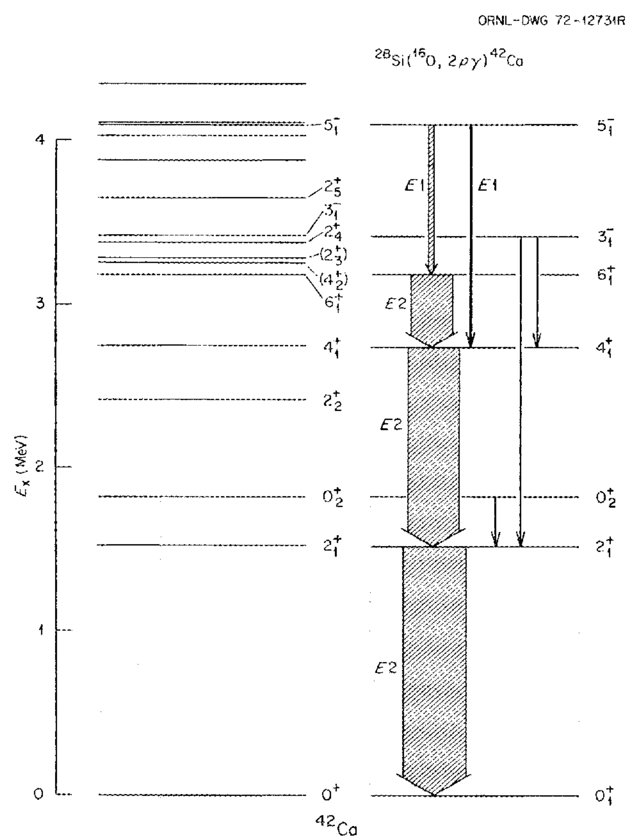

Fig. 1. Gamma decay in ^{42}Ca.

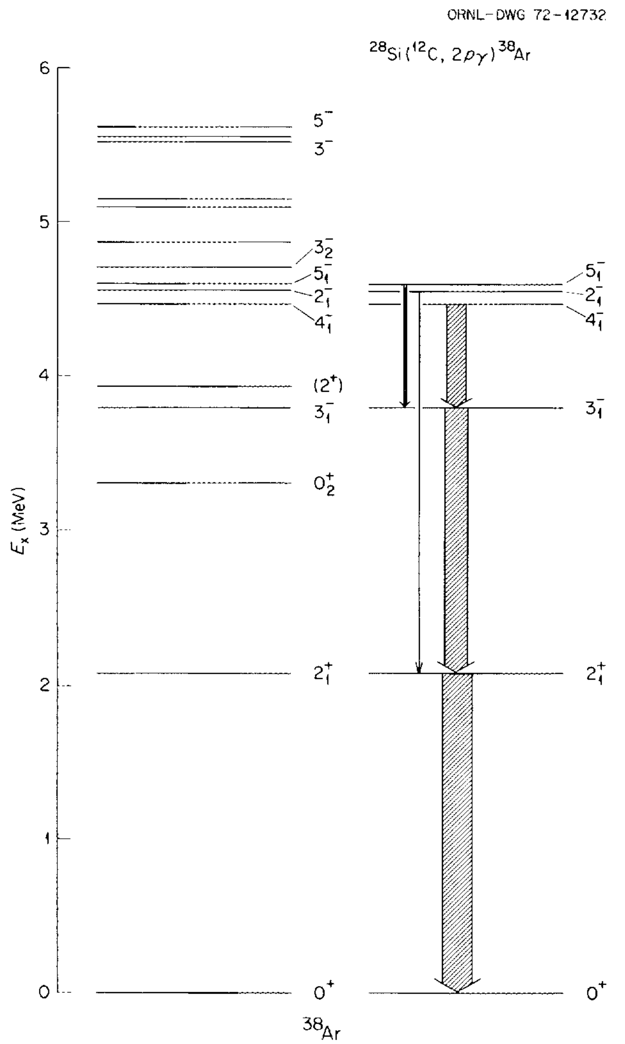

Fig. 2. Gamma decay in ^{38}Ar.

THE ^{110}Pd, ^{116}Cd $(p,p'\gamma)$ REACTIONS[1]

J. A. Deye[2] R. L. Robinson J. L. C. Ford, Jr.

NUCLEAR REACTIONS: ^{110}Pd$(p,p'\gamma)$, E_p = 13 MeV, ^{116}Cd$(p,p'\gamma)$, E_p = 12 MeV; measured $\sigma(E_{p'}, E_\gamma)$. ^{110}Pd, ^{116}Cd deduced levels, J, π, γ-branching. Enriched targets.

The possibility of extending our knowledge about higher-energy collective-type states among the vibrational nuclei by observing gamma rays from states excited by inelastically scattered protons has been examined. Gamma rays from ^{110}Pd and ^{116}Cd were detected in coincidence with inelastically scattered protons; the incident protons had energies of 12 and 13 MeV. Gamma rays, most of them previously unreported, were observed from 17 levels in ^{110}Pd and 14 levels in ^{116}Cd below ~2.5 MeV. The results are compared with predictions of a phonon-model interpretation of the levels. Evidence is shown for the existence of the three-quadrupole phonon quintet in ^{110}Pd.

1. Abstract of paper submitted for publication in *Nuclear Physics*.

2. Present address: Radioisotope Lab., General Hospital, Cincinnati, Ohio.

ELASTIC AND INELASTIC PROTON SCATTERING FROM ^{86}Sr[1]

A. V. Ramayya[2] J. L. C. Ford, Jr. R. L. Robinson J. H. Hamilton[2]

NUCLEAR REACTIONS: $^{86}Sr(p,p')$, $E_p = 12$ MeV; measured $\sigma(\theta)$. ^{86}Sr deduced levels, deformation parameters. DWBA and coupled-channel calculations. Enriched target.

Angular distributions of elastically and inelastically scattered 12-MeV protons from ^{86}Sr have been measured for angles between 24 and 165°. Inelastic scattering to 20 levels in ^{86}Sr was observed, and angular distributions were measured for the ground state and excited states at 1076, 1854, 2482, and 2997 keV. The 2482-keV level appears to be the octopole state, rather than the 2997-keV level, which also has spin-parity 3^-. Quadrupole and octopole deformation parameters $\beta_2 = 0.130$ and $\beta_3 = 0.153$ were extracted from the experimental cross sections for inelastic scattering to the 2^+ and 3^- states at 1076 and 2482 keV, respectively, by means of DWBA theory and coupled-channel calculations. The coupled-channel calculation for the differential cross section for the possible two-phonon 2^+ state at 1854 keV indicates that this state has a limited phonon-like character.

1. Abstract of published paper: *Nucl. Phys.* **A193**, 186–92 (1972).
2. Vanderbilt University, Nashville, Tenn.

3*d*. $A > 100$

TOTAL REACTION CROSS-SECTION MEASUREMENTS FOR 30- TO 60-MeV PROTONS AND THE IMAGINARY OPTICAL POTENTIAL[1]

J. J. H. Menet[2] E. E. Gross J. J. Malanify[3] A. Zucker

We have measured total reaction cross sections for 30-, 40-, 49.5-, and 60.8-MeV protons incident on thin separated isotopes covering the range from ^{12}C to ^{208}Pb. Our results are consistent with previous data at 60 MeV. We find a strong dependence of the reaction cross section on neutron excess for a series of iron and nickel isotopes. Little, if any, such dependence is observed for the $N = 28$ isotones. The data are well represented by the relation $\sigma_R = \pi(r_0 A^{1/3} + \bar{\lambda})^2$ with $r_0 = 1.23 \pm 0.01$ F. When analyzed with the conventional optical model, our data require the volume absorption to increase and the surface absorption to decrease with increasing proton energy E_p. The analysis reveals a striking $(N - Z)/A$ dependence for the product $W_D a'$. Using the Oak Ridge parameters for the real spin-orbit potentials, we arrive at the following parametrization for the imaginary potential: volume absorption potential, $W_0 = 1.2 + 0.09 E_p$ MeV; surface absorption potential, $W_D = 4.2 - 0.05 E_p + 15.5(N - Z)/A$ MeV; imaginary diffusivity, $a' = 0.74 - 0.008 E_p + 1.0(N - Z)/A$ F.

1. Abstract of published paper: *Phys. Rev. C* **4**, 1114 (1971).
2. Institut de Sciences Nucleaires, Grenoble, France.
3. Los Alamos Scientific Laboratory, Los Alamos, N.M.

PROPERTIES OF THE 2′ AND 2″ STATES IN $^{106,112}Cd$ AND ^{114}Cd[1]

Z. W. Grabowski[2] R. L. Robinson

NUCLEAR REACTIONS: $^{106,112,114}Cd(\alpha,\alpha'\gamma\gamma)$, $E_\alpha = 11.0$ MeV; measured $\gamma\gamma(\theta)$. $^{106,112,114}Cd$ deduced δ, $B(E2)$, $B(M1)$. Enriched targets.

Angular correlations have been measured between gamma rays from the 2 → 2 → 0 cascades in $^{106,112,114}Cd$ and the beam of 11.0-MeV alpha particles effecting Coulomb excitation. Multipole admixtures for the 2 → 2 transitions, as deduced from these correlations, when combined with earlier results

establish their $B(E2)$ and $B(M1)$ values. For the transitions from the 1312- and 1208-keV states in ^{112,114}Cd the $B(E2)$ values in single-particle units are 18 ± 4 and 24 ± 7. These values are typical for transitions from "two-quadrupole phonon" states in this mass region, whereas that of the 1718-keV transition in ^{106}Cd has the smaller value of 7.0 ± 2.3. The $B(E2)$ values of the $2'' \rightarrow 2$ transitions in ^{112,114}Cd from the 1468- and 1363-keV states are <0.3 single-particle unit. The $B(M1)$ values of all five transitions are $\sim 10^{-2}$ $(e\hbar/2Mc)^2$.

1. Abstract of paper to be submitted for publication in *Nuclear Physics*.
2. Present address: Purdue University, Lafayette, Ind.

PROTON EXCITATIONS IN ^{109}Ag

R. L. Auble D. J. Horen F. E. Bertrand Y. A. Ellis

NUCLEAR REACTIONS: ^{108}Pd(^{3}He,d)^{109}Ag, E = 27 MeV; measured $\sigma(E_d, \theta)$. ^{109}Ag deduced levels, l_p, C^2S', J, π.

Proton states in ^{109}Ag are being studied by means of the ^{108}Pd(^{3}He,d) reaction using 27-MeV ^{3}He ions from ORIC. Deuteron spectra were recorded on photographic emulsions placed in the focal plane of the broad-range spectrograph. Approximately 30 levels are excited up to 3.28 MeV of excitation. A state at 0.706 MeV is excited by a probable l = 0 transfer and may be analogous to the 0.746-MeV, $J^\pi = 1/2^+$, level in ^{117}In, which was recently excited in the ^{116}Cd(^{3}He,d) reaction.[1] The angular distributions are being compared with DWBA predictions calculated with the code JULIE to extract l values and spectroscopic strengths.

1. S. Harar and R. N. Horoshko, *Nucl. Phys.* **A183**, 161 (1972).

PROTON EXCITATIONS IN ^{108,110}Cd FROM (^{3}He,d) REACTIONS[1]

R. L. Auble D. J. Horen F. E. Bertrand J. B. Ball[2]

NUCLEAR REACTIONS: ^{107,109}Ag(^{3}He,d), E = 27 MeV; measured $\sigma(E_d, \theta)$. ^{108,110}Cd deduced levels, l_p, C^2S', J, π.

The nuclear energy levels of ^{108,110}Cd up to 4 MeV of excitation are examined by the ^{107,109}Ag(^{3}He,d) reactions. Approximately 30 levels are populated in each nucleus, many of which were previously unreported. l values and spectroscopic strengths are given for the more strongly excited states. The data are compared with previously reported levels and J^π assignments and are used to resolve several discrepancies in reported ^{110m}In decay schemes.

1. Abstract of published paper: *Phys. Rev. C* **6**, 2223 (1972).
2. Present address: Niels Bohr Institute, Copenhagen, Denmark.

SEARCH FOR A ZERO-PHONON GAMMA-RAY TRANSITION IN ^{108}Pd AND ^{134}Ba[1]

P. H. Stelson S. Raman J. A. McNabb[2] R. W. Lide[2] C. R. Bingham[2]

RADIOACTIVITY: ^{108m}Ag and ^{134}Cs; measured γ singles and coin. Set limits on low-energy gamma rays between two-phonon states.

The nuclear quadrupole vibrational model allows one-phonon transitions but forbids both two-phonon and zero-phonon transitions. Whereas there exists a large amount of experimental information on the degree of forbiddenness of two-phonon transitions, there is little meaningful information on zero-phonon transitions. We have looked for the zero-phonon transition between the first 4^+ state and the second 2^+ state (between members of the two-phonon triplet) in the vibrational-type nuclei ^{108}Pd and ^{134}Ba. We were not able to detect the zero-phonon gamma rays. The limits set on the intensities of these transitions lead to notable degrees of forbiddenness. For ^{108}Pd and ^{134}Ba, respectively, the ratio $B(E2)_{4\to 2}/B(E2)_{4\to 2'}$ is greater than 80 and 360 (limits based on two standard deviations). For these nuclei the forbiddenness of a zero-phonon transition is at least as large as the forbiddenness of a two-phonon transition.

1. Abstract of a paper submitted for publication to the *Physical Review*.

2. University of Tennessee, Knoxville 37916.

THE ^{110}Pd, ^{116}Cd $(p,p'\gamma)$ REACTIONS[1]

J. A. Deye[2] R. L. Robinson J. L. C. Ford, Jr.

NUCLEAR REACTIONS: ^{110}Pd$(p,p'\gamma)$, E_p = 13 MeV, ^{116}Cd$(p,p'\gamma)$, E_p = 12 MeV; measured $\sigma(E_{p'}, E_\gamma)$. ^{110}Pd, ^{116}Cd deduced levels, J, π, γ branching. Enriched targets.

The possibility of extending our knowledge about higher-energy collective-type states among the vibrational nuclei by observing gamma rays from states excited by inelastically scattered protons has been examined. Gamma rays from ^{110}Pd and ^{116}Cd were detected in coincidence with inelastically scattered protons; the incident protons had energies of 12 and 13 MeV. Gamma rays, most of them previously unreported, were observed from 17 levels in ^{110}Pd and 14 levels in ^{116}Cd below ~2.5 MeV. The results are compared with predictions of a phonon-model interpretation of the levels. Evidence is shown for the existence of the three-quadrupole phonon quintet in ^{110}Pd.

1. Abstract of paper submitted for publication in *Nuclear Physics*.

2. Radioisotope Laboratory, General Hospital, Cincinnati, Ohio.

p-WAVE RESONANCES IN ^{111}Cd$(n,\gamma)^{112}$Cd[1]

O. A. Wasson[2] B. J. Allen[3]

NUCLEAR REACTIONS: ^{111}Cd(n,γ) E < 2300 eV; measured $\sigma_{n,\gamma}$, $\sigma(n; E_\gamma)$. Deduced 162 levels, Γ_n, π, l, S^0, S^1. Enriched target.

Gamma-ray spectra and total capture yields were measured for resonant neutron capture in an enriched ^{111}Cd sample for neutron energies less than 2.3 keV. The experiment utilized the 40-m flight path of the Oak Ridge Electron Linear Accelerator and a nonhydrogenous liquid scintillator gamma-ray detector. A total of 162 resonances were observed in this interval, and the resonance energies and neutron widths were deduced. Approximately 14% of the resonances are assigned to p-wave capture on the basis of the gamma-ray spectral measurements, while an additional 23% are assigned to s-wave capture on the basis of their large neutron widths. The parity of the remainder is undetermined. A lower limit of 0.9×10^{-4} is observed for the p-wave neutron strength function, $\Sigma g\Gamma_n{}^1/(2l+1)\Delta E$, while the s-wave neutron strength function, $\Sigma g\Gamma_n{}^0/\Delta E$, is 0.15×10^{-4}.

1. Abstract of paper submitted for publication to *Physical Review C*.

2. Present address: Brookhaven National Laboratory.

3. Present address: Australian Atomic Energy Commission, Lucas Heights, Australia.

COULOMB EXCITATION OF $^{117,119}Sn$[1]

P. H. Stelson W. T. Milner F. K. McGowan
R. L. Robinson S. Raman

NUCLEAR REACTIONS: $^{117,119}Sn(\alpha,\alpha'\gamma)$ and $^{117,119}Sn(^{16}O,^{16}O'\gamma)$. Measured E_γ, I_γ, $\gamma(\theta)$, Doppler broadening. Deduced levels, J, π, $B(E2)$, $B(M1)$, $T_{1/2}$. Enriched targets.

A total of five states in ^{117}Sn and four states in ^{119}Sn were observed to be Coulomb excited with alpha-particle and ^{16}O projectiles. Level energies, spins, $B(E2)$ and $B(M1)$ transition probabilities, and mean lives were obtained. For ^{117}Sn, spin $3/2^+$ states were observed at 158.7 and 1005 keV, and spin $5/2^+$ states were observed at 1020, 1180, and 1447 keV. For ^{119}Sn, spin $3/2^+$ states were observed at 23.9 and 920.5 keV, and spin $5/2^+$ states were observed at 921.4, 1090, and 1354 keV. A total of 20 $B(E2)$ values were obtained, and they varied in magnitude from 1/10 to 10 times the single-particle estimate. About 12 $B(M1)$ values were obtained, and they range from 10^{-1} to 10^{-4} times the single-particle estimate. Evidence was found for the existence of quadrupole collective states built on low-lying excited quasi-particle states.

1. Abstract of published paper: *Nucl. Phys.* **A190,** 197–217 (1972).

NEUTRON SHELL STRUCTURE IN ^{125}Sn BY (d,p) AND $(\alpha,^3He)$ REACTIONS[1]

C. R. Bingham[2] D. L. Hillis[2]

NUCLEAR REACTIONS: $^{124}Sn(d,p)$, $^{124}Sn(\alpha,^3He)$ E_d = 33.3 MeV, E_α = 65.7 MeV; measured $\sigma(\theta)$; deduced levels, l, j, Sj. Enriched target.

Differential cross sections for $^{124}Sn(d,p)$ at 33.3 MeV were measured in 5° increments from 12.5 to 47.5° lab. The resolution was about 30 keV FWHM. The $(\alpha,^3He)$ spectra with ~55 keV resolution were obtained at 15 and 20° lab with 65.7-MeV alpha particles. Distorted-wave calculations were made, allowing the assignment of l values, some of which were not made in earlier neutron transfer studies. Spin assignments and spectroscopic factors were obtained in accordance with the shell model. Consistent spectroscopic factors were obtained from the (d,p) and $(\alpha,^3He)$ reactions. Sums of spectroscopic factors and centers of gravity are presented for the levels observed and are compared with the results of pairing theory. Essentially all the neutron strength remaining in the neutron shell between $N = 50$ and $N = 82$ was located. Most of the strength in the $2f_{7/2}$, $3p_{3/2}$, and $1h_{9/2}$ levels of the next major shell was located.

1. Abstract of paper submitted for publication to *Physical Review C.*
2. University of Tennessee, Knoxville.

NUCLEAR SPECTROSCOPY OF NEUTRON-DEFICIENT LANTHANUM, DYSPROSIUM, AND ERBIUM ACTIVITIES[1]

B. Harmatz T. H. Handley[2]

RADIOACTIVITY: $^{131,132m,132g}La$, $^{153,155}Dy$, $^{158,161}Er$ [from (α,xn) reactions]; measured E_γ, I_{ce}. ^{131}Ba, ^{132}La, $^{153,155}Tb$, $^{158,161}Ho$ deduced levels, gamma multipolarity, J, π. Enriched targets.

A large accumulation of conversion-electron data has made it feasible to study the properties of nuclear levels in the rare-earth region of neutron numbers 88 to 94. The first experimental level scheme for ^{153}Tb ($N = 88$) is constructed; 84 transitions originate from 21 states excited below 1 MeV. The conversion spectrum of ^{155}Tb is augmented from 40 to 120 transitions below 1.1 MeV energy. Multipole orders are deduced for 55 of

the 96 transitions placed between 28 levels in ^{155}Tb. Rotational parameters and gamma-ray branching ratios are evaluated for ^{155}Tb. Levels in the 0.5-to-1-MeV region are interpreted as β and γ vibrations of the $3/2^+$ [411] state, and a single-particle $1/2^+$ [411] band. Our data on ^{158}Ho consist of 41 transitions, of which 30 are new, and almost all of the transition intensity is accounted for in the level spectrum. Neutron orbital $3/2^-$ [521] is found to be common to each of four low-lying intrinsic configurations in doubly odd ^{158}Ho. The order of odd-proton orbitals coupled to $3/2^-$ [521] corresponds to that of single-particle states observed in neighboring ^{159}Ho. Eighty conversion-electron transitions are observed below 1 MeV in ^{161}Ho, a sixfold increase over preceding studies. Using photon intensities from independent research, multipole orders are deduced for most of the transitions deexciting 18 nuclear levels in ^{161}Ho. More evidence is presented on decay spectra of ^{131,132m}La, including transition multipolarity assignments.

1. Abstract of published paper: *Nucl. Phys.* **A191**, 497 (1972).
2. Analytical Chemistry Division.

NEUTRON HOLE STATES IN ^{138}La AND ^{140}Pr[1]

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NUCLEAR REACTIONS: ^{139}La(p,d), E = 31.6 MeV; ^{141}Pr(p,d), E = 30.0 MeV; ^{142}Nd(p,d), ^{144}Sm(p,d), E = 29.5 MeV; measured $\sigma(E, \theta)$, Q. ^{138}La, ^{140}Pr deduced levels, ln, J, π, spectroscopic strengths. ^{139}La(p,p), ^{141}Pr(p,p), E = 29.3 – 30.0 MeV; ^{141}Pr(d,d), E = 22.7 MeV; measured $\sigma(E, \theta)$. Optical-model analysis, deduced potentials. Natural and enriched targets.

Protons accelerated to 30 MeV were used to investigate low-lying states in the odd-odd nuclei ^{138}La and ^{140}Pr with (p,d) reactions. The elastic scattering of 30-MeV protons and 23-MeV deuterons was also studied to determine optical potentials. Experimental angular distributions are compared with distorted-wave Born approximation calculations to extract spin, parity, and spectroscopic factors for levels up to 432 keV of excitation in ^{140}Pr and 530 keV in ^{138}La. Comparisons with the simple shell-model predictions and extended shell-model calculations are presented. The ^{140}Pr levels appear experimentally to have an almost pure particle-hole structure, whereas the ^{138}La levels exhibit substantial mixing.

1. Abstract of paper submitted for publication to *Nuclear Physics*.
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ENERGY LEVELS IN ^{142}Nd[1]

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D. Spalding[4] L. Bimbot[2] B. H. Wildenthal[5]

RADIOACTIVITY: ^{142}Pm; measured $T_{1/2}$, E_γ, I_γ. ^{142}Nd deduced levels, J, π, γ-branching.

NUCLEAR REACTIONS: ^{142}Nd(p,p') at analog resonances, E = 9.505, 10.245, 10.805, and 11.070 MeV; measured $\sigma(E_p, \theta)$. ^{142}Nd deduced levels, J, π, particle-hole states.

The excited states of ^{142}Nd were studied by means of the decay of 40-sec ^{142}Pm and the ^{142}Nd(p,p') reaction via isobaric analog resonances. Approximately 60 levels of ^{142}Nd were observed below 5.3 MeV excitation, including several neutron particle-hole states excited strongly in (p,p') at $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ resonances. We have collected together all known energy levels in ^{142}Nd and have proposed J^π assignments for 22 excited states. We have also compared the experimental level spectrum (positive-parity states only) with a calculated one based on the shell model.

1. Abstract of paper to be published in *Nuclear Physics A*.
2. Université de Montréal, Quebec, Canada.
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THE LOW-LYING EXCITED STATES OF ^{145}Nd POPULATED BY THE CAPTURE OF THERMAL NEUTRONS[1]

D. A. McClure[2] S. Raman J. A. Harvey

NUCLEAR REACTIONS: ^{144}Nd(n,γ), E = thermal; measured E_γ, I_γ. ^{145}Nd deduced levels. Enriched targets.

The low-lying excited states of ^{145}Nd populated by both primary and secondary gamma-ray transitions following the ^{144}Nd(n,γ)^{145}Nd reaction were studied. Both singles and two-parameter coincidence techniques were employed with the exclusive use of Ge(Li) detectors. The decay characteristics of the most intensely populated levels are given.

1. Abstract of paper to be published in proceedings of Conference on Nuclear Structure Study with Neutrons, Budapest, July 1972.
2. Georgia Institute of Technology, Atlanta.

NEUTRON SHELL STRUCTURE OF ^{145}Nd FROM (d,p) AND ($\alpha,^3$He) REACTIONS

C. R. Bingham[1] D. L. Hillis[2] J. B. Ball

NUCLEAR REACTIONS: ^{144}Nd(d,p), ^{144}Nd($\alpha,^3$He), E_d = 33.3 MeV, E_α = 66.6 MeV; measured $\sigma(\theta)$; deduced levels, l, j, Sj. Enriched target.

Differential cross sections for ^{144}Nd(d,p) at 33.3 MeV were measured in 5° increments from 12.5 to 32.5° lab. The ^{144}Nd($\alpha,^3$He) cross sections were measured at 15°. The results were compared with

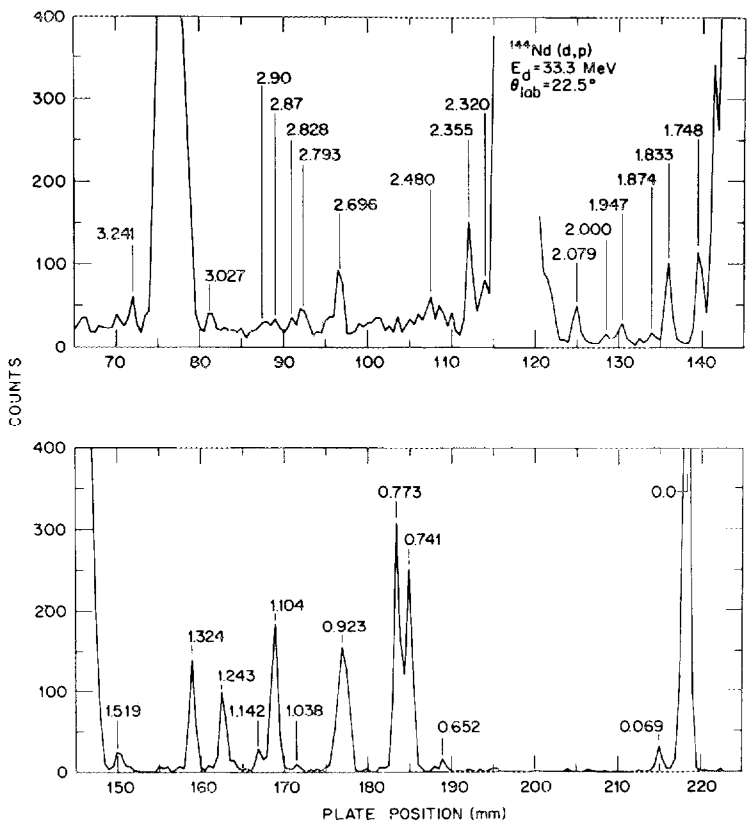

Fig. 1. The ^{144}Nd(d,p) spectrum at 22.5°. The large unlabeled peaks are due to carbon and oxygen impurities in the target.

distorted-wave calculations in order to obtain spin assignments and spectroscopic factors. Since high l transfers are enhanced in the (α,^{3}He) reaction, it provides a good check of the spin assignments and the spectroscopic factors from the (d,p) reaction. The bombarding energies were chosen to be near energies where elastic scattering has been studied; hence, the optical-model parameters are well known.

The (d,p) spectrum at 22.5° is shown in Fig. 1. The resolution, typical of all the proton spectra, is ~20 keV FWHM. The resolution of the (α,^{3}He) spectrum was about 45 keV, and there was an unexplained background problem. The (α,^{3}He) cross sections will be remeasured. For this reason the present results should be considered preliminary.

The (d,p) angular distributions and the (α,^{3}He) cross sections at 15° were compared with distorted-wave calculations. To get agreement between (d,p) and (α,^{3}He), some peaks were treated as doublets. An example is the peak at 0.923 MeV, which is clearly broader than neighboring peaks (see Fig. 1). The energies, spin assignments, and spectroscopic factors of the levels observed are listed in Table 1. Essentially none of these results have been reported in earlier neutron transfer studies.

The spectroscopic factors were summed, and the center of gravity of each quasi-particle state was calculated as $\epsilon_j = \Sigma E^* S_j / \Sigma S_j$. The results are given in Table 2. These preliminary results indicate that a large fraction of the single-particle strength has been located.

Table 1. Excitation energies, spin assignments, and spectroscopic factors of the levels observed in ^{144}Nd (d,p)

E^* (MeV)	j^π	$S_{d,p}$	$S_{\alpha,{}^3\text{He}}$
0.0	$7/2^-$	0.68	0.48
0.069[a]	$(3/2^-, 5/2^-)$	0.03, 0.025	
0.652	$(3/2^-)$	0.03	
0.741	$9/2^-$	0.36	0.36
0.773	$3/2^-$	0.53	
0.923[a]	$5/2^-, (9/2^-)$	0.40, 0.07	0.40, 0.07
1.104	$13/2^+$	0.30	0.39
1.142	$(5/2^-)$	0.025	
1.243	$(5/2^-)$	0.08	0.09
1.324	$(5/2^-)$	0.13	0.16
1.519	$9/2^-$	0.06	0.044
1.579	$(5/2^-)$	0.034	
1.639	$(5/2^-)$	0.011	
1.673	$(5/2^-)$	0.01	
1.748[a]	$(5/2^-, 9/2^-)$	0.11, 0.04	0.11, 0.04
1.833	$13/2^+$	0.17	0.14
1.874	$(3/2^-)$	0.04	
1.947[a]	$(5/2^-, 13/2^+)$	0.03, 0.02	0.03, 0.02
2.000	$9/2^-$	0.034	0.042
2.079	$9/2^-$	0.11	0.12
2.137[a]	$(5/2^-, 9/2^-)$	0.08, 0.05	0.08, 0.04
2.203[a]	$(3/2^-, 9/2^-)$	0.14, 0.07	0.14, 0.07
2.268	$5/2^-$	0.06	
2.320	$(3/2^-)$	0.17	
2.355	$5/2^-$	0.13	
2.480[a]	$(3/2^-, 9/2^-)$	0.07, 0.09	0.07, 0.087
2.696	$5/2^-$	0.07	
2.793 + 2.828	$(1/2^-)$	0.42	
2.87 + 2.90	$(13/2^+)$	0.10	0.09
2.97	$(13/2^+)$		0.12
3.027[a]	$(5/2^-, 13/2^+)$	0.04, 0.05	0.04, 0.06
3.141	$(1/2^-)$	0.38	
3.241	$(9/2^-)$	0.09	

[a]Peaks treated as doublets to obtain agreement between (d,p) and (α,^{3}He).

Table 2. Summary of results

Subshell	Number of levels observed	Spectroscopic factor sum		ϵ_j (MeV)
		Measured	Expected	
$7/2^-$	1	0.68	0.75	0
$3/2^-$	(7)	1.01	1.00	1.369
$5/2^-$	(15)	(1.235)	1.00	1.565
$9/2^-$	(10)	(0.974)	1.00	1.607
$13/2^+$	(6)	(0.79)	1.00	1.881
$1/2^-$	(2)	(0.80)	1.00	2.967

1. Consultant from the University of Tennessee.
2. Graduate student from the University of Tennessee.

DECAY OF 5.9-DAY ^{145}Eu TO LEVELS IN ^{145}Sm[1]

E. Newman K. S. Toth I. R. Williams[2]

The level structure of ^{145}Sm was studied by observing the electron-capture decay of 5.9-day ^{145}Eu. The radioactive source was prepared by bombarding ^{144}Sm with protons accelerated in the Oak Ridge Isochronous Cyclotron. Both singles and gamma-gamma coincidence spectra were measured. From these measurements, transition energies were obtained to an accuracy better than previously available, and the following new transitions were assigned to the decay of ^{145}Eu: 519.4, 526.2, 713.9, 910.3, 949.9, ~1625, 2340.8, 2508.1, and 2513.0 keV. Because of decay energy considerations the latter three transitions establish the existence of new ^{145}Sm levels at 2340.8, 2508.1, and 2513.0 keV. From the coincidence data, levels at 1607.6 ($1/2^-$) and 1843.6 ($1/2, 3/2^-$) keV were also established; these states apparently correspond to those previously observed in ^{144}Sm(*d,p*) studies at about 1611 and 1854 keV. A survey of available data for N = 83 isotones (^{137}Xe → ^{147}Gd) indicated a systematic shift in excitation energy for seven rather well-established single-neutron states as their location was traced from nuclide to nuclide. On this basis it was then possible to predict in ^{137}Xe, ^{141}Ce, and ^{147}Gd the approximate excitation energies of some of these states, so far unreported.

1. Abstract of a paper accepted for publication in *Physical Review C.*
2. Knoxville College, Knoxville, Tenn.

HIGH-LYING 2$^+$ STATES IN ^{148}Sm OBSERVED IN THE DECAY OF 5$^-$ ^{148}Eu[1]

K. S. Toth E. Newman

Buss and Smither recently studied levels in ^{148}Sm by investigating the thermal-capture reaction ^{147}Sm(n,γ). Of the 32 levels that they considered (many of these were proposed as new states), only 18 have been observed in ^{148}Eu decay. Our investigation of the ^{148}Eu decay scheme has produced strong corroborative evidence for the existence of seven additional states proposed by Buss and Smither. Their energies (in keV) and spin assignments are as follows: 1454.6, 2^+; 1664.2, 2^+; 1903.8, 3^+ or 4^+; 2173.2, 2^+; 2339.4, 2^+ or 3^-; 2390.0, 3^+; and 2570.5, 2^+. The 1454.6-keV level is apparently the second 2^+ level, expected from energy-level systematics to be at ~1.4 MeV, for which no conclusive evidence has been available.

1. Abstract of a paper accepted for publication in *Physical Review C.*

THE LOW-LYING EXCITED STATES OF ^{145}Nd POPULATED BY THE CAPTURE OF THERMAL NEUTRONS[1]

D. A. McClure[2] S. Raman J. A. Harvey

NUCLEAR REACTIONS: ^{144}Nd(n,γ)^{145}Nd, E_n = thermal; measured E_γ, I_γ. ^{145}Nd deduced levels. Enriched target.

The low-lying excited states of ^{145}Nd populated by both primary and secondary gamma-ray transitions following the ^{144}Nd(n,γ)^{145}Nd reaction were studied. Both singles and two-parameter coincidence techniques were employed with the exclusive use of Ge(Li) detectors. The decay characteristics of the most intensely populated levels are given.

1. Abstract of paper published in *Contributions to IAEA Conference on Nuclear Structure Study with Neutrons, Budapest, Hungary, July 31–August 5, 1972,* p. 128 (1972).
2. Georgia Institute of Technology, Atlanta.

STUDY OF HAFNIUM ALPHA EMITTERS: NEW ISOTOPES ^{159}Hf, ^{160}Hf, AND ^{161}Hf[1]

K. S. Toth R. L. Hahn[2] C. R. Bingham[3] M. A. Ijaz[4] R. F. Walker, Jr.[5]

With the use of alpha spectroscopy and the helium gas-jet technique the alpha decay of the previously unknown isotopes ^{159}Hf, ^{160}Hf, and ^{161}Hf was observed. These hafnium nuclides were produced by bombarding targets of ^{144}Sm and ^{147}Sm with ^{20}Ne ions accelerated in the Oak Ridge Isochronous Cyclotron. The decay characteristics and mass assignments (made on the basis of yield curve measurements, cross bombardments, and parent-daughter relationships) of the three new alpha emitters are as follows: (1) ^{159}Hf, E_α = 5.09 ± 0.01 MeV, $T_{1/2}$ = 5.6 ± 0.05 sec; (2) ^{160}Hf, E_α = 4.77 ± 0.02 MeV, $T_{1/2} \sim$ 12 sec; and (3) ^{161}Hf, E_α = 4.60 ± 0.01 MeV, $T_{1/2}$ = 17 ± 2 sec. The latter two isotopes, with neutron numbers of 88 and 89, are of some interest with respect to alpha-decay systematics in the 82-neutron region. The only 88-neutron alpha emitters known up to now are naturally occurring ^{152}Gd and long-lived ^{154}Dy, while ^{161}Hf is the first 89-neutron nuclide to exhibit alpha decay.

1. Abstract of a paper submitted for publication in *Physical Review C.*
2. Chemistry Division.
3. University of Tennessee, Knoxville.
4. Virginia Polytechnic Institute, Blacksburg.
5. Centenary College of Louisiana, Shreveport.

NONSTATISTICAL EFFECTS IN THE 4*s* GIANT RESONANCE[1]

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G. W. Cole[2] O. A. Wasson[2] G. G. Slaughter

NUCLEAR REACTIONS: ^{163}Dy(n,γ), E = 5 eV–5 keV; measured E_n, E_γ, I_γ; ^{164}Dy deduced levels, J. Enriched target.

Gamma-ray spectra due to radiative neutron capture in individual resonances of ^{163}Dy and ^{173}Yb are measured. Nonstatistical aspects of the neutron radiative capture process in the 4*s* giant resonance are considered.

1. Abstract of paper published in *Contributions to IAEA Conference on Nuclear Structure Study with Neutrons, July 31–August 5, 1972, Budapest, Hungary,* p. 214 (1972).
2. Brookhaven National Laboratory.
3. AECL, Chalk River, Canada.

LIFETIME MEASUREMENTS OF 8$^+$, 10$^+$, AND 12$^+$ ROTATIONAL STATES IN ^{164}Dy

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W. T. Milner L. L. Riedinger[2]

NUCLEAR REACTION: ^{164}Dy(^{40}Ar,^{40}Arγ), E = 152.8 MeV; measured $\sigma(E_\gamma)$, Doppler shift attenuation. ^{164}Dy levels deduced $T_{1/2}$. Enriched target.

Rotational states up to spin 12 in ^{164}Dy were populated by inelastic scattering of 153-MeV ^{40}Ar from a thick target of ^{164}Dy. Gamma rays were detected in two Ge(Li) detectors at 0 and 90° to the beam and were recorded in coincidence with ^{40}Ar ions backscattered (160°) into an annular detector.

Lifetimes were inferred from the Doppler-broadened shapes of the gamma transitions $8^+ \rightarrow 6^+$, $10^+ \rightarrow 8^+$, and $12^+ \rightarrow 10^+$ by comparing the observed line shapes with those calculated taking into account the stopping power of projectiles and recoiling ions as well as the reaction kinematics and detector geometry.

The data for the three transitions are presented in Fig. 1, along with representative theoretical fits to the Doppler-broadened shapes. Lifetime values for the transitions are given in Table 1 along with the energy of each transition. The lifetime values are preliminary, because the effect of cascade feeding has not yet been included in the analysis. The quoted uncertainties also

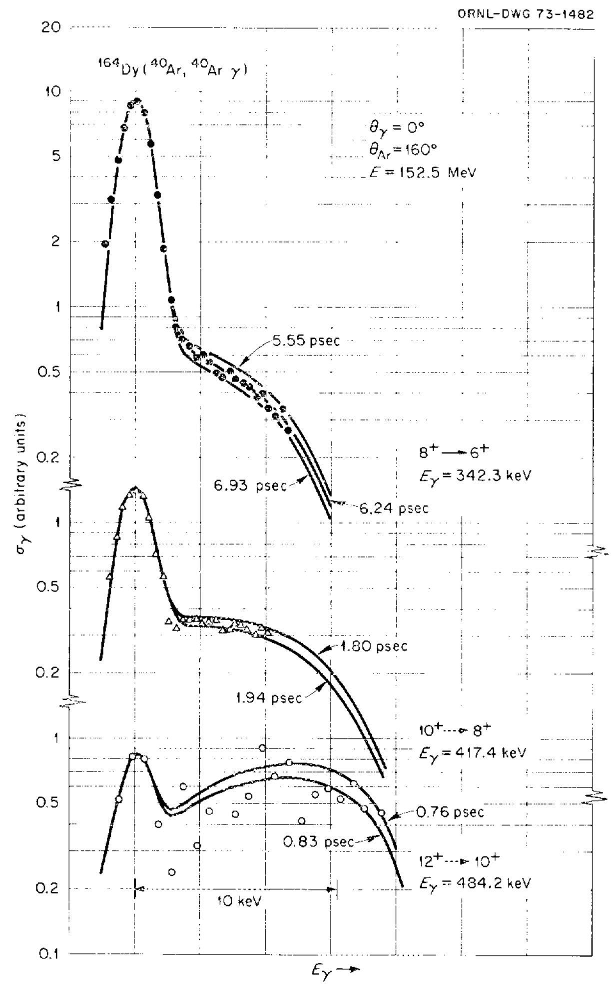

Fig. 1. Doppler-broadened shapes for gamma transitions in ^{164}Dy observed at 0° in the ^{164}Dy(^{40}Ar,^{40}Arγ) reaction.

Table 1. Lifetimes for $E2$ transitions in ^{164}Dy

Transition	E_γ (keV)	$T_{1/2}$ (psec)	$B(E2)/B(E2)_{rot.}$
$8^+ \rightarrow 6^+$	342.3	6.32 × 0.42	1.00
$10^+ \rightarrow 8^+$	417.4	1.91 × 0.21	1.17 × 0.1
$12^+ \rightarrow 10^+$	484.2	0.82 × 0.10	1.35 × 0.2

do not include the uncertainty in the absolute value of the stopping powers.

The last column in Table 1 gives the $B(E2)$ values deduced from the lifetimes divided by the corresponding $B(E2)$ value predicted by the rigid-rotor model. Because of the uncertainty in the absolute value for the stopping power, the ratios have been scaled so that the ($8^+ \rightarrow 6^+$) ratio is 1.0. These ratios should be fairly independent of any errors arising either from the cascade feeding or from the absolute value of the stopping power.

Similar measurements on ^{160}Dy are in progress.

1. Chemistry Division.
2. University of Tennessee.

EVIDENCE FOR THE ALPHA DECAY OF THE NEW ISOTOPE ^{169}Os[1]

K. S. Toth   R. L. Hahn[2]   C. R. Bingham[3]   M. A. Ijaz[4]   R. F. Walker, Jr.[5]

In a series of ^{20}Ne bombardments of ^{156}Dy a new alpha emitter was identified with a half-life of 3.0 ± 0.5 sec and an alpha-decay energy of 5.56 ± 0.02 MeV. On the basis of alpha-decay systematics and the variation of its yield with bombarding energy, the most likely nuclidic assignment for this alpha group is ^{169}Os.

1. Abstract of published paper: *Phys. Rev. C* **6**, 2297 (1972).
2. Chemistry Division.
3. University of Tennessee, Knoxville.
4. Virginia Polytechnic Institute, Blacksburg.
5. Centenary College of Louisiana, Shreveport.

ALPHA-DECAY PROPERTIES OF THE NEW OSMIUM ISOTOPES ^{170}Os AND ^{171}Os[1]

K. S. Toth R. L. Hahn[2] M. A. Ijaz[3] R. F. Walker, Jr.[4]

Borggreen and Hyde recently reported the discovery of three new alpha-emitting osmium isotopes, ^{172}Os, ^{173}Os, and ^{174}Os. The present study deals with a search for osmium nuclides with $A < 172$. These osmium isotopes were produced by bombarding ^{156}Dy with the 160-MeV $^{20}Ne^{6+}$ beam from the Oak Ridge Isochronous Cyclotron. With the use of alpha spectroscopy and the helium gas-jet technique, two new alpha groups were observed. Their mass assignments and decay characteristics are as follows: (1) ^{170}Os, $E_\alpha = 5.40 \pm 0.01$ MeV, $T_{1/2} = 7.1 \pm 0.5$ sec, and (2) ^{171}Os, $E_\alpha = 5.24 \pm 0.01$ MeV, $T_{1/2} = 8.2 \pm 0.8$ sec.

1. Abstract of published paper: *Phys. Rev. C* **5**, 2060 (1972).
2. Chemistry Division.
3. Virginia Polytechnic Institute, Blacksburg.
4. Centenary College of Louisiana, Shreveport.

SEARCH FOR INTERMEDIATE-STATE STRUCTURE FROM RESONANCE NEUTRON CAPTURE IN ^{185}Re AND ^{187}Re

J. A. Harvey N. W. Hill[1] A. Stolovy[2] A. I. Namenson[2]

NUCLEAR REACTIONS: ^{185,187}Re; measured $\sigma(n,\gamma)$ for $E_\gamma > 1$ and 4 MeV; $E_n = 20$ to 3000 eV.

In recent years, considerable effort has been directed to searching for nonstatistical effects or intermediate structure in the interaction between neutrons and nuclei. In addition to such striking examples as subthreshold neutron fission and valency neutron capture, evidence for intermediate structure from resonance neutron capture has been reported in ^{115}In by Coceva et al.[3] and in ^{187}Re by Stolovy et al.[4] The evidence for a very narrow intermediate state in ^{187}Re only ~30 eV wide was obtained from the analysis of neutron time-of-flight gamma-ray data taken at the NRL linear accelerator, where the neutron energy resolution was sufficient to permit analysis for the first 46 resonances in each isotope up to ~200 eV. A careful statistical analysis of these data resulted in a conclusion that it was highly likely that there was a nonstatistical effect in ^{187}Re, since the probability that the observed fluctuations would occur by pure chance was only 0.5%. Since resonance data could be obtained on these nuclides at ORELA up to several keV, the present measurements were undertaken primarily to look for the presence of additional intermediate structure and to confirm the earlier structure at ~120 eV in ^{187}Re.

The four large NaI detectors and shielding used in the NRL experiment were installed at the 80-m station at ORELA. The neutron beam was collimated to a 3-in. diameter, which irradiated the ^{185}Re and ^{187}Re samples, which were 3½ in. in diameter and ~0.5 g/cm^2 thick. The accelerator was operated at 800 pulses/sec with 25 kW of 120-MeV electrons and a burst width of 25 nsec. The neutron energy resolution was determined by the moderator thickness and was ~0.06%. Resonances were observed up to ~3 keV, and data were obtained on ~1200 resonances in ^{185}Re and ^{187}Re. For each resonance, the intensity of the capture gamma rays above 4.0 MeV was normalized to the intensity of the gamma rays above 1.0 MeV. The high-bias data represent primary gamma-ray transitions from the capturing states to low-lying states in the compound nucleus. The low-bias data represent a sum over many cascade transitions. Although the present data comprise an order of magnitude more resonances, we find no significant evidence for additional intermediate structure in either isotope. Also, two additional small resonances found in the ORELA data in the energy region where the intermediate structure in ^{187}Re had been reported decrease the probability that this structure is significant. The data will be analyzed to obtain estimates of $g\Gamma_n$, and various statistical tests will be applied.

1. Instrumentation and Controls Division.
2. Naval Research Laboratory, Washington, D.C.
3. C. Coceva, F. Corvi, P. Giacobbe, and M. Stefanon, *Phys. Rev. Lett.* **25**, 1047 (1970).
4. A. Stolovy, A. I. Namenson, and T. F. Godlove, *Phys. Rev. C* **4**, 1466 (1971).

COMMENTS ON THE DOORWAY STATE IN ^{206}Pb[1]

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NUCLEAR REACTIONS: ^{206}Pb(n,γ), E = 260–680 keV; measured $\sigma_{n\gamma}$. Deduced little or no enhancement of Γ_γ for l = 0 levels, but l = 1 enhancement. Enriched target.

The neutron capture cross section of ^{206}Pb(n,γ) has been measured with high resolution at the Oak Ridge Electron Linear Accelerator. The capture results show that the reported s 1/2 doorway in ^{206}Pb is not observed in the photon channel.

1. Abstract of paper submitted for publication in *Physical Review C*, Comments and Addenda.
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3. Neutron Physics Division.
4. Present address: Denison University, Granville, Ohio.

INVESTIGATION OF THE ^{208}Pb(^{12}C,^{11}B)^{209}Bi AND ^{208}Pb(^{12}C,^{13}C)^{207}Pb REACTIONS AT HIGH BOMBARDING ENERGIES[1]

J. S. Larsen[2] J. L. C. Ford, Jr. R. M. Gaedke[3] K. S. Toth
J. B. Ball R. L. Hahn[4]

NUCLEAR REACTIONS: ^{208}Pb(^{12}C,^{11}B), (^{12}C,^{13}C), E = 77, 98, 116 MeV; measured $\sigma(E_t, \theta)$.

States in ^{207}Pb and ^{209}Bi were populated in interactions of ^{208}Pb with 77.98- and 116-MeV ^{12}C ions. Angular distributions indicated that the neutron pickup and proton stripping reactions were compatible, respectively, with mechanisms dependent on final and initial systems alone.

1. Abstract of published paper: *Phys. Lett.* **42B**, 205 (1972).
2. Visiting scientist from Niels Bohr Institute, Copenhagen, Denmark.
3. Oak Ridge Associated Universities Research Participant from Trinity University, San Antonio, Tex.
4. Chemistry Division.

GIANT RESONANCES IN THE HIGH-ENERGY HELIUM INELASTIC SCATTERING[1]

M. B. Lewis

An analysis of earlier reported cross-section data from ^{208}Pb(α,α'), (^{3}He,^{3}He'), and ^{197}Au(^{3}He,^{3}He') reactions at E_α = 90 MeV and $E_{^3\mathrm{He}}$ = 75 MeV confirms the discovery of a new giant resonance at $E^* \approx 11$ MeV in heavy nuclei. From the magnitude of the cross sections and theoretical sum-rule prescriptions, it is found that the resonance may be interpreted as a giant quadrupole state but not, as recently suggested, a giant monopole state.

1. Abstract of paper to be published in *Physical Review Letters.*

INVESTIGATION OF THE ^{208}Pb(p,p') REACTION AT E = 54 MeV[1]

M. B. Lewis F. E. Bertrand C. B. Fulmer

NUCLEAR REACTIONS: ^{208}Pb(p,p'), E = 54 MeV; measured absolute $\sigma(E, \theta)$. ^{208}Pb levels, deduced L, $\beta_L{}^2$. Spectrograph.

Collective excitations of ^{208}Pb were investigated by inelastic proton scattering at 54 MeV. The spectra covered the entire bound-state region for scattering angles between 11 and 58°, and scattered particles were detected in a broad-range spectrograph with energy resolution ≈35 to 40 keV (FWHM). The experimental angular distributions were compared with those predicted by DWBA calculations, utilizing a collective-model form factor. The location of the low-spin members of a sequence (2^+–8^+) of positive-parity states was confirmed. Likely candidates for $J > 8$ states were found, as well as several collective fragments of 3^- and 4^+ strengths. No appreciable fragmentation of the 2^+ strength was found. Energy-weighted sum-rule strengths were estimated for all multipoles studied and were compared with the measured values.

1. Abstract of paper to be published in the *Physical Review.*

POSSIBILITY OF STRONG MULTIPOLE VIBRATIONS IN THE LOW-EXCITATION REGION OF THE NUCLEAR CONTINUUM[1]

M. B. Lewis   F. E. Bertrand

Estimates for ^{208}Pb(α,α') cross sections at 65 MeV show strong preference for high angular momentum transfers and, if the maximum allowable collective strength is invoked, yield absolute cross sections comparable with those recently measured in the 10-to-25-MeV excitation region of ^{208}Pb.

1. Abstract of published paper: *Phys. Rev. C* **6**, 1108 (1972).

THE SIGN OF THE HEXADECAPOLE MOMENTS OF ^{232}Th AND ^{238}U NUCLEI[1]

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The ambiguity in the sign of the hexadecapole moments of ^{232}Th and ^{238}U, as determined from alpha-particle Coulomb excitation experiments, has been resolved by experiments using 145-MeV ^{40}Ar to multiply Coulomb excite these nuclei up to their 12^+ states. Excellent agreement with the experimental results was obtained with predictions from the Winther–de Boer program when positive $M(E4)$ values were used, while significant disagreement was found when the negative $M(E4)$ values were used.

1. Abstract of paper submitted for publication in *Physical Review Letters.*
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COMPOUND-NUCLEAR AND TRANSFER REACTIONS IN ^{12}C REACTIONS WITH ^{238}U AND ^{239}Pu[1]

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Studies of the interactions of heavy ions (H.I.) with heavy elements, besides adding to our knowledge of the different mechanisms operative[3] in reactions such as (H.I.,xn) and (H.I.,αyn), and of the ensuing competition between particle emission and fission,[4] also have application in attempts to produce and identify new nuclides. For example, knowledge of the details of the angular distributions of recoil nuclei has been used as support for identification of transactinide elements.[5]

At the Oak Ridge Isochronous Cyclotron, we have investigated the reactions ^{238}U(^{12}C,5n and 6n) and ^{239}Pu(^{12}C,α2n and α3n), which lead to the same products, ^{245}Cf and ^{244}Cf. Relative excitation functions were determined by collection of recoil nuclei with a gas-jet system followed by alpha-particle spectrometry. Separate experiments involving radiochemical techniques gave absolute cross-section values. The results for the ^{238}U target were consistent with published data[4] that indicated that the (^{12}C,xn) reaction proceeds via the compound-nucleus mechanism with cross sections of ~50 to 100 μb. For the ^{239}Pu + ^{12}C reactions, maximum cross sections of 7.1 μb at 69 MeV and 4.8 μb at 74 MeV were found, respectively, for ^{245}Cf and ^{244}Cf. Furthermore, no activity ascribable to fermium nuclides from ^{239}Pu(^{12}C,xn) reactions was detected in these experiments; a limit of (^{12}C,xn)/(^{12}C,αyn) $\lesssim$ 0.01 was set. These results clearly indicate that ^{245,244}Cf are not produced from ^{239}Pu + ^{12}C in compound-nuclear interactions because evaporation of charged particles from such heavy nuclei is much less probable than for neutrons.

To learn more about the reaction mechanisms involved, we measured, at different ^{12}C energies, the range and angular distributions for $^{245,244}Cf$ that recoiled out of thin ^{238}U and ^{239}Pu targets. Figure 1 shows range distributions obtained with stacks of thin carbon foils that collected recoils from 0 to 10° with respect to the beam (corrections for energy loss in the targets are not included in the figure). The distributions for ^{238}U + ^{12}C are approximately Gaussian, with centroids (average ranges) that increase with increasing ^{12}C energy in a manner consistent with full momentum transfer. For ^{239}Pu, the results are quite different. The distributions are asymmetric, with tails that extend to large range values, yet the centroids decrease rapidly with increasing ^{12}C energy.

The angular distributions, determined by collecting recoils in ~9-mg/cm² aluminum foils placed at various angles with respect to the beam, are also different for the two targets. For ^{238}U + ^{12}C, the angular distributions monotonically decrease with increasing lab angle, while for ^{239}Pu + ^{12}C, they display a peak at ~15 to 20°.

All of the data support the conclusion that the $^{238}U(^{12}C,xn)$ reactions occur via compound-nucleus formation and decay. The results for the $^{239}Pu(^{12}C,\alpha yn)$ reactions are clearly not ascribable to compound-nuclear processes and qualitatively agree with work[6] that concludes that direct transfer to the target nucleus of part of the projectile, possibly ^{8}Be, occurs in such reactions, followed by neutron emission from the excited residual nucleus.

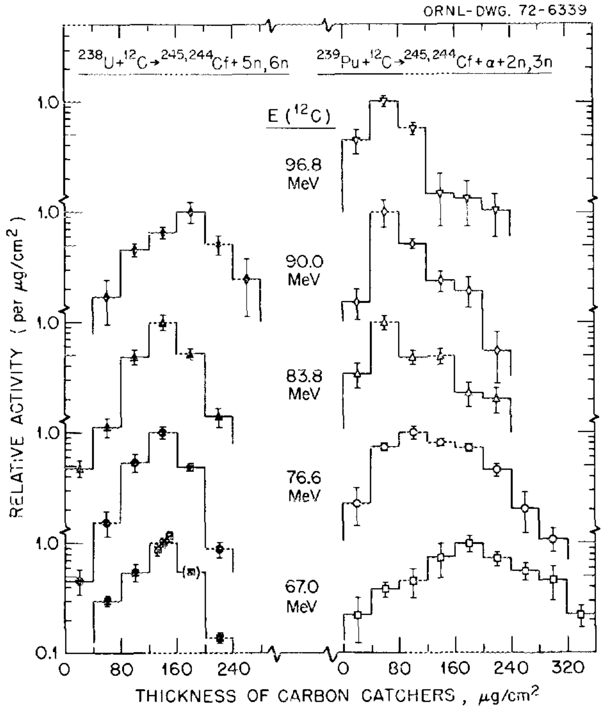

Fig. 1. Range distributions measured for $^{244,245}Cf$ recoils produced in the interaction of ^{12}C ions with targets of ^{238}U and ^{239}Pu.

1. Paper published in *Proceedings of the European Conference on Nuclear Physics, Aix-en-Provence, France, June 26–July 1, 1972,* vol. II, p. 96.

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NEUTRON TOTAL CROSS SECTION OF ^{248}Cm AND ^{242}Pu FROM 0.5 to 5000 eV

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NUCLEAR REACTIONS: ^{248}Cm, ^{242}Pu; measured σ_{nT}, E_n = 0.5 to 5000 eV. Deduced resonance parameters. Enriched targets.

Neutron transmission measurements have been made from 0.5 to ~5000 eV upon samples of ^{248}Cm and ^{242}Pu, which are of interest in the production of the heavy nuclides. Previous fission and capture cross-section measurements[4] upon ^{248}Cm using the Physics 8 underground nuclear explosion had been analyzed to give parameters for 3 resonances up to 100 eV. Until our measurements upon ^{242}Pu, parameters were only available for 20 resonances[5] in ^{242}Pu up to 400 eV.

Three sample thicknesses of ^{248}Cm were used with inverse thicknesses of 637, 3192, and 22,087 b/atom. The ^{248}Cm sample had been produced from the decay of ^{252}Cf and separated by J. B. Knauer of the TURF californium facility. Since only 13 mg of ^{248}Cm (97% pure) was available, the cross-sectional areas were very small, only 2 mm^2 for the thickest sample and 7 mm^2 for the other two. A single ^6Li neutron detector (4½ in. in diameter and 0.5 in. thick) was located 18 m from the ORELA neutron target, resulting in a neutron energy resolution of 0.3%. The samples were cooled to liquid nitrogen temperature to reduce the Doppler broadening, which is greater than the instrumental resolution below 50 eV. For the lower energy region a cadmium overlap filter was used and ~15 kW of electron beam power at 400 pulses/sec. For the higher energies a ^{10}B overlap filter was used with 50 kW of electron beam power at 1000 pulses/sec and 25-nsec pulses. Room background and time-dependent background using the blacking-out resonance technique were determined for these measurements. Over 40 resonances have been observed below 1 keV. Analysis of the data to obtain resonance parameters is in progress.

The measurements upon ^{242}Pu have been made using an 80-m flight path in addition to the 18-m flight path. Three sample thicknesses of ^{242}Pu metal were used, with inverse thicknesses of 41.19, 175.5, and 763.9 b/atom. The samples were cooled to liquid nitrogen temperature. For the 80-m data, the neutron energy resolution was 0.07% and hence less than the Doppler width up to ~1 keV. Analyses of the data are in progress, and incomplete results of the resonance energies and reduced neutron widths are given in Table 1, based on an assumed Γ_γ of 29 meV.

Table 1. ^{242}Pu resonance parameters

E_0 (eV)	Γ_n° (meV)	E_0 (eV)	Γ_n° (meV)
2.675		273.7	0.75 ± 0.06
22.57	0.055 ± 0.004	274.9	0.010 ± 0.002
40.95	0.070 ± 0.006	281.1	0.008 ± 0.003
53.46	6.93 ± 0.22	298.8	0.45 ± 0.04
67.62	0.60 ± 0.05	303.7	1.02 ± 0.08
88.46	0.070 ± 0.005	320.0	13.1 ± 0.4
107.4	1.72 ± 0.15	332.5	3.9 ± 0.1
131.4	0.54 ± 0.02	374.4	0.35 ± 0.02
141.4	0.010 ± 0.002	379.6	0.014 ± 0.002
149.8	1.07 ± 0.06	382.4	2.53 ± 0.13
163.6	0.045 ± 0.004	400.0	0.080 ± 0.010
205.0	3.80 ± 0.25	410.7	0.34 ± 0.02
210.1	0.028 ± 0.006	424.1	0.185 ± 0.015
215.4	0.36 ± 0.02	425.2	0.013 ± 0.002
219.6	0.020 ± 0.002	473.5	0.040 ± 0.004
232.9	0.30 ± 0.03	482.7	0.91 ± 0.08
264.7	0.024 ± 0.002	494.7	0.012 ± 0.003
271.9	0.010 ± 0.002		

1. Instrumentation and Controls Division.
2. Savannah River Laboratories, Aiken, S.C.
3. Aerojet Nuclear Co., Idaho Falls, Idaho.
4. M. S. Moore and G. A. Keyworth, *Phys. Rev. C* **3**, 1656 (1971).
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ELECTRIC HEXADECAPOLE MOMENTS IN THE ACTINIDE NUCLEI

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NUCLEAR REACTIONS: $^{230,232}Th(\alpha,\alpha')$, $^{234,236,238}U(\alpha,\alpha')$, $^{238,240,242,244}Pu(\alpha,\alpha')$, $^{244,246,248}Cm(\alpha,\alpha')$, E = 17 MeV; measured $\sigma(E_{\alpha'}, \theta)$; deduced $B(E2)$, $B(E4)$. Enriched targets.

Large contributions to the excitation of 4^+ rotational states from $E4$ transitions have been observed in precision Coulomb-excitation experiments with 17-MeV ^4He ions for 12 even-A actinide nuclei ($230 \leqslant A \leqslant 248$). This hexadecapole moment is of particular interest because it most probably results from the intrinsic shape of the deformed nuclei.

Elastically and inelastically scattered ions from isotopically pure targets (~30 μg/cm^2) were detected at θ_L = 150° with 15- to 20-keV resolution in the focal plane of the Enge split-pole magnetic spectrometer by a position-sensitive gas proportional counter. The "shaped" targets, which were a principal reason for the success of these experiments, were prepared using a

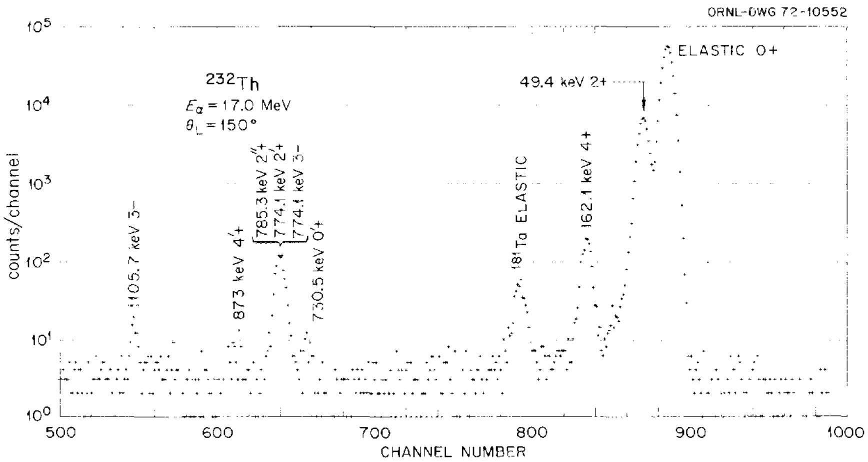

Fig. 1. Spectrum of ^{4}He ions scattered from ^{232}Th at a laboratory angle of 150°.

150-cm-radius electromagnetic isotope separator. A spectrum of the scattered ^{4}He ions from ^{232}Th implanted on 80-μg/cm^2 carbon backing is shown in Fig. 1. The ratio of the counts in the peak channel for the elastic peak to the background near the 4^+ peak is 20,000. This spectrum, which was accumulated at a rate of 3 counts/sec, contains 454,000 counts. In addition to excitation of the 2^+ and 4^+ states of the ground-state rotational band, states are observed at 730.5 keV, $0'^+$; 774.1 keV, 3^- and $2'^+$; 785 keV, $2''^+$; 873 keV, $4'^+$; and 1105.7 keV, 3^-. The ^{181}Ta impurity results from the target preparation in the isotope separator, namely, a molecular ion ^{181}Ta^{16}O^{35}Cl with mass 232.

The excitation probabilities for the 2^+ and 4^+ states were determined relative to the elastic scattering peak from the measured peak areas with an accuracy of 1% for the 2^+ state and 3 to 4% for the 4^+ state. These uncertainties include the error in background subtraction and the uncertainty in resolving the 2^+ peak from the elastic peak. The $E2$ and $E4$ transition moments are extracted from the experimental excitation probabilities for the 2^+ and 4^+ states with the aid of the Winther–de Boer computer program for multiple Coulomb excitation (a semiclassical treatment). Quantum mechanical corrections for $E2$ excitations have been included in the analysis.

If the measured $E2$ and $E4$ transition moments are assumed to result from the intrinsic shape of deformed nuclei, then rather detailed information about the shape of the nuclear charge distribution can be obtained from the measured transition moments. Model-dependent deformation parameters, β_{20} and β_{40}, have been extracted from the measured $E2$ and $E4$ transition moments for distributions of nuclear charge represented

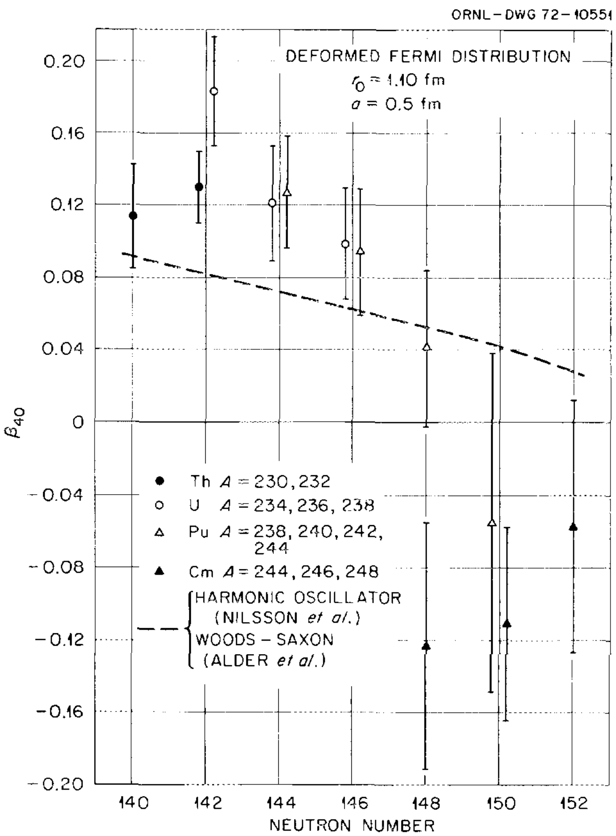

Fig. 2. Hexadecapole deformations β_{40} extracted from the measured $E2$ and $E4$ transition moments for a distribution of nuclear charge represented by a deformed Fermi distribution. The equilibrium deformations from calculations by Nilsson et al. and by Alder et al. are displayed by the dashed curve.

by a deformed homogeneous distribution and by a deformed Fermi distribution by solving the equation

$$\langle I_f = \lambda \| M(E\lambda) \| 0 \rangle = \int r^\lambda \, Y_{\lambda 0}(\theta) \, \rho(r, \theta) \, d\tau$$

numerically. The quadrupole deformations $\beta_{2\,0}$ deduced from the Fermi charge distribution are about 17% larger than the equilibrium deformations which have been calculated on the basis of a modified harmonic-oscillator potential model by Nilsson et al. and for a Woods-Saxon potential model by Alder et al. The hexadecapole deformations $\beta_{4\,0}$ are rather large for the thorium, uranium, and plutonium nuclei. These are displayed in Fig. 2 as functions of neutron number together with the equilibrium values from the calculations by Nilsson et al. and Alder et al. The data support the general trend of the calculations with neutron number, but near N = 142 the data are about 1.5 to 2 times the ground-state equilibrium calculations.

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4. Fission

STUDIES OF ^{235}U AND ^{237}Np (SUBTHRESHOLD) FISSION AT ORELA, USING POLARIZED NEUTRONS AND POLARIZED TARGETS

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NUCLEAR FISSION: ^{237}Np and ^{235}U(n,f) E_n = 1 eV–50,000 eV measured prompt n's, transmitted n's (^{237}Np only); deduced (relative) J using pol. n's, pol. targets; enriched targets.

First sets of runs on ^{235}U in the form of US and UGe_2 and on ^{237}Np in the form of $NpAl_2$ have been completed. Relative J values have been obtained for a large number of resonances. Because the target polarization in these runs was low (10 to 15%), no K-value information was obtained.

The experimental setup consists of a neutron polarizer, a polarized nuclear target, 12 fast (fission) neutron detectors, and a slow neutron (transmission) detector. The latter was used only in the last group of runs and was found useful in (1) maximizing the neutron polarization and (2) determining the spins of resonances not associated with fission (in ^{237}Np).

Many of the problems of these measurements, particularly background reduction and discrimination between fission neutrons and gamma rays in the fast neutron detectors, were satisfactorily resolved. Difficulties with cryostat leaks and certain minor operational problems were very satisfactorily overcome. Very reliable operation of the equipment was obtained in the last group of runs, ending January 8, 1973. A substantial reduction in incorrectly stored events being fed to the data acquisition computer (DAC) was obtained by a redesign of the identification and tag bit generation system. Figure 1 is a block diagram of the system used. Note that the gamma count rate was sufficiently high in the large detectors to require a scale-down of a factor of 100 to prevent overloading the input of the DAC.

The general arrangement of the experiment proper is shown in Fig. 2. (Since the camera was about 9 ft above floor level, this photograph tends to minimize the actual size of the equipment.) The 37-in.-diam cryostat (at right) houses a 20.5-kg superconducting magnet and the lanthanum (neodymium) (Nd) magnesium nitrate (LMN) crystals, held at 1°K, which served as the neutron polarizer. These crystals contain 24 waters of hydration, and the polarization of the paramagnetic (neodymium) electrons is "pumped" into the proton system in the waters of hydration by an applied microwave field (about 1 W power absorption at 4 mm wavelength) which induced mutual spin flips in the combined system. The long (about 1 hr) relaxation time of the protons plays an important role in their dynamic polarization. Transmission of neutrons through the 1.8-cm-thick LMN crystals gave a polarization of 55 to 60% in the best runs by virtue of the large difference between singlet and triplet scattering and removed 80% of the neutrons. A large wall of ^{6}Li-loaded paraffin just after the neutron polarizer (not shown in Fig. 2) protected the detectors around the smaller cryostat. Additional bulk shielding was found necessary at the beam entrance to the "electron" room, where the experiment was located in flight path 2, and at the in-room collimator just ahead of the LMN polarizer.

The target cryostat, which was also designed and fabricated at LASL, was located at 13.4 m from the accelerator target in flight path 2. This cryostat was built around a dilution refrigerator head originally manufactured commercially.[3] The dilution refrigerator was capable of cooling an attached copper rod to 8 mK under no load, and with the ^{235}US (0.9 g U) in place, cooled the mixing chamber to 25 mK with the ORELA beam on; with $^{237}NpAl_2$ (2.4 g Np ≡ 50 μW) a temperature of 135 mK was typically obtained. These temperatures were at the mixing chamber. Effective on-actual-target temperatures were of course higher and probably were considerably higher, based on results to date. In Fig. 2 a large granite slab is seen supporting the polarized target cryostat. The internal superconducting magnet would have induced large eddy-current heating in the samples and cold parts of the refrigerator if appreciable building vibration were present. This slab was decoupled from the three floor-mounted columns by airbag-piston systems with position-controlled valves.[4] The 12 liquid scintillator detectors and their associated photomultipliers were suspended from the target cryostat in ferromagnetic tubes without touching a lead shield house around them (shown partially built up in Fig. 2). This arrangement was changed to individual lead houses for each detector in the neptunium case, to reduce background from the sample itself.

In Fig. 2, the beam enters from the right and exits at the left. A transmission detector consisting of a 0.5-mm ^{6}Li glass sheet and a 5-in. photomultiplier was mounted inside the flight tube at the extreme left of the photo during the neptunium measurements at 15 m from the accelerator target. Not shown are the 3000-cfm Roots blower which pumped the LMN cryostat down to 1.2°K and the ^{3}He-^{4}He dilution refrigerator circulating and purifying system. These large units are behind their respective cryostats in Fig. 2.

Figure 3 is a comparative plot of a small portion of the data on ^{237}Np in the neighborhood of the 40-eV group of fission resonances. The target peak corresponds to a maximum fission cross section of only 5 b and is the largest subthreshold fission resonance in ^{237}Np. The two curves correspond to runs in which the neutron polarizations were "positive" and "negative" respectively. All resolvable resonances in this group had the same spin, as expected from double-humped fission theory.

Figure 4 is a comparative plot of a similar segment of the ^{237}Np data but taken with the transmission detector instead of the fast neutron detectors. The effect is of course reversed in this case. Note the different energy scale and the larger number of resonances recorded. These are resonances that do not lead to fission.

The absolute values of J for the spin states observed have not been firmly established at this writing. However, a number of disagreements with the results obtained by scattering vs total measurements[5] at Geel have been found. Further analysis is in progress.

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4. "Serva-Levl," Barry Div. of Barry Wright Corp., Burbank, Calif.
5. F. Poortmans, H. Ceulemans, J. Theobald, and E. Migneco, *Proc. 3rd Conf. on Neutron Cross Sections and Technology, Knoxville, Tenn., March 1971*, CONF-710301 (vol. 2), p. 667.

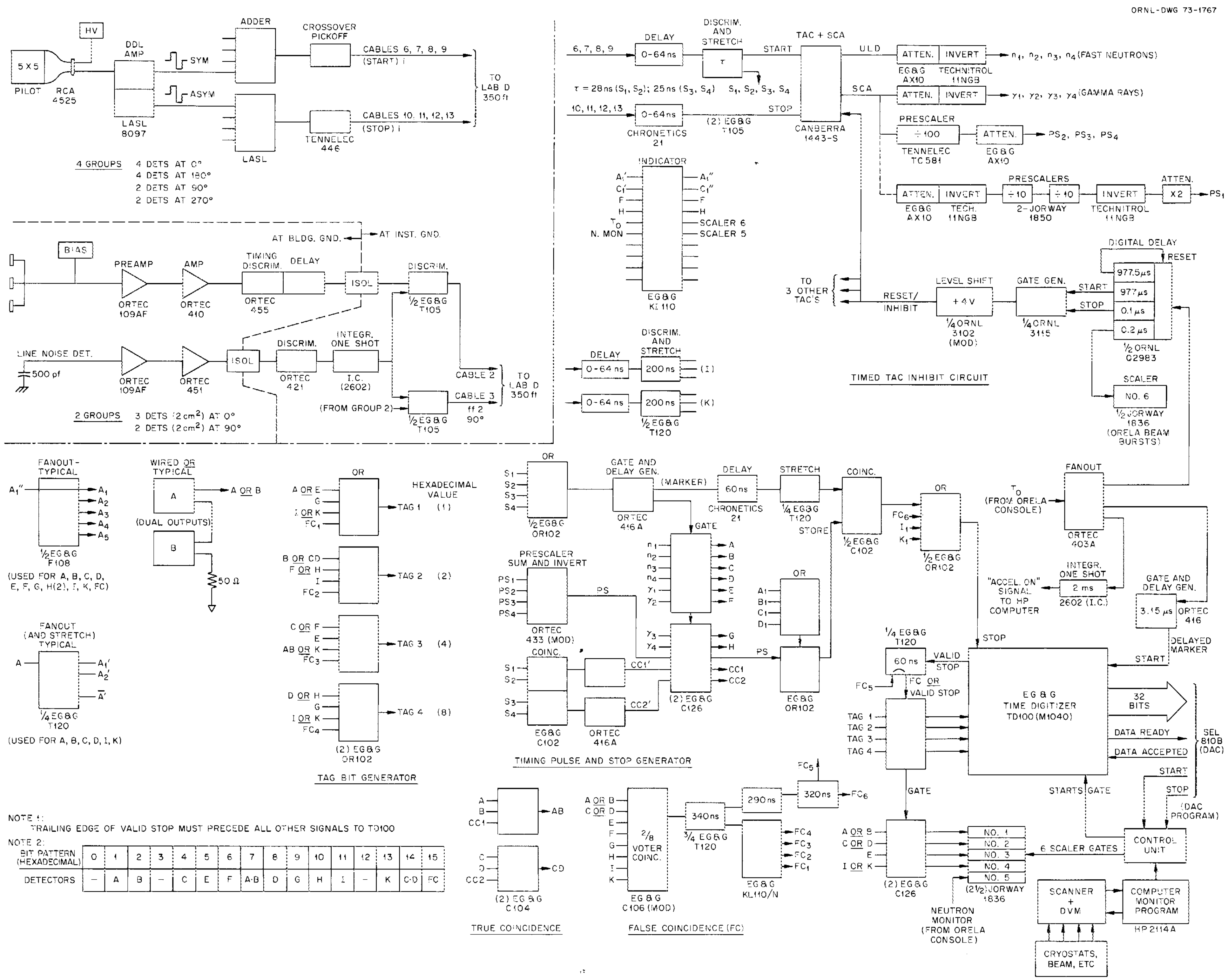

Fig. 1. Block diagram of data acquisition electronics detector systems (in "electron" room) are shown at upper left. Solid-state detectors gave very low count rates with ^{235}U and were not used except for estimating alignment in ^{237}Np. The remainder of the equipment was located in Lab D of the ORELA building. Note that prescalers were used on all gamma-ray pulses. (Gamma-ray data were used in determining time dependence of backgrounds.) The time digitizer at lower right measured all time intervals in units of 4 nsec and transmitted data as 32-bit words to the data acquisition computer (DAC).

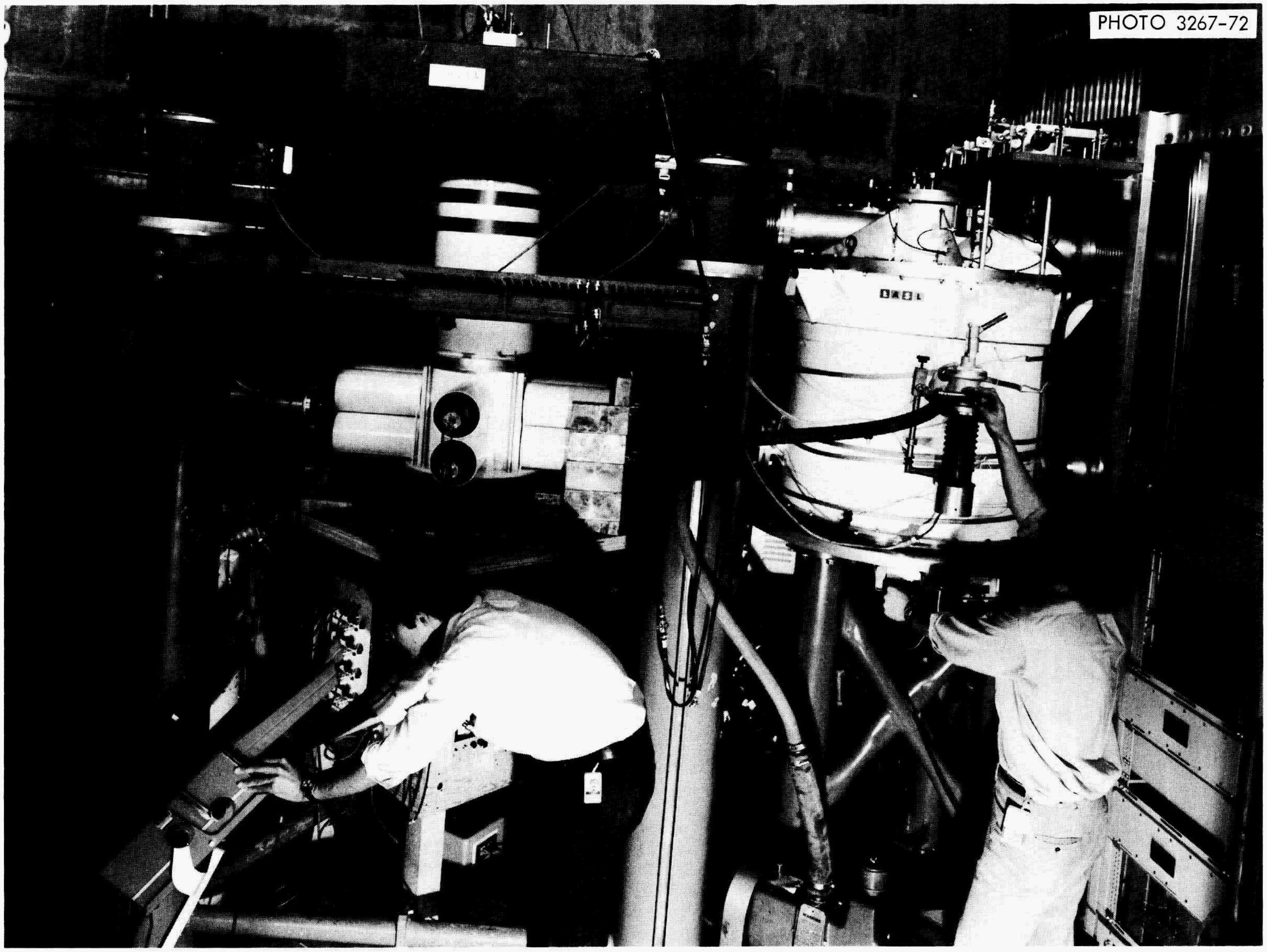

Fig. 2. Photograph of cryostat installation. The neutron beam enters at the right. The cryostats and their associated equipment were built at LASL. See text for description.

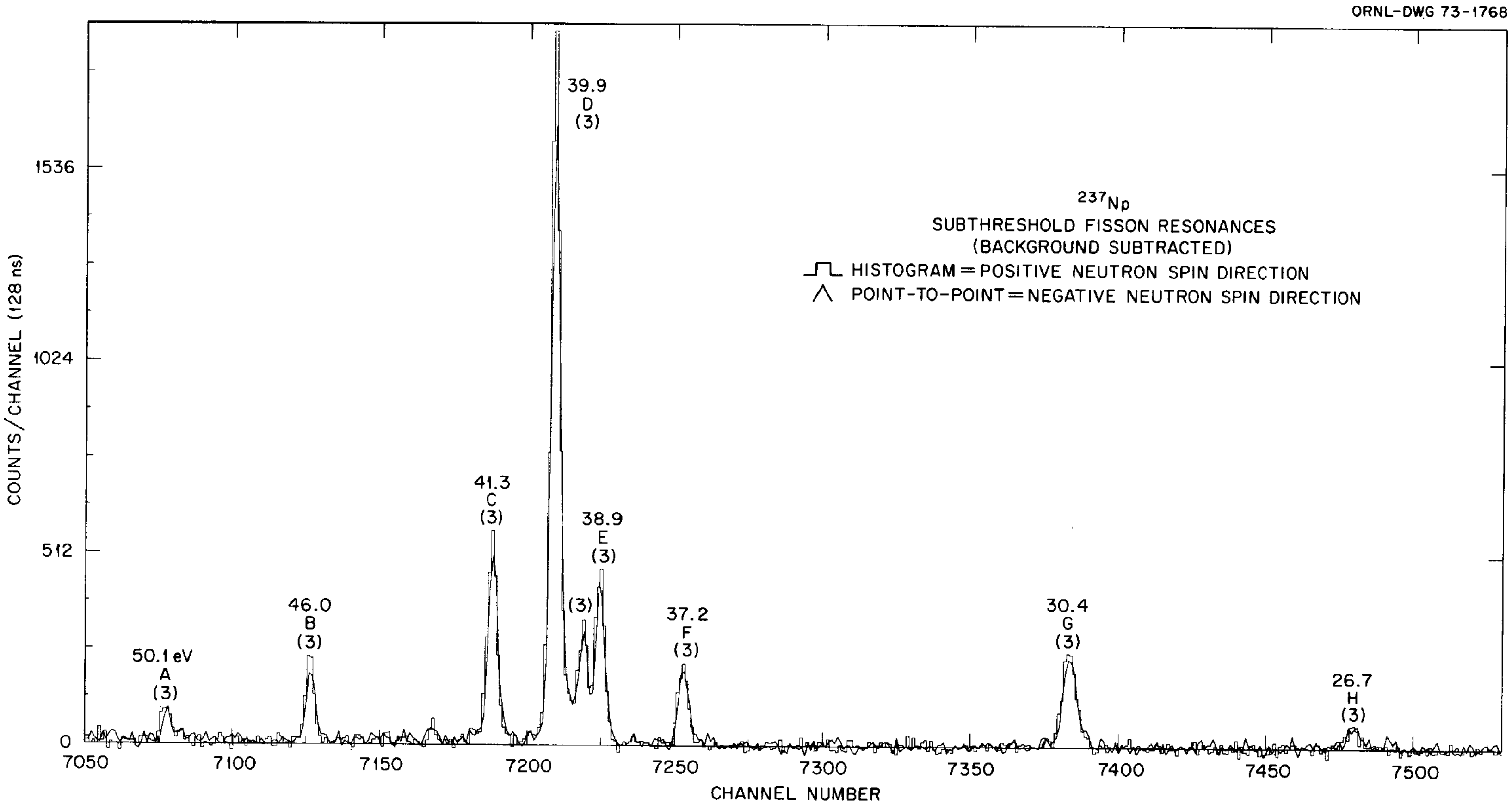

Fig. 3. Portion of ^{237}Np fission neutron detector data; comparison of "positive" neutron polarization runs with "negative" neutron polarization runs. The direction of the differences indicates the spin of the level. Letters A–H are to be compared with Fig. 4. All members of this group have a tentative *J* value assignment of 3.

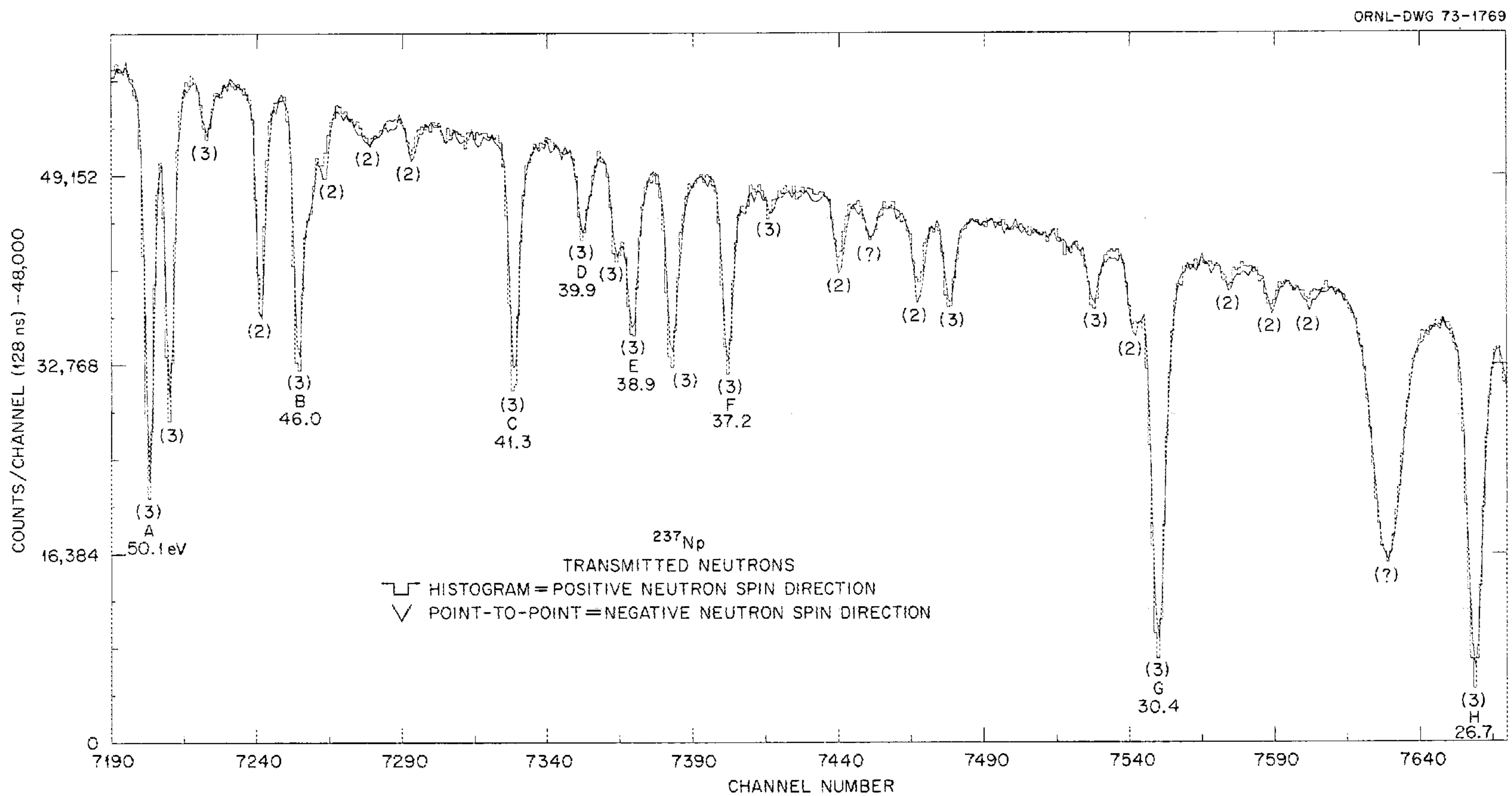

Fig. 4. Portion of ^{237}Np transmission detector data; comparison of "positive" and "negative" polarization runs. The direction of differences is reversed from Fig. 3. These data include all resonances rather than only those which lead to fission. Energies are in electron volts. Matching resonances to those in Fig. 3 are labeled A–H. Resonances have tentative *J* value assignments marked.

SMALL-SAMPLE FISSION CROSS-SECTION MEASUREMENTS ON ^{249}Cf

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NUCLEAR FISSION: ^{249}Cf(n,f),E = 0.3 eV – 1 MeV; measured $\sigma_{n,f}(E_n)$ relative to $\sigma_{n,f}(E_n)$ for ^{235}U, resonances. Enriched target.

A new technique for measurement of fission cross sections on ~100-μg samples, which was noted in the previous annual report,[4] has been applied to ^{249}Cf in flight path 2 at ORELA. The use of a detector nearly in contact with the sample, together with the short flight path and high intensity of ORELA, affords a means for such measurements which is competitive with underground nuclear explosions for nuclides with alpha half-lives $\lesssim$300 years and spontaneous fission half-lives $\lesssim 10^8$ years. In addition, the possibilities of repeating and modifying such measurements give a distinct and important advantage to this type of measurement.

A 128.25-μg sample of ultrapure ^{249}Cf, deposited in a 1.2-cm-diam area on a stainless steel backing, was placed at a distance of 0.86 mm from a 6-cm^2 diffused-junction detector.[5] This gave a solid angle of 0.93 × 2π. The sample *and detector* were mounted directly in the neutron beam from ORELA at 9.635 m from the target. As noted previously,[4] a pulse approximately equal to that from a single fission fragment was observed at the time of arrival of the gamma flash from the linac target. This small pulse size can be understood on the basis of the small sensitive volume of the detector silicon in the beam (0.014 cc). Since the alpha-decay half-life of ^{249}Cf is 352 ± 6 years, an alpha count rate of ~10^7 per second was expected and found. It was found necessary to use an extremely fast current preamplifier with rise and fall times of ~1.5 and 15 nsec to reduce pileup. A discriminator setting of ~25 MeV (~5 times the alpha pulse height) was used to eliminate alpha counts from the results. It was verified that no fission counts were lost by this procedure in subsidiary measurements.

An identical detector was placed in a nearly 2π geometry with a sample of ^{235}U at 9.735 m (4 in. downstream) in the same beam, and measurements were taken from this detector at the same time. Less exotic electronic equipment was used because of the lower alpha count rate. This detector geometry was more complex; a thick disk with a circular hole was interposed between the detector and a large-area ^{235}U source of 406 (±3%) μg/cm^2 to give an effective source of 458.2 μg. A Monte Carlo calculation of the solid angles in the two cases was required to obtain their ratio.

It was found that radiation damage from the high alpha count rate caused a substantial reduction in the ^{249}Cf fission count rate with time at constant discriminator setting and detector bias. The count rate could be raised toward its original value by increasing the bias. As much as 500 V bias was used on the 125-μm-thick detectors. In one run (No. 20313) the count rate was found to decay to seven-tenths of its original value (relative to the ^{235}U detector) after 15 hr. Integration of the area under this curve was compared with the integral under a constant line at the initial count rate ratio. All runs may thus be normalized to this initial count rate ratio.

A graph of the total fission counts per channel is shown in Fig. 1. The various channel widths and times were as shown in Table 1. The most obvious and surprising result is the appearance of a very large resonance at 0.715 eV in ^{249}Cf. This resonance has a full width at half maximum of 0.15 eV and a peak which is approximately 4000 b. Previous measurements[6] utilizing an underground nuclear explosion as a pulsed neutron source have been made down to ~20 eV. We found 11 new resonances between 0.31 and 20 eV, including the large resonance mentioned above. In general a comparison of these data from 20 eV to 2 keV shows good agreement. Unresolved data up to ~1 MeV were obtained in the present measurements.

Table 1. Time-of-flight "crunch" program parameters

Starting time (μsec)	No. of channels	Channel width (nsec)	Starting channel
0	2000	16	0
32	1000	32	2000
64	1000	64	3000
128	1000	128	4000
256	1000	256	5000
512	1000	512	6000
1024	250	1024	7000
1280[a]			7249[b]

[a]Clock reset at 1245 μsec (1250 μsec between accelerator pulses).
[b]Ending channel of data storage.

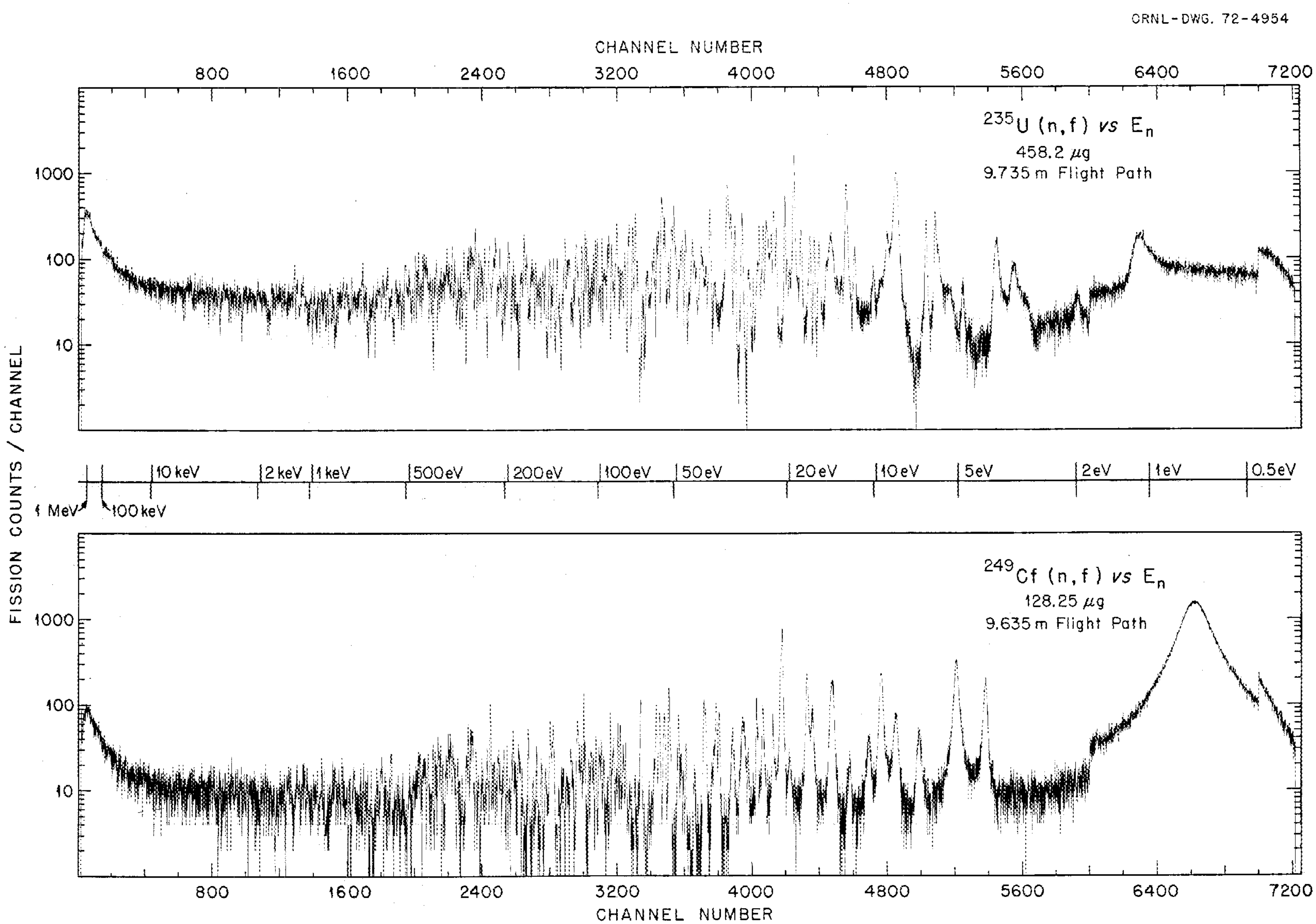

Fig. 1. ^{249}**Cf and** ^{235}**U fission fragments – log (counts/channel) vs channel number (time-of-flight spectra).** Steps in the plots at channels 2000, 3000, etc., are caused by a doubling of the channel width at each step. The first 2000 channels are 16 nsec wide (see Table 1). Sum of runs 20312 and 20313, approximately 30 hr at 26 kW average accelerator power. No background subtraction. Zero of time at 20–21 nsec, both plots. Detectors purchased from Solid State Radiations, Inc. (model 600-PIN-125).

Analysis of the data has been delayed by the work on polarized neutrons on polarized fissionable targets[7] but is now in progress.

1. Chemistry Division.
2. Instrumentation and Controls Division.
3. Los Alamos Scientific Laboratory.
4. *Phys. Div. Annu. Progr. Rep. Dec. 31, 1971*, ORNL-4743, p. 88.
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ASYMMETRIC FISSION IN THE TWO-CENTER MODEL[1]

M. G. Mustafa[2] U. Mosel[3] H. W. Schmitt

Four-dimensional potential energy surfaces have been calculated in the asymmetric two-center model for ^{252}Fm, ^{258}Fm, ^{264}Fm, and ^{236}U. Symmetric fission is found to be preferred in ^{258}Fm, consistent with a recent observation; symmetric mass division is strongly preferred in ^{264}Fm. Asymmetric fission is preferred in ^{252}Fm and in ^{236}U, for which the fission path is investigated in more detail. The development of asymmetry in the fission of ^{236}U is described.

1. Abstract of published paper: *Phys. Rev. Lett.* 28, 1536 (1972).
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ASYMMETRY IN NUCLEAR FISSION[1]

M. G. Mustafa[2] U. Mosel[3] H. W. Schmitt

The two-center shell model for fission has been generalized to include asymmetric deformations. The calculation of the potential energy involves four independent shape variables, where only two were required in the symmetric calculations. Potential energy calculations have been carried out for ^{202}Pb, ^{210}Po, ^{236}U, ^{248}Cm, ^{252}Fm, ^{258}Fm, and ^{264}Fm. Asymmetric fission is found to be energetically preferred in ^{236}U, ^{248}Cm, and ^{252}Fm; and symmetric fission is preferred in ^{202}Pb, ^{210}Po, ^{258}Fm, and ^{264}Fm. Two of these nuclei, namely, ^{236}U and ^{210}Po, have been studied in detail. It is seen that the asymmetry in ^{236}U remains almost constant from the second saddle to scission, whereas in ^{210}Po (and also in ^{202}Pb) the preferred shape changes from asymmetry in the region of the second saddle to symmetry in the region of scission. The results for fermium isotopes indicate that there is a transition from asymmetric fission in the lighter fermium isotopes to symmetric fission in the heavier fermium isotopes. The preference for symmetric mass division in ^{264}Fm is very strong, since two double-magic $^{132}_{50}Sn_{82}$ fragments are formed at symmetry. In general: the structures which appear in the potential energy surfaces are the results of an interplay between compound-nucleus shell structure, fragment shell structures, and liquid-drop-model energies. Comparisons of our results with experimental observations indicate that the observed mass distribution is correlated with the potential energy surface in the neighborhood of scission.

1. Abstract of paper submitted for publication in *Physical Review C.*
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POTENTIAL ENERGY FOR THE FISSION OF A SUPERHEAVY NUCLEUS

M. G. Mustafa[1] U. Mosel[2] H. W. Schmitt

The existence of an island of stable superheavy nuclei in the region of $Z = 114$ and $N = 184$ has been predicted by theoretical calculations.[3] For the last several years, extensive searches have been made both to find them in nature and to produce them in the laboratory. Although no conclusive evidence for their existence has yet resulted out of these attempts, the theoretical investigation of the properties of these nuclei, for example, spontaneous fission and other decay modes, and the experimental searches have been continued. We are here investigating the potential energy for fission of the nucleus $^{298}_{114}X_{184}$, which has been predicted to be a double-closed-shell nucleus and the most stable one in the island of superheavy nuclei.

Our investigation consists of calculations of the potential energy of this nucleus as a function of four deformation variables. The general nature of the shape parameterization permits study of a suitably broad range of shapes, including both symmetric and asymmetric degrees of freedom, from the ground state of a nucleus to the scission region. We have used the Strutinsky shell-correction method[4] in our two-center model for fissioning nuclei, as reported previously.[5]

Results show that reflection-symmetric shapes are energetically preferred all along the minimum-potential-energy path in the potential surface for fission of $^{298}_{114}X_{184}$; however, the potential is soft toward asymmetry along the entire path. The first barrier is much higher than the second, and the second minimum is shallow.

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DEPENDENCE OF FISSION MASS ASYMMETRY ON THE INTERNAL EXCITATION ENERGY OF THE FISSIONING NUCLEUS

M. G. Mustafa[1] H. W. Schmitt

Introduction

The observed mass asymmetry in the spontaneous and low-energy nuclear fission of heavy nuclei decreases with increasing internal excitation of the compound fissioning nucleus. The yield of fragments in the valley of the asymmetric mass distribution for actinides increases with increasing excitation energy and finally reaches a yield comparable with that in the asymmetric peaks, after which the mass yield distribution is peaked at symmetry. Recent theoretical studies[2-4] have shown that the mass asymmetry at low compound-nucleus excitation energy can be related directly to nuclear shell effects. We have therefore begun an investigation of the dependence of shell effects on internal nuclear excitation and to see how this influences the effective potential surface for fission and hence the mass yield distribution.

We assume that internal excitation in a nucleus gives rise to a probability distribution for the occupation of the single-particle levels and that this distribution may be represented by a Fermi distribution function:

$$1/[1 + e^{(\epsilon_n - \epsilon_F)/T}] \ ,$$

where ϵ_n is the energy of a single-particle level, ϵ_F is the Fermi energy, and T is the nuclear temperature. Such a function would exist for both protons and neutrons.

In this formulation, when $T > 0$, all energy levels from zero to infinity will have an occupation probability associated with them and should therefore be taken into account; since this is impractical in the required numerical procedures, we introduce a cutoff at 530 single-particle levels. Thus far, this seems to suffice.

In our preliminary investigations to date, we have carried out calculations for two values of the asymmetry parameter[2] λ in the fission of ^{236}U, namely, 118/118 and 140/96, and have calculated the shell correction δU_T and total potential energy V near scission as a function of temperature. Pairing effects have been neglected in calculations to date.

The Model

In accordance with the above assumptions, we can write the sum of single-particle energies of the excited nucleus as the sum of two terms, one for protons and one for neutrons, of the form

$$E_T = 2 \sum_{n=1}^{\infty} \frac{\epsilon_n}{1 + e^{(\epsilon_n - \epsilon_{FT})/T}} \ , \qquad (1)$$

where ϵ_n is the energy of a single-particle level for a given nuclear shape; these values are obtained from our two-center model calculations,[2] which, in turn, make use of the Strutinsky prescription.[3] The Fermi energy ϵ_{FT} is different for protons and neutrons and is determined for each type of particle and for each temperature by the conservation of particle number N, that is,

$$\frac{N}{2} = \sum_{n=1}^{\infty} \frac{1}{1 + e^{(\epsilon_n - \epsilon_{FT})/T}} . \tag{2}$$

The smoothly varying part of the total energy (protons or neutrons) is given by a formula analogous to that of the usual Strutinsky prescription[3] but incorporating the Fermi function as follows:

$$\widetilde{E}_T = 2 \int_{-\infty}^{\infty} \sum_{n=1}^{\infty} \frac{\epsilon\, \widetilde{g}(\epsilon, \epsilon_n)}{1 + e^{(\epsilon - \widetilde{\epsilon}_{FT})/T}} d\epsilon , \tag{3}$$

where $\widetilde{\epsilon}_{FT}$ is the Fermi energy of the smooth distribution of levels and is determined by proton or neutron conservation:

$$\frac{N}{2} = \int_{-\infty}^{\infty} \sum_{n=1}^{\infty} \frac{\widetilde{g}(\epsilon, \epsilon_n)}{1 + e^{(\epsilon - \widetilde{\epsilon}_{FT})/T}} d\epsilon . \tag{4}$$

The function $g(\epsilon, \epsilon_n)$ is the usual Gaussian smoothing function used in the Strutinsky prescription, given by

$$\widetilde{g}(\epsilon, \epsilon_n) = \frac{1}{\gamma\sqrt{\pi}} e^{-(\epsilon - \epsilon_n)^2/\gamma^2} \cdot \sum_{m=0}^{p} c_m H_m\left(\frac{\epsilon - \epsilon_n}{\gamma}\right) ,$$

where

$$c_m = \frac{(-)^{m/2}}{2^m (m/2)!} , \quad m \text{ even} ,$$

$$= 0 \quad , \quad m \text{ odd}.$$

$H_m(x)$ are Hermite polynomials; these differ from the usual Hermite function in that each H_m is normalized to unity with a suitable Gaussian weighting factor γ. The summation over m extends only to p, which defines the order of the shell correction. The quantities γ and p are not physical quantities and must be chosen so that over some range the smooth energy, $\widetilde{E}_T$, is independent of them. For $T = 0$, the values of $\gamma = 1.2 \times 41$ MeV/$A^{1/3}$ and $p = 6$ are nearly optimum choices,[2] and we have used these values in the calculations to date.

We may now define the shell correction δU_T at temperature T as

$$\delta U_T = (E_T - \widetilde{E}_T)_{\text{protons}} + (E_T - \widetilde{E}_T)_{\text{neutrons}} . \tag{5}$$

For $T = 0$, Eqs. (1–5) reduce to those of the standard Strutinsky prescription.[2]

The effective total potential energy at a given temperature is given by

$$V = E_{\text{LDM}} + \delta U_T , \tag{6}$$

where E_{LDM} is the liquid-drop-model energy.

The internal excitation energy E_x for a given nuclear shape may be obtained from the relation

$$E_x = (E_T - E_{T0})_{\text{protons}} + (E_T - E_{T0})_{\text{neutrons}} , \tag{7}$$

where E_{T0} for protons or neutrons is the sum of single-particle energies up to the usual ($T = 0$) Fermi surface.

Calculations and Results

Preliminary calculations based on the above model have been carried out for the fissioning nucleus ^{236}U, for shapes near scission. We have used the same computer program as was used in our earlier two-center-model calculations[2] to generate the single-particle energies for shapes corresponding to $D = 2.5$ fm, $\lambda = 118/118$ and $D = 2.4$ fm, $\lambda = 140/96$. The quantity D is the neck radius, and λ is the volume ratio of those portions of the nucleus on either side of the neck plane. (The reader is referred to the longer paper of ref. 2 for an explanation of the shape parameterization and other details of the calculations.)

The purpose of the calculations reported here, which are carried out for shapes near scission ($D = 2.5$), is to compare the effective potential energy as a function of temperature for a symmetric shape ($\lambda = 118/118$) with that for the asymmetric shape ($\lambda = 140/96$) that corresponds to the minimum $T = 0$ potential energy valley.

Results are shown in Fig. 1. The lower part of the figure shows the total potential energy, V, given by Eq. (6), as a function of nuclear temperature in MeV. The

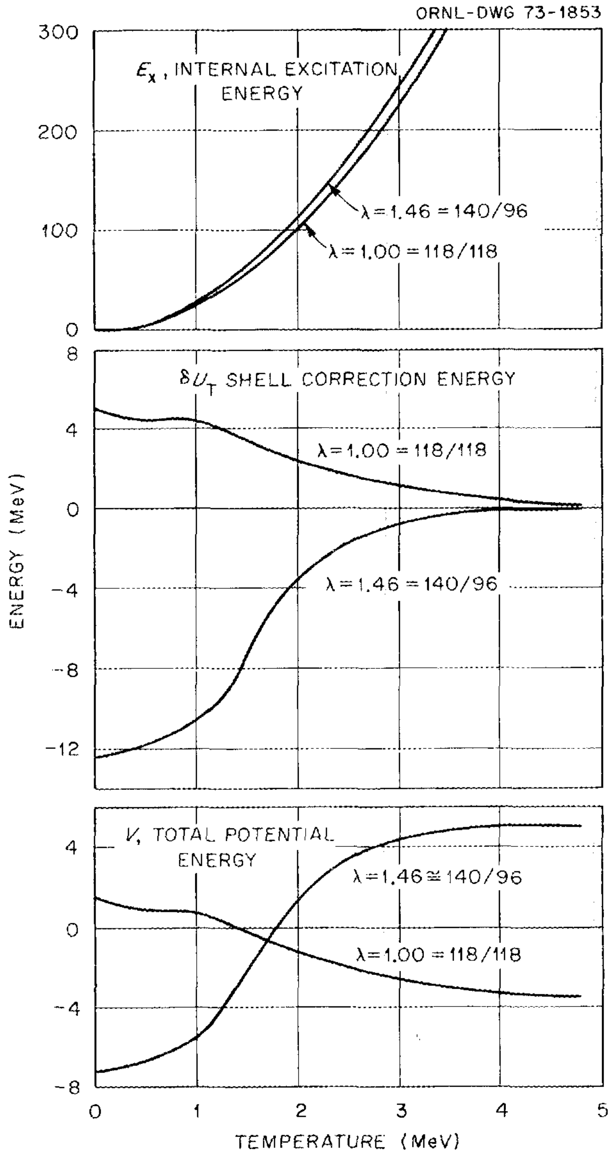

Fig. 1. Preliminary results for ^{236}U for two shapes near scission. Calculations have been made for asymmetry (volume ratio) parameters 118/118 and 140/96; the neck radius D is 2.5 fm for both cases. Lower part: Effective total potential energy vs nuclear temperature. Middle part: Shell-correction energy vs nuclear temperature. Upper part: Internal excitation energy vs nuclear temperature.

corresponding shell correction, δU_T, given by Eq. (5) and excitation energy, E_x, given by Eq. (7), are shown in the middle and upper parts of the figure. It is significant that for both cases the shell correction approaches zero as the temperature increases, and finally, at $T = 4$ to 5 MeV, it essentially vanishes. The total potential energies for the two shapes cross at $T \approx 1.7$ MeV.

If the potential energy dominates the fission process (i.e., if dynamic effects do not affect the course of the process) and if the scission region is most important in determining the mass division, then the mass distribution might be expected to become symmetric at $T \approx 1.7$ MeV.

The results shown here do not include any pairing effects, however, and more complete calculations, which will include pairing and will be carried out over a wider range of both symmetric and asymmetric shapes from ground state to scission, are clearly required before we draw firm conclusions.

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REALISTIC SINGLE-PARTICLE K MATRIX FOR DEFORMED AND FISSIONING NUCLEI

R. Y. Cusson[1] D. Kolb[1] H. W. Schmitt

A low-order approximation for the Brueckner-Goldman density-dependent and momentum-dependent single-particle Hamiltonian, recently proposed by Meldner,[2] has been used to construct a computer code which obtains the self-consistent shape of deformed and fissioning nuclei. A double-oscillator (two-centers) basis is used to speed up convergence, and a novel method for expanding the Coulomb and nuclear potentials in terms of Gaussians is used.[3] Starting with reasonable nuclear matter parameters, preliminary results show that one can adequately predict the binding energies, radii, deformation parameters, and single-particle energies of most light nuclei from ^{4}He to ^{40}Ca. Similar calculations for heavy and fissioning nuclei are being set up and will be reported in the future.

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SYSTEMATICS OF FRAGMENT MASS AND ENERGY DISTRIBUTIONS FOR PROTON-INDUCED FISSION OF ^{233}U, ^{235}U, AND ^{238}U[1]

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NUCLEAR FISSION: ^{233}U(p,f), ^{235}U(p,f), ^{238}U(p,f), E_p = 7–13 MeV; measured correlated fragment energies, deduced fragment mass and total kinetic energy distributions, averages, and widths, as functions of bombarding energy.

Thin targets of ^{233}U, ^{235}U, and ^{238}U were bombarded with protons of several energies between 7 and 13 MeV. Correlated energies of fission fragment pairs were measured with silicon surface-barrier detectors. Fragment mass vs total kinetic energy distributions were deduced, and their systematic variation with bombarding energy was studied. It was found that the yield in the valley of the mass distributions for symmetric divisions increases with increasing excitation energy and that the peaks move slightly toward symmetry. The average total kinetic energy for mass divisions with one fragment mass $\simeq$132 amu was found to decrease with increasing excitation energy, while for other mass divisions little change was observed. The average overall total kinetic energy was found to decrease with increasing bombarding energy, and widths of both the kinetic energy distributions and the mass distributions were found to increase somewhat. The results are discussed in terms of fragment shell effects, which appear to persist to our highest excitation energy (~18 MeV), and also in terms of the two-component fission hypothesis.

1. Abstract of paper submitted for publication in *Physical Review C.*
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FISSION OF ^{209}Bi BY 36.1-MeV PROTONS: SEARCH FOR AN ASYMMETRIC COMPONENT IN THE MASS DISTRIBUTION, AND NEUTRON EMISSION RESULTS[1]

Franz Plasil Robert L. Ferguson[2] Frances Pleasonton H. W. Schmitt

NUCLEAR REACTIONS, FISSION: ^{209}Bi(p,f), E = 36.1 MeV; measured fragment kinetic energies, deduced prompt n's and pre-neutron-emission fragment mass and total kinetic energy distributions.

A thin deposit of ^{209}Bi was bombarded with 36.1-MeV protons from the Oak Ridge Isochronous Cyclotron, and correlated energies of fission fragment pairs were measured with silicon surface-barrier detectors. The mass-yield distribution obtained from these energies was compared with the radiochemical results of Sugihara, Roesner, and Meadows; we do not confirm the existence of the small asymmetric peak that appears in the wings of their distribution. Studies of statistical uncertainties and dispersion effects in our experiment indicate that they are not large enough to wash out such peaks. The average number of neutrons emitted as a function of fragment mass was obtained from a cumulative yield calculation and is consistent with an earlier measurement for ^{4}He-induced fission of ^{209}Bi. Pre-neutron-emission mass and kinetic energy distributions are presented.

1. Abstract of paper submitted for publication in *Physical Review C.*
2. Chemistry Division.

MASS AND TOTAL KINETIC ENERGY DISTRIBUTIONS FROM THE SPONTANEOUS FISSION OF ^{246}Cm

Frances Pleasonton   Robert L. Ferguson[1]   Franz Plasil   C. E. Bemis, Jr.[1]

NUCLEAR FISSION: Spontaneous fission of ^{246}Cm, measured correlated fragment energies, deduced mass and total fragment kinetic energy distributions.

In recent years a number of fissioning systems in the transplutonium region have been studied.[2,3] The measurements involve both radiochemical techniques, in which yields of radioactive fission products are determined, and physical techniques, in which fragment energies of correlated fragment pairs are measured. At Argonne National Laboratory an extensive study of mass distributions from the spontaneous and neutron-induced fission of transplutonium elements is being undertaken.[2,4] The present report presents our results from the spontaneous fission of ^{246}Cm, which is one of the fissioning systems not investigated either at Argonne National Laboratory or at Los Alamos Scientific Laboratory. Considerable data from the fission of other curium isotopes do, however, exist. Thus, radiochemical measurements have been made for spontaneous fission of ^{244}Cm,[5] and physical measurements have been made for spontaneous fission of ^{248}Cm[2] and ^{250}Cm[6] and also for neutron-induced fission of ^{245}Cm.[2] This last system is of particular interest to us, since the fissioning nucleus is the same as in our work. Thus our study can be regarded, in the light of the data from other laboratories, as contributing to the systematic study of this interesting region of fissioning nuclei. Extensive comparisons and correlations will be made with the Argonne and Los Alamos data at a later time.

A spontaneously fissioning ^{246}Cm source was made by depositing the material with an isotope separator onto a thin carbon backing foil. The thickness of the deposit was about 50 $\mu g/cm^2$, and the thickness of the carbon foil was 40 $\mu g/cm^2$.

The standard energy-correlation technique was used.[7] Pulse heights related to energies of correlated fragment pairs were measured by means of silicon surface-barrier detectors and were recorded event by event on magnetic tape by means of a multiparameter pulse-height analyzer. The data were processed by the method described in ref. 8, and a standard calibration based on ^{252}Cf fragments was used.[9] The fragment masses were obtained from the energy data by applying the principles of conservation of mass and momentum. In the absence of neutron-emission data for our system, we were not able to correct for the effect of neutron emission, and our fragment masses are thus the "provisional" masses of ref. 7. They are, however, very nearly equal to pre-neutron-emission masses for cases in which the two fragments evaporate about equal numbers of neutrons and are not in error by more than about 2 amu for cases of very unequal neutron evaporation.

To obtain an indication of the overall quality of our data, we have performed a companion ^{252}Cf fragment-energy correlation experiment, using the same detectors and electronics. The results from the ^{252}Cf experiment are shown by open circles in Fig. 1. The solid line indicates the corresponding results (i.e., results not corrected for experimental resolution or neutron evaporation) from ref. 7. It can be seen that our results have a somewhat smaller peak-to-valley ratio than those of ref. 7. The difference, however, is not very large and can be accounted for by the relatively poor quality of the particular ^{252}Cf source that was used in our experiment. It can be concluded that the quality of our data is roughly comparable with that of ref. 7.

The mass-yield distribution from the spontaneous fission of ^{246}Cm which we have obtained is shown by closed circles in Fig. 1. The distribution is normalized to 200% and consists of about 60,000 events. It is evident that the valley of symmetric mass divisions is considerably deeper for spontaneous fission of ^{246}Cm than for spontaneous fission of ^{252}Cf.

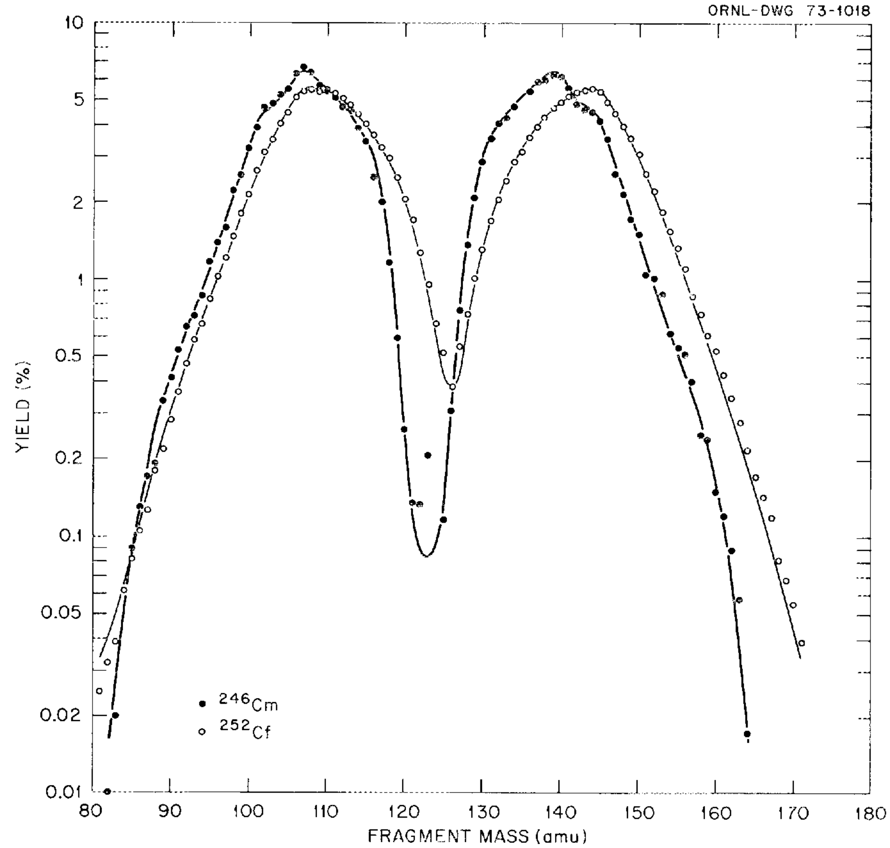

Fig. 1. Mass distribution from ^{246}Cm(SF) (solid points) not corrected for experimental resolution or neutron emission. The curve through the points is reflected through symmetry and normalized to 200%. The open points indicate corresponding results from our ^{252}Cf(SF) comparison experiment; the light curve shows the ^{252}Cf(SF) results of Schmitt et al., *Phys. Rev.* **141**, 1146 (1966).

Table 1 gives various averages and rms widths obtained from our distribution and compares them with similar numbers from ref. 4 for the neutron-induced fission of ^{245}Cm and for the spontaneous fission of ^{248}Cm. Given in the table are $\langle m_L \rangle$ and $\langle m_H \rangle$ the average light- and heavy-fragment masses; σ_m, the root-mean-square width of the heavy-fragment mass peak; $\langle E_K \rangle$, the average total fragment kinetic energy; and σ_{EK}, the rms width of the total kinetic energy distribution. None of the results are corrected for experimental resolution effects. It can be seen from Table 1 that our results are, on the whole, consistent with those of ref. 4. It is interesting to note that $\langle m_H \rangle$ for the curium isotopes remains in the vicinity of 140 amu, once more reaffirming the well-known constancy of the heavy-fragment group. In the mass region of 130 to 132 amu the mass yield curve for ^{246}Cm(SF) obtained here virtually coincides with the mass yield curves from numerous other systems, such as those from neutron-induced fission of uranium and plutonium isotopes.

Table 1. Average values and widths of mass and total kinetic energy distributions

Fissioning system	$\langle m_L \rangle$	$\langle m_H \rangle$	σ_m	$\langle E_K \rangle$	σ_{EK}
^{246}Cm(SF)[a,c]	106.5	139.5	6.6	181.3	10.8
^{245}Cm(*n,f*)[b]	105.3	140.7	6.7	184.2	11.7
^{248}Cm(SF)[b,c]	107.0	141.0	6.6	182.1	10.5

[a]This work.

[b]From preprint of chap. II in the annual report of the Chemistry Division of Argonne National Laboratory for fiscal year 1972.

[c]Preliminary results.

One surprising difference between our results and those for ^{245}Cm(*n,f*) in Table 1 is in the values of $\langle E_K \rangle$.

The uncertainty in $\langle E_K \rangle$ in our experiment is expected to be less than ±1 MeV, and thus the two $\langle E_K \rangle$ values do not agree within experimental errors. The difference in excitation energy between the two cases is not expected to account for the discrepancy. In general, $\langle E_K \rangle$ values seem to correlate rather well with $Z^2/A^{1/3}$, where Z and A are the charge and mass number of the fissioning nucleus, respectively. If the ^{245}Cm(n,f) $\langle E_K \rangle$ value is plotted against $Z^2/A^{1/3}$, it falls slightly below the extrapolated curve from neutron-induced fission given in Fig. III.3 of ref. 10. Our value for ^{246}Cm(SF) falls slightly above the line calculated from the empirical relationship given by Viola,[11] in better agreement with earlier values from other spontaneously fissioning systems also plotted in ref. 10. These differences are not yet understood.

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NEUTRON MULTIPLICITY DISTRIBUTIONS IN THE SPONTANEOUS FISSION OF ^{246}Cm, ^{248}Cm, AND ^{252}Cf[1]

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The neutron multiplicities $P(n)$ in the spontaneous fission of ^{246}Cm, ^{248}Cm, and ^{252}Cf have been measured in a ^{3}He neutron counter assembly. The efficiency ϵ for detection of a single neutron was measured to be 0.360, based on $\bar{\nu}$ (average number of neutrons per fission) = 3.73 for ^{252}Cf spontaneous fission. Using this value of ϵ and assuming a Gaussian distribution $p(\nu)$ for the emitted neutrons, we fitted our observed $P(n)$, corrected for small background and pile-up effects, to the model by the method of least squares in which the Gaussian width σ_ν and $\bar{\nu}$ were the parameters of fit. Values of $p(\nu)$ were then calculated from the resulting Gaussian function. In the case of ^{252}Cf, our values of $p(\nu)$ agree well with literature values; the $p(\nu)$ values for the curium isotopes have not been measured previously as far as we know. The values of $\bar{\nu}$ for both ^{246}Cm and ^{248}Cm fall on a straight line through existing experimental values for the nuclides ^{242}Cm, ^{244}Cm, and ^{250}Cm in a plot of $\bar{\nu}$ vs mass number; our values were 2.86 ± 0.06 and 3.14 ± 0.06 for ^{246}Cm and ^{248}Cm respectively.

1. Abstract of paper accepted for publication in *Nuclear Science and Engineering*.
2. Chemistry Division.

PROMPT GAMMA RAYS EMITTED IN THE THERMAL-NEUTRON-INDUCED FISSION OF ^{233}U, ^{235}U, AND ^{239}Pu AND THE SPONTANEOUS FISSION OF ^{252}Cf

Frances Pleasonton Robert L. Ferguson[1] H. W. Schmitt

NEUTRON FISSION: ^{233}U, ^{235}U, ^{239}Pu, n_{th}, and $^{252}Cf_{SF}$; measured correlated γ-ray energies, fragment kinetic energies, and time; deduced average multiplicity and average energy of γ rays as functions of fragment mass.

A series of four experiments, corresponding to four different fission reactions, were performed to determine the average energy and average number of gamma rays emitted within ~5 nsec after fission as functions of two variables, fragment mass and fragment total kinetic energy. The experimental apparatus and instrumentation were identical for all four experiments, and conditions were as nearly identical as possible.

The experiments were conducted at the Oak Ridge Research Reactor, with a thermal-neutron beam of $\sim 10^8$ neutrons cm^{-2} sec^{-1} impinging on thin targets of ^{233}U, ^{235}U, and ^{239}Pu respectively. For the fourth set of measurements, on a ^{252}Cf spontaneous-fission source, the apparatus remained in position and the neutron beam was shut off. Details of the experimental arrangements are shown in Fig. 1.

Energies of coincident fragment pairs were measured with heavy-ion surface-barrier detectors (ORTEC), and gamma-ray energies were measured with a large NaI(Tl) detector, which was located 89 cm from the target and positioned coaxially with the fragment detectors. The time difference between detection of a fission fragment and a gamma ray was also measured, to allow time-of-flight discrimination against fission neutrons. The correlated four-parameter data were recorded and analyzed, event by event.

A thorough discussion of the experimental method and of the procedures of analysis is included in ref. 2, which presents detailed results on the emission of prompt gamma rays from the fission of ^{236}U. The present report constitutes a preliminary and limited survey of the results obtained in all four experiments.

Figures 2*a* and 2*b* give the results for the average energy $\bar{E}_\gamma$ and the average number $\bar{N}_\gamma$ of prompt gamma rays as functions of pre-neutron-emission mass. For ease of comparison, the results are shown as smooth curves without the data points; poor statistics in the data near symmetry preclude definition of most curves in the region about symmetric mass divisions. All of these results exhibit a sawtooth behavior, as found previously and discussed in detail for $^{235}U(n_{th},f)$.[2] The similarity of these sawtooth functions describing $\bar{E}_\gamma(m)$ and $\bar{N}_\gamma(m)$ to those describing the number of neutrons emitted in fission, $\nu(m)$, was first noted for ^{252}Cf spontaneous fission[3] and $^{235}U(n_{th},f)$.[4] In Fig. 2*c* we show, for comparison, the average number of neutrons $\bar{\nu}$ emitted as a function of fragment mass, from work by Bowman et al.[5] for ^{252}Cf and by Apalin et al.[6] for ^{234}U, ^{236}U, and ^{240}Pu.

A striking feature of Fig. 2 is the near congruence of the results within each section, for all four nuclei, for fragment masses lighter than ~105 amu and heavier than ~135 amu. In all parts of Fig. 2 the peaks and dips of the sawteeth appear at nearly the same mass number for a given nucleus; also, all three functions exhibit steeper slopes in the heavy-fragment regions than in the light-fragment regions.

For the thermal-neutron-induced fissioning systems, the average masses for the heavy-fragment groups $\langle m_H \rangle$ are ~139 or 140 amu, while the average masses for the

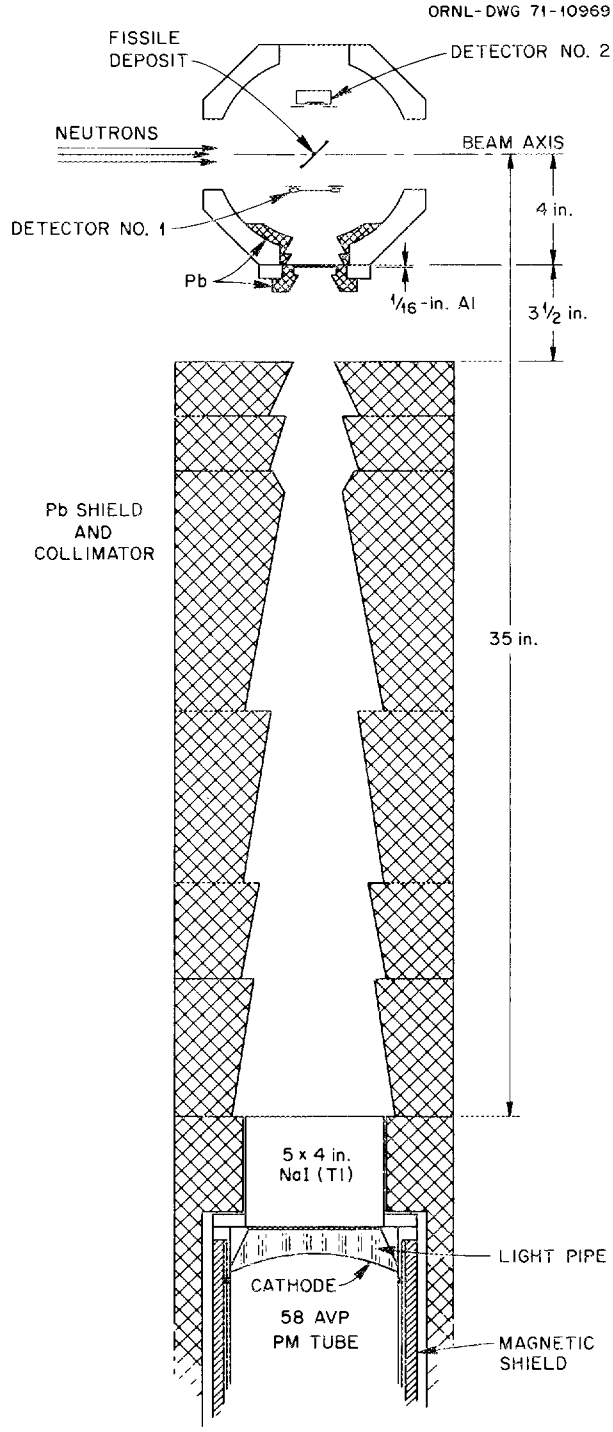

Fig. 1. Scale drawing of the experimental arrangements. Scattering of the gamma rays into the crystal was minimized by the interior design of the lead collimator.

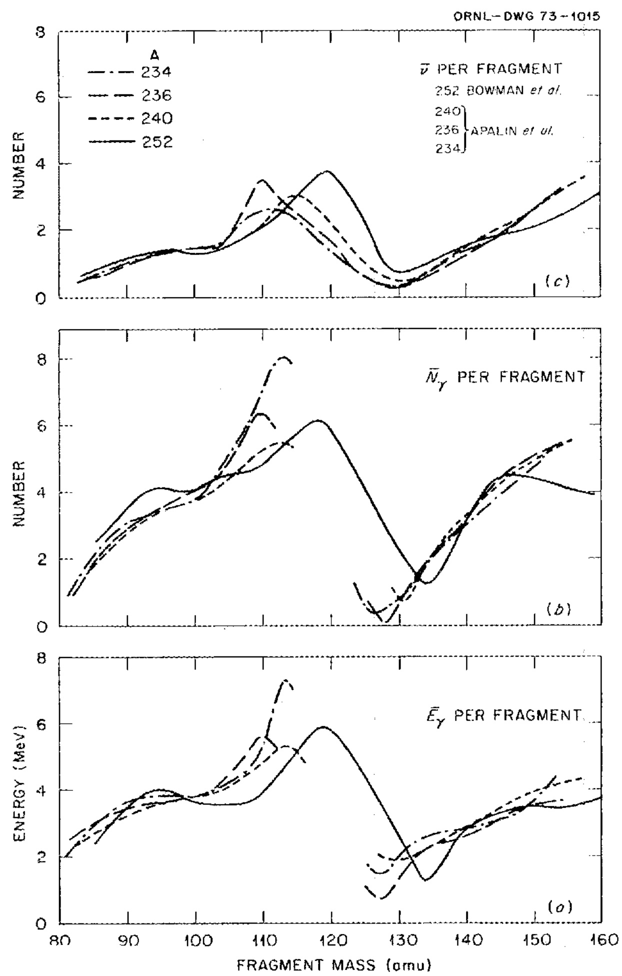

Fig. 2. ***(a)* The average energy $\bar{E}_\gamma$ and *(b)* the average number $\bar{V}_\gamma$ of gamma rays emitted as functions of fragment mass; *(c)* the average number of neutrons $\bar{\nu}$ emitted as functions of fragment mass, from Bowman et al., *Phys. Rev.* 129, 2133 (1963), and Apalin et al., *Nucl. Phys.* 71, 553 (1965).** In all cases the mass A of the fissioning nucleus is used to differentiate the results of the four experiments.

light-fragment groups $\langle m_L \rangle$ range from 95 to 100 amu; for ^{252}Cf, $\langle m_H \rangle \sim 144$ amu and $\langle m_L \rangle \sim 108$ amu. Looking at Figs. 2*a* and 2*b*, we see that average values of $\bar{E}_\gamma$ and $\bar{N}_\gamma$ for the light fragments will therefore be greater than the average values for the heavy fragments; that is, $\langle \bar{E}_{\gamma L} \rangle > \langle \bar{E}_{\gamma H} \rangle$ and $\langle \bar{N}_{\gamma L} \rangle > \langle \bar{N}_{\gamma H} \rangle$. In Fig. 2*c*, however, one can see that the inequality between average values of $\bar{\nu}$ for the two groups will be reversed; that is $\langle \bar{\nu}_L \rangle < \langle \bar{\nu}_H \rangle$.

Figure 3*a* gives the results for the average quantum energy $\bar{\epsilon} = \bar{E}_\gamma / \bar{N}_\gamma$ as a function of fragment mass; only in the case of ^{252}Cf did the data permit us to estimate this quantity through the valley of the mass distribution. The decrease seen in $\bar{\epsilon}$ as one moves away from

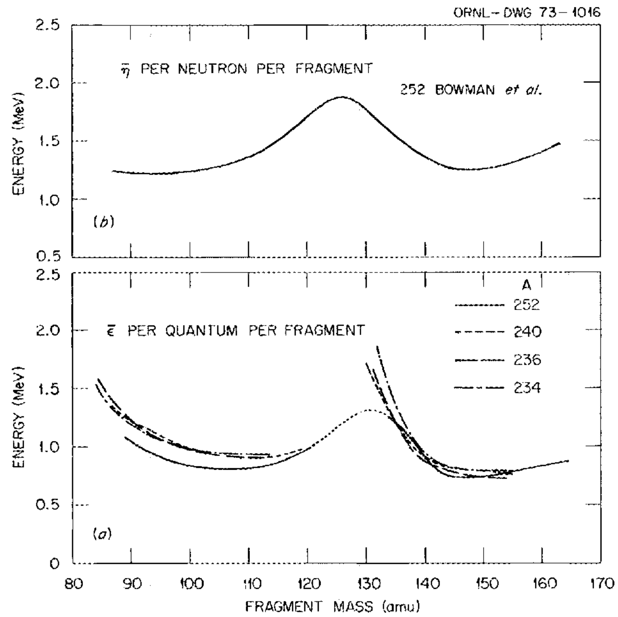

Fig. 3. *(a)* The average photon energy $\bar{\epsilon}$ per fragment; *(b)* the average neutron center-of-mass kinetic energy $\bar{\eta}$ per fragment, from Bowman et al., *Phys. Rev.* 129, 2133 (1963).

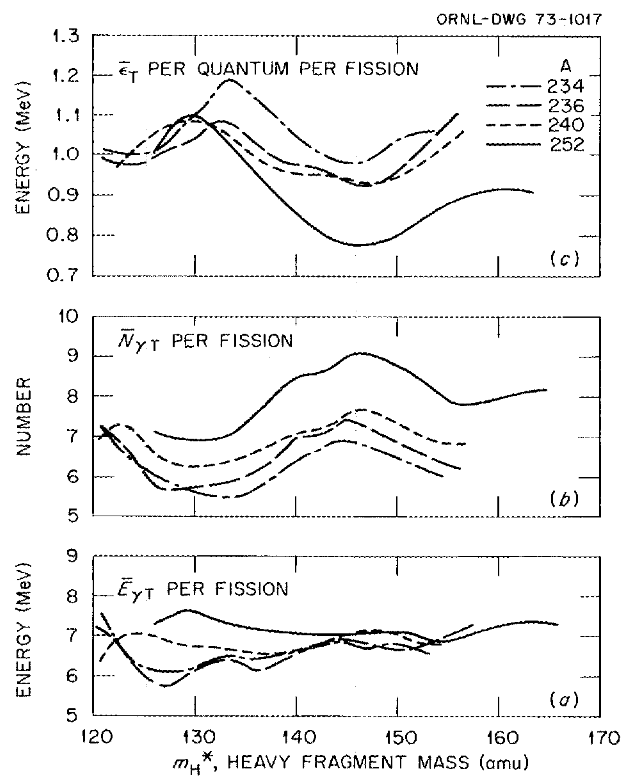

Fig. 4. *(a)* The average total energy $\bar{E}_{\gamma T}$ and *(b)* the average total number $\bar{N}_{\gamma T}$ of gamma rays emitted per fission; *(c)* the average photon energy $\bar{\epsilon}_T$ per fission.

Table 1. Average numbers and energies of prompt gamma rays emitted in the fission of ^{234}U, ^{236}U, ^{240}Pu, and ^{252}Cf

	^{234}U	^{236}U	^{240}Pu	^{252}Cf
Overall average values per fission				
$\langle \bar{E}_{\gamma T} \rangle$, MeV	6.69 ± 0.3	6.43 ± 0.3	6.73 ± 0.35	7.06 ± 0.35
$\langle \bar{N}_{\gamma T} \rangle$	6.31 ± 0.3	6.51 ± 0.3	6.88 ± 0.35	8.32 ± 0.4
$\langle \bar{\epsilon}_T \rangle$, MeV per gamma	1.06 ± 0.07	0.99 ± 0.07	0.98 ± 0.07	0.85 ± 0.06
Average values for light- and heavy-fragment groups				
$\langle \bar{E}_{\gamma L} \rangle$, MeV	3.84 ± 0.45	3.78 ± 0.45	3.86 ± 0.55	4.18 ± 0.6
$\langle \bar{E}_{\gamma H} \rangle$, MeV	2.85 ± 0.35	2.66 ± 0.35	2.86 ± 0.5	2.88 ± 0.5
$\langle \bar{N}_{\gamma L} \rangle$	3.57 ± 0.5	3.63 ± 0.5	3.87 ± 0.75	4.82 ± 0.9
$\langle \bar{N}_{\gamma H} \rangle$	2.74 ± 0.45	2.88 ± 0.5	3.00 ± 0.7	3.50 ± 0.85
$\langle \bar{\epsilon}_L \rangle$, MeV per gamma	1.07 ± 0.2	1.04 ± 0.2	1.00 ± 0.25	0.87 ± 0.2
$\langle \bar{\epsilon}_H \rangle$, MeV per gamma	1.04 ± 0.2	0.92 ± 0.2	0.95 ± 0.25	0.82 ± 0.25

magic configurations in each fragment group may be attributed to a decrease in vibrational energy as the fragments become softer.[2]

Figure 3*b* shows the average center-of-mass kinetic energy of neutrons emitted in the fission of ^{252}Cf, taken from ref. 5. Note the similarity between this curve and the $\bar{\epsilon}(m)$ curve for ^{252}Cf in Fig. 3*a*.

In Fig. 4 the results for the average total gamma energy (for both fragments) $\bar{E}_{\gamma T}$, average total number (for both fragments) $\bar{N}_{\gamma T}$, and average quantum energy $\bar{\epsilon}_T = \bar{E}_{\gamma T}/\bar{N}_{\gamma T}$ per fission are plotted against the mass of the heavy member of the fragment pair; no scale is shown for the complementary light fragment, since it changes with the A of the fissioning nucleus. The trends in each part of Fig. 4 can be understood by referring to the preceding figures. For example, from Fig. 3*a* one sees that the peaks in $\bar{\epsilon}_T$ in the region of $m_H = 130$ to 133, in Fig. 4*c*, are clearly a result of the high values of ϵ_H and that the increases in $\bar{\epsilon}_T$ in the vicinity of $m_H = 150$ result from the increase in $\bar{\epsilon}_L$ as the complementary masses $m_L = A - m_H$ slide into the region $m_L \lesssim 100$ amu. Thus, the shapes of these functions may also be interpreted in terms of closed-shell nuclei and preferred modes of deexcitation associated with the stiffness or softness of the fragments.

Average values for all functions are listed in Table 1; the uncertainties include both statistical and estimated systematic errors other than those associated with anisotropy.[2]

1. Chemistry Divison.
2. F. Pleasonton, R. L. Ferguson, and H. W. Schmitt, *Phys. Rev. C* **6**, 1023 (1972).
3. S. A. E. Johansson, *Nucl. Phys.* **60**, 378 (1964).
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5. H. R. Bowman, J. C. D. Milton, S. G. Thompson, and W. J. Swiatecki, *Phys. Rev.* **129**, 2133 (1963).
6. V. F. Apalin, Yu. N. Gritsyuk, I. E. Kutikov, V. I. Lebedev, and L. A. Mikaelyan, *Nucl. Phys.* **71**, 553 (1965).

LIMITS OF ANGULAR MOMENTUM IN HEAVY-ION COMPOUND-NUCLEUS REACTIONS[1]

M. Blann[2] Franz Plasil

Experimentally measured fusion excitation functions for the reactions induced on ^{27}Al with ^{16}O and on ^{107}Ag with ^{20}Ne are interpreted in terms of an equilibrium model with fission competition during deexcitation of the compound nucleus. The results of the calculation are in excellent agreement with experimental results, thereby predicting limits to angular momenta for nuclei surviving deexcitation of the compound nucleus.

1. Abstract of published paper: *Phys. Rev. Lett.* **29**, 303 (1972).
2. Department of Chemistry, University of Rochester, Rochester, N.Y. 14627.

PREDICTIONS FOR HEAVY-ION REACTIONS BASED ON THE ROTATING LIQUID DROP MODEL[1]

Franz Plasil

The rotating liquid drop model has been used to predict ratios of complete fusion cross sections to total reaction cross sections for a number of heavy ions ranging from ^{16}O to ^{238}U incident on various targets. The calculation was based on the vanishing of the fission barrier due to high angular momentum, and the predicted complete fusion cross sections are upper limits. The sharp cut-off model was used. It was shown that no nucleus can support an angular momentum greater than 95 $\hbar$.

1. Abstract of paper published in proceedings of European Conference on Nuclear Physics, Aix-en-Provence, June–July 1972, vol. II, p. 51, *J. Phys.*, Paris, France (1972).

EQUILIBRIUM CONFIGURATIONS OF ROTATING CHARGED OR GRAVITATING LIQUID MASSES WITH SURFACE TENSION. PART II[1]

S. Cohen[2] Franz Plasil W. J. Swiatecki[3]

Saddle-point and ground-state equilibrium shapes of idealized charged or gravitating liquid drop masses with surface tension have been calculated. Results presented include critical values of rotational parameters at which families of equilibrium shapes change character or cease to exist. The results also include graphs of principal axes and of moments of interia of equilibrium shapes, as well as of their energies. Emphasis is placed on the region relevant to nuclei and to heavy-ion reactions. Fission barriers as a function of angular momentum are given. Effects on heavy-ion reaction cross sections are discussed, and the possible existence of superdeformed nuclei with high angular momenta is considered.

1. Submitted for publication to *Annals of Physics.*
2. Argonne National Laboratory, Argonne, Ill.
3. Lawrence Berkeley Laboratory, Berkeley, California.

5. Mössbauer Spectroscopy

EXPERIMENTAL TEST OF WEYL'S GAUGE-INVARIANT GEOMETRY[1]

E. G. Harris[2] Paul G. Huray[3] Felix E. Obenshain J. O. Thomson[3] R. A. Villecco[2]

Weyl's gauge-invariant geometry predicts that the periods of clocks are affected by their previous history in electromagnetic fields. We have used the Mössbauer effect to search for such an effect with negative results.

1. Abstract of paper accepted for publication in the *Physical Review*.
2. University of Tennessee, Knoxville.
3. Consultant from the University of Tennessee, Knoxville.

GIANT MAGNETIC HYPERFINE FIELDS OF ^{61}Ni ON TETRAHEDRAL SITES OF SPINELS

John C. Love[1] Felix E. Obenshain

The ^{61}Ni nuclear gamma resonance (NGR) spectrum of the nickel chromite ($NiCr_2O_4$) spinel shows both the largest magnetic dipole and electric quadrupole hyperfine (hf) interactions yet reported for nickel in any host lattice. The magnetic interaction is equivalent to an effective hf field of $H_n = \pm 440$ kOe, the sign of the field undetermined. This number may be compared with the case of other Ni^{2+} oxide compounds such as NiO ($|H_n| = 100$ kOe) and $NiFe_2O_4$ ($|H_n| = 94$ kOe). It seems plausible that the unusual size of $H_n(^{61}Ni)$ in the chromite is related to the fact that nickel occupies the tetrahedrally coordinated *A* sites in this spinel, whereas nickel has octahedral coordination in the other cases. In cubic tetrahedral coordination the electronic ground state of Ni^{2+} ($3d^8$) is $^3T_{1g}$, which is orbitally degenerate with unquenched orbital angular momentum ($L = 1$), whereas in octahedral coordination the ground state is $^3A_{2g}$, an orbital singlet ($L = 0$). However, the Jahn-Teller effect (an intrinsic instability of an electronically degenerate complex against distortions that remove the degeneracy) produces a tetragonal distortion ($c/a > 1$) at *A*-site Ni^{2+} in $NiCr_2O_4$, and this completely quenches the orbital angular momentum *L*. Thus, rather exact knowledge of higher order effects (such as *d-p* mixing) will be needed before an assessment of orbital hf field contributions can be made.

In order to experimentally investigate the origin of this large field, we measured the ^{61}Ni NGR spectra in the series of mixed spinels $NiFe_xCr_{2-x}O_4$ ($0 \leqslant x \leqslant 2$), which spans the range from the "anomalous" $NiCr_2O_4$ to the ferrite $NiFe_2O_4$. Previous studies have indicated that the Ni^{2+} ions have a preference for the octahedral (*B*) sites in the spinel lattice, second only to that of the Cr^{3+} ions, and that the nickel ions tend to shift from the *A* sites (at $x = 0$) to the *B* sites as iron is substituted for chromium. The distribution of the cations between the two sites that has been assumed in almost all previous papers in this series is given by the formula $(Ni^{2+}{}_{1-x}Fe^{3+}{}_x)[Ni^{2+}{}_xCr^{3+}{}_{2-x}]O_4$ for $0 \leqslant x \leqslant 1$, where the ions in parentheses are in *A* sites and those in brackets are in *B* sites. One notes that at $x = 1$, all the Ni^{2+} ions should be in the octahedral sublattice if this formula were correct. Our ^{61}Ni Mössbauer spectra show a large, rather well defined (single-site) field of ± 440 kOe for $x = 0$, as mentioned, and small single-site fields less than 100 kOe for $x = 1.5$ and 2.0. For intermediate values of *x*, two (or more) hf patterns are seen, with small- and large-field components, the first growing in intensity at the expense of the second as *x* is increased. Thus, these spectra show directly the varying distribution of Ni^{2+} ions among the two sites. Two conclusions derived from our data were unexpected: (1) the *A*-site field increases to ± 630 kOe for $x = 0.5$ and 1.0, the largest nickel fields yet reported, and (2) a large fraction, of the order of 0.3 to 0.35, of the nickel ions are yet found on *A* sites for $x = 1$, in contradiction to the traditional formula mentioned above. The samples with $x = 0.5$ and 1.0 were subsequently annealed at

600°C for 110 hr, and additional NGR spectra were accumulated, but the hf parameters were found to be essentially unchanged by the annealing procedure.

The source of the very large fields seen for samples with $x = 0.5$ and 1.0 is not yet known, but we suspect that the deviation from the ±440-kOe field in $NiCr_2O_4$ is due to unquenching of L at A-site nickel. In the region $0.28 \leqslant x \leqslant \sim 1.2$, the lattice distortion from cubic is tetragonal ($c/a < 1$), of opposite sign to that of $NiCr_2O_4$. It has been postulated that this distortion is due to a collective spin-orbit interaction, which produces such a distortion at A-site Ni^{2+} and thus maximizes the value of L and the spin-orbit energy. Further work is needed to determine the signs of these fields as an aid to ascertaining their origins.

The second result, our discovery of the sensitivity of the ^{61}Ni Mössbauer effect to the cationic distribution in the spinel lattice, is a result significant to the study of the magnetic structures of these materials and will allow a fruitful reconsideration of the earlier work on bulk magnetic studies.

1. Clarkson College of Technology, Potsdam, N.Y.

THE ^{61}Ni MÖSSBAUER EFFECT IN NICKEL-PALLADIUM ALLOYS[1]

John E. Tansil[2]

The 67.4-keV transition from ^{61}Ni was used to obtain Mössbauer absorption spectra with nickel-palladium alloy absorbers throughout the concentration range 0 to 99.5 at. % Pd. The source contained the parent isotope ^{61}Co, produced by the reaction $^{64}Ni(p,\alpha)^{61}Co$, in a nonmagnetic ^{64}Ni–V (14 at. %) foil. Both source and absorber were immersed in liquid helium.

In the ferromagnetic region, 0 to 98 at. % Pd, the spectra showed a partly resolved magnetic hyperfine splitting with a distribution of magnetic hyperfine fields. For each absorber a value was obtained for the ^{61}Ni recoilless fraction, energy shift, absolute value of the hyperfine field, and second moment of the magnetic field distribution. The ^{61}Ni average hyperfine field is negative in pure nickel (−76 kOe), changes sign near 50 at. % Pd, and rises to a large positive value (+173 kOe) at 90 at. % Pd. Qualitative agreement with these results is obtained with a model based on the assumption that $\langle H_{hf}^{Ni} \rangle$ in nickel-palladium has the same contributions from core polarization and bulk conduction-electron polarization as in other nickel-based alloys, *plus* a large positive contribution from palladium atoms on neighboring lattice sites.

An external magnetic field was applied to the alloys containing 50 to 99.5 at. % Pd. From these measurements and a model formulation of the effective field distribution, it is found that the calculated average hyperfine fields $\langle H_{hf}^{Ni} \rangle_{calc}$ are in agreement with the values expected for no distribution of fields, and the distribution width of hyperfine fields is $\Delta H = 80 \pm 9$ kOe in the midconcentration range. From the effective field behavior in a dilute Ni-Pd (99.5%) alloy, the nickel moment was determined to be

$$\mu = [J/(J + 1)]\,(0.73 \pm 0.05)\mu_B \,.$$

A large decrease of the ^{61}Ni recoilless fraction in dilute nickel-palladium alloys is interpreted as being caused by localized modes of vibration due to the light nickel impurities in the heavy palladium host matrix. From a temperature-dependence study of the second-order Doppler shift, we have deduced the relative isomer shift between ^{61}Ni in palladium and ^{61}Ni in nickel to be $\delta_{IS}{}^{Pd} - \delta_{IS}{}^{Ni} = -23 \pm 15\ \mu/sec$.

1. Abstract of ORNL-TM-3930.
2. Former student guest assignee from University of Tennessee, Knoxville, ORNL-NSF Environmental Program.

MÖSSBAUER STUDIES OF ELECTROSTATIC HYPERFINE INTERACTIONS IN ^{238}U, ^{236}U, AND ^{234}U[1]

Joyce Anne Monard[2]

The nuclear gamma resonance (NGR) for ^{238}U, ^{236}U, and ^{234}U in the compound $(UO_2)Rb(NO_3)_3$ has been established at 4.2°K following the alpha decay of PuO_2 sources. The ratios of the electric quadrupole moments of these isotopes have been determined, and the electric field gradient at the uranium site has been calculated from the data. The isomer shift in ^{234}U has been measured for both PuO_2 and $PuAl_4$ sources, and the change in nuclear radius between the excited and the ground state has been calculated.

1. Abstract of ORNL-TM-3931.
2. Student guest assignee with Chemistry Division from the University of Tennessee, Knoxville.

6. Atomic and Molecular Physics

ELECTRON-OPTICAL FACTORS LIMITING RESOLUTION IN TRANSMISSION ELECTRON MICROSCOPES[1]

T. A. Welton

A comprehensive theory is given for information limitation, transfer, and extraction in phase-contrast electron microscopy, with weak objects. This theory is particularly relevant to biological problems with adequately thin, unstained samples, but useful validity appears to be retained for stained samples and perhaps even for thin (approximately) crystalline samples, in which gross defects have been produced by heavy damage. An object function is defined, representing the detailed pattern of retardation and attenuation produced on the illuminating electron wave by the sample. A kernel (function of the displacement between an object point and an image point) is derived for the situation of interest. This kernel ("point spread function") contains the essential parameters of the microscope, namely, source coherence, source energy spread, chromatic aberration, spherical aberration, defocus, astigmatism, and detector properties. It describes the detector response at a given point in the image produced by unit value of the object function at a given object point. The resulting image function (detector response as a function of position in the image plane) is nearly equal (for the case of phase contrast) to the result of convoluting the object function with the point spread function. It deviates by addition of a random function, the statistical error (noise), the formulation being entirely parallel to one originally given in communication theory by Wiener. Another kernel is defined (analogous to that given in a different context by Wiener) and justified as being that function which when convoluted with the *measured* image function gives the best linear (and hence *simple*) approximation to the object function. At the same time, the information content of the micrograph is defined, so that the possible gain by the above-indicated processing can be predicted. Detailed calculations are given of such information content in a variety of simple situations, and the whole formulation is presented with a view to practical, numerical processing of actual micrographs.

1. Abstract of published paper: pp. 125–57 in *Proceedings of Workshop Conference on Microscopy of Cluster Nuclei in Defected Crystals (Chalk River, Canada, September 1971)*, CRNL-622-1, ed. by J. R. Parsons (1972).

RELATIVE ENERGIES OF THE LOWEST LEVELS OF THE f^qps^2, f^qds^2, AND $f^{q+1}s^2$ ELECTRON CONFIGURATIONS OF THE LANTHANIDE AND ACTINIDE NEUTRAL ATOMS[1]

K. L. Vander Sluis   L. J. Nugent[2]

Linearization of the differences between the lowest levels of the f^qps^2, f^qds^2, and $f^{q+1}s^2$ electron configurations as a function of q is demonstrated for the lanthanide and actinide series. A linear extrapolation of these differences estimates the energy of the lowest level of the $4f^{14}6p6s^2$ electron configuration of lutetium to be 3.5 kilokaysers higher than the measured value. This deviation from linearity is attributed to expected discontinuities at the $q = 0$ and $q = 14$ ends of the f^qds^2 series. In the actinide series the corresponding linear extrapolation predicts the lowest level of the $5f^{14}7p7s^2$ electron configuration of lawrencium to be 2.3 ± 3 kilokaysers above the expected $5f^{14}6d7s^2$ ground state, after correction for a corresponding 3.3-kilokayser deviation expected at the end of the actinide series.

1. Abstract of published paper: *Phys. Rev.* **60A**, 86 (1972).
2. Chemistry Division.

SYSTEMATICS IN THE RELATIVE ENERGIES OF SOME LOW-LYING ELECTRON CONFIGURATIONS IN THE GASEOUS ATOMS AND IONS OF THE LANTHANIDE AND ACTINIDE SERIES[1]

K. L. Vander Sluis L. J. Nugent[2]

We observe a linear characteristic and a common irregular characteristic in the energy differences associated with many lanthanide and actinide electronic configurations involving a change in the number of f electrons by 1. The differences in energy, $\Delta_d E$, between the lowest energy levels of the two principal electron configurations in the atoms of the lanthanide and actinide series exemplify these characteristics. By assuming that the common irregular characteristic involves only electrostatic and spin-orbit interaction energy differences between the parent f-electron core configurations, we obtain linearization functions -- one for the lanthanide series and one for the actinide series -- which linearize the $\Delta_d E$ data. These same linearization functions are found applicable to the energy differences between all electronic configurations involving the same number of f electrons, including the neutral and the singly, the doubly, and the triply ionized gaseous lanthanides and actinides.

1. Abstract of paper submitted for publication in the *Journal of the Optical Society of America.*
2. Chemistry Division.

STUDIES ON THE ORIGIN OF THE 3400-cm^{-1}-REGION INFRARED BANDS OF NATURAL AND SYNTHETIC ALPHA QUARTZ

O. C. Kopp[1] P. A. Staats

The infrared spectrum of synthetic quartz in the 3400-cm^{-1} region differs appreciably from that of natural quartz, the latter having many more bands. These bands have been attributed to impurities in the lattice,[2-4] and presumably the lack of bands in synthetic quartz would indicate a higher purity. This assumption is born out by analyses[5] as well as the fact that synthetic quartz has practically replaced natural quartz as a source of oscillator plates in the electronics industry.

It would seem, then, that bands observed in natural quartz could be produced in synthetic quartz by doping with the appropriate impurities and that one should be able to generate or remove a band at will by controlling the nutrient ingredients. We are reporting on results of a series of experiments which attempt to produce in synthetic quartz the 3400-cm^{-1} bands found in natural quartz.

All crystals were grown hydrothermally.[6,7] Dopants were added to the nutrient quartz at a concentration of 2 to 4% by weight of the nutrient. Infrared spectra were recorded with the crystal at liquid nitrogen temperature, because the bands are much more intense and sharp at low temperatures.

Table 1 lists various dopants which have been added to the growth solution as well as the solvent used. With the exception of H_3BO_3, most of these have failed to produce bands that could be associated with the dopant. In the case of H_3BO_3, we have succeeded in producing a band at 3594 cm^{-1} whose absorption coefficient is reasonably sensitive to the concentration of dopant and whose frequency is very close to that of a band (3593 cm^{-1}) often found in the spectra of natural quartz.

Figure 1 shows spectra obtained from a synthetic quartz crystal grown from pure RbOH solution and

Table 1. Dopants, solvents, and nutrients used in synthetic quartz production

Dopant	Solvent	Nutrient
H_3BO_3	NaOH	Natural quartz
Al_2O_3	NaOH	Natural quartz
$BaCO_3$	NaOH	Natural quartz
$NaHPO_4$	NaOH	Natural quartz
$Ba(OH)_2$	NaOH	Natural quartz
$SrCO_3$	NaOH	Natural quartz
BeO	NaOH	Natural quartz
CaO	NaOH	Natural quartz
MgO	NaOH	Natural quartz
$CaCO_3$	NaOH	Natural quartz
Al_2O_3	CsOH	Natural quartz
Al_2O_3	High-purity RbOH	Natural quartz
TiO_2	High-purity RbOH	Natural quartz
Y_2O_3	High-purity RbOH	Natural quartz
LiOH	High-purity RbOH	Natural quartz
CsOH	High-purity RbOH	Natural quartz
KOH	High-purity RbOH	Natural quartz
NaOH	High-purity RbOH	Natural quartz
$H_3{}^{10}BO_3$	High-purity RbOH	Natural quartz
H_3BO_3	High-purity RbOH	Natural quartz
H_3BO_3	High-purity RbOH	High-purity silica glass

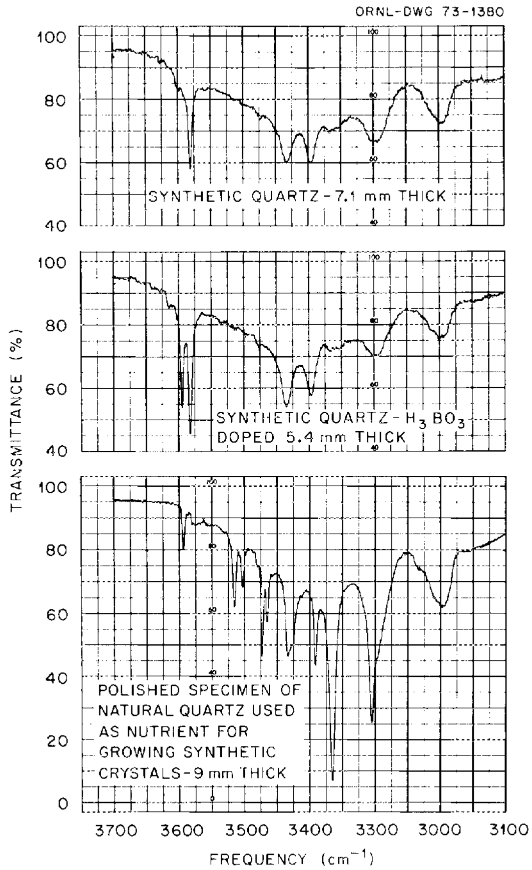

Fig. 1. Infrared absorption spectra of synthetic and natural quartz at 77°K.

from a crystal grown from RbOH doped with H_3BO_3. Natural quartz was used as the nutrient in both cases. For comparison, the spectrum from a sample of natural quartz similar to the nutrient material is shown. The band at 3594 cm^{-1} caused by the H_3BO_3 doping is quite noticeable and agrees well with its counterpart in natural quartz. We are aware that this may be pure coincidence. However, two samples of natural quartz were analyzed by spark-source mass spectrometry, and the concentration of boron found was the same level as that found in some of the boron-doped synthetic crystals. While we cannot be certain that the band in natural quartz is caused by the presence of boron, we are certain that we have produced a band in synthetic quartz that correlates with boron content.

The bands at 3580, 3438, and 3396 cm^{-1} are always found in synthetic quartz and agree fairly well with bands found in amethyst[8] but not with bands found in other natural quartzes. It can be seen that the series of bands are superimposed on a broad background, which is generally attributed to absorption by hydrogen-bonded OH. The intensity of this absorption varies from crystal to crystal and depends to some extent on the dopants and solution used.

We have had a series of crystals grown from doped solutions analyzed by spark-source mass spectrometry to ascertain whether the dopant could be found in the crystal. The boron results were excellent. The parts per million by weight that were found correlated very well with the quantity of dopant added to the solvent. One sample was doped with ^{10}B, and the analysis showed ^{10}B to be the dominant isotope present. The titanium- and yttrium-doped samples showed no increase over nondoped ones. The aluminum-doped crystal showed an increase over nondoped samples but not by a significant factor. For example, the doped sample had 90 wt ppm Al, as compared with 30 wt ppm found in a crystal grown from high-purity RbOH and high-purity synthetic silica glass nutrient, where we should expect the aluminum content to be low.

Previous work[9,10] has shown that boron exists as BO_2^- ions in solid solution in alkali halides. We wonder whether some of the impurities in quartz might be present as complex ion groups instead of individual ions – particularly in view of our negative results when attempting to produce bands in the OH region by adding various metal ions.

We are in the process of growing quartz crystals using a variety of oxygen-containing anions to see what effect these have on the infrared spectra in the OH region.

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1. Consultant to Metals and Ceramics Division from the Department of Geology, University of Tennessee, Knoxville.

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VIBRATIONAL DETERMINATION OF CRYSTAL STRUCTURES[1]

John M. Springer[2] E. Silberman[2] Henry W. Morgan

Raman spectra of very small crystals and of oriented polycrystalline films have been obtained with laser excitation. The techniques for producing crystals at low temperatures, from the vapor and the liquid phases, and of orienting the samples will be illustrated. The series of crystals POX_3 and PSX_2 (X = halogen) have been studied by infrared absorption and by the Raman effect at temperatures down to 4°K. Analyses of the band splittings, frequency shifts between Raman and infrared spectra, Raman polarization data, and density—close-packing factors have provided structural data on the crystalline phases. The structures are in agreement with the few previous studies made by x ray and indicate that a vibrational study may uniquely determine crystal structure.

1. Abstract of chapter in book *Proceedings of the Third International Conference on Raman Spectroscopy*, to be published by Heyden and Son, Ltd., London, 1973.
2. Fisk University, Nashville, Tenn.

PHOTOELECTRON CHEMICAL SHIFTS IN INORGANIC COMPOUNDS[1]

Gary Elder McGuire[2]

Selected inner-shell ionization energies of a variety of inorganic compounds were examined by using x-ray photoelectron spectroscopy. Attempts were made to relate the chemical shifts in the core level energies to structural and bonding properties of the compounds.

An attempt was made to use photoelectron spectroscopy to distinguish groups attached in bridging and terminal positions within some selected compounds. This study was conducted on a series of halides of aluminum, gallium, indium, niobium, and tantalum for which various x-ray crystallographic techniques indicate the existence of nonequivalent halogens. From very simple calculations involving geometric and electronegativity considerations, it was predicted that the core electrons in these groups would display slightly different binding energies. It was found that these differences were only enough to cause a small degree of broadening in the halogen spectral lines when compared with the halogen spectral lines of the reference compounds NaF, NaCl, and NaBr. It was concluded that photoelectron spectra can be used as supportive evidence for the existence of bridging and terminal groups but that the absence of line broadening cannot be employed to rule out the existence of such nonequivalent groups, since the effect is often quite small.

An attempt was made to determine if the structure of Re_2S_7 has nonequivalent groups. Although the structure of Re_2S_7 is unknown, the sulfur spectra display two photoelectron peaks. It was determined that the two peaks were probably not the result of nonequivalent positions of sulfur in Re_2S_7.

The alkali halides were examined to ascertain the factors causing chemical shifts in solid ionic compounds. This involved comparing the experimentally observed chemical shifts with theoretical values. The theoretical values take into consideration the change in valence electron density and the change in crystal potential. The theoretical values were found to approximate the experimental values when appropriate radii were assigned to the constituent entities. It was found that, in general, theoretical values calculated on the basis of ionic radii gave better agreement with experimental values than theoretical values calculated on the basis of atomic radii or radii obtained from electron density mapping.

The treatment applied to the alkali halides was extended to the alkaline-earth halides of barium, calcium, and magnesium. It was found that radius values intermediate between ionic and atomic radii gave theoretical values that approximate the experimental values for the magnesium compounds, but ionic radii gave theoretical values that approximate the experimental values for barium and calcium compounds.

When this treatment was extended to a group of aluminum and gallium compounds, it was found that the theoretical values based on atomic radii gave better agreement with experimental values than those based on ionic radii.

When this same treatment was applied to a group of fluorine compounds, the theoretical values based on atomic radii gave the best agreement with the experimental values.

The O 1*s* binding energies in a series of metal acetylacetonates were studied to observe any chemical shifts caused by the variation of the metal to which the acetylacetonate groups are attached. It was found that the O 1*s* binding energies remained relatively constant, which correlates with the known resonance in the ring formed by the complex. Any alterations in electron density of the oxygens may tend to be spread throughout the ring.

Certain oxides of uranium may be prepared in pure form. It was desirable to show that photoelectron spectroscopy can distinguish UO_2, UO_3, and U_3O_8. It was found that uranium core electrons have slightly different binding energies in each of these compounds. It was noticed that the chemical shift observed from uranium metal to the uranium oxides was much smaller than the shift observed in going from the metal to the metal oxide in the case of other metals. It was found that a uranium oxide layer may be formed with sufficient thickness to mask the pure metal underneath.

Analogous aluminum, gallium, and indium compounds, as well as analogous niobium, tantalum, and tungsten compounds, were compared experimentally to determine relative chemical shifts. This method was based on the assumption that crystal potentials of analogous compounds might be similar. Of the group III-A elements studied, aluminum was found to give shifts similar to those of gallium and larger than those of indium. All three of the transition elements niobium, tantalum, and tungsten were found to give similar chemical shifts when their analogous compounds were compared.

1. Abstract of ORNL-TM-3820.

2. Former student guest assignee from the University of Tennessee, now with ORNL Analytical Chemistry Division.

USE OF X-RAY PHOTOELECTRON SPECTROSCOPY TO STUDY BONDING IN CHROMIUM, MANGANESE, IRON, AND COBALT COMPOUNDS[1]

J. C. Carver[2] G. K. Schweitzer[3] Thomas A. Carlson[4]

The photoelectron spectra of some 40 transition metal compounds have been measured using Al K_α (1487 eV) and Mg K_α (1254 eV) x rays. The compounds included both simple salts (halides and chalcogenides) and hexacoordinated complexes (cyano and fluoro) of Cr(III), Mn(II,III), Fe(II,III), and Co(III). From these data we have determined the chemical shifts of the core electrons and related these results to a calculated charge based on Pauling's electronegativities. In addition, multiplet splitting has been obtained for photoionization in the 3*s* shell and is discussed in terms of the exchange interaction between the partially filled 3*s* and 3*d* orbitals. To help in this explanation, calculations were made using both (1) Hartree-Fock solutions of the wave functions for free ions and (2) a qualitative evaluation of the behavior of the exchange integral. The value of using x-ray photoelectron spectroscopy for studying chemical bonding for transition metal compounds is amply illustrated.

1. Abstract of published paper: *J. Chem. Phys.* 57, 973 (1972).

2. Former student guest assignee at ORNL from University of Tennessee supported by a National Science Foundation grant. Present address: Department of Chemistry, University of Geoigia, Athens 30601.

3. University of Tennessee.

4. On loan from Chemistry Division.

STUDY OF THE X-RAY PHOTOELECTRON SPECTRUM OF TUNGSTEN–TUNGSTEN OXIDE AS A FUNCTION OF THICKNESS OF THE SURFACE OXIDE LAYER[1]

Thomas A. Carlson[2] G. E. McGuire[3]

The photoelectron spectrum of tungsten metal using Al K_α x rays has been studied as a function of a tungsten oxide layer on the surface. The photoelectron lines arising from the 4*f* shell of tungsten metal are clearly separated in energy from those coming from WO_3. The ratio of the intensities of these two sets of lines was measured for a series of metal samples which were anodized to a determined level of tungsten oxide. The data were shown to be consistent with a uniform deposition of oxide film. The escape depth, or thickness from which half the photoelectron intensity is derived, was found for a 1450-eV photoelectron to be 8.9 and 18.3 Å for W and WO_3 respectively.

1. Abstract of published paper: *J. Electron Spectrosc.* 1, 161 (1972).

2. On loan from Chemistry Division.

3. Former student guest assignee from the University of Tennessee, now with ORNL Analytical Chemistry Division.

PRESENT AND FUTURE APPLICATIONS OF AUGER SPECTROSCOPY[1]

Thomas A. Carlson[2]

Because of the high scattering cross section for low-energy electrons in matter, studies on the Auger effect have been somewhat limited. However, in two situations, gases at low pressures and surfaces of solids, Auger electrons may be measured with ease. During the last few years, increased attention has been paid to Auger spectroscopy as a means for studying other atomic and molecular properties. With gases, Auger spectroscopy has been helpful in yielding information regarding initial excitation phenomena and the nature of doubly charged molecules, as well as providing a method for gas analysis. With solids, Auger spectroscopy has become a powerful tool for surface analysis, especially when combined with other surface techniques such as low-energy electron diffraction (LEED) and scanning electron microscopy. An outline of the present uses of Auger spectroscopy will be given, together with some suggestions for the future.

1. Abstract of paper to be published in *Inner Shell Ionization Phenomena and Future Applications,* vol. IV, R. W. Fink, S. T. Manson, J. M. Palms, and P. V. Rao, eds., Technical Information Center, USAEC, Oak Ridge, Tenn.
2. On loan from Chemistry Division.

ANGULAR DISTRIBUTION OF THE PHOTOELECTRON SPECTRUM OF CO_2, COS, CS_2, N_2O, H_2O, AND H_2S[1]

Thomas A. Carlson[2] G. E. McGuire[3]

The photoelectron spectra of the triatomic molecules CO_2, COS, CS_2, N_2O, H_2O, and H_2S have been measured as a function of the angle θ between the direction of the incoming photon and outgoing photoelectron. The photoelectron spectra have been measured with a double-focusing electrostatic electron spectrometer to which has been attached a chamber containing a gas discharge lamp that can be freely rotated. (The photon source used was the 21.22-eV He I resonance line). From the dependence of intensity as a function of θ, the angular parameter β was determined for each ionization band observed in the photoelectron spectra. A correlation was noted between the values of β and the molecular orbitals relative to the contributions of oxygen and sulfur atomic orbitals. Individual β values were also obtained for most of the vibrational bands seen in the photoelectron spectra. In most cases the vibrational structure showed little or no change in the angular parameter for a given electronic state. In certain cases, however, such as the fourth ionization band in CS_2, CO_2, and COS, rather sizable changes in β were observed for the different vibrational bands.

1. Abstract of published paper: *J. Electron Spectrosc.* **1**, 209 (1973).
2. On loan from Chemistry Division.
3. Former student guest assignee from the University of Tennessee, now with ORNL Analytical Chemistry Division.

STUDY OF THE ANGULAR DISTRIBUTION FOR THE PHOTOELECTRON SPECTRA OF HALOGEN-SUBSTITUTED METHANE MOLECULES[1]

Thomas A. Carlson[2] R. M. White[3]

The intensity of photoelectrons ejected from randomly oriented gaseous molecules as a function of the angle θ between the direction of the incoming photon and outgoing photoelectron is given from theory to be $1 + (\beta/2)(^3\!/_2 \sin^2 \theta - 1)$. The angular parameter β is dependent on two factors: the photoelectron energy and the nature of the molecular orbital from which the photoelectron is ejected. Angular measurements should provide a powerful method for identifying an orbital associated with a given ionization band. The angular parameters β have been determined for most of the ionization bands found in photoelectron spectra for the following molecules: CH_3F, CH_2F_2, CHF_3, CF_4, CH_3Cl, CH_2Cl, $CHCl_3$, CCl_4, CH_3Br, and CH_3I. To obtain these results, a dispersion electron spectrometer was employed, to which was attached a chamber containing a freely rotating gas discharge lamp that provided a directed beam of He I (584 Å) radiation. An attempt is made to correlate β with calculated population densities and atomic angular parameters. A brief discussion is also made of the dependence of β on the vibrational structure.

1. Abstract of paper to be published by the Chemical Society as part of the General Discussion on the Photoelectron Spectroscopy of Molecules, University of Sussex, 12–14 September 1972, sponsored by the Faraday Society.
2. On loan from Chemistry Division.
3. On sabbatical leave from Baker University, Baldwin, Kan.

X-RAY PHOTOELECTRON SPECTRA OF ETHYLENEDIAMINETETRAACETIC ACID AND ITS METAL COMPLEXES[1]

K. L. Cheng[2] J. C. Carver[3] Thomas A. Carlson[4]

The x-ray photoelectron spectra were taken of ethylenediaminetetraacetic acid and the following salts and complexes: Na_2H_2EDTA, Na_4EDTA, MgH_2EDTA, Mg_2EDTA, $CaNa_2EDTA$, $CuNa_2EDTA$, and $ZnNa_2EDTA$. The binding energies for the 1*s* shell of nitrogen formed two groups separated by about 2 eV. These binding energies are believed to be associated with a protonated and unprotonated form of nitrogen, and structures consistent with this proposal are illustrated.

1. Abstract of paper to be published in *Inorganic Chemistry*.
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ON THE Z^2 DEPENDENCE OF THE X-RAY PRODUCTION CROSS SECTION BY 5-MeV/amu HEAVY IONS[1]

A. van der Woude[2] M. J. Saltmarsh C. A. Ludemann R. L. Hahn[3] E. Eichler[4]

Large deviations from a Z^2 dependence for the x-ray production cross sections are found for *K* x rays of Ti, Fe, Co, Zr, Sn, and Nd and *L* x rays of Sn and Nd using 5-MeV/amu He, C, O, and Ne ions as projectiles. At least in the case of the *K* x rays of Zr, Sn, and Nd, these deviations very likely reflect the behavior of the ionization cross section and point out the necessity of adding a Z^3 term to the expression for the ionization cross section. In the other cases the uncertainty of the fluorescence yield prevents the drawing of any definite conclusions.

1. Abstract of paper in *Inner Shell Ionization Phenomena and Future Applications*, ed. by R. W. Fink, S. T. Manson, J. M. Palms, and P. V. Rao, published by USAEC Technical Information Center, Oak Ridge, 1973, p. 1388.
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ENERGY SHIFTS AND RELATIVE INTENSITIES OF *K* X RAYS PRODUCED BY SWIFT HEAVY IONS[1]

M. J. Saltmarsh A. van der Woude[2] C. A. Ludemann

The energy shifts of Fe, Co, Zr, and Sn *K* x rays produced by 5-MeV/amu He, Co, O, and Ne and 10-MeV/amu C ions depend nearly linearly on the stopping power for the bombarding ion. The shifts and the $K\beta/K\alpha$ ratios show a projectile energy dependence similar to that predicted for the *L* ionization cross section. This suggests that these phenomena can be explained by existing Coulomb excitation theories.

1. Abstract of published paper: *Phys. Rev. Lett.* 29(6), 329 (1972).
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METASTABLE STATES OF HIGHLY EXCITED HEAVY IONS[1]

D. J. Pegg[2] P. M. Griffin I. A. Sellin[2] W. W. Smith[3] B. Donnally[4]

Results of a number of our recent experiments concerning spectroscopic and lifetime measurements on the electrons emitted by fast beams of excited heavy ions undergoing decay in flight are described. The main results of our earlier investigations[5] will be summarized and more recent unpublished results described. A substantial number of metastable autoionizing states — frequently metastable against radiative decay as well — have been identified, belonging to charge states of the various accelerated ions ranging from those containing 3 to at least 11 electrons. Oxygen, fluorine, chlorine, and argon beams at energies ranging from 2 to 87 MeV have been used in this work. The copious production of a large number of such metastable states (all with lifetimes several orders of magnitude longer than anticipated for Coulomb autoionization processes) was not initially expected. For example, under appropriate conditions $\lesssim 1\%$ of the emergent lithium-like charge state following carbon foil excitation has been found to exist in the highest angular momentum state ($J = 5/2$) belonging to the lowest three-electron quartet configuration ($1s2s2p\ ^4P^o$), for all of the ions O^{5+}, F^{6+}, Cl^{14+}, and Ar^{15+}. This state is well known to be metastable against decay by both the Coulomb and spin-orbit interactions[6] but can decay by the spin-spin interaction. By combining our high-Z lifetime measurements with those[7] on He^- and Li, the lifetime scaling with Z has been established. In the case of Cl^{14+} and Ar^{15+}, it is possible to measure the electronic energies of these same states sufficiently accurately to test various relativistic corrections to nonrelativistic variational energy calculations.

A number of more highly excited quartet states have been observed; some energies and lifetimes have been obtained for these. Several unidentified metastable autoionizing states have been produced. There is evidence that some of these belong to heavier alkali-like ions such as sodium-like Cl^{6+}. Spectroscopic and lifetime results on these states will be described. There are indications that some highly excited electrons may play a spectator role in the various decay processes.

A model for the relatively frequent formation of long-lived states accompanying penetration of energetic heavy ions in matter will be described. It is plausible that many excited heavy ions should exhibit them. It is interesting to note that in the instance of the decay of the metastable Ar^{15+} ions discussed previously, for example, a lifetime of 0.66 ± 0.04 nsec is obtained despite an excitation energy of more than 2 keV available in the process. Many unobserved short-lived states of similarly high excitation energy are presumably created with similar probabilities. Some relations to the work of Bohr and Lindhard[8] on the distribution of excitation will be discussed.

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1. Abstract of paper to be published in *Atomic Physics*, Plenum Press.
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5. *Phys. Rev. Lett.* (to be published); *Phys. Rev. Lett.* **27**, 1108 (1971); *Phys. Rev.* **A6**, 122 (1971); *Book of Abstracts*, Seventh International Conference of the Physics of Electronic and Atomic Collisions, North-Holland Publishing Co., Amsterdam, 1971, p. 513.
6. The papers in ref. 1 list numerous references to the considerable earlier theoretical and experimental work concerning isoelectronic systems of low Z.
7. P. Feldman M. Levitt, and R. Novick, *Phys. Rev. Lett.* **21**, 331 (1968); *Phys. Rev.* **A3**, 130 (1971); L. M. Blau, R. Novick, and M. Weinflash, *Phys. Rev. Lett.* **24**, 1261 (1970).
8. N. Bohr and J. Lindhard, *Kgl. Dan. Vidensk. Selsk., Mat. Fys. Medd.* **28**, No. 7 (1954).

ON METASTABLE AUTOIONIZING STATES OF HIGHLY EXCITED HEAVY IONS[1]

I. A. Sellin[2] D. J. Pegg[2] P. M. Griffin W. W. Smith[3]

We report the electronic energies (-5.658 ± 0.024 and -6.369 ± 0.033 keV) and electron emission lifetimes (0.91 ± 0.04 and 0.66 ± 0.04 nsec) of the longest-lived autoionizing quartet states of lithium-like Cl^{14+} and Ar^{15+} ions, respectively, firmly establishing the energy and lifetime scaling with Z. Observable relativistic corrections to nonrelativistic variational energy calculations are discussed. Production of metastable states belonging to lower charge states is discussed, and it is concluded that many excited heavy ions should exhibit them.

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1. Abstract of published paper: *Phys. Rev. Lett.* **28**, 1229 (1972).
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METASTABLE AUTOIONIZING STATES[1]

I. A. Sellin[2]

Research on the electron decay in flight of metastable states of elementary atomic systems of high Z was initiated at the Oak Ridge National Laboratory in 1970. This paper reviews our progress to date and comments on capabilities and limitations of the technique.

1. Abstract of paper presented at the Third International Conference on Beam-Foil Spectroscopy, Tucson, Arizona, October 1972, and to be published in the proceedings, which will be published in *Nuclear Instruments and Methods.*
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ELECTRON SPECTROSCOPY OF FOIL-EXCITED CHLORINE BEAMS[1]

D. J. Pegg[2] P. M. Griffin I. A. Sellin[2] W. W. Smith[3]

We report on a recent spectroscopic study of autoionization electrons emitted by fast foil-excited chlorine ion beams. The observed electrons originated in the decay of certain core-excited metastable autoionizing states in lithium-like and sodium-like chlorine. Such states are metastable since they are forbidden to autoionize via the strong Coulomb interaction but decay instead via second-order magnetic interactions (or in some cases, radiatively).

Chlorine beams from the Oak Ridge tandem accelerator were passed through thin carbon foils ($\sim$15 μg/cm^2) which served to both strip and excite the ions. Electrons emitted in the decay of autoionizing states thus formed were energy analyzed after the foil by a cylindrical mirror analyzer, the position of which could be varied with respect to the foil to facilitate time-of-flight lifetime studies. Beam energies were chosen to maximize the production of the lithium-like (Cl^{14+}) and sodium-like (Cl^{6+}) charge states.

The results of a measurement of the energy and the lifetime of the $(1s2s2p)\ ^4P_{5/2}$ state of Cl^{14+} will be presented. A spectrum of autoionization electrons from Cl^{6+} will also be shown; however, firm identification of many of the states of this system is at present difficult due to the almost complete lack of theoretical calculations of the energies and lifetimes of such states.

1. Abstract of paper presented at the Third International Conference on Beam-Foil Spectroscopy, Tucson, Arizona, October 1972, and to be published in the proceedings, which will be published in *Nuclear Instruments and Methods.*
2. Consultant in the Physics Division from the University of Tennessee.
3. University of Connecticut, Storrs.

PROJECTILE STRUCTURE EFFECTS ON NEON *K* X-RAY PRODUCTION BY FAST, HIGHLY IONIZED ARGON BEAMS[1]

J. R. Mowat[2] D. J. Pegg[3] R. S. Peterson[4] P. M. Griffin I. A. Sellin[3]

An already large yield of neon K x rays produced by a high-energy (60 to 80 MeV) stripped argon beam has been observed to undergo a tenfold increase when the *projectile* charge state is changed from +6 ($2p$ shell full) to $\sim$+14 ($2p$ shell empty). This increase may be understood qualitatively in terms of a transfer of $1s$ neon electrons to the empty $2p$ shell of the more highly stripped ions during collisions. Other possible interpretations are also discussed.

1. Abstract of published paper: *Phys. Rev. Lett.* **29**, 1577 (1972).
2. Guest assignee with the Physics Division and faculty member from the University of Tennessee.
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BEAM FRACTIONS IN THE LOWEST QUARTET METASTABLE AUTOIONIZING STATE FOR O^{5+} AND F^{6+} BEAMS AFTER PASSAGE THROUGH FOILS[1]

W. W. Smith[2] B. Donnally[3] D. J. Pegg[4] M. D. Brown[5] I. A. Sellin[4]

When fast beams of oxygen and fluorine ions are incident on carbon and metal foils thick enough to produce charge-state equilibrium, a significant portion of the lithium-like beam fraction emerges in excited metastable autoionizing states. The decay in flight of the lowest of these states, the $(1s2s2p)\ {}^4P^o_{5/2}$, is monitored with observation of the spectrum of ejected electrons. We find, for example, that the maximum yield of this single state per incident beam particle is approximately 0.8% and 0.6% for oxygen and fluorine, respectively, on carbon. The energy dependences and target material dependences are measured and discussed. Comparison is made with related work of Dmitriev et al.

1. Abstract of paper to be published in the *Physical Review*.
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TIME-DEPENDENT THEORY OF STARK QUENCHING OF 2S STATES IN HYDROGEN AND HELIUM[1]

H. K. Holt[2] I. A. Sellin[3]

A nonperturbative time-dependent theory which gives Stark quenching lifetimes in agreement with experiment for both one- and two-electron 2S states is presented. This theory differs from the conventional Bethe-Lamb theory of Stark quenching but reduces to this older theory, for one-electron atoms only, when a well-known sum rule is applied.

1. Abstract of published paper: *Phys. Rev.* **A6**, 508 (1972).
2. National Bureau of Standards, Washington, D.C.
3. Consultant in the Physics Division from the University of Tennessee.

PROJECTILE STRUCTURE EFFECTS IN X-RAY PRODUCTION BY FAST, HIGHLY STRIPPED HEAVY IONS

I. A. Sellin[1] D. J. Pegg[1] P. M. Griffin J. R. Mowat[2]
W. W. Smith[3] R. S. Peterson[4]

We plan to follow up our recently published work on the large cross sections for neon K x rays by Ar^{q+} ion impact, with q in the range 6 to 14. An order of magnitude variation in an already large cross section has been found,[5] depending upon the number of L-shell vacancies in the incident ion. Comparisons of data for chlorine and argon ions at the same velocity are planned. Evidence for strong ionization of the target will be further explored.

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3. Oak Ridge Associated Universities, consultant from the University of Connecticut, Storrs.
4. Graduate student from the University of Tennessee.
5. *Phys. Rev. Lett.* **29**, 1577 (1972).

AUTOIONIZATION OF FAST HEAVY IONS: SPECTRA AND LIFETIMES

I. A. Sellin[1] D. J. Pegg[1] P. M. Griffin J. R. Mowat[2] W. W. Smith[3]
M. D. Brown[4] J. R. Macdonald[5] R. S. Peterson[6]

Many of the new electron spectrum features described in our recent papers on this subject[7] have recently been studied in more detail. Analysis of this data is well under way. A review article on this subject will appear shortly in *Nuclear Instruments and Methods*. A comprehensive paper following completion of the analysis of the new data will be submitted to the *Physical Review*. Copious production of a large number of long-lived, previously unknown nonradiative autoionizing excited levels of heavy ions continues to be the central interest in this work.

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2. Guest Assignee from the University of Tennessee, Knoxville.
3. Oak Ridge Associated Universities consultant from the University of Connecticut, Storrs.
4. Oak Ridge Associated Universities consultant from Kansas State University, Manhattan.
5. Kansas State University, Manhattan.
6. Graduate student from the University of Tennessee.
7. *Phys. Rev. Lett.* **27**, 1108 (1971); **28**, 1229 (1972); **28**, 1615 (1972).

SPIN-FORBIDDEN TRANSITION PROBABILITIES IN METASTABLE STATES OF HELIUM-LIKE HEAVY IONS

I. A. Sellin[1] D. J. Pegg[1] P. M. Griffin J. R. Mowat[2] W. W. Smith[3]
M. D. Brown[4] J. R. Macdonald[5] R. S. Peterson[6]

The $1s^2\ {}^1S_0 - 1s2p\ {}^3P_1$ transition is a strong feature of the solar soft x-ray spectrum for all abundant elements from carbon to iron. The spontaneous transition probability for this transition enters sensitively into estimates of electron density in solar active regions based on observation of the solar spectrum for ions in the range $Z = 6$ to 10. The spin flip occurs mainly because of the nuclear contribution to the spin-orbit interaction. We have made transition probability measurements (see Fig. 1) by the decay-in-flight method for F^{7+} ions and find excellent agreement with recent calculations of the corresponding lifetime (0.52 nsec). It is interesting to note that the scaling with Z is $\gtrsim Z^{10}$, mainly due to a mixing of singlet and triplet levels $\sim Z^3$ by the nuclear part of the spin-orbit interaction. The ordinary Z^4 dependence of allowed dipole transition probabilities times the square of the mixture amplitude produces the Z^{10} dependence. It is also of interest to note that a SiLi detector could be used very successfully to detect the 0.73-keV line involved.

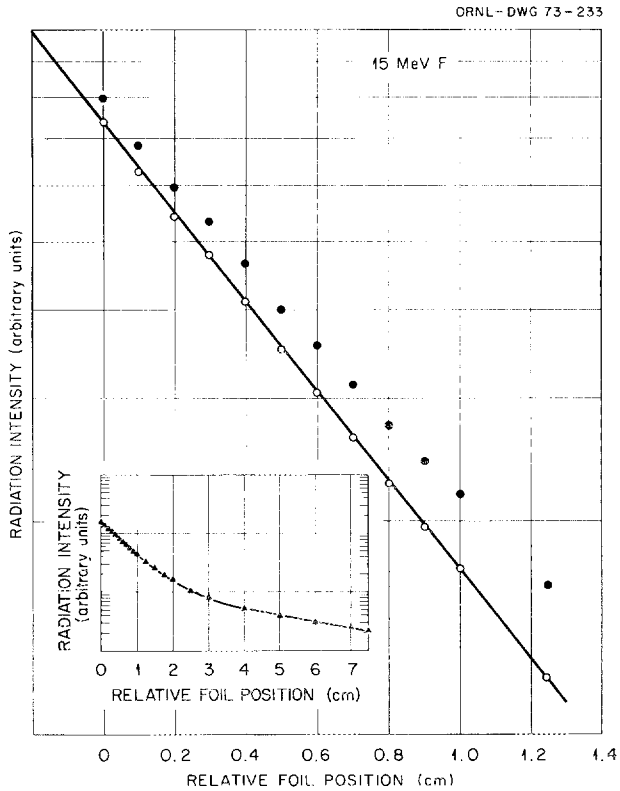

Fig. 1. Semilogarithmic plot of $1s^2\ {}^1S_0 - 2s2p\ 2^3P_1$, radiation intensity vs distance, for a 15-MeV F^{7+} beam. The background is of unknown origin and is under investigation.

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HYPERCHANNELING: AN AXIAL CHANNELING PHENOMENON[1]

B. R. Appleton[2] C. D. Moak T. S. Noggle[2] J. H. Barrett[2]

We have studied the behavior of 21.6-MeV iodine ions undergoing proper axial channeling (hyperchanneling) in silver. Ions of this special class traverse the crystal within a single axial channel and, as a result, exhibit conspicuously lower energy losses and an order of magnitude smaller acceptance angles than ordinary axially channeled ions. Analysis of the results indicates that hyperchanneled ions provide a new means of studying multiple scattering radiation damage and ion-atom potentials in solids.

1. Abstract of published paper: *Phys. Rev. Lett.* 28(20), 1307–11 (1972).
2. Solid State Division.

COLLISIONAL X-RAY EXCITATION IN SOLID AND GASEOUS TARGETS BY HEAVY-ION BOMBARDMENTS[1]

H. O. Lutz[2] J. Stein[2] S. Datz[3] C. D. Moak

Large differences have been found in the x-ray yields produced by 22.5- and 48-MeV iodine ions incident on solid ($_{34}Se$) and gaseous ($_{35}Br$ and $_{36}Kr$) targets. These differences are attributable to the steady-state excitation of the penetrating ion prior to the vacancy-producing collision and yield information on the state of energetic ions in solids.

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1. Abstract of published paper: *Phys. Rev. Lett.* **28**(1), 8–10 (1972).
2. Kernforschungsanlage Jülich, Jülich, West Germany.
3. Chemistry Division.

METASTABLE AUTOIONIZING STATES IN SODIUM-LIKE CHLORINE[1]

D. J. Pegg[2] I. A. Sellin[2] P. M. Griffin W. W. Smith[3]

We have observed metastable autoionizing states associated with partially stripped, highly excited chlorine ions. Charge-state fraction, electron energetic, and series limit arguments indicate that these states are primarily associated with *sodium-like chlorine* (Cl^{6+}), but few energy-level calculations exist for firm identification. Prominent peaks occur in the electron spectrum at 90 ± 3, 101 ± 3, 138 ± 3, and 182 ± 3 eV. A long-lived component of the 182-eV peak has a lifetime ⩾43 nsec.

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1. Abstract of published paper: *Phys. Rev. Lett.* **28**, 1615 (1972).
2. Consultant in the Physics Division from the University of Tennessee.
3. University of Connecticut, Storrs.

7. Instrumentation and Experimental Techniques

MEASUREMENT OF SURFACE CONTAMINATION USING OXYGEN-ION-INDUCED X RAYS[1]

M. J. Saltmarsh A. van der Woude[2] C. A. Ludemann

X rays induced by 20-MeV oxygen ions have been used to search for trace quantities of lanthanum on the surface of NaCl crystal. The results demonstrate the sensitivity of the method to small quantities of heavy elements present on low-Z matrices.

1. Abstract of published paper: *Appl. Phys. Lett.* **21**(2), 64 (1972).
2. Present address: Kernfysisch Versneller Instituut, Universiteitscomplex Paddepoel, Groningen, Netherlands.

HYDROGEN CONTAMINATION ON THE SURFACE OF THIN METAL FOILS

M. J. Saltmarsh G. E. McGuire[1] A. Wolfenden[2]

We have used a technique based on $p + p$ scattering[3] to measure hydrogen contamination on the surfaces of a number of thin (10 to 20 mg/cm^2) metal foils. The measurements were performed using an 11.5-MeV proton beam from the Oak Ridge tandem Van De Graaff accelerator. The beam intensity was $\cong$2 nA, and the beam spot diameter was approximately 1 mm. Counting times were in the range of 5 to 10 min for each measurement.

The foil samples were made from three types of stainless steel and one alloy of aluminum. The surfaces were cleaned by either electropolishing or chemical

Table 1. Surface hydrogen concentration

In nanograms per square centimeter

Absolute normalization error = 7%

Material	Chemical etch		Electropolished	
	Side A	Side B	Side A	Side B
Aluminum				
Fresh	28.0 ± 2.8 25.8 ± 2.6	31.1 ± 2.9	51.9 ± 3.6	79.6 ± 4.3
Old	53.5 ± 3.8	41.7 ± 4.4	47.5 ± 2.5	925 ± 24
Stainless steel, Ti mod.				
Fresh	34.4 ± 3.1	33.9 ± 3.0	18.7 ± 1.6	17.9 ± 1.3
Old	37.8 ± 1.5	58.7 ± 3.8	18.1 ± 1.2	21.2 ± 1.5
Stainless steel 19-4-S-2				
Fresh	32.6 ± 3.0	26.0 ± 2.7	19.9 ± 2.3	54.5 ± 3.6
Old	29.2 ± 1.8 25.3 ± 1.7	28.2 ± 2.5 33.5 ± 1.7	19.0 ± 1.4	21.9 ± 1.6
Stainless steel 17-4-A				
Fresh	32.6 ± 2.8	27.6 ± 2.7	21.2 ± 2.4	22.0 ± 2.2
Old	43.5 ± 2.3	44.6 ± 2.4	16.7 ± 1.2	25.9 ± 1.9

etching. One sample set was prepared three weeks prior to the measurements, and a second a few hours in advance.

The results for all the samples studied are shown in Table 1. The quoted errors are statistical only and do not include the overall normalization uncertainty of 7%. The two values underlined correspond to large localized concentrations of hydrogen, presumably introduced during handling.

The results for the aluminum samples show such large variations that no conclusions can be drawn as to any differences between samples which have different histories. However, in the case of stainless steel, differences are evident. Table 2 shows the combined results of all the stainless steel samples. Clearly the electropolished samples were cleaner than those which were chemically etched, but there was no significant difference between the fresh and old samples.

Table 2. Average hydrogen concentrations in all stainless steel samples

In nanograms per square centimeter

Material	Chemical etch	Electropolished
Fresh	31.2 ± 1.2	19.2 ± 0.8
Old	34.4 ± 0.7	19.6 ± 0.6

1. Presidential Intern, Analytical Chemistry Division.
2. Metals and Ceramics Division.
3. B. L. Cohen, C. L. Fink, and J. H. Degnan, *J. Appl. Phys.* **43**, 19 (1972).

HALF-VALUE THICKNESS OF ORDINARY CONCRETE FOR NEUTRONS FROM CYCLOTRON TARGETS[1]

H. M. Butler[2] K. M. Wallace[2] C. B. Fulmer

Half-value thicknesses (or half-value layers) of ordinary concrete were determined for neutrons emitted from a variety of cyclotron beam-target combinations. Targets of carbon, aluminum, copper, and tantalum were each bombarded with beams of protons, deuterons, alpha particles, and carbon ions at the Oak Ridge Isochronous Cyclotron. Measurements were made of neutron attenuation by an 80-cm-thick wall for each target-beam combination. For protons, deuterons, and alpha particles a range of bombarding energies was used; maximum neutron energies were as high as 60 MeV. The half-value thicknesses for neutrons from all of these particle-target combinations are in the range of 9 to 10.5 cm.

1. Abstract of a paper to be published in *Health Physics*.
2. Health Physics Division.

RADIATION LEAKAGE THROUGH THIN CYCLOTRON SHIELD WALLS[1]

C. B. Fulmer H. M. Butler[2] K. M. Wallace[2]

Thick targets of carbon, aluminum, copper, and tantalum were each bombarded with beams of protons, deuterons, alpha particles, and carbon ions. The target station was 5.5 m from an 80-cm-thick ordinary concrete shield wall. Measurements were made of radiation levels of fast neutrons, thermal neutrons, and gamma radiation on the shielded side of the wall for each target-beam combination. Total radiation levels due to leakage through the wall were thus determined as a function of beam intensity for targets of a wide range of atomic mass and for a variety of incident beam particles with energies in the range of 8 to 66 MeV/amu. Deuteron beams result in the highest radiation levels (for a given beam energy). Measurements on both sides of the wall indicate that neutrons are the principal radiation leakage through the wall. Neutron-induced reactions in the wall, however, result in significant levels of gamma radiation on the shielded side of the wall which are ~50% of the total rem dose.

1. Abstract of published paper: *Particle Accel.* **4**, 63–68 (1972).
2. Health Physics Division.

NEUTRON YIELD FROM A SMALL HIGH-PURITY $^{238}PuO_2$ SOURCE[1]

J. K. Bair H. M. Butler

The neutron yield from a small high-purity $^{238}PuO_2$ source has been measured to be 1.705×10^4 neutrons/sec per gram of ^{238}Pu with an accuracy of better than 1%.

1. Abstract of paper submitted for publication in *Nuclear Technology,* Technical Note.

DELAYED GAMMA RADIATIONS FROM THE ORELA TARGET

C. H. Johnson N. W. Hill[1]

A scintillator of NE110 is presently used to detect proton recoils from neutrons in transmission measurements at ORELA. This plastic allows for detection[2] of low-energy ($\gtrsim$10 keV) neutrons but not for straightforward pulse-shape discrimination against the gamma rays that arise from cosmic rays, from various sources in the target room, and from neutron inelastic scattering or capture in the detector and its environs. Corrections are straightforward for the cosmic rays and for time-independent radiation from the source but not for the other time-dependent radiations. We must measure the time-dependent radiations in order either to eliminate them or to correct for their presence.

Here we have limited our attention to the source radiations. We placed the detector at 200 m, just as in a normal transmission experiment, but removed most of the neutrons from the beam by interposing either an 8- or 12-in.-long polyethylene scatterer in the flight path at either 8 or 80 m. An 8-in. block of polyethylene removes essentially all neutrons below 1 MeV and nearly all at higher energies but does not seriously attenuate gamma rays above 100 keV. For example, it transmits 14.5% of the 511-keV radiation from positron annihilation and 39% of the 2.2-MeV radiation from neutron capture by hydrogen.

With the polyethylene in place, we proceeded by placing various scatterers of beryllium, calcium, and lead in the beam and recording in each case four simultaneous time spectra, one for detector pulses above a certain integral bias and one each for three lower differential pulse-height windows.[3] In all we recorded 21 sets with four time spectra each. The interpretation of these spectra is different from that for a normal transmission measurement in that, except for the fast neutrons that leak through the polyethylene filter, the time scale represents the time-dependent radiation from the source room rather than the neutron time of flight, and the attenuation in the scatterers results from scattering of gamma rays rather than neutrons.

Figure 1 shows a typical time spectrum for pulses exceeding the integral bias level. This was obtained with 8 in. of polyethylene at 80 m and with no additional scatterer. The time scale has been corrected for the gamma-ray transit time. The counts in the first 1.7 μsec must be ignored because the photomultiplier was gated off for 1.2 μsec and required an additional 0.5 μsec to recover stable operation. Furthermore, the counts out to about 10 μsec are to be ignored; they arise partially from the fast neutrons (>2 MeV) that leak through the polyethylene filter. After 10 μsec the count rate falls uniformly; the straight solid curve is obtained by subtracting the time-independent background from a smoothed curve through the data.

We conclude that these counts are due to 2.2-MeV radiation from capture of thermalized neutrons in the source cooling water. The imposition of any additional scatterer in the beam reduces the entire curve by a constant factor. From 19 measurements with and

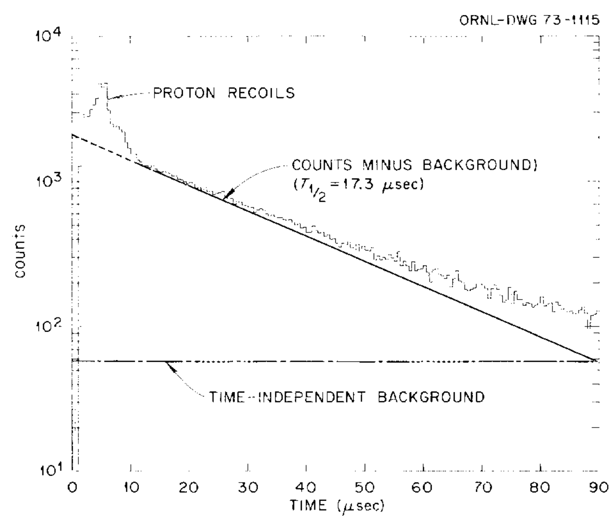

Fig. 1. The spectrum for high pulses in an NE110 scintillator with 8 in. of polyethylene in the beam.

without scatterers, we find a decay half-life of 17.3 ± 0.1 μsec, and we attribute this to the leakage of the thermalized neutrons from the source. From nine transmission measurements with two lead samples (0.25 and 1.0 in.), we find a cross section of 15.20 ± 0.3 b, corresponding to 2.3 ± 0.2 MeV gamma rays.[4] We also find cross sections of 2.74 b for calcium and 0.55 b for beryllium, both of which are consistent[4] with gamma rays of about 2.2 MeV.

The counting rate for pulses falling within the first differential window below the integral bias also has a half-life of about 17 μsec; however, the cross sections are all larger than above. We find 33.7 ± 1.3, 4.25, and 0.88 b for lead, calcium, and beryllium respectively. These correspond to gamma rays of 0.71 ± 0.02, 1.0, and 0.9 MeV. Our explanation is that these pulses have their origin in the 2.2-MeV radiation but that Compton scattering in the source gives rise to a degraded spectrum which is preferentially detected in this lower window.

The other two lowest windows show somewhat different spectra. Figure 2 shows the counts observed in the middle window under the same conditions as for Fig. 1. (The spectrum for the lowest window is quite similar.) The solid curve is obtained as above by subtraction of the time-independent background from the smoothed data. The curve appears to be approaching a slope corresponding to the 17.3-μsec half-life, but it also shows pronounced peaks at early times.

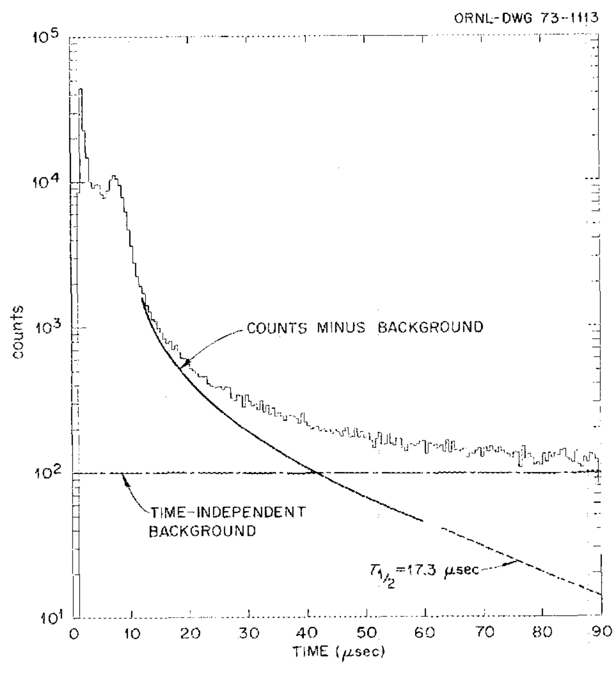

Fig. 2. Time spectrum for pulses in a low differential window with 8 in. of polyethylene in the beam.

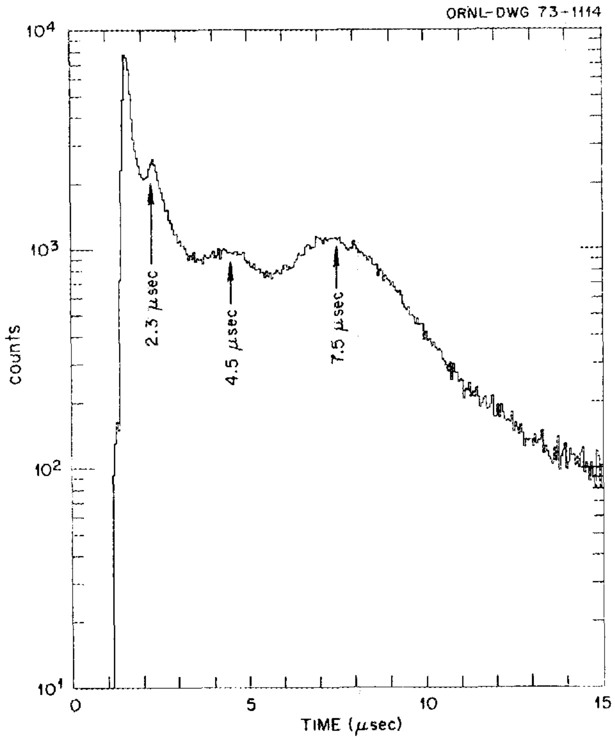

Fig. 3. Expansion of the first 15 μsec from Fig. 2.

Figure 3 is an expanded view of the first 15 μsec from Fig. 2, with the time channel widths reduced a factor of 10. Four peaks are observed. The first is to be ignored; it is associated with the turn-on of the photomultiplier. The other three at about 2.3, 4.5, and 7.5 μsec appear to be real. Transmission measurements show clearly that the 2.3- and 7.5-μsec peaks are associated with gamma rays from the source or source room. The evidence for the central peak at 4.5 μsec is not quite so convincing because, when a 1-in. lead scatterer is interposed to remove all but 1% of the gamma rays, a peak due to fast neutrons is revealed at about 5 μsec. Nevertheless, any scatterer of moderate thickness attenuates all of the peaks about the same amount, and all of the evidence taken together indicates that these peaks all originate from gamma rays of about the same energy.

Transmission measurements for the 7.5-μsec peak give cross sections of 64, 5.8, and 1.2 b for lead, calcium, and beryllium respectively. The corresponding gamma-ray energies[4] are 0.45, 0.5, and 0.45 MeV. These gamma rays certainly originate in the source or its environs, and probably, although not certainly, they are due to 511-keV positron annihilation radiations and the associated Compton gamma rays.

At present we have no explanation for the time dependence in Fig. 3. We see no good reason for the three peaks and, in fact, no clear reasons for the long delays for the 0.5-MeV radiation.

One possible explanation for the peaks might have been that they are electronic oscillations. To check this, we operated the detector in the beam just as in the above experiments and generated a random count rate by placing a californium fission chamber near the detector and counting only pulses in the NE110 coincident with fission events. These data show that the photomultiplier recovers within 0.5 μsec after the turn-on time. Thus, the peaks appear to be real phenomena associated with the source, the source room, and the various collimators and shields at the exit to the source room.

In regard to the neutron transmission experiments, these backgrounds are significant but manageable. Differential windows can be found at most neutron energies such that these backgrounds become less than 1% and can be readily subtracted. At higher energies >2 MeV, these backgrounds might be several percent even for carefully selected pulse-height windows, but in those cases a uranium filter can be inserted to remove most of the gamma rays.

1. Instrumentation and Controls Division.

2. J. A. Harvey, N. W. Hill, and W. E. Kinney, *Bull. Amer. Phys. Soc.* **17**, 901 (1972).

3. The gain was set so that the Compton edge from a 661-keV gamma-ray source situated at the side of the detector corresponded to a pulse of 60 mV at the discriminator monitor output. The lower sides of the three windows and the integral level were then set approximately at 3.5, 5, 15, and 43 mV respectively.

4. E. Storm, E. Gilbert, and H. Israel, *Gamma-Ray Absorption Coefficients for Elements 1 through 100 Derived from the Theoretical Values of the National Bureau of Standards*, LA-2237 (1958).

A SIMPLE METHOD FOR ACCURATE MEASUREMENTS OF TOTAL INTERNAL CONVERSION COEFFICIENTS[1]

S. Raman

We describe a simple method employing a Ge(Li) detector for determining total internal conversion coefficients. This method can significantly increase the number of accurately known conversion coefficients of high-multipolarity ($\Delta L \geqslant 3$) transitions. When an isomer deexcites via two transitions in cascade, one of which has a small total conversion coefficient (determined from theory or experiment), it is possible to deduce the other (high) conversion coefficient by measuring relative photon intensities only. This method is demonstrated by measuring the total conversion coefficient of the 88.5-keV, $M4$ transition occurring in the $11/2^-$ (120-day ^{123}Te isomer) $\rightarrow 3/2^+$ (159.0-keV level) $\rightarrow 1/2^+$ (^{123}Te ground state) cascade. The experimental value is 1076 ± 42, compared with the theoretical value of 1149.

1. Abstract of published paper: *Nucl. Instrum. Methods* **103**, 407 (1972).

HIGH-RESOLUTION ELECTRON MICROSCOPY PROGRAM

R. E. Worsham J. E. Mann E. G. Richardson N. F. Ziegler

Design and construction of the field-emission electron gun for the high-coherence microscope column were completed. The gun is designed to produce a transverse coherence length of ~1000 Å in the illuminating wave on the specimen at energies up to 150 keV. This long coherence length makes possible the correction for the spherical aberration of the objective lens by application of the techniques of image analysis to the micrographs.

The basic structure of the gun consists of a field emission tip, a conically shaped two-electrode accelerating lens, an aperture, and a single condenser lens. Vacuum of 10^{-10} to 10^{-11} torr, required for stable field emission tip operation, is obtained with a 400-liter/sec ion pump. A high-voltage terminal, adjacent to the gun, houses the power supplies for tip forming, the first accelerating voltage supply, and a vernier high-voltage supply for voltage focusing.

The gun was set up for testing independently of the remainder of the microscope column. Voltage holding capability to 150 kV was checked. Field emission tips made of (111)-oriented tungsten wire appear to operate reliably using only voltage forming to obtain stability.

Commissioning of the mechanical and electrical controls was completed. Further measurements of the gun operating characteristics and beam brightness were in progress.

The commissioning of the superconducting objective lens column using the existing thermionic gun continued independently.

TRACK DETECTOR CALIBRATION

H. R. Hart, Jr.[1] M. J. Saltmarsh A. van der Woude[2]

We have used beams of 182-MeV Ar^{9+} and 130-MeV Fe^{9+} from the ORIC to irradiate a variety of materials in order to calibrate their response as track detectors. The Fe^{9+} beam was of particular interest because of the high natural cosmic abundance of ^{56}Fe which is reflected in cosmic ray spectra. The materials irradiated included phosphate glass and various plastics, carried as track detectors on recent Apollo missions, as well as samples of lunar and terrestrial minerals. Some of the preliminary data have already been used in studies of the track record in lunar soil and rock from Apollo XV[3] and in a measurement of the cosmic ray spectrum taken during the Apollo XVI mission.[4]

1. General Electric Research and Development Center, Schenectady, N.Y. 12301.
2. Kernfysisch Versneller Instituut, Groningen, Netherlands.
3. R. L. Fleisher and H. R. Hart, Jr., *Phys. Rev. Lett.* **30**, 31 (1973).
4. R. L. Fleischer and H. R. Hart, Jr., to be published in *Earth and Planetary Science Letters.*

A SIMPLE π^+ DETECTOR FOR ENERGIES OF 10 TO 70 MeV[1]

M. J. Saltmarsh B. M. Preedom[2] R. D. Edge[2] C. W. Darden III[2]

A simple π^+ detector telescope based on NE102A plastic scintillator has been developed for use in the energy range 10 to 70 MeV. The detector has a relatively high efficiency ($\gtrsim$75%), a useful degree of particle identification, and a resolution capability ($\lesssim$1 MeV FWHM) sufficient for a number of nuclear physics applications using high-quality pion beams, such as those which will be available at the Los Alamos Meson Physics Facility.

1. Abstract of published paper: *Nucl. Instrum. Methods* **105**, 311 (1972).
2. Physics Department, University of South Carolina, Columbia.

π^+ DETECTOR DEVELOPMENT

M. J. Saltmarsh E. E. Gross C. A. Ludemann B. Preedom[1]

We have continued with the development of the π^+ detector telescope[2] intended for use at the Los Alamos Meson Physics Facility, exploring the effect on the resolution capabilities of changes in the dimensions of the large stopping (E) segment. This element is a piece of plastic scintillator in the form of a truncated cone which is viewed directly from the larger end by a 3-in. photomultiplier tube. The cone has a length $l \cong 5$ in., a small-end diameter $d = 1$ in., and a large-end diameter $D \cong 3$ in.

Measurements of the response of a number of segments were made using a 67-MeV proton beam from the ORIC. The protons were scattered at approximately 13° by a thin (400 keV) carbon target and entered the scintillator axially through a ⅝-in.-diam collimator placed in front of the 1-in.-diam end surface. Energy spectra were stored in 400-channel arrays and analyzed for the positions and widths of the peaks corresponding to ^{12}C (ground state) and $^{12}C^*$ (4.43 MeV). Figure 1 shows the relevant portion of a spectrum obtained with the best of the scintillator geometries investigated.

Table 1. Measured energy resolution (FWHM) of scintillator segments

l (in.)	D (in.)	FWHM	
		MeV	Percent
5	2.25	1.17	1.7
5	2.50	1.26	1.9
5	2.75	1.09	1.6
5	3.00	1.12	1.7
4.5	2.70	1.02	1.5

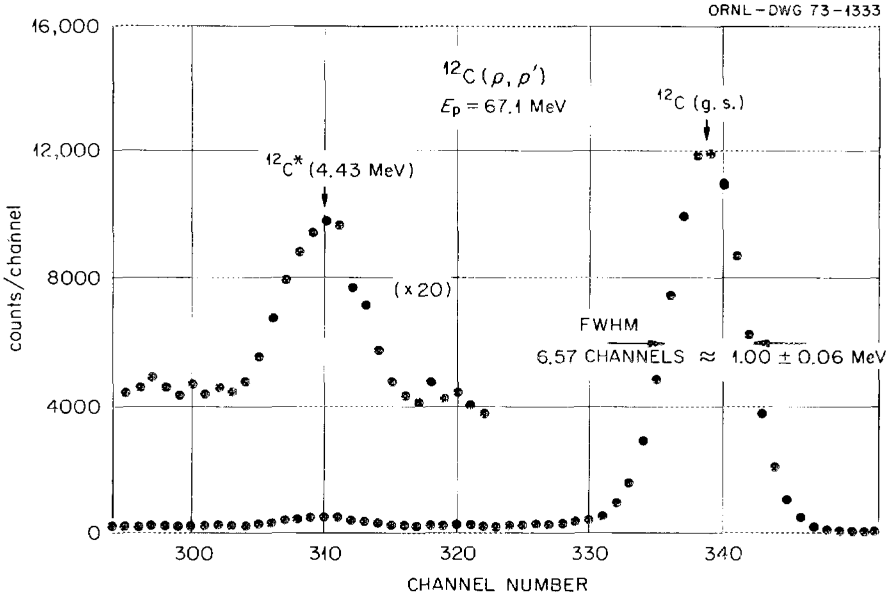

Fig. 1. Pulse-height spectrum obtained with a plastic scintillator element with l = 4.5 in., D = 2.7 in., and d = 1.0 in.

In every case, several measurements were made at different values of the photomultiplier high voltage to ensure that the system was operating in a region of linear response. The resolution was calculated by fitting Gaussian peaks to the data and assuming a linear energy response between the ground and first excited states. Table 1 summarizes the results obtained for the various geometries. The resolution for the D = 2.50 in. scintillator appears to be inconsistent with the data from the other detectors. In addition, the elastic peak, as seen with this detector, had a considerable high-energy tail. This anomalous behavior is presumed to be due to a poor photomultiplier tube.

From these results, we believe that we can achieve our goal of a π^+ detector with a resolution $\lesssim$1 MeV for energies $\lesssim$60 MeV.

1. Physics Department, University of South Carolina.
2. *Nucl. Instrum. Methods* **105**, 311 (1972).

DETERIORATION OF LARGE Ge(Li) DIODES CAUSED BY FAST NEUTRONS[1]

P. H. Stelson J. K. Dickens S. Raman R. C. Trammell[2]

The large Ge(Li) gamma-ray detector has become a powerful tool for the investigation of nuclear reactions. Unfortunately, these detectors are quite susceptible to fast-neutron damage, and this makes it difficult to decide whether or not to risk using a detector to study reactions at accelerators, where fast neutrons are inevitably present. After ruining several detectors, we decided to study the problem in a controlled way. A 30-cm^3 true coaxial diode was systematically irradiated by neutrons from a plutonium-beryllium source. An increase in the width of the 2.614-MeV gamma ray from ^{208}Tl was first detected after an irradiation of 5 × 10^7 neutrons/cm^2. When the total irradiation had reached 6 × 10^8 neutrons/cm^2, the peak width had increased by more than 50%. The irradiated detector was then reprocessed to remove the damage. The diode was again subjected to neutron irradiation. The second curve of resolution deterioration as a function of neutron flux was quite similar to the first one. The procedure was repeated a third time with similar results. Thus, reprocessing a detector effectively removes the neutron damage at a cost of only about 10 to 15% of the original price. A method was also developed for using the gamma-ray spectrum to evaluate the amount of neutron flux incident on the detector. The number of counts in the 693-keV peak [from (n, n') reaction with the ^{72}Ge in the detector] can be multiplied by 20 to get a rough measure of the neutron flux in neutrons per square centimeter.

1. Abstract of published paper: *Nucl. Instrum. Methods* **98**, 481–84 (1972).
2. ORTEC, Inc., Oak Ridge, Tenn.

THE MEASUREMENT OF THE ABSOLUTE TRANSPORT EFFICIENCY FOR RECOILS FROM HEAVY-ION REACTIONS WITH HELIUM JET SYSTEMS[1]

W.-D. Schmidt-Ott[2] R. L. Mlekodaj[3] C. R. Bingham[4]

The complex problems involved in the transport of reaction recoils with helium jet systems have been investigated. The recoils ^{149,150,151}Dy produced in the reactions ^{141}Pr(^{14}N; 6,5,4*n*) were stopped in helium gas and transported with the helium flow through Teflon, stainless steel, and glass capillaries. From the recoils knocked out of the target, 65% were transported through an 0.86-mm-ID Teflon capillary of 5 m length, 75% through a 2.25-m stainless steel capillary. The dependence of the transport efficiency on various parameters was investigated. The transport efficiency was increased by a small amount of carbon tetrachloride injected into the target chamber.

In order to transport the reaction products from the high-pressure region necessary to stop the recoils into a low-pressure region where in future experiments an ion source can be operated, various glass-capillary-skimmer systems and also a double vacuum chamber evacuated by booster jet pumps have been tested. With the glass-capillary-skimmer system and using differential pumping with mechanical pumps only, about 30% of the recoils were brought into a region with a 3×10^3 times smaller pressure. Using two booster pumps and the double vacuum chamber with one 1.5-mm brass skimmer, 46% of all the recoils were introduced into the second vacuum chamber, where the pressure is 10^6 times smaller than in the target chamber. The opening angle of the cone into which the recoils from the helium jet are emitted has been measured by radiograms to be 3°. The double vacuum chamber was put on high potential during the operation without the occurrence of a gas discharge.

1. Abstract of paper to be published in *Nuclear Instruments and Methods.*
2. School of Chemistry, Georgia Institute of Technology, and UNISOR.
3. UNISOR.
4. University of Tennessee, Knoxville.

PROPOSAL FOR A NATIONAL HEAVY-ION LABORATORY

P. H. Stelson

During 1972, ORNL prepared a proposal for a National Heavy-Ion Laboratory. Twenty-two people from the Physics Division directly participated in the preparation of the proposal. The abstract from the NHL proposal is reprinted below.

The Oak Ridge National Laboratory proposes to establish a National Heavy-Ion Laboratory with the mission to provide the nation's scientists with beams of all ions from helium to uranium. The energies of the ions will range from 100 MeV/amu for the lower masses to 10 MeV/amu for the heaviest projectiles. Expected intensities are 10^{12} to 10^{13} ions/sec. A special effort is made to assure beams of low emittance and low energy spread and to provide for ease of energy variation.

At the heart of the National Heavy-Ion Laboratory is a three-accelerator complex. The main accelerator, a large separated-sector cyclotron, provides the second stage of acceleration for beams injected either from a 20-MV tandem or from the Oak Ridge Isochronous Cyclotron (ORIC). Either the ORIC or the tandem, when it is not used as the injector, is available for independent research suited to its special capabilities. The proposed system is based on a combination of accelerator types with long histories of successful use in nuclear physics.

The Laboratory is designed to support a variety of experiments and will be available for use to all scientists in the nation. Sufficient experimental area (28,000 ft^2) and a complete beam transport system will be provided to service 18 experimental stations initially, with the possibility of expanding to 25 or more. Experiment setup areas and laboratory and office space are planned for the use of visiting research groups.

This proposal develops the compelling scientific motivation for research with fast heavy-ion beams. Whole new regions of nuclear behavior can be opened for study and exploitation. New nuclear phenomena and new nuclear laws are to be expected; these are important to achieve a greater understanding of nuclear physics and chemistry. The collision between a fast heavy ion and a target atom can literally denude the atom of its electrons. This feature of the collision process allows measurements of atomic properties which were formerly not possible and, with the lighter available ions, has already led to a number of surprising results. The "channeling" of heavy-ion beams in single crystals is an important experimental tool for the solid-state physicist. Finally, the high rate of energy deposition produced by heavy ions has interesting research possibilities for materials science and biology.

No less important are the possibilities opened up for applied research. These include radiation damage, since heavy ions present a great opportunity to simulate damage processes caused by neutrons on time scales 100 times shorter than can be obtained in reactor irradiation. Interesting applications are foreseen in medicine and biology because of the high LET radiation, in the production of very small pores in plastic material, and in the implantation of ions for development of new solid-state devices.

This proposal provides the scientific motivation, a description of the accelerators and their mode of operation, and a description of the building, beam transport system, experimental areas, and some equipment. The construction of the Laboratory will take four years, and the total cost is estimated at $25 million.

A PROPOSED NATIONAL HEAVY-ION ACCELERATOR AT OAK RIDGE[1]

J. A. Martin E. D. Hudson R. S. Lord M. L. Mallory[2]
W. T. Milner S. W. Mosko P. H. Stelson

The proposed National Heavy-Ion Laboratory will be provided with a multistage accelerator system integrated with the existing Oak Ridge Isochronous Cyclotron (ORIC) facilities. The main accelerator stage is to be a four-sector isochronous cyclotron that will provide beam energies up to 100 MeV/amu. Ions may be injected into the large cyclotron either from a 20-MV tandem electrostatic accelerator or from the ORIC. The ion energies range from 100 MeV/amu for oxygen to 10 MeV/amu for uranium. Maximum beam intensities range from $\sim 10^{13}$ particles/sec for oxygen to 2×10^{12} particles/sec for uranium. The sector magnet angle for the cyclotron is 52°, which yields radial and axial focusing frequencies of ν_r = 1.1 to 1.2 and ν_z = 0.6 to 0.8. The field-radius product of the magnet is 3018 kG-cm at a maximum magnetic field of 16 kG. The rf system is tunable over the range 6 to 14 MHz to accommodate acceleration on harmonics 2 to 11. Second-harmonic resonators are provided to increase the phase acceptance and/or the energy resolution.

1. Abstract of published paper: *Cyclotrons – 1972,* AIP Conference Proceedings No. 9 (Vancouver, Canada, 18–21 July 1972), pp. 54–62, ed. by J. J. Burgerjon and A. Strathdee, American Institute of Physics, New York, 1972.
2. Chemistry Division.

ALTERNATES TO THE CYCLOTRON FOR HEAVY-ION ACCELERATION[1]

J. A. Martin

The status and future possibilities for several alternates to the cyclotron for heavy-ion acceleration are discussed. Linear accelerators, both conventional and superconducting, tandem electrostatic accelerators, and the electron ring accelerator are among the accelerator types and concepts reviewed and compared.

1. Abstract of published paper: *Cyclotrons – 1972,* AIP Conference Proceedings No. 9 (Vancouver, Canada, 18–21 July 1972), pp. 33–53, ed. by J. J. Burgerjon and A. Strathdee, American Institute of Physics, New York, 1972.

THE ORIC AS A HEAVY-ION INJECTOR FOR A SEPARATED-SECTOR CYCLOTRON[1]

E. D. Hudson R. S. Lord M. L. Mallory[2] P. H. Stelson

The characteristics of the Oak Ridge Isochronous Cyclotron (ORIC) for the injection of heavy ions into a separated-sector cyclotron have been studied and found to be excellent. With a carbon foil between the accelerators, the output energy of the ORIC is sufficient to give a stripped ion beam at least twice the charge state of the ORIC's extracted beam up to mass 200. This allows an ideal magnetic field match to a separated-sector cyclotron with a magnet fraction of 0.58. The 37-MeV $^{40}Ar^{4+}$ beam from the ORIC was used to test the lifetime of 20-μg/cm^2 carbon foils. It was found that the stripping characteristics were unchanged after a total transmission of 5×10^{17} particles/cm^2. Results of the measurement of the ORIC beam loss as a function of pressure in the cyclotron tank and beam line are also presented.

1. Abstract of published paper: *Cyclotrons – 1972,* AIP Conference Proceedings No. 9 (Vancouver, Canada, 18–21 July 1972), pp. 274–82, ed. by J. J. Burgerjon and A. Strathdee, American Institute of Physics, New York, 1972.
2. Chemistry Division.

A MULTIACCELERATOR SYSTEM FOR HEAVY IONS[1]

E. D. Hudson R. S. Lord C. A. Ludemann M. L. Mallory[2] J. A. Martin
W. T. Milner S. W. Mosko P. H. Stelson A. Zucker

The heavy-ion accelerator system being planned for the National Heavy-Ion Laboratory will provide a wide variety of beams and great flexibility of use. Two new accelerators, a four-sector isochronous cyclotron with an energy rating of $440q^2/A$ MeV and a 20-MV tandem electrostatic accelerator, will be integrated with the Oak

Ridge Isochronous Cyclotron (ORIC) facility. The large cyclotron acts as an energy booster for ions from either the 20-MV tandem or the ORIC. One of the two smaller accelerators will always be available for independent research. Maximum energies and intensities of the NHL beams range from 100 MeV/amu for oxygen at 10^{13} ions/sec to 10 MeV/amu for uranium at $\sim 2 \times 10^{12}$ ions/sec. Beam emittance less than 10 mm-mrad and energy spread less than 0.1% at full intensity are expected.

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1. Abstract of paper to be published in proceedings of the 1973 Particle Accelerator Conference (San Francisco, California, March 5–7, 1973).
2. Chemistry Division.

ION STRIPPING CONSIDERATIONS FOR TANDEM-CYCLOTRON HEAVY-ION ACCELERATOR DESIGN[1]

J. A. Martin P. H. Stelson

Two-stage heavy-ion accelerators which employ a tandem electrostatic accelerator as the injector for a second-stage cyclotron depend upon the use of gas or foil stripping between stages to increase the ion charge. We have systematically studied the influence of the variation of average charge with energy and the influence of the appreciable widths of the charge distributions on the design of tandem-cyclotron accelerators. Intensity vs energy results are obtained for a wide range of ion mass and for various stripper combinations, including foils, ordinary gases, and fluorocarbon vapor in the tandem terminal and between the two stages. It is shown that to obtain good energy variation and multiparticle capability, the cyclotron injection system must be designed to provide variation of the ion injection radius if intensity loss is to be avoided. Evaluation of operation at charge states above the peak of the charge distribution shows significant increases in energy for some cost in intensity. With a 20-MV tandem injecting into a cyclotron with an energy rating of $440q^2/A$ MeV, a 50% increase in energy can be achieved for a tenfold reduction in intensity.

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1. Abstract of paper to be published in proceedings of the 1973 Particle Accelerator Conference (San Francisco, California, March 5–7, 1973).

ENERGY MULTIPLICATION BY BEAM RECYCLING IN AN ISOCHRONOUS CYCLOTRON[1]

E. D. Hudson M. L. Mallory[2] R. S. Lord A. Zucker
H. G. Blosser[3] D. A. Johnson[3]

We have made an initial computer study of a recycling method for increasing the final energy of heavy-ion beams from the ORIC. The system involves simultaneous acceleration of two beams. A first beam originating either in an ion source or external injector is accelerated, extracted, and reinjected in a higher charge state obtained by means of a foil located between the turns of the first-pass beam. For example, with a 20-MV tandem injecting into the ORIC, the energy for ^{208}Pb after the first pass would be 1.9 or 2.3 MeV/amu and after the second pass 5.2 or 6.3 MeV/amu, depending on the injection charge. The requirements of this scheme are: (1) sufficient dee voltage to override the differing mass increase factors of the two beams, (2) good beam quality and accelerator stability to ensure spatial separation of orbits, (3) an all-magnetic extraction system to assure identical paths for the two beams, and (4) relatively standard external beam separation and reinjection equipment.

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1. Abstract of paper to be published in proceedings of the 1973 Particle Accelerator Conference, San Francisco, California, March 5–7, 1973.
2. Chemistry Division.
3. Michigan State University.

APPENDIX A: CYCLOTRONS – 1972, AVF AND FM[1]

F. T. Howard

This catalogue of cyclotron installations of the world lists 70 of the newer-type machines that use azimuthally varying magnetic field configurations to maintain isochronism and 17 of the remaining older large machines that use frequency modulation to accommodate the loss of isochronism at relativistic energies. Most of the installations have provided detailed two-page data reports which well describe each machine.

The chief activity at the higher energy range is the construction of large machines with sectored magnets. Azimuthal field variations are being incorporated into one or two FM machines. In the low-energy field, compact isochronous cyclotrons are being supplied commercially, largely for biomedical applications. Mid-energy machines are increasingly active in the heavy-particle field. No attempt is made here to account for the few remaining standard fixed-frequency cyclotrons.

1. Abstract of published paper: *Cyclotrons – 1972*, AIP Conference Proceedings No. 9 (Vancouver, Canada, July 18–21, 1972), pp. 689–829, ed. by J. J. Burgerjon and A. Strathdee, American Institute of Physics, New York, 1972.

COMPUTER CONTROL OF THE OAK RIDGE ISOCHRONOUS CYCLOTRON[1]

C. A. Ludemann J. M. Domaschko S. W. Mosko K. Hagemann[2]

The controls of the Oak Ridge Isochronous Cyclotron are being interfaced to a computer system. The initial implementation of the system is designed to reduce the time for setting up the cyclotron between experiments and to closely monitor the operation of the accelerator's power supplies. The system will be expanded to include the monitoring and control of the rf, beam-line, and vacuum systems. Later, diagnostic devices will be interfaced so that beam quality and intensity may be optimized. The operator communicates with the cyclotron via a CRT interactive display and a control console containing reassignable function keys and LED readout devices. The computer is a Modular Computer Systems MCS III/5. Operation data and programs for controlling the cyclotron are stored on disk and magnetic tape libraries.

1. Abstract of paper to be published in proceedings of the 1973 Particle Accelerator Conference, San Francisco, California, March 5–7, 1973.
2. On leave from Niels Bohr Institute, Denmark.

COMPUTER CONTROL SYSTEM FOR THE ORIC[1]

C. A. Ludemann J. M. Domaschko S. W. Mosko

A computer control system is being implemented for the Oak Ridge Isochronous Cyclotron (ORIC). At the start of a run, operating parameters are set automatically using data stored in a disk library. Adjustments of these parameters are made through an operator-computer interface consisting of a CRT unit with a keyboard. An array of assignable push-button switches is available for fine tuning various machine parameters. The ORIC has 43 ungrounded power supplies requiring adjustment resolution to within 1 part in 10^3 to 1 part in 10^5 depending upon their function. These supplies are controlled by reference voltages derived from 12- to 16-bit digital-to-analog converters (DAC's). A programmable comparator associated with each power supply relays information on power supply performance to the computer. The power supplies, DAC's, and comparators are isolated from the computer by optical couplings and blocking capacitors. The control system sets and fine tunes the rf system, monitors and controls binary functions, switches power supplies to required circuits, alerts the operator if any cyclotron parameter exceeds the specified limits, and processes and stores new run parameters.

1. Abstract of published paper: *Cyclotrons – 1972*, AIP Conference Proceedings No. 9 (Vancouver, Canada, July 18–21, 1972), pp. 500–509, ed. by J. J. Burgerjon and A. Strathdee, American Institute of Physics, New York, 1972.

LIST OR SORT? – SOME EXPERIENCE WITH THE ORIC MULTIPARAMETER DATA ACQUISITION SYSTEM[1]

D. C. Hensley

The data acquisition system at the ORIC is reviewed, and several of the data acquisition techniques used are described. The experience of two years of data acquisition with the system is discussed, and a special effort is

made to assess the merits and capabilities of an associative memory technique. A current development in the programs for data acquisition is sketched, and a simple graphics technique for line printers is presented which permits plotting three data points per line.

1. Abstract of paper to be published in the February 1973 *IEEE Transactions on Nuclear Science*.

A NEW RF SYSTEM FOR THE ORIC[1]

S. W. Mosko

The rf system of the Oak Ridge Isochronous Cyclotron has been converted from an RCA 6949 power amplifier to an RCA 4648 power amplifier. The primary purpose for the conversion was to reduce tube replacement cost; however, improved system performance and reliability were also realized. Existing servo-tuned driver amplifier stages were retained, but their performance requirements were somewhat relaxed. Typical noise levels for the accelerating potential have been reduced from about 0.05% to 0.01% peak-to-peak noise per peak rf voltage.

1. Abstract of paper to be published in proceedings of the 1973 Particle Accelerator Conference, San Francisco, California, March 5–7, 1973.

CYCLOTRON LABORATORY ACCELERATOR DEVELOPMENT PROGRAM

E. D. Hudson R. S. Lord C. A. Ludemann M. L. Mallory[1] M. B. Marshall
J. A. Martin S. W. Mosko W. R. Smith J. M. Domaschko K. Hagemann[2]

The major emphasis of this program during 1972 was directed toward the implementation of the Cyclotron Improvement Program, which includes installation of a computer control system, design and fabrication of a new internal source for heavy ions, and improvement of heavy-ion beam intensity by providing better vacuum with additional external and internal pumping. The RCA 6949 power amplifier tube was replaced with a more compact higher-gain and lower-cost tube. Other activities include a study of some of the problems involved in increasing the energy of the ORIC (and other isochronous cyclotrons) by recycling the beam, and preparation of the accelerator sections of the proposal for a National Heavy-Ion Laboratory.[3] Some effort was also devoted to developing a system for dc extraction of ions from the source. Some details on a few of these items are given below.

A Modcomp III computer (16 bit, 24 K) has been acquired for control of the ORIC. It will be used initially to set and monitor the cyclotron magnet and external ion optics power supplies according to stored information from previous runs. A prototype interface channel has been built and is being tested prior to fabrication of the complete system.

Data have been obtained on heavy-ion beam attenuation due to interaction with the residual gas in the cyclotron vacuum tank (Fig. 1). For most beams a vacuum improvement of a factor of 10 would result in an increase in beam intensity of approximately a factor of 10. Methods of achieving lower pressure in the cyclotron are being studied. Five additional pumping stations have been acquired for use in the external beam lines.

The conversion of the ORIC power amplifier from the 6949 triode to the 4648 tetrode was accomplished during a six-week period in October and November. The new tube is only about one-half the size of the old one

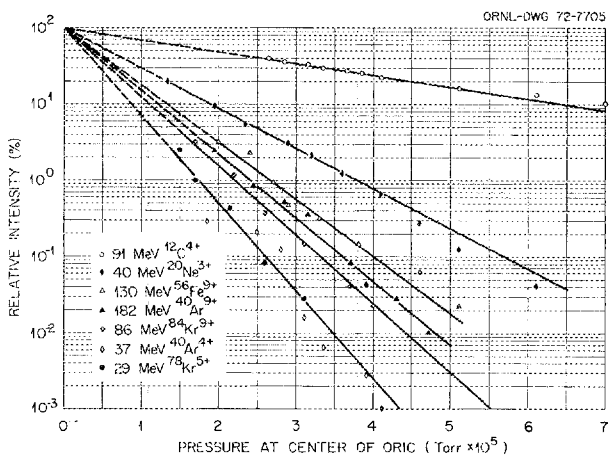

Fig. 1. Attenuation of the ORIC external beam as a function of internal pressure. All beams are normalized to 100% for zero pressure.

and is quite different electrically, requiring substantial hardware modifications. It has been operated over the whole frequency range from 7.5 to 22.45 MHz and has equaled the performance of the 6949 in some respects. Empirical optimization of the circuitry will be necessary, however, before the full capability is realized. Power gain in excess of 27 dB is possible in our "grid driven" configuration without benefit of neutralization circuitry. Drive requirements are such that in the future an all-solid-state driven amplifier is possible using the latest generation of power transistors. Replacement of the new tube can be accomplished much more simply than with the 6949. It will no longer be necessary to break cyclotron vacuum and lower the resonator from the crane. The cost of the conversion including the new tube was approximately equal to the price of a replacement 6949.

Direct current extraction from the ion source has the potential capability of increasing the intensity for beams accelerated on harmonics 3, 5, 7, 9, and possibly 11. Under normal conditions, with rf voltage being used for extraction of ions from the source, beam intensity for harmonic acceleration decreases with increasing harmonic number. The factors contributing to this condition are the gap transit time, the initial starting phase, and the effective electric field for ion extraction. If dc ion extraction is provided, the transit time for the first gap is reduced, and, since ions are continuously extracted from the source, the initial starting phase and the electric field can be independently adjusted for optimum external beam. In a test, a dc extraction electrode was interposed between the ion source and the rf accelerating electrode on the dee. For an Ne^+ beam on seventh harmonic the external beam intensity was a factor of 15 greater than that obtained when the dc electrode was removed. The external beam was optimized in each case. Application of this technique will provide heavy-ion beams of greater intensity for experiments requiring relatively low energies, for example, stripping foil lifetime measurements and radiation damage studies for reactors.

1. On loan from the Chemistry Division.

2. Visiting scientist from Niels Bohr Institute, Copenhagen, Denmark.

3. *National Heavy-Ion Laboratory – a Proposal,* ORNL, October 1972.

CYCLOTRON INTERNAL ION SOURCE WITH DC EXTRACTION[1]

M. L. Mallory[2] E. D. Hudson R. S. Lord

This paper describes a method for increasing the intensities for heavy-ion beams accelerated in isochronous cyclotrons at high harmonics ($h \geqslant 5$) of the orbit frequency. Normally, only small intensities are obtained at high harmonics because of the low effective accelerating voltage and associated small phase acceptance that result from the large transit time of the ions between the ion source and the puller electrode. We have developed and tested a dc ion extraction system for the Oak Ridge Isochronous Cyclotron. Use of the dc extraction system has increased beams of $^{40}Ar^{3+}$ on the fifth harmonic and $^{20}Ne^+$ on the seventh harmonic from the nanoampere range to the microampere range.

1. Abstract of paper to be published in proceedings of the 1973 Particle Accelerator Conference, San Francisco, California, March 5–7, 1973.

2. Chemistry Division.

FEASIBILITY AND COST OF A SUPERCONDUCTING HEAVY-ION LINEAR ACCELERATOR[1]

C. M. Jones

Design, cost, and feasibility studies for a heavy-ion linear accelerator utilizing superconducting resonant cavities are described. Comparisons are presented between this accelerator and several other conceptual designs.

1. Abstract of paper to be published in *Particle Accelerators.*

SUPERCONDUCTING RESONANT CAVITIES

J. P. Judish C. M. Jones F. K. McGowan P. Z. Peebles, Jr.[1]

The results achieved with our first superconducting cavity have been previously reported.[2,3] They were sufficiently encouraging to lead us to design a somewhat more elaborate and versatile system. The helically loaded cavity remains nominally the same as our first model, but the arrangement of the transmission lines leading to the cavity has been altered significantly.

The new design has three coaxial transmission lines. The inner conductor of each of these is separately movable to allow the rf coupling of each line to the cavity to be adjusted independently. This arrangement will allow a simple interpretation of the electrical measurements and should also permit thorough exploration of the problems associated with tuning a high-Q high-field device. The vacuum pumping system has been improved, particularly with respect to possible contamination of the superconducting surfaces when they act as a cryopump.

All parts of the new system have been fabricated, assembled, leak-tested, and outgassed at a temperature of 250°C. Lead plating of the cavity components is now under way.

1. Consultant from the University of Tennessee, Knoxville.
2. C. M. Jones, J. P. Judish, R. F. King, F. K. McGowan, W. T. Milner, and P. Z. Peebles, Jr., ORNL-4742, Dec. 31, 1971, p. 126.
3. C. M. Jones, J. P. Judish, R. F. King, F. K. McGowan, W. T. Milner, and P. Z. Peebles, Jr., *Particle Accel.* 3, 103–13 (1972).

RESONANT FREQUENCY CONTROL OF SUPERCONDUCTING RF CAVITIES[1]

P. Z. Peebles, Jr.[2]

Resonant frequency of superconducting radio-frequency (rf) cavities, which are used in linear accelerator research, may rapidly shift over many bandwidths because of vibration. In this paper an all-electrical method is analyzed which can correct for these frequency shifts. The method depends upon the use of a voltage-variable reactance to control frequency. The general characteristics of control, such as the form and extent of frequency control and their dependence on design parameters, are first determined. Power distribution in the system is then found.

1. Abstract of paper accepted for publication in the proceedings of the 1973 Particle Accelerator Conference, March 1973.
2. Consultant from the University of Tennessee, Knoxville.

MEASUREMENT SYSTEM FOR SUPERCONDUCTING RF RESONANT CAVITIES[1]

P. Z. Peebles, Jr.[2]   C. M. Jones   R. F. King[3]   J. P. Judish

Special considerations must be given to measurement techniques when making measurements on superconducting rf resonant cavities. A system is described that is especially designed to overcome most problems associated with narrow bandwidth (Q's of 10^8 or more), high field levels, and instabilities.

1. Abstract of paper presented at IEEE Region 3 Conference, April 1972.
2. Consultant from the University of Tennessee, Knoxville.
3. ORNL retiree.

DESIGN AND EVALUATION OF A HIGH-POWER VOLTAGE-VARIABLE REACTANCE[1]

S. F. Smith[2]   P. Z. Peebles, Jr.[3]

Several methods for realizing a high-power voltage-variable reactance at 136 MHz have been investigated. A design based upon a "reactance modulator" principle was selected and constructed. Realized parameters were: nominal reactance of 200 Ω (capacitive) variable ± 15% minimum and quality factor (Q) of 2.9. The unit was designed to handle a peak voltage of at least 100 V.

1. Summary of final report on subcontract with the Electrical Engineering Department, the University of Tennessee, Knoxville.
2. Graduate student, University of Tennessee, Knoxville.
3. Consultant from the University of Tennessee faculty, Knoxville.

A SLOW TUNER FOR SUPERCONDUCTING HELICALLY LOADED RESONANT CAVITIES[1]

C. M. Jones J. L. Fricke[2] B. Piosczyk[2] J. E. Vetter[2]

We have developed a concept for a device to control the static resonant frequency of superconducting helically loaded cavities over a wide range and have applied this concept to the particular problem of the Karlsruhe proton accelerator. Basically, the device consists of a niobium plunger attached to a dielectric cylinder which provides support and a path by which the plunger may be cooled with liquid helium. Model tests on the second Karlsruhe cavity show that two such plungers can give a tuning range of 100 kHz at high field levels without significant surface field enhancement or disturbance of the flatness. Furthermore, with radiation pressure-induced static frequency shifts of up to 500 kHz, they permit constant frequency operation at arbitrary axial field levels without surface fields significantly in excess of those present at maximum axial field and without significant flatness disturbance. Related materials problems have been studied and will be discussed.

1. Abstract of published paper: *Proceedings of the 1972 Proton Linear Accelerator Conference*, LA-5115, pp. 163–67.
2. Institut für Experimentalle Kernphysik, Kernforschungszentrum Karlsruhe, Karlsruhe, West Germany.

STATUS OF THE UNISOR PROJECT[1]

H. K. Carter R. L. Mlekodaj W. D. Schmidt-Ott E. H. Spejewski

Introduction

UNISOR is a cooperative effort to study nuclides far from the line of beta stability by employing an isotope separator installed on-line to the Oak Ridge Isochronous Cyclotron (ORIC). The facility is housed in an addition to the ORIC building constructed for that purpose. This report outlines the development of the facility during 1972.

The UNISOR Annex

Construction of the UNISOR annex (Fig. 1) was essentially completed in February. After the delivery of the isotope separator, additional shielding walls and high-voltage rooms were constructed in July. The installation of the cyclotron-beam line, including magnets, pumping stations, controls, etc., was concluded on September 1. The first cyclotron beam (approximately

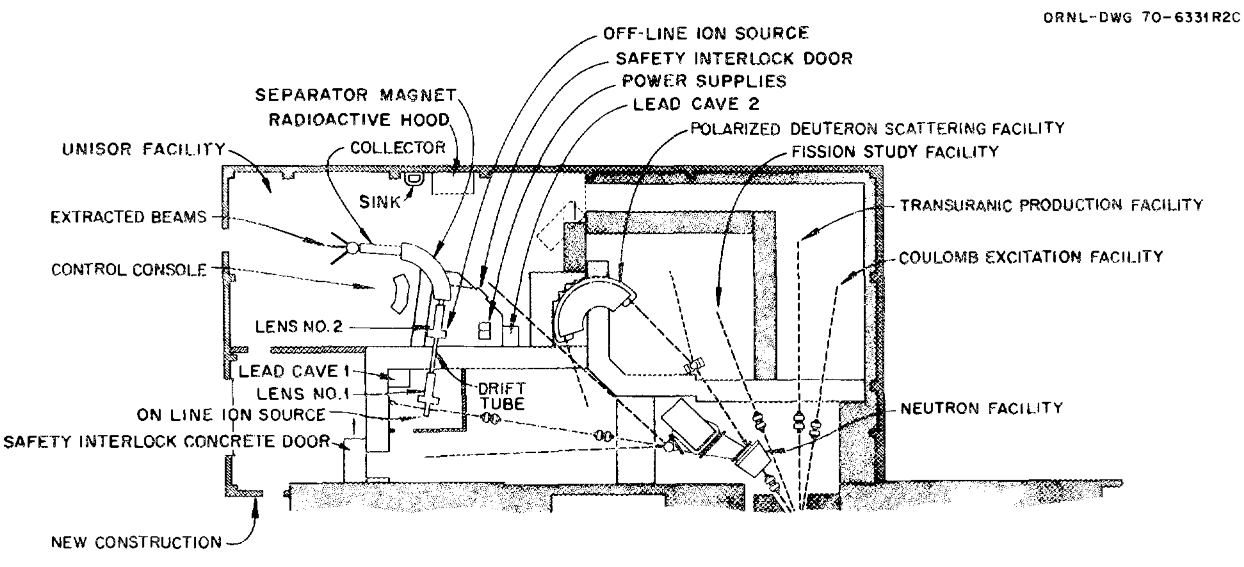

Fig. 1. Additions to the ORIC building. The UNISOR facility is at the left.

1 μA of 100-MeV ^{14}N) was placed on a target in this annex on the same date.

Isotope Separator

The isotope separator, having a 90° homogeneous-field magnet, was delivered by the Danish firm Danfysik in April. Installation, training of UNISOR personnel, and testing required somewhat more than a month. The final acceptance tests were completed by the end of May, the required resolution $\Delta m/m \leqslant 1/2000$ being met easily. Further work with the separator was then suspended until construction of the high-voltage room and electrical safety interlocks was completed. Since that time, further experience has been obtained with the operation of the separator including the two types of ion sources provided, Nielsen oscillating electron and Sidenius hollow cathode, from both the on- and off-line positions.

Target–Ion Sources

The crucial component of an on-line isotope separator system is the target or target–ion-source combination. This component must be designed to separate the reaction products from the target material and introduce them into the ion source of the isotope separator. Two types of target–ion-source combinations are under development, both of which take advantage of the high linear momentum transfer that occurs with heavy-ion bombardment.

"Pingis" type. A schematic drawing of one of these is shown in Fig. 2. The target, typically a metallic foil, forms part of the anode cylinder of a standard Nielsen oscillating-electron ion source. Holes are cut through the ion-source vacuum-chamber wall and the heat shields to permit entrance of the cyclotron beam. The recoiling product atoms enter the plasma region and are stopped either within the plasma itself or in a catcher foil which is shown mounted on the filament. For most elements, the temperature of the catcher foil is sufficiently high that the stopped reaction products very quickly diffuse out of the catcher into the plasma.

A recent modification has been to replace the filament and the catcher foil with a single foil which serves both functions. The ion source itself appears to operate equally well whether the filament is the standard coil or whether it is a foil strip. By using the catcher as a filament, however, it is at the highest possible temperature (approximately 2500°C) of any portion of the ion source, and, therefore, the shortest product diffusion times are obtained.

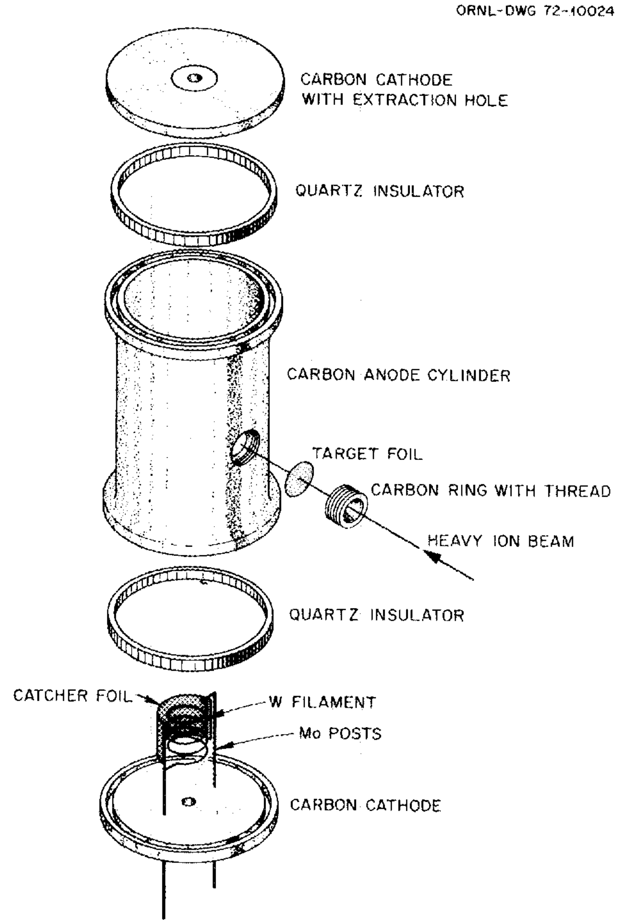

Fig. 2. "Pingis"-type ion source.

This type of ion source is suitable for target material with high melting points since, residing near the plasma boundary, it is at a temperature of approximately 1000°C. This is an advantage because those reaction products produced near the outer surface of the target and stopped within the target have a high probability of diffusing into the plasma region.

This "Pingis"-type ion source, at least in principle, works as planned. In test runs of the system, we have successfully obtained through the isotope separator the following: Cd and Ag isotopes from a Zr target irradiated with 100-MeV ^{14}N beams; Ag isotopes from a Zr target irradiated with a 100-MeV ^{14}N beam; and Kr, Br, Se, and As isotopes from Ni targets irradiated with 100-MeV ^{14}N and 80-MeV ^{16}O beams. Yields of product nuclei obtained through the system, however, are rather low. This is probably a result of small production cross sections at the energies used, but may be caused by lower ion-source efficiency and/or much longer ion-source dwell times than expected. An additional problem is the stability of some materials used. The filament/catcher foil has a tendency to weaken with use and to rupture, as do some of the target foils.

Helium jet. The second type of target–ion source under development employs a helium jet, shown schematically in Fig. 3. In this system, the recoiling products are stopped in helium gas at a pressure of about 1 atm. The helium is allowed to flow out of the chamber through a capillary tube, carrying along the stopped reaction products. By means of a system of "skimmers" (Fig. 4), a portion of the helium gas can be removed from the stream without radically affecting the flow of the reaction products. Used off-line,[2] the system has yielded transport efficiencies of 40 to 50%

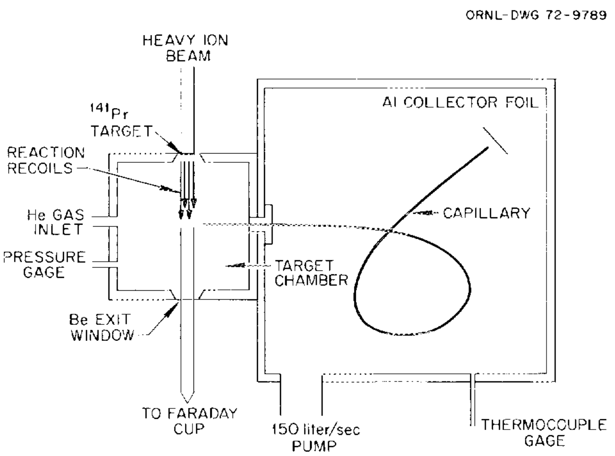

Fig. 3. Helium-jet system.

with one skimmer only, and about 20% in the configuration shown in Fig. 4 using two skimmers. The gas pressure is reduced from 1 atm in the reaction chamber to about 10^{-3} torr in the collection chamber.

Although these conditions appear to be ideal for connecting to an ion source of the isotope separator, simply doing so has not resulted in an operable system. There appears to be some interference with the helium flow by the ion source which is not present for a static collection chamber. This problem remains to be solved before the system can be used on-line.

Tape Transport

In order to place the separated isotopes before appropriate detectors, the tape transport system, shown schematically in Fig. 5, was constructed. In operation, a single-mass beam is allowed to pass through the primary focal plane of the separator and is then focused onto the conducting side of an aluminum-coated Mylar tape. From this collection point, the collected isotopes can be transported to any detector station downstream, or to each one successively, with a transport time as low as 0.9 sec.

The system is modular in design so that a special module can be designed for any required detector arrangement. The modules initially constructed are shown in Fig. 5. All have detector "portholes" which are closed by vacuum flanges that can be designed to fit any particular detector. The collection module, in addition to the beam opening, is provided with five portholes. Two of these can accommodate particle detectors, and each faces the collection side of the tape

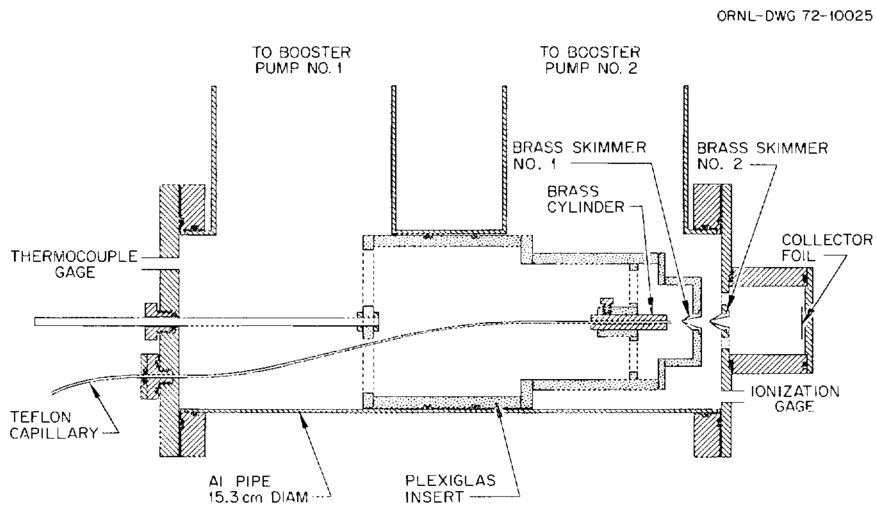

Fig. 4. "Skimmers" for the helium-jet system.

(the front) at a 45° angle. The other three face the back and the edges of the tape. The next two modules have four detector positions each, viewing the front, the back, and the edges of the tape. The 90° module provides space for two detectors viewing the front of the tape and two others viewing the edges.

The electronic control unit[3] for this system was designed to synchronize the operation of the separator beam deflector, the tape control electronics, and the data acquisition system(s). It consists of four sequentially operating clocks and logic circuits to determine beam collection time, delay time, data accumulation time, and transport plus delay time. Each clock can be set from 0 to 99,999 in increments of 1 or 0.1 sec. By choice of the proper cycle and clock times, it is possible to maximize the data collection rate for any member of a given decay sequence.

Data Acquisition Systems

A computer-based multiparameter pulse-height analysis system has been ordered. It will be capable of collecting three-parameter time-correlated events at high count rates. All three singles spectra will be stored in core with list-mode storage of the coincidence events on magnetic tape. Purchase of a magnetic disk system to facilitate programming and data handling is being considered.

Procedures for the use of the ORIC SEL computer as a data acquisition system have been developed, and data lines have been installed. Some computer codes for the gathering and analysis of data have also been written.

Operations

The isotope separator has been in operating condition since the beginning of September. Formal review of the

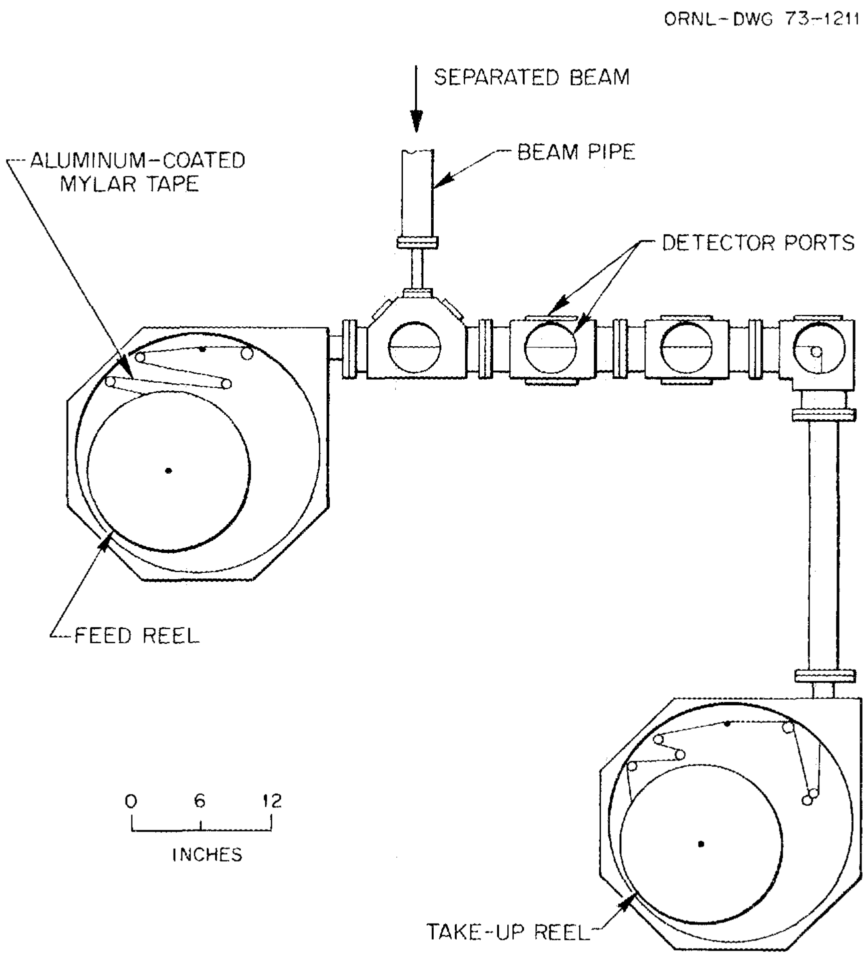

Fig. 5. Tape transport system.

facility by the Radiation and Accelerators Safety Committee was not completed by the end of the year, so only test operations involving radioactive material could be performed. Seven cyclotron runs were made during this period to test designs and modifications of the on-line target–ion sources, some of the results being described above.

Several separations of small amounts of short-lived radioactive material were performed. These were made in an attempt to discover the extent of the contamination of the separator arising from off-line separations, and to test decontamination procedures. With the level of activity used, appreciable contamination was found only on the extraction electrode. However, this appears to be easily cleaned. Further tests of off-line separation procedures with higher activity levels await approval of the facility by the safety committee.

1. UNISOR is a consortium of University of Alabama in Birmingham, Georgia Institute of Technology, Emory University, Furman University, University of Kentucky, Louisiana State University, University of Massachusetts, University of South Carolina, University of Tennessee, Tennessee Technological University, Vanderbilt University, Virginia Polytechnic Institute and State University, Oak Ridge Associated Universities, and Oak Ridge National Laboratory. It is supported by these institutions and by the U.S. Atomic Energy Commission.

2. W.-D. Schmidt-Ott, R. L. Mlekodaj, and C. R. Bingham, to be published in *Nuclear Instruments and Methods*.

3. Provided by the Ames Laboratory AEC through the courtesy of J. R. McConnell and W. L. Talbert.

STATUS REPORT ON THE 3-MV VAN DE GRAAFF ACCELERATOR

J. P. Judish

During 1972, as in the previous year,[1] the 3-MV Van de Graaff provided pulsed proton beams for use by the Health Physics Division in their studies of atomic excitations in noble gases. The Van de Graaff has performed reliably. The accelerator tube installed in May 1971 shows no sign of deterioration.

1. J. P. Judish, ORNL-4743, Dec. 31, 1971, p. 145.

STATUS REPORT OF THE 6-MV VAN DE GRAAFF ACCELERATOR

J. A. Biggerstaff W. T. Newton[1]

During the first quarter of 1972 the 6-MV accelerator was used for Coulomb-excitation angular correlation measurements and for charged-particle-induced x-ray yield measurements. The last three quarters have been spent in making major modifications to prepare the accelerator to provide heavy-ion beams for use in radiation damage studies.

An improved post-acceleration gas stripping tube has been installed, and the original mass × energy product 12 magnet has been replaced with a product 34 magnet (originally the analyzing magnet on the tandem accelerator). An improved crossed-field velocity analyzer has been constructed and installed in the terminal of the accelerator in order to provide better selection of mass species. The post-acceleration stripper and analyzing magnet will be used for diagnostic purposes. The analyzing magnet has been mounted on a movable platform since the radiation damage experiments need to be performed directly below the machine in order to quickly change ion species.

A bakeable differentially pumped test specimen chamber has been constructed and is being tested. It is fitted with a foil wheel which will hold foils that will degrade the energy of H and He beams to energies giving them the same penetration into the test specimen as the heavy ions which produce the damage being studied.

A heavy-ion source has been installed in the terminal and has produced usable beams of F, Cl, Al, and Fe ions.

1. Instrumentation and Controls Division.

STATUS REPORT OF THE TANDEM VAN DE GRAAFF ACCELERATOR

G. F. Wells[1] R. L. Robinson

The tandem Van de Graaff accelerator performed 3634 hr of research during the year, apportioned among experimenters as shown in Table 1. Scheduled operational and maintenance support for the research program, which was provided for 4016 hr during the year, was utilized as shown in Table 2.

Maintenance time was primarily devoted to the accelerator charging system. Of eight tank entries, five were to replace belt drive motors and/or terminal generators. The average lifetime of these units was 800 hr. The last installation, made in October, has new bearing housings and reground shafts for a more precise bearing fit. An internal spring was placed in the bearing housings to axially load the inner bearing race, thus assuring ball-to-race rolling contact. This combination of units has now given over 1000 hr of operation.

An electrostatic quadrupole lens was installed in the terminal in May to examine its effect on beam transmission of higher-charge-state, foil-stripped heavy ions. A 50% increase in analyzed beam current of a Cl^{6+} beam was noted. Since the quadrupole system used occupied too much space to allow gas stripping as well as foil stripping, it was removed after the test.

In November, new screens were installed on the charging system. These screens were bias cut from 40-mesh stainless steel screen wire. Bias cutting the screens provides more wire edge contact with the belt and better individual wire support against flexural breakage. Screen deterioration has been noted by measuring the down-charge screen current. When screens were new and in good contact with the belt, the down-charge current was negative. In approximately 200 hr this current reduced in value to zero and as the screens wore became more and more positive. Terminal

Table 1. Research activities on the tandem Van de Graaff accelerator

Type	Projectile	Investigators	Percent of research time
$(^{16}O,\alpha)$, $(^{16}O,d)$ reactions	^{16}O	Ford, Del Campo, Robinson, Thornton,[a] and Stelson	19
$(^{16}O,X\gamma)$ in-beam γ	^{16}O	Kim, Robinson, and Milner	6
(O,n) cross sections	$^{16,18}O$	Bair, Johnson, Stelson, and Dress	6
$(^{16}O,X)$ cross sections	^{16}O	Robinson, Kim, Ford, Jr., Wells,[b] and Lin[b]	9
Coulomb excitation	α	McGowan, Bemis, Stelson, Milner, Ford, Robinson, Hamilton,[c] Varnell,[d] Lange,[c] Gupta,[c] Ramayya,[c] and Reich[e]	27
Short-lived radioactivities	p	Raman, Gove, and Walkiewicz[f]	2
X-ray energy shifts	p, ^{16}O	Saltmarsh, Van de Woude, and Ludemann	3
Trace elements	p	Saltmarsh, Van de Woude, Gross, Ludemann, and McGuire[g]	2
Radiohalo studies	α	Gentry[h] and Collins[h]	0.3
Stopping power	O,Br,I,U	Moak, Datz,[h] Appleton,[i] Biggerstaff, and Menendez[j]	4
X-ray and Auger electron studies	I	Moak, Datz,[h] Appleton,[i] Brown,[k] Sellin,[l] and Biggerstaff	4
Channeling	I	Moak, Datz,[h] Appleton,[i] Biggerstaff, Barrett,[i] Noggle,[i] and M. Robinson[i]	4
Heavy-ion atomic physics	O,F,Cl	Sellin,[l] Brown,[k] Donnally,[m] Griffin, MacDonald,[k] Mowat,[k] Pegg,[l] Peterson,[l] and Smith[n]	12
Ionization cross section	^{16}O,p	Duggan,[o] McCoy,[p] Chaturvedi,[q] E. Robinson,[r] Humphrey,[s] Creighton,[t] Sachlebehn,[u] Carlton,[v] Lin,[b] Ferree,[l] Callman,[l] and Datz[h]	2

[a]University of Virginia.
[b]Tennessee Technological Institute.
[c]Vanderbilt University.
[d]Yale University.
[e]Aerojet Nuclear Co., Idaho Falls.
[f]Edinboro College.
[g]Analytical Chemistry Division.
[h]Chemistry Division.
[i]Solid State Division.
[j]University of Georgia.
[k]Kansas State University.
[l]University of Tennessee.
[m]Lake Forest College.
[n]University of Connecticut.
[o]Oak Ridge Associated Universities.
[p]University of Tulsa.
[q]SUNY College, Cortland.
[r]University of Alabama.
[s]Western Kentucky University.
[t]University of Omaha.
[u]Hastings College.
[v]Middle Tennessee State University.

screen replacement started the cycle over. The new bias-cut screens have not been replaced since installation, and down-charge currents still read negative after approximately 800 hr of operation.

Beginning in March 1972, an ion source upgrading program was begun. A Hortig[2]-type sputter-ion source and a Heineke[3] Penning source are being purchased. A new charge-exchange source has been fabricated by ORNL. These sources are to be housed in off-ground vacuum housings capable of 100-kV operation. A new injection magnet capable of bending mass-energy product 25 (amu-MeV) negative-ion beams from either of two 30° injection legs is being purchased. Installation of this system of ion sources is expected to begin in March 1973.

Experience has already been gained with the new charge-exchange ion source, mounted in the existing on-ground vacuum housing since November. Two of the design features of this source have proven themselves in providing ease of changeover from one ion species to another and in long-term continuous operation. The first of these features, the interchangeable exchange canal unit, allows one to remove an oven-heated canal and replace it with a gas-fed Freon-cooled canal without disturbing the remainder of the extraction-lens assembly. The second feature, a technique for shielding electrode insulators, has allowed continuous operation without insulator failure due to conductive deposits on the insulator surfaces. The assembly was placed in operation in November and has more than 800 hr of operation without insulator replacement. Table 3 summarizes the operational experience to date with the source.

Ideal optics for beam injection into the accelerator have not yet been achieved, since the source has been limited to 30-kV operation. When the ion source system is completed it will be capable of up to 160-kV beam energy, and improved beam transmission through the accelerator is anticipated.

Table 2. Utilization of scheduled operation on maintenance support time[a]

Function	Hours	Percent of time
Maintenance	1180	29.4
Changeover[b]	290	7.2
Development	488	12.2
Research[c]	2058	51.2
Total	4016	100.0

[a]Sixteen hours per day, five days a week.

[b]Time required to change from one experiment to another.

[c]1576 hr of additional research was performed in non-scheduled time (between midnight and 8 AM and on weekends and holidays). This gives a utilization factor of

$$\frac{3634 \text{ research hr}}{4016 \text{ scheduled support hr}} = 89\%.$$

Table 3. Negative-ion species produced in ORNL charge-exchange source

Source gas	Exchange medium	Ion species	Intensity (μA)
He	Ca (650°C)	He^-	7
98% He, 2% O_2	NH_3	O^-	15
He	CCl_4	Cl^-	15
He	SF_6	F^-	15
He	CH_2I_2	I^-	8

1. Instrumentation and Controls Division.

2. M. Mueller and G. Hortig, "An Ion Source for Negative Ions," *IEEE Trans. Nucl. Sci.* NS-16, 38–40 (1969).

3. E. Heineke and H. Baumann, "Penning Source for MP Accelerator," *Nucl. Instrum. Methods* 74, 229–32 (1969).

STATUS REPORT ON THE OAK RIDGE ELECTRON LINEAR ACCELERATOR (ORELA)

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Accelerator Operation

For the past year, ORELA has been used for research for over 5200 hr, with a considerable amount of it with 50 kW of beam on the target and a peak current of about 15 A. The accelerator is operated 24 hr a day, seven days a week except for holidays, with four days of routine maintenance scheduled each month at the convenience of the experimenters. Scheduled major shutdowns to install a new vacuum pump for the target room, a new target positioner, and a new water-cooled tantalum target with beryllium walls in January and to install the new gun tank in April accounted for most of the accelerator downtime. The old gun tank is now used for gun and injection development and to "condition" new or rebuilt electron guns and test them before their installation on the accelerator. The principal reasons for the unscheduled shutdowns were the failure of the old target room vacuum pump, problems with Eimac guns early in the year, failures in the electronics in the old

Table 1. Electron beam hours for experimenters at ORELA, 1972

Month	Research hours
January	0
February	150.0
March	593.2
April	317.2
May	416.7
June	542.5
July	583.4
August	505.7
September	586.8
October	608.2
November	518.7
December	380.2
Total for 1972	5202.6

Table 2. Klystron lifetimes at ORELA, 1972

Klystron No.	High-voltage hours	Date
2003	18,309	Original–December 1972[a]
2006	12,922	November 1969–May 1972[b]
2007	7,850	December 1969–April 1971 (spare)
2004R1	7,406	September 1971–December 1972[a]
2010	5,727	April 1971–April 1972 (spare)
2012	4,027	April 1972–December 1972[a]
2013	3,994	April 1972–December 1972[a]
2009	3,106	September 1970–April 1971 (spare)
2011	2,327	April 1971–September 1971 (spare)
2002	1,447	Original–November 1969 (spare)

[a]Still in accelerator.
[b]At Litton factory for repair.

Table 3. Electron gun lifetimes for ORELA, 1972

Gun No.	Beam hours	Failure date
Eimac 5-4	494.4	January 11, 1972
Eimac 7-2	1088.0	April 28, 1972[a]
Eimac 4-4	1548.3	August 1, 1972[a]
ORELA No. 1	2622.8	Still good on December 31, 1972
Total	5753.5	

[a]Eimac guns 7-2 and 4-4 developed vacuum leaks at a flange and may still be good.

gun tank, problems with heat exchangers in August, and flooding of the accelerator and modulator rooms due to torrential rains in mid-December. A monthly tabulation of the ORELA operation for experimenters is shown in Table 1. Much of the operation the last four months was at 1000 pulses/sec and about 50 kW, made possible by the new gun, the new gun tank, and modifications made to the modulators such as replacing old capacitors in the pulse-forming network and high-voltage feed-through connectors to the klystron tanks.

Klystrons are continuing to operate exceedingly well, and one of the original klystrons has over 18,000 high-voltage hours and is still in the accelerator. During this year, one of the original klystrons which had operated for 12,922 hr was returned to Litton for repair. Details of the lifetimes of the klystrons are given in Table 2 and the electron guns in Table 3. The gun built by ORNL which was installed in the accelerator on August 2 has performed exceedingly well. It has operated in the accelerator for a longer period than any earlier gun, has produced more peak current on the target, more than 20 A, due in part to the higher accelerating voltage it can stand, and has operated a great deal at 1000 pulses/sec. Descriptions of the neutron time-of-flight experiments and results may be found in this progress report, last year's report (ORNL-4743), and the Neutron Physics Division annual reports (ORNL-4800 and ORNL-4705).

Data Handling System[3]

In January, acceptance tests were completed for the immediate-analysis computer, a PDP-10 computer located at the ORNL Computing Center in Building 4500N, and its associated equipment. ORELA has three interactive displays, each containing a PDP-15 computer, and three remote Teletypes with hard-wired computer links. The original data links between the ORELA displays and the PDP-10 were found to be too slow and were replaced with purchased modems that were newly developed with an operating speed of 9600 bits/sec. A lower operating cost has resulted. Acceptance tests for the peripheral equipment controller at ORELA were completed in October, with integration into the data handling system by mid-November. This controller operates the line printer, Calcomp plotter, card reader, magnetic tape drives, etc., at ORELA and permits the two SEL data acquisition computers to be devoted solely to the accumulation of data. Data acquisition programs were written for two more experimenters, bringing the total to nine. Experimental data at ORELA can be transferred to an experimenter's disk on the PDP-10 at the Computing Center. The data can be scanned on the ORELA display units before and after data processing on the PDP-10 (or the IBM 360/91), such as dead time corrections and the calculation of cross sections and energies. The results can then be plotted or printed at ORELA or the Computing Center. Although several programs for analyzing data on the PDP-10 are now available to experimenters, the full potential of the system will not be realized until next year.

1. Instrumentation and Controls Division.
2. Neutron Physics Division.
3. Details of the system may be found in the recent annual progress reports of the Instrumentation and Controls and the Mathematics divisions.

OAK RIDGE ISOCHRONOUS CYCLOTRON OPERATIONS

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Introduction

The Oak Ridge Isochronous Cyclotron (ORIC) continued to be operated on a 16-shift/week schedule in 1972. Nuclear research programs used about 59% of the total hours available, which was about 3% more than in 1971. Heavy-particle experiments used about 52% of the total nuclear research time.

Research Bombardments in 1972

A total of 6164 hr was the scheduled available time for ORIC operations in 1972 (see Table 1). Research bombardments were assigned a total of about 3660 hr, or about 59% of the total time available. A usable beam was on target about 2672 hr, or about 43% of the total time available. Distribution of the research experiments for 1972 is shown in Table 2. A total of 257 bombardments were made with the various particle types and energies noted in Table 3.

Operations Summary

Operation has been on a 16-shift/week, 128-hr/week schedule. Initial operation of two new beam stations in the South Research Addition was achieved. These are the UNISOR and the transuranic research station (Fig. 1). In addition, one of the existing experiment rooms was partitioned by a concrete block wall to provide a location for a lead-shielded gamma counting facility. This is now in routine operation.

Unscheduled outage decreased from 19.6% to about 15% of the total available time. However, rf outage increased from 4.0% to 5.5%. No major component failures were experienced during the year. Scheduled engineering was substantially higher than last year, increasing from about 3% to about 9%. This was primarily because of the replacement of the old power amplifier tube (RCA-6949) with a new tube, RCA-4648. This required extensive changes to the existing rf enclosures and associated hardware.

In a routine examination of the water passages of the aluminum conductors of the main magnet coils, evidence of corrosion was discovered. Inspection of the defects with an electron microscope revealed the presence of copper at the site of the defects. It is postulated that, because of the higher temperatures

Table 1. ORIC operations – operation analysis

	Hours	Percent
Beam on target	2671.7	43.4
Beam adjustment	246.7	4.0
Target setup	76.6	1.2
Startup and machine shutdown	562.8	9.1
Machine research	733.6	11.9
Total machine operable time	4291.4	~70.0
Source change	256.3	4.2
Vacuum outage	49.8	0.8
Rf outage	336.6	5.5
Power supply outage	102.1	1.7
Electrical component outage	63.0	1.0
Mechanical component outage	12.3	0.2
Water leak outage	101.5	1.6
Total unscheduled outage	951.6	~15.0
Scheduled maintenance	399.0	6.5
Scheduled engineering	552.0	8.9
	951.0	~15.0
Total time available	6164	100
Total nuclear research experiments	3660, or ~59% of total time available	

Table 2. ORIC research bombardments in 1972

Affiliation	Reactions	Investigators	Hours	Percent of total available time (6164 hr)
Physics Division	$^{144}Sm(^{14}N,xn)$, $^{144}Sm(^{19}F,xn)$, $^{144}Sm(^{20}Ne,xn)$, $^{156}Dy(^{20}Ne,xn)$	Toth, Hahn, Schmidt-Ott, C. Bingham, Ijaz, Walker	224	3.6
	$^{16}O(d,\alpha_1)^{14}N^*(2.31\ MeV)$, $^{90}Zr(d,{}^3He)^{89}Y$, $^{141}Pr(^{12}C,6n)^{147}Tb$	Newman, Toth, Kocher, Gross, Fulmer, Hensley	120	2.0
	$^{156}Gd(^{12}c,xn)$, $^{150}Nd(^{20}Ne,xn)$, $^{148}Nd(^{22}Ne,xn)$, $^{154}Sm(^{22}Ne,xn)$	Stelson, Robinson, Johnson, Eichler, G. Hagemann, Riedinger, Hensley	240	3.9
	$^{16}O + {}^{16}O$ elastic scattering, $^6Li(^3He,t)$	Halbert, Saltmarsh, Raman, Stelson, H. Bingham, Hensley	56	0.9
	^{16}O induced particle reactions, (p,d) (p,t) recoils, ^3He induced reactions, $^{144}Nd(d,p)$, $^{90}Zr(^3He,\alpha)^{89}Zr$, $^{86,84}Sr(p,t)$	Ball, Larsen, Ford, Fulmer, Toth, Gaedke, Hillis, Riley, C. Bingham, Rester	576	9.4
	Heavy-ion-induced fission research	Plasil, Schmitt, Ferguson, Pleasonton, Bemis, Freisleben, Huizenga	140	2.3
	$(p,2n)$, (p,p'), $(^3He,d)$, $^{208}Pb(^{12}C,{}^{12}C')$	Bertrand, Lewis, Horen, Auble, Ball, Ellis	216	3.5
	$^{40}Ar \rightarrow$ metastable He-like quenching by collisions on carbon foils, H, He, Ne, and Ar gas	Sellin, Pegg, Griffin, Smith, Mowat, Peterson	128	2.1
	Hydrogen contamination in metal foils; test π^+ detectors for LAMPF exper. ($^{40}Ar^{9+}$ and $^{56}Fe^{10+}$ and K production; calibration of lunar glass, plastics, minerals, terrestrial minerals, and Apollo 16 detectors	Saltmarsh, van der Woude, Ludemann, Preedom, Gross, Hart	86	1.3
	Excitation function measurements	Fulmer, Williams, Pinajian	37	0.6
	$^{10}B + d \rightarrow {}^6Li$ or ^6He, $^{11}B + d \rightarrow {}^6Li$ or ^6He, or ^7Be or ^7Li	Goodman, Hensley	431	7.0
	Isotope production for medical applications	Newman, Ratledge	56	0.9
		Physics total hours	2310	37.5
In collaboration with universities				
Fulmer, Hensley	Large-angle elastic and inelastic scattering	Eidson, Drexel University; Foster, University of Missouri; O'Fallon, University of Missouri	136	2.2
Chemistry Division	$^{136}Ce(^3He,3n)^{136}Nd$, $^{136}Ce(^3He,2n)^{137}Nd$	Ketelle, Brosi	56	0.9
	$^{238}U(^{12}C,xn)$, $^{239}Pu(^{12}C,\alpha xn)$ angular and range distributions	Hahn, Toth, Dittner, Keller	56	0.9

Table 2 (continued)

Affiliation	Reactions	Investigators	Hours	Percent of total available time (6164 hr)
	Coulomb excitation experiments – Ar, Ne, O; (^{18}O, $\alpha 3n$) x-ray identification of Z-103, 104, 106; (^{18}O,$\alpha 4n$) (α,2n)	Johnson, Eichler, Sayer, O'Kelley, Dittner, Bemis, Plasil, Ferguson, Silva, Keller, Zvara, Hensley	558	9.1
		Chemistry total hours	670	10.9
Metals and Ceramics Division				
	^{4}He, surface bubbling, study of voids in stainless steel	Wiffen, King, Wolfenden, Davis	120	1.9
UNISOR	(^{14}N,5n), (^{14}N,6n), (^{16}O,4n), (^{16}O,5n)	Spejewski, Mlekodaj, Carter, Schmidt-Ott, Rester, C. Bingham	248	4.0
Outside users				
Florida State University	Alphas – inelastic scattering; (p, t) reactions on Ni	Fox, Greenfield, Kemper, Gunn, Obst, Vourvopoulos, DeMeiyer	72	
University of Kentucky	(^{12}C,xn), (α,4n), (^{3}He,xn), (^{14}N,xn); decay studies	Hofstetter, Stickler	32	
University of Georgia	^{92}Mo(p,p')	Scott, Owais, Whitten, Herren	72	
		Total hours	176	2.9
		Total research bombardments	3660	59.4
		Total machine research	734	11.9
			4394	71.3

experienced during the last two years of heavy-ion runs, an oxidation process has taken place, catalyzed by the copper ions that enter the demineralized water from other components. Prior to the recent long periods of operation at full power, no damage had been seen. A new pump has been ordered to provide enough cooling to reduce the temperature to pre-heavy-ion levels. In addition the dissolved oxygen is now being reduced by sparging with nitrogen. The heat transfer surfaces were thoroughly cleaned with a solution of phosphoric and chromic acids before operation was resumed.

Radiation Safety

Radiation safety at the ORIC during 1972 remained good. There were no personnel exposures or contaminations beyond permissible limits. The maximum integrated dose received by any one individual associated with cyclotron operations was 0.85 rem. The cyclotron operators, who received the highest exposures, received doses which averaged about 460 millirems, with the highest single exposure being that indicated above.

Continuously operating beta-gamma and alpha air monitors in and around the facility indicated effective containment of particulate radioactive materials. No responses significantly above background variance were observed.

1. Health Physics Division.
2. Instrumentation and Controls Division.

Table 3. Analysis of beam usage by types

Particle	Energy (MeV)	Hours	Percent (approx)
Carbon	59–176	576	15.7
Argon	9–182	398	10.9
Neon	5–162	366	10.0
Nitrogen	100–130	228	6.2
Oxygen	22–148	92	2.5
Boron	72–137	72	2.0
Chlorine	64–129	88	2.4
Fluorine	170	72	2.0
Total heavy-ion experiments		1892	51.7
Deuterons	18–40	568	15.5
Protons	11–67	496	13.6
Alphas	28–80	435	11.9
^{3}He	25–107	269	7.3
Total light-ion experiments		1768	48.3
Total nuclear research experiments		3660	100.0
Machine research			
Heavy ions		421.0	57.4
Light ions		240.6	32.8
Miscellaneous		72.0	9.8
Total		733.6	100.0

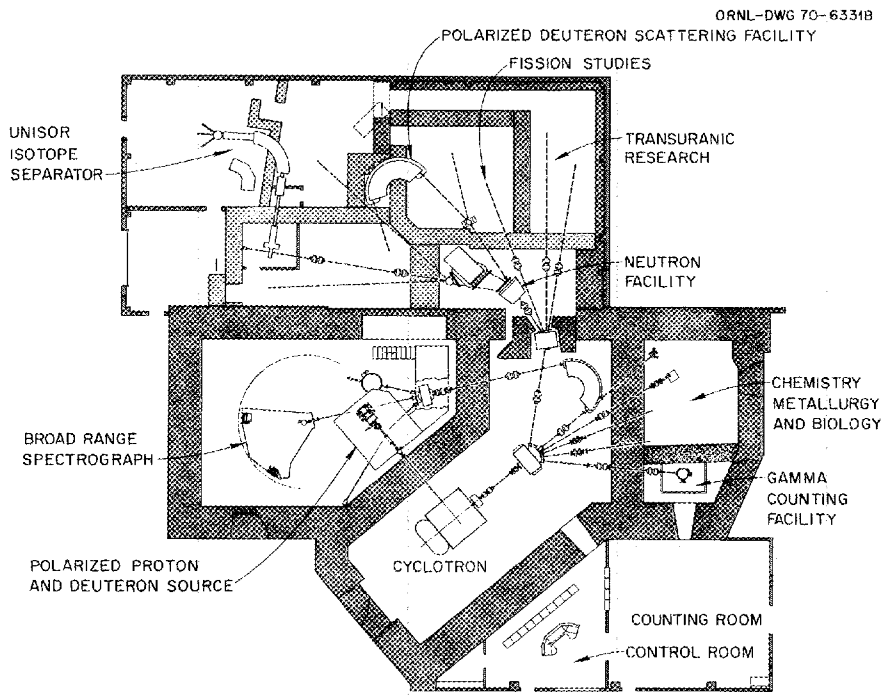

Fig. 1. Plan of the ORIC experiment rooms.

8. Omniana

PUBLICATIONS

The following listing of publications includes primarily those articles by Physics Division staff members and associates[1] *which have appeared in print during 1972.* It is not possible to include open-literature publications for the entire calendar year, however, as some journals for 1972 will be received only after this report has gone to press; thus eight 1971 open-literature publications *not previously reported in an annual report* are included, and a few 1972 articles yet to be published will be listed in the next report for the period ending December 31, 1973.

NOTE: The following listing includes only publications in the open literature which appeared in print during 1972 or those for which references first became available during that year. The 100 articles now in preprint stage and pending publication are not included, nor are there any duplications of publications which were listed in last year's report (ORNL-4743).

Book and Journal Articles

Alvar, K. R., and S. Raman, "Nuclear Data Sheets for $A = 70$," *Nucl. Data Sheets* **B8**, 1–28 (July 1972).

Appleton, B. R., C. D. Moak, T. S. Noggle, and J. H. Barrett, "Hyperchanneling, an Axial Channeling Phenomenon," *Phys. Rev. Lett.* **28**, 1307–11 (1972).

Auble, R. L., "Nuclear Data Sheets for $A = 194$," *Nucl. Data Sheets* B7, 95–127 (February 1972).

Auble, R. L., "Nuclear Data Sheets for $A = 123$," *Nucl. Data Sheets* B7, 363–94 (April 1972).

Auble, R. L., "Nuclear Data Sheets for $A = 125$," *Nucl. Data Sheets* B7, 465–509 (May 1972).

Auble, R. L., "Nuclear Data Sheets for $A = 127$," *Nucl. Data Sheets* B8, 77–121 (August 1972).

Auble, R. L., and J. B. Ball, "Energy Levels of ^{122,124}Te Populated by (^{3}He,*d*) and (*p*,*t*) Reactions," *Nucl. Phys.* **A179**, 353–70 (1972).

Auble, R. L., D. J. Horen, F. E. Bertrand, and J. B. Ball, "Proton Excitations in ^{108,110}Cd from (^{3}He,*d*) Reactions," *Phys. Rev.* **C6**, 2223–31 (1972).

Ball, J. B., "A Remark on the Level Structure of ^{93}Mo and the Failure of j-Determination by Spectroscopic Factor Ratios Near Closed Shells," *Phys. Lett.* **41B**, 55–58 (1972).

Ball, J. B., "^{91}Zr(*p*,*t*) Reaction and the Level Structure of ^{89}Zr," *Phys. Rev.* **C6**, 2139–47 (1972).

Ball, J. B., and J. S. Larsen, "Systematics of $L = 0$ Transitions Observed in the (*p*,*t*) Reaction on Nuclei Near $N = 50$," *Phys. Rev. Lett.* **29**, 1014–17 (1972).

Ball, J. B., J. B. McGrory, and J. S. Larsen, "Calculated Energy Levels for ^{89}Y, ^{90}Zr, ^{91}Nb, ^{92}Mo, ^{93}Tc, and ^{94}Ru," *Phys. Lett.* **41B**, 581–84 (1972).

Bertrand, F. E., "Nuclear Data Sheets for $A = 108$," *Nucl. Data Sheets* B7, 33–67 (January 1972).

Bertrand, F. E., "Nuclear Data Sheets for $A = 122$," *Nucl. Data Sheets* B7, 419–63 (May 1972).

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1. Associates include consultants, guest assignees, graduate students, members of other ORNL divisions, faculty member collaborators, etc.

Bertrand, F. E., W. R. Burrus, N. W. Hill, T. A. Love, and R. W. Peelle, "A High Resolution Spectrometer System with Particle Identification for 1 MeV Through 60 MeV Hydrogen and Helium Particles," *Nucl. Instrum. Methods* **101**, 475–92 (1972).

Bertrand, F. E., and D. J. Horen, "Nuclear Data Sheets for $A = 107$," *Nucl. Data Sheets* **B7**, 1–31 (January 1972).

Blann, M., and F. Plasil, "Limits on Angular Momentum in Heavy Ion Reactions," *Phys. Rev. Lett.* **29**, 303–6 (1972).

Brown, M. D., "Charge States of 29.2 MeV to 45.7 MeV Uranium Ions Emerging from Solid Foils," *Phys. Rev.* **A6**, 229–33 (1972).

Brown, M. D., and C. D. Moak, "Stopping Powers of Some Solids for 30–90 MeV ^{238}U Ions," *Phys. Rev.* **B6**, 90–94 (1972).

Bugg, W. M., G. T. Condo, E. L. Hart, H. O. Cohn, R. D. McCulloch, M. M. Nussbaum, R. Endorf, and C. P. Horne, "Higher Mass Bosons from 7.87 GeV/c $\pi^+ d$ Interactions," *Phys. Rev.* **6D**, 3047–50 (1972).

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Theses

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Carver, J. C., "Photoelectron Multiplet Splitting and Chemical Shifts in Transition-Metal Compounds," Ph.D. thesis, March 1972, University of Tennessee.

Greenfield, M. B., "A Study of the (^{3}He,*n*) Reaction at 25 MeV," Ph.D. thesis, December 1972, University of Tennessee.

McGuire, G. E., "Photoelectron Chemical Shifts in Inorganic Compounds," Ph.D. thesis, June 1972, University of Tennessee.

Monard, Joyce A., "Mössbauer Studies of Electrostatic Hyperfine Interactions in ^{238}U, ^{236}U, and ^{234}U," Ph.D. thesis, August 1972, University of Tennessee.

Rao, C. L., "Target Excitations and the Higher Order Corrections to the Optical Model Potential for Protons," Ph.D. thesis, December 1972, University of Tennessee.

Tansil, J. E., "The Nickel-61 Mössbauer Effect in Nickel-Palladium Alloys," Ph.D. thesis, August 1972, University of Tennessee.

NOTE: *The above includes only theses by candidates for the Ph.D. degree who engaged in full-time research with the Physics Division during 1972 and who received their degrees during that year. In addition, six theses were accepted for doctoral and master of science degrees from candidates who conducted part of their research under the direct supervision and/or guidance of Physics Division staff members; titles of these theses are listed in two later sections of this report entitled "Ph.D. Thesis Research" and "M.S. Thesis Research" and include:*

Elizabeth C. Miller, *University of Tennessee*	*Ph. D. theses*
John Springer, *Vanderbilt University*	*Ph. D. theses*
J. P. Forester, *University of Tennessee*	*M.S. theses*
Lawrence Hess, *Fisk University*	*M.S. theses*
D. U. O'Kain, *University of Tennessee*	*M.S. theses*
R. A. Villecco, *University of Tennessee*	*M.S. theses*

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Bell, W. K., and G. R. Satchler, "Folded Form Factors and the Code Fold," ORNL-TM-3896 (August 1972).

Blazier, S. D., "Conversion to Double Precision in FØrtran," ORNL-TM-3977 (September 1972).

Good, W. M., "Report to the U.S. Nuclear Data Committee," ORNL-TM-3808 (April 1972).

Goodman, C. D., "The ORIC ADC System," ORNL-TM-3946 (September 1972).

Peebles, Peyton Z., Jr., "Fast Frequency Tuning of Superconducting Resonant RF Cavities for Heavy Ion Linear Accelerators," ORNL-TM-3654 (February 1972).

PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS

American Chemical Society Meeting (St. Joseph Valley Section), South Bend, Indiana, January 14–15, 1972

T. A. Carlson (invited paper), "Recent Developments in the Use of Electron Spectroscopy for the Study of Chemical Problems."

American Chemical Society Meeting (Maryland Section), Baltimore, Maryland, January 26–27, 1972

T. A. Carlson (invited paper), "Recent Developments in the Use of Electron Spectroscopy for the Study of Chemical Problems."

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B. J. Allen, R. L. Macklin, C. Y. Fu, and R. R. Winters, "Neutron Capture Cross Sections of the Lead Isotopes"; *Bull. Amer. Phys. Soc.* **17**, 18 (1972).

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J. W. Hutcherson and P. M. Griffin, "Self-Broadened Absorption Line Widths for the Krypton Resonance Transitions"; *Bull. Amer. Phys. Soc.* **17**, 372 (1972).

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C. E. Bemis, Jr., F. K. McGowan, J. L. C. Ford, Jr., W. T. Milner, R. L. Robinson, and P. H. Stelson (invited paper), "Equilibrium Quadrupole and Hexadecapole Deformations for Even-Even Transuranium Nuclei."

Institute of Electrical and Electronics Engineers Region Three Conference, Knoxville, Tennessee, April 10–12, 1972

P. Z. Peebles, Jr., C. M. Jones, R. F. King, and J. P. Judish, "Measurement System for Superconducting Rf Resonant Cavities."

International Conference on Inner Shell Ionization Phenomena – On the Production and Decay of Atomic Inner Shell Vacancies, Atlanta, Georgia, April 17–21, 1972

M. J. Saltmarsh, A. van der Woude, and C. A. Ludemann, "Energy Shifts and Relative Intensities of K X-Rays Produced by Swift Heavy Ions."

A. van der Woude, M. J. Saltmarsh, C. A. Ludemann, R. L. Hahn, and E. Eichler, "X-Ray Production Cross Sections by Swift Heavy Ions."

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T. A. Carlson (invited paper), "Present and Future Applications of Auger Spectroscopy."

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J. B. Ball, J. S. Larsen, and J. B. McGrory, "Calculated Energy Levels for ^{89}Y, ^{90}Zr, ^{91}Nb, ^{92}Mo, ^{93}Tc, and ^{94}Ru"; *Bull. Amer. Phys. Soc.* 17, 446 (1972).

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F. E. Bertrand, M. B. Lewis, and C. B. Fulmer, "Investigation of the Collective Properties of ^{208}Pb by the ^{208}Pb(p,p') Reaction at $E = 55$"; *Bull. Amer. Phys. Soc.* 17, 462 (1972).

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J. C. Hafele, P. T. Sewell, C. C. Foster, N. M. O'Fallon, and C. B. Fulmer, "Diffraction-Like Structure in the Excitation Function for 180° Elastic Alpha Scattering from ^{58}Ni"; *Bull. Amer. Phys. Soc.* 17, 604 (1972).

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D. C. Kocher and D. J. Horen, "Evaluation of Nuclear Data for $A = 92$"; *Bull. Amer. Phys. Soc.* **17**, 513 (1972).

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M. G. Mustafa, H. W. Schmitt, and U. Mosel, "Asymmetry in Nuclear Fission"; *Bull. Amer. Phys. Soc.* **17**, 581 (1972).

E. Newman, K. S. Toth, and I. R. Williams, "Level Structure of ^{145}Sm"; *Bull. Amer. Phys. Soc.* **17**, 557 (1972).

S. Raman, R. Gunnink, T. A. Walkiewicz, and B. Martin, "Precise $M4$ Conversion Coefficient in ^{117}Sn"; *Bull. Amer. Phys. Soc.* **17**, 468 (1972).

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G. G. Slaughter, O. A. Wasson, S. F. Mughabghab, R. E. Chrien, G. W. Cole, and M. R. Bhat, "$^{163}Dy(n,\gamma)^{164}Dy$ Reaction Revisitied"; *Bull. Amer. Phys. Soc.* **17**, 580 (1972).

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K. G. Tirsell, L. G. Multhauf, and S. Raman, "Gamma-Rays from 1.1-min ^{58}Mn and 1.7-min ^{57}Mn"; *Bull. Amer. Phys. Soc.* **17**, 604 (1972).

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T. A. Walkiewicz, S. Raman, and H. J. Kim, "Decay of 14.4-min ^{112}In"; *Bull. Amer. Phys. Soc.* **17**, 467 (1972).

O. A. Wasson, B. J. Allen, R. R. Winters, R. L. Macklin, and J. A. Harvey, "Cross Section Measurements of $^{92}Mo + n$"; *Bull. Amer. Phys. Soc.* **17**, 556 (1972).

I. R. Williams, C. B. Fulmer, and W. C. Palmer, "Evidence of Large Stripping Cross Sections for $^{56}Fe(h,\chi)^{57}Co$"; *Bull. Amer. Phys. Soc.* **17**, 604 (1972).

C. Y. Wong, "Doubly-Magic Toroidal and Bubble Nuclei"; *Bull. Amer. Phys. Soc.* **17**, 581 (1972).

American Society of Mechanical Engineers, Nashville, Tennessee, April 25, 1972

K. L. Vander Sluis, "Lasers and Holography."

Symposium on Molecular Structure and Spectroscopy, Columbus, Ohio, June 12–16, 1972

H. W. Morgan, P. A. Staats, and E. Silberman, "Infrared Spectra of FSO_3^- and $OHSO_3^-$ in Alkali Halide Solid Solutions."

H. W. Morgan, P. A. Staats, and E. Silberman, "Infrared Spectra of SCN^- in Alkali Halide Solid Solutions."

American Association of Physicists in Medicine, Philadelphia, Pennsylvania, June 26–28, 1972

L. B. Hubbard, "Cube-Root of Mass Dependence of the Absorbed Fraction for Small Objects."

Gordon Research Conference on Nuclear Chemistry, New London, New Hampshire, June 26–30, 1972

F. E. Bertrand (invited paper), "Application of the Intranuclear Cascade Model to Continuum Spectra from 30–60 MeV Proton Bombardment."

European Conference on Nuclear Physics, Aix-en-Provence, France, June 26–July 1, 1972

R. L. Hahn, P. F. Dittner, K. S. Toth, and O. L. Keller, "Compound-Nuclear and Transfer Reactions in ^{12}C Reactions with ^{238}U and ^{239}Pu."

W. T. Milner, F. K. McGowan, C. E. Bemis, Jr., J. L. C. Ford, Jr., R. L. Robinson, and P. H. Stelson, "Equilibrium Quadrupole and Hexadecapole Deformations in Actinide Nuclei."

F. Plasil, "Predictions for Heavy-Ion Reactions Based on the Rotating Liquid Drop Model."

K. S. Toth and R. L. Hahn, "New Osmium Isotopes: ^{170}Os and ^{171}Os."

C. Y. Wong, "New Islands of Toroidal and Bubble Stability?"

Sixth International Cyclotron Conference, Vancouver, B.C., Canada, July 18–21, 1972

E. D. Hudson, R. S. Lord, M. L. Mallory, and P. H. Stelson, "The ORIC as a Heavy-Ion Injector for a Separated Sector Cyclotron."

C. A. Ludemann, J. M. Domaschko, and S. W. Mosko, "Computer Control System for ORIC."

J. A. Martin (invited paper), "Alternates to the Cyclotron for Heavy-Ion Acceleration."

J. A. Martin, E. D. Hudson, R. S. Lord, M. L. Mallory, W. T. Milner, S. W. Mosko, and P. H. Stelson, "A Proposed National Heavy-Ion Accelerator at Oak Ridge."

Gordon Research Conference on Nuclear Structure Physics, Tilton, New Hampshire, July 24–28, 1972

J. L. C. Ford, Jr. (invited paper), "Nuclear Hexadecapole Moments."

Gordon Research Conference on the Chemistry and Physics of Solids,
New Hampton, New Hampshire, July 31–August 4, 1972

T. A. Carlson (invited paper), "Use of Multiplet Splitting in the Determination of Chemical Bonding in Transition Metal Compounds."

International Conference on Nuclear Structure Study with Neutrons,
Budapest, Hungary, July 31–August 5, 1972

C. H. Johnson, J. L. Fowler, and R. M. Feezel, "R-Matrix Analysis with a Diffuse-Edge Potential for $^{16}O + n$ Data."

D. A. McClure, S. Raman, and J. A. Harvey, "The Low-Lying Excited States of ^{145}Nd Populated by the Capture of Thermal Neutrons."

S. F. Mughabghab, M. R. Bhat, G. A. Bartholomew, R. E. Chrien, G. W. Cole, O. A. Wasson, and G. G. Slaughter, "Nonstatistical Effects in the 4*s* Giant Resonance."

G. R. Satchler and F. G. Perey (invited paper), "The Optical Model."

G. J. Vanpraet, R. L. Macklin, B. J. Allen, and R. R. Winters, "Neutron Capture Cross Section Measurements for ^{86}Sr, ^{87}Sr, and ^{88}Sr."

O. A. Wasson and G. G. Slaughter, "Test of the Valency Model of Neutron Capture in ^{92}Mo + Neutron."

Third International Conference on Atomic Physics, Boulder, Colorado, August 7–11, 1972

D. J. Pegg, P. M. Griffin, I. A. Sellin, W. W. Smith, and B. Donnally, "Metastable States of Highly Excited Heavy Ions."

Twenty-second Fisk Infrared Institute, Nashville, Tennessee, August 14–18, 1972 and August 25, 1972

H. W. Morgan, "Laser Raman Spectroscopy."

H. W. Morgan, "Optimum Conditions for Infrared Instrument Operation."

H. W. Morgan, "Future Developments in Interpretation of Infrared and Raman Spectra."

P. A. Staats, "Absorption Spectra of Liquids and Solutions."

P. A. Staats, "Experimental Infrared Spectroscopy."

Thirtieth Annual Electron Microscopy Society of America Meeting, Los Angeles, California, August 14–18, 1972

T. A. Welton (invited paper), "Image Theory and Image Processing."

R. E. Worsham, J. E. Mann, and E. G. Richardson, "A Field-Emission Gun."

N. F. Ziegler, "A High-Voltage Terminal for a Field-Emission Gun."

Kingston Nuclear Theory Symposium at Queen's University, Kingston, Ontario, Canada, August 24–25, 1972

J. B. McGrory (invited paper), "Shell Model Hodge-Podge."

American Chemical Society Meeting, New York, New York, August 27–September 1, 1972

K. S. Toth and R. L. Hahn (invited paper), "Study of New Alpha-Emitting Isotopes Far from Stability."

International Conference on Few Particle Problems in the Nuclear Interaction, Los Angeles, California, August 28–September 1, 1972

M. L. Halbert, P. Paul, K. A. Snover, and E. K. Warburton, "Radiative Capture of Protons by Deuterium."

Third International Conference on Raman Spectroscopy, Reims, France, September 8–13, 1972

E. Silberman, J. R. Lawson, and H. W. Morgan, "Vibrational Determination of Crystal Structures."

International Conference on Perspectives for Hyperfine Interactions in Magnetically Ordered Solids by NMR and Other Methods, L'Aquila, Italy, September 11–15, 1972

J. C. Love and F. E. Obenshain, "Mössbauer Effect Study of ^{61}Ni Hyperfine Interactions in Heusler Alloys."

F. E. Obenshain, J. E. Tansil, and G. Czjzek, "Magnetic Hyperfine Fields at ^{61}Ni Nuclei in Dilute Pd:Ni Alloys."

General Meeting on Photoelectron Spectroscopy of Molecules, Sussex, England, September 12–14, 1972

T. A. Carlson and R. M. White, "Study of the Angular Distribution for the Photoelectron Spectra of Halogen Substituted Methane Molecules."

American Nuclear Society Meeting (Topical Meeting on New Developments in Reactor Physics and Shielding Calculations), Kiamesha Lake, New York, September 12–15, 1972

J. A. Harvey (invited paper), "keV Neutron Total Cross Section Measurements at ORELA."

Symposium on Present Status and Novel Developments in the Nuclear Many-Body Problem, Rome, Italy, September 19–23, 1972

R. L. Becker (invited paper), "The Renormalized Brueckner-Hartree-Fock Approximation."

W. F. Ford, R. C. Braley, R. L. Becker, and M. R. Patterson, "Deformed Brueckner-Hartree-Fock Calculations."

Third International Conference on Beam-Foil Spectroscopy, Tucson, Arizona, October 2–6, 1972

D. J. Pegg, P. M. Griffin, I. A. Sellin, and W. W. Smith, "Electron Spectroscopy of Foil-Excited Chlorine Beams."

I. A. Sellin (invited paper), "Metastable Autoionizing States."

1972 Proton Linear Accelerator Conference, Los Alamos, New Mexico, October 10–13, 1972

C. M. Jones, J. L. Fricke, B. Piosczyk, and J. E. Vetter, "A Slow Tuner for Superconducting Helically Loaded Resonant Cavities."

1972 Fall Meeting of Optical Society of America, San Francisco, California, October 17–20, 1972

L. J. Nugent and K. L. Vander Sluis, "Extension of Free-Atom and Free-Ion f-Electron Systematics to General Lanthanide and Actinide Phenomenology."

K. L. Vander Sluis and L. J. Nugent, "Systematics in the Relative Energies of Some Low-Lying Electron Configurations in the Gaseous Atoms and Ions of the Lanthanide and Actinide Series."

Fifth Symposium on the Structure of Low-Medium Mass Nuclei, Lexington, Kentucky, October 27, 1972

F. B. Malik and M. G. Mustafa (invited paper), "A Pedestrian Approach to the Intermediate Structure in Photonuclear Reaction in Light Nuclei."

American Physical Society Meeting, Seattle, Washington, November 2–4, 1972

C. R. Bingham, D. L. Hillis, and J. B. Ball, "Neutron Shell Structure of ^{145}Nd from (d,p) and $(\alpha,^{3}\text{He})$ Reactions"; *Bull. Amer. Phys. Soc.* 17, 899 (1972).

J. K. Dickens, G. L. Morgan, and G. G. Slaughter, "Cu$(n,x\gamma)$ Reactions"; *Bull. Amer. Phys. Soc.* 17, 901 (1972).

J. L. C. Ford, Jr., J. Gomez del Campo, S. T. Thornton, R. L. Robinson, and P. H. Stelson, "Investigation of the $^{10}\text{B}(^{16}\text{O},d)$, $^{10}\text{B}(^{16}\text{O},\alpha)$, and $^{12}\text{C}(^{16}\text{O},\alpha)$ Reactions"; *Bull. Amer. Phys. Soc.* 17, 920 (1972).

C. B. Fulmer and J. C. Hafele, "Optical Model Family Ambiguity Resolved for Helion Scattering from ^{60}Ni"; *Bull. Amer. Phys. Soc.* 17, 895 (1972).

R. M. Gaedke, J. B. Ball, J. L. C. Ford, Jr., J. S. Larsen, and K. S. Toth, "$^{208}\text{Pb}(^{12}\text{C},^{11}\text{B})^{209}\text{Bi}$ and $^{208}\text{Pb}(^{12}\text{C},^{13}\text{C})^{207}\text{Pb}$ Reactions at High Bombarding Energies"; *Bull. Amer. Phys. Soc.* 17, 914 (1972).

C. D. Goodman, D. C. Hensley, A. van der Woude, and S. Raman, "Isospin Conservation and the Reactions $^{11}\text{B}(d,^{6}\text{He})^{7}\text{Be}$ and $^{11}\text{B}(d,^{6}\text{Li}^{*})^{7}\text{Li}$"; *Bull. Amer. Phys. Soc.* 17, 929 (1972).

N. B. Gove and S. Raman, "Log $f_1 t$ Values for First-Forbidden Unique Beta-Transitions and the Decay of ^{90m}Y"; *Bull. Amer. Phys. Soc.* 17, 909 (1972).

J. A. Harvey, N. W. Hill, and W. E. Kinney, "A Proton Recoil Detector for keV Energy Neutrons"; *Bull. Amer. Phys. Soc.* 17, 901 (1972).

D. J. Horen, R. L. Auble, F. E. Bertrand, and J. B. Ball, "A Study of the $^{107}\text{Ag}(^{3}\text{He},d)^{108}\text{Cd}$"; *Bull. Amer. Phys. Soc.* 17, 906 (1972).

E. T. Jurney, S. Raman, G. G. Slaughter, J. A. Harvey, J. C. Wells, Jr., J. Lin, and D. A. McClure, "Observation of the 7120-keV, $3^- \to 2_1^+$ Primary γ-Ray in ^{144}Nd"; *Bull. Amer. Phys. Soc.* 17, 898 (1972).

H. J. Kim, R. L. Robinson, W. T. Milner, and J. C. Wells, Jr., "Ratio of $E2$ Effective Charges for ^{42}Ti and ^{42}Ca"; *Bull. Amer. Phys. Soc.* 17, 932 (1972).

R. L. Macklin and R. R. Winters, "Neutron Capture in Fluorine from 2.5 to 1500 keV"; *Bull. Amer. Phys. Soc.* 17, 900 (1972).

F. K. McGowan (invited paper), "Electric Hexadecapole Moments in the Actinide Nuclei"; *Bull. Amer. Phys. Soc.* 17, 890 (1972).

S. Raman, J. A. Harvey, T. A. Walkiewicz, G. J. Lutz, L. G. Multhauf, and K. G. Tirsell, "Gamma Transitions in ^{119}Sn"; *Bull. Amer. Phys. Soc.* **17**, 906 (1972).

R. L. Robinson and Z. W. Grabowski, "Properties of the 2′ and 2″ States in ^{106,112,114}Cd"; *Bull. Amer. Phys. Soc.* **17**, 906 (1972).

R. O. Sayer, N. R. Johnson, E. Eichler, D. C. Hensley, and L. L. Riedinger, "Coulomb Excitation of ^{160,162,164}Dy with ^{35}Cl Ions"; *Bull. Amer. Phys. Soc.* **17**, 899 (1972).

J. P. Svenne and R. L. Becker, "A Problem of Level Inversion in Nuclear HF and BHF Calculations"; *Bull. Amer. Phys. Soc.* **17**, 910 (1972).

L. Varnell, J. H. Hamilton, J. Lange, R. L. Robinson, P. H. Stelson, and J. L. C. Ford, Jr., "Coulomb Excitation Studies of ^{176}Hf"; *Bull. Amer. Phys. Soc.* **17**, 899 (1972).

O. A. Wasson and G. G. Slaughter, "Valency Neutron Capture in ^{92}Mo$(n,\gamma)^{93}$Mo"; *Bull. Amer. Phys. Soc.* **17**, 902 (1972).

J. C. Wells, Jr., J. Lin, S. Raman, R. L. Auble, and E. Newman, "The ^{143}Nd(d,p) Reaction at 25 MeV"; *Bull. Amer. Phys. Soc.* **17**, 898 (1972).

Southeastern Section Meeting of American Physical Society, Birmingham, Alabama, November 16–18, 1972

J. M. Springer, E. Silberman, and H. W. Morgan, "Vibrational Determination of Crystal Structures," Paper EB9 in Program 39th Meeting SESAPS.

P. H. Stelson (invited paper), "On the Shapes of Heavy Nuclei," Paper CB1 in Program 39th Meeting SESAPS.

1972 IEEE Nuclear Science Symposium, Miami Beach, Florida, December 6–8, 1972

D. C. Hensley (invited paper), "List or Sort? – Some Experiences from the ORIC Multiparameter Data Acquisition System."

ANNOUNCEMENTS

Alexander Zucker returned to ORNL after a two-year leave of absence in Washington, D.C., where he served as Executive Director of the Environmental Studies Board of the National Academy of Sciences. Since his return, Mr. Zucker has been appointed Associate Director for Basic Physical Sciences at Oak Ridge National Laboratory.

C. M. Jones was appointed group leader for the Ion Source Development program.

In October 1972 the first issue of the *Journal of Electron Spectroscopy* appeared. The coeditors are C. R. Brundle of the University of Bradford, England, and T. A. Carlson of Oak Ridge National Laboratory. The journal will be published bimonthly by Elsevier Scientific Publishing Company and is an international journal devoted to all aspects of electron spectroscopy, both theoretical and experimental. The journal is in response to the tremendous growth of activity in the field of electron spectroscopy during the last few years, some of which was pioneered at ORNL.

PERSONNEL ASSIGNMENTS

During 1972 the Physics Division has been host to approximately 34 guests from abroad and from throughout the U.S. Some of these are short-term assignments, such as those sponsored by the Oak Ridge Associated Universities. Other appointments may extend for one or two years and are usually sponsored by fellowships or the individual's home institution. In addition, a number of Ph.D. staff members have been guests of other laboratories in the United States and abroad. A list of participants follows:

Guest Assignees from Abroad

J. B. Allen (Exchange Assignee), Australian Atomic Energy Commission Lucas Heights Research Establishment, Sutherland, New South Wales – Nuclear

Geophysics and Oak Ridge Electron Linear Accelerator Neutron *Time-of-Flight* Spectroscopy Programs (completed 2½-year assignment in March 1972).

Tzun-Ren Chang, Institute of Nuclear Energy Research, Taiwan, Republic of China – Oak Ridge Electron Linear Accelerator Program (began two-month assignment in December 1972).

Jen-Chang Chou, Institute of Nuclear Energy Research, Taiwan, Republic of China – Oak Ridge Electron Linear Accelerator Program (completed two-week assignment in November 1972).

E. D. Earle, Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada – Oak Ridge Electron Linear Accelerator Program (completed two-week assignment in July 1972).

Gudrun Hagemann (Exchange Assignee), Niels Bohr Institute, University of Copenhagen, Denmark – Nuclear Physics Program (completed one-year assignment in July 1972).

K. A. Hagemann (Exchange Assignee), Niels Bohr Institute, University of Copenhagen, Denmark – Nuclear Physics Program (completed one-year assignment in July 1972).

G. D. James (Exchange Assignee), Atomic Energy Research Establishment, Harwell, England – Oak Ridge Electron Linear Accelerator Program and part time with Molecular Anatomy Program of Director's Division (began one-year assignment in October 1972).

J. S. Larsen (Exchange Assignee), Niels Bohr Institute, University of Copenhagen, Denmark – Nuclear Physics Program (completed ten-month assignment in June 1972).

Tove Larsen, Technical University of Denmark, Lyngby, Denmark – Nuclear Physics Program (completed ten-month assignment in June 1972).

R. L. Mössbauer, Technical University of Munich, Munich, Germany – Mössbauer Experimental Program (completed one-month assignment in February 1972).

Suresh C. Pancholi, University of Delhi, Delhi, India – Nuclear Data Project (completed three-month assignment in December 1972).

P. Perrin, Centre Etude Nucleaire Grenoble, Grenoble, France – Van de Graaff Program (completed two-week assignment in February 1972).

W. D. Schmidt-Ott, University of Goettingen, Goettingen, Germany – University Isotope Separator at Oak Ridge Program (began one-year assignment in June 1972).

Guest Assignees from the United States

G. R. Bethune,[1] Bethune-Cookman College – Physics of Fission Program (completed three-month assignment in August 1972).

C. R. Bingham,[1] University of Tennessee – Nuclear Physics Program (completed three-month assignment in August 1972, now consultant under subcontract).

H. K. Carter, Oak Ridge Associated Universities – University Isotope Separator at Oak Ridge Program (began one-year assignment in June 1972).

G. T. Condo, University of Tennessee – High Energy Physics Program (summer appointment closed in September 1972, now consultant under subcontract).

N. C. Fernelius, Research Consultants, Inc. – Electron Spectroscopy Program (completed 13-month assignment in June 1972).

R. M. Gaedke,[1] Trinity University – Nuclear Physics Program (completed three-month assignment in August 1972).

D. Goss,[1] Nebraska Wesleyan University – Theoretical Physics Program (completed three-month assignment in August 1972).

Z. W. Grabowski, Purdue University (sabbatical leave) – Charged Particle Cross Section Data Center (completed seven-month assignment in February 1972).

E. L. Hart, University of Tennessee – High Energy Physics Program (continued part-time assignment begun in October 1969).

P. G. Huray, University of Tennessee – Mössbauer Experimental Program (guest assignment closed in April 1972, now consultant under subcontract).

G. A. Keyworth, Los Alamos Scientific Laboratory – Oak Ridge Electron Linear Accelerator Program (completed five-month assignment in December 1972).

R. L. Mlekodaj – University Isotope Separator at Oak Ridge Program (began indefinite appointment in January 1972).

J. R. Mowat, University of Tennessee – Van de Graaff Program (began one-year appointment in June 1972).

1. Research participant sponsored by Oak Ridge Associated Universities.

A. V. Ramayya,[1] Vanderbilt University — Nuclear Physics Program (completed three-month assignment in August 1972).

A. C. Rester, Jr. — University Isotope Separator at Oak Ridge Program (completed six-month appointment in April 1972).

F. T. Seibel, Los Alamos Scientific Laboratory — Oak Ridge Electron Linear Accelerator Program (completed five-month assignment in December 1972).

E. H. Spejewski, Oak Ridge Associated Universities — assigned as Director of University Isotope Separator at Oak Ridge Program (began indefinite assignment in June 1972).

O. A. Wasson, Brookhaven National Laboratory — Oak Ridge Electron Linear Accelerator Neutron Time-of-Flight Spectroscopy Program (completed one-year assignment in August 1972).

J. C. Wells,[1] Tennessee Technological University — Van de Graaff Program (completed three-month assignment in September 1972).

R. M. White, Baker University (sabbatical leave) — Electron Spectroscopy Program (completed one-year assignment in August 1972).

R. R. Winters, Denison University (sabbatical leave) — Nuclear Geophysics Program (completed five-month assignment in May 1972, followed by one-month summer appointment completed in June 1972, now a consultant under contract arrangement with Oak Ridge Associated Universities).

Staff Assignments

J. B. Ball — Nuclear Physics. Began in July 1972 one-year exchange assignment to Niels Bohr Institute, Copenhagen, Denmark.

J. A. Biggerstaff — Van de Graaff Laboratory. Completed in March 1972 18-month assignment to Australian Atomic Energy Commission in Lucas Heights Research Establishment, Sutherland, New South Wales, Australia.

W. B. Dress — Van de Graaff Program. Began in July 1972 15-month assignment with Institute Laue-Langevin in Grenoble, Grenoble, France.

W. B. Ewbank — Nuclear Data Project. Completed in February 1972 13-month leave of absence with Free University, Amsterdam, Netherlands — temporary Lecturer in Physics.

C. D. Goodman — Nuclear Physics. Began in September 1972 nine-month assignment at University of Colorado as visiting professor of physics.

E. E. Gross — Nuclear Physics. Completed in August 1972 one-year exchange assignment to Niels Bohr Institute, Copenhagen, Denmark.

Edith Halbert — Theoretical Physics. Completed in August 1972 one-year assignment with State University of New York at Stony Brook and with Brookhaven National Laboratory (part time).

M. L. Halbert — Nuclear Physics. Completed in August 1972 one-year exchange assignment with Brookhaven National Laboratory.

C. M. Jones — Ion Source Development Program. Completed in July 1972 one-year assignment to Institut fur Experimentelle Kernphysik of Kernforschungszentrum Karlsruhe, Karlsruhe, Germany.

P. D. Miller — Van de Graaff Program. Began in July 1972 15-month assignment with Institute Laue-Langevin in Grenoble, Grenoble, France.

A. Zucker — Nuclear Physics. Completed in July 1972 two-year leave of absence with Environmental Studies Board of National Academy of Sciences in Washington, D.C., as Executive Director.

Staff Appointments

H. G. Bingham, Jr. — Nuclear Physics. Began in October 1972 three-year appointment.

J. M. Domaschko — Nuclear Physics. Completed in December 1972 one-year appointment as NSF Presidential Intern.

D. C. Kocher — Nuclear Data Project. Began in September 1971 two-year assignment (Nuclear Information Research Associate under National Science Foundation Grant).

M. G. Mustafa — Physics of Fission. Began in May 1972 ten-month assignment (formerly a consultant under sister-laboratory agreement between ORNL and Pakistan Atomic Energy Commission).

Staff Termination

A. van der Woude — Nuclear Physics. Completed in July 1972 temporary appointment. Now with Kernphysisch Versneller Instituut, Groningen, The Netherlands.

Staff Appointees – Intralaboratory Loans

T. A. Carlson (Electron Spectroscopy Program), Chemistry Division, continued loan assignment with Physics Division.

W. M. Good [Oak Ridge Electron Linear Accelerator (ORELA) Program] completed in July 1972 eleven-month loan assignment with Environmental Reports Project.

M. L. Mallory (Electronuclear Systems Development Program), Chemistry Division, began in July 1972 loan assignment with Physics Division.

F. Plasil (Physics of Fission Program) completed in September 1972 one-year loan assignment with Director's Division, Planning and Analysis Program.

H. W. Schmitt (Physics of Fission Program) completed in May 1972 four-month loan assignment with Director's Division, Planning and Analysis Program.

P. A. Staats (Atomic and Molecular Spectroscopy Program) completed in February 1972 one-month loan assignment with Information Division Program of Declassification at AEC-ORO.

T. A. Welton (Academic Affairs Director and Theoretical Physics Program) began in October 1972 approximate six-month loan assignment with Oak Ridge Gaseous Diffusion Plant (K-25) Centrifuge Program.

MISCELLANEOUS PROFESSIONAL ACTIVITIES OF DIVISIONAL PERSONNEL

Staff members of the Physics Division are frequently requested or appointed to assume certain professional duties which are incident to their primary responsibilities at ORNL. Such duties may be in connection with scientific journals, societies, conferences, committees, institutes, etc. During 1972 such activities have included the following:

R. L. Becker – reviewer for the *Physical Review, Physical Review Letters,* and *Nuclear Science and Engineering*; instructor for the Oak Ridge Resident Graduate Program of the University of Tennessee; member of the advisory committees of several Ph.D. students at the University of Tennessee.

T. A. Carlson[1] – reviewer for the *Physical Review*; member of program Advisory Board, International Symposium on Future Application of Inner Shell Ionization Phenomena, Atlanta, Georgia, April 22, 1972; Joint Editor-in-Chief of the *Journal of Electron Spectroscopy.*

H. O. Cohn – member of Accelerator Users Group at National Accelerator Laboratory, Stanford Linear Accelerator Center, Brookhaven National Laboratory, and Argonne National Laboratory.

K. T. R. Davies – reviewer for the *Physical Review* and *Physical Review Letters.*

J. L. C. Ford, Jr. – Organizing Committee member of the ORNL Heavy-Ion Summer Study.

J. L. Fowler – member of Executive Committee of Council of the American Physical Society (1970–1973); representative of the American Physical Society on the Governing Board of the American Institute of Physics (1972–1974); member of the Manpower Statistics Advisory Committee of the American Institute of Physics (1972–1973); member of Publications Committee of the Council of the American Physical Society (1970–1972); Divisional Councilor of the American Physical Society for the Division of Nuclear Physics (1970–1973); member of Executive Committee of Division of Nuclear Physics of the American Physical Society (1970–1973); member of Program Committee for the Division of Nuclear Physics of the American Physical Society (1972–1973); member of Nominating Committee of the Division of Nuclear Physics of the American Physical Society – appointed by Council (1972); chairman of the Publications Committee for the Division of Nuclear Physics of the American Physical Society for the *Physical Review C* and *Physical Review Letters* (1972–1973); member of Program Committee for the 1972 Fall Meeting of the Southeastern Section of the American Physical Society; secretary of the Commission on Nuclear Physics of the International Union of Pure and Applied Physics (1972–1975); ex officio member of U.S. National Committee for the International Union of Pure and Applied Physics; referee for the *Physical Review* and *Physical Review Letters.*

C. B. Fulmer – member of the ORNL Accelerator and Radiation Sources Review Committee; referee for the *Physical Review* and *Physical Review Letters.*

1. On loan from the Chemistry Division to the Physics Division.

C. D. Goodman – member of program committee for IEEE 1972 Nuclear Science Symposium; member of advisory committee for the Information Division of the American Institute of Physics; referee for the *Physical Review* and *Physical Review Letters.*

E. E. Gross – member of the Technical Advisory Panel (TAP) for the Los Alamos Meson Facility; reviewer of proposals for the Research Corporation.

E. C. Halbert – referee for the *Physical Review.*

M. L. Halbert – referee for the *Physical Review C* and *Physical Review Letters.*

J. A. Harvey – secretary-treasurer of the Division of Nuclear Physics of the American Physical Society (1967–1973); member of the editorial board of *Nuclear Data Tables*, a journal published by Academic Press; reviewer for the *Physical Review* and *Nuclear Science and Engineering*; labor coordinator for the Physics Division.

D. J. Horen – member of the Committee on Nuclear Data Compilations of the Division of Nuclear Physics of the American Physical Society (1971–1973); member of Ad Hoc Panel on Nuclear Data Compilations of the National Academy of Sciences (1971–1973); U.S. member of IAEA International Working Group on Compilation Evaluation, and Dissemination of Nuclear Structure and Reaction Data (1971–1973); member of U.S. Nuclear Data Committee (1972); reviewer for the *Physical Review.*

C. M. Jones – reviewer for *Particle Accelerators.*

C. A. Ludemann – Physics Division representative to the Union Carbide Nuclear Division Affirmative Action Program; member of UCCND Advisory Panel to study the feasibility of computer control of the calutrons.

R. L. Macklin – member of the Oak Ridge Gaseous Diffusion Plant Nuclear Safety Committee; chairman of the Subcommittee on Neutron Capture Cross Sections of the United States Nuclear Data Committee; reviewer for *Il Nuovo Cimento*, the *Physical Review, Nuclear Physics, Physical Review Letters, Nuclear Instruments and Methods, Astrophysical Journal, Nuclear Applications, Nuclear Science and Engineering, and Nuclear Science and Technology.*

J. A. Martin – vice-president of the Nuclear and Plasma Sciences Society of the Institute of Electrical and Electronics Engineers; member of the Administrative Committee of the IEEE Nuclear and Plasma Sciences Society (1971–1975); member of the Technical Committee on Particle Accelerator Science and Technology of the IEEE-NPSS; member of Editorial Advisory Board of *Particle Accelerators*; reviewer for *Particle Accelerators*; consultant to the National Science Foundation Physics Section as a member of the Visiting Committee for the Indiana University Cyclotron Project; member of the Organizing and Program Committees for the 1973 Particle Accelerator Conference (San Francisco, California, March 1973).

F. K. McGowan – member of the Editorial Board of *Nuclear Data Tables*, a journal published by Academic Press; reviewer for the *Physical Review* and *Physical Review Letters.*

J. B. McGrory – chairman, 1972 Gordon Research Conference on Nuclear Structure; referee for the *Physical Review* and *Physical Review Letters.*

H. W. Morgan – faculty member of Fisk University Infrared Spectroscopy Institute; on the Membership Committee for the Southeastern Section of the American Physical Society (1971–1972); member of the Program Committee for the Southeastern Section of the American Physical Society (Birmingham, Alabama, November 1972); chairman of the Board of Directors of the Tennessee Partners of the Alliances for Scientific Exchange between universities in Tennessee, Brazil, and Venezuela; Senior Research Associate, Department of Natural Sciences, Hollins College.

E. Newman – member of the ORNL Graduate Fellow Selection Panel; reviewer for the *Physical Review* and *Physical Review Letters*; scientific secretary for the ORNL Heavy-Ion Summer Study.

F. E. Obenshain – part-time faculty member with the Department of Physics of the University of Tennessee; reviewer for the *Physical Review* and *Physical Review Letters.*

S. Raman – reviewer for the *Physical Review, Physical Review Letters*, and *Nuclear Physics.*

R. L. Robinson – reviewer for the *Physical Review* and *Physical Review Letters.*

M. J. Saltmarsh – scientific secretary for the ORNL Heavy-Ion Summer Study; coauthor of Section 5 (Applications of Heavy Ions) in the National Heavy-Ion Laboratory Proposal.

G. R. Satchler – member of editorial board of *Particles and Nuclei*, a journal published by F.U. Research Institute, Athens, Ohio; member of editorial board of

Nuclear Data Tables, a journal published by Academic Press; member of panel of "Contributors" to *Comments on Nuclear and Particle Physics*, a journal published by Gordon and Breach, Inc.; reviewer for the *Physical Review, Physical Review Letters, Nuclear Physics*, and *Physics Letters.*

H. W. Schmitt -- reviewer for the *Physical Review, Physical Review Letters, Nuclear Physics*, and *Nuclear Science and Engineering*; member of editorial board of *Nuclear Data Tables*; member of Committee on ORNL Sister-Laboratory Arrangement with the Pakistan Atomic Energy Commission; consultant to Tri-Universities Nuclear Laboratory of Duke University; organizing committee member of the ORNL Heavy-Ion Summer Study.

G. G. Slaughter – reviewer for *Nuclear Science and Engineering* and the *Physical Review.*

P. A. Staats – faculty member of Fisk University Infrared Spectroscopy Institute.

P. H. Stelson – part-time faculty member with the Department of Physics of the University of Tennessee; associate editor of *Nuclear Physics*; member of the executive committee of the Southeastern Section of the American Physical Society; member of committee for the International Conference of Nuclear Physics (Munich, Germany, August 27–September 1, 1973).

K. S. Toth -- reviewer for the *Physical Review* and *Physical Review Letters*; liaison man between Physics Division and UNISOR Project. In particular, attended all executive committee and users meetings, acted as chairman of the UNISOR Scheduling Comittee, and participated in numerous technical matters as a member of the UNISOR Technical Committee.

K. L. Vander Sluis – member of the Committee on Line Spectra of the Elements of the National Academy of Sciences – National Research Council.

T. A. Welton – part-time faculty member with the Department of Physics of the University of Tennessee, teaching graduate nuclear physics course; taught (fall quarter) a senior-level quantum mechanics course to students from Great Lakes College Association; reviewer for *Journal of Applied Physics.*

COLLOQUIA AND SEMINARS PRESENTED BY THE PHYSICS DIVISION STAFF

Scientists with the Physics Division receive numerous requests to present seminars and colloquia, both in this country and abroad. Some of these are supported through the Traveling Lecture Program, administrated by the Oak Ridge Associated Universities. Funds for transportation for the lectures are provided by the Oak Ridge Associated Universities. The institution requesting the lectures in turn provides funds for the local expense. Following is a list of these talks:

H. G. Bingham, Jr. – Florida State University, November 14, 1972, "Lithium-Induced Three-Nucleon Transfer Reactions on $N = Z$ Nuclei."

T. A. Carlson (on loan from Chemistry Division) – Rutgers University, April 5, 1972, Research Laboratories of Eastman Kodak, July 10, 1972, "Recent Developments in the Application of Electron Spectroscopy to Chemical Problems"; Yale University (Photoelectron Spectroscopy Symposium), November 30, 1972, "The Use of Multicomponent Lines in X-Ray Photoelectron Spectroscopy"; Instituto de Fisica, University of Mexico, Mexico City, Mexico, May 10, 1972, "General Survey of Electron Spectroscopy."

J. L. C. Ford, Jr. -- University of Virginia, April 11, 1972, "Equilibrium Quadrupole and Mexadecapole Deformations in Actinide Nuclei."

J. L. Fowler -- North Carolina State University, February 7, 1972, "The History of the Technological Development of the Arms Race"; North Carolina State University, February 8, 1972, "Toroidal Nuclei: A Speculation."

C. D. Goodman – University of Colorado, December 7, 1972, "Can We Learn about Complicated Nuclear Reactions from the Simple Symmetry of Isospin Conservation?"

E. E. Gross – University of Birmingham, Birmingham, England, April 18, 1972, "Polarization -- Asymmetry Test of Time Reversal Invariance"; Harwell Scientific Laboratory, England, April 21, 1972, University of Heidelberg, Germany, May 23, 1972, "Violation of the Barshay-Temmer Theorem in the Reaction $^{2}H(^{4}He,^{3}H)^{3}He$"; University of Marburg, Germany, May 23, 1972, "Testing Time Reversal Invariance in Nuclear Physics"; University of Georgia, November 30, 1972, "Interference between Coulomb and Nuclear Excitation in Inelastic Scattering of ^{16}O."

M. L. Halbert – University of Virginia, November 8, 1972, "Resonances in ^{3}He?"; National Bureau of Standards, Center for Radiation Research, November 9, 1972, "Are There Resonances in ^{3}He?"

E. D. Hudson – University of California, Davis (representatives of Crocker Nuclear Laboratory, the Naval Research Laboratory, and Oak Ridge National Laboratory), July 13–14, 1972, "Heavy Ions at ORIC."

C. M. Jones – Daresbury Nuclear Physics Laboratory, Daresbury, England, March 7, 1972, "Feasibility of Accelerating Heavy Ions with a Superconducting Linear Accelerator."

R. S. Lord – University of California, Davis (representatives of Crocker Nuclear Laboratory, the Naval Research Laboratory, and Oak Ridge National Laboratory), July 13–14, 1972, "ORIC Improvement Programs."

J. B. McGrory – University of South Carolina, February 3, 1972, Texas A & M University, March 16, 1972, Tulane University, March 17, 1972, Florida State University, May 22, 1972, "The Use of the Nuclear Shell Model to Study Quantum Collective Systems"; University of Pennsylvania, April 21, 1972, "Shell Model Calculations in the Calcium and Lead Region"; Duke University, November 2, 1972, "Recent Shell Model Investigations at Oak Ridge."

C. D. Moak – University of Witwatersrand, Johannesburg, South Africa, February 22–25, 1972, "Heavy-Ion Nuclear Physics"; Heavy-Ion Solid-State Physics"; "Accelerator Technology."

H. W. Morgan – Hollins College, May 5, 1972, "Lasers and Their Applications to the Sciences, Particularly Physics and Medicine."

S. W. Mosko – University of California, Davis (representatives of Crocker Nuclear Laboratory, the Naval Research Laboratory, and Oak Ridge National Laboratory), July 13–14, 1972, "The New ORIC Power Amplifier."

F. E. Obenshain – University of Louisville, September 29, 1972, "Magnetic Properties of Transition Metals and Their Alloys Determined by Mössbauer Measurements with ^{61}Ni"; Rice University, November 15, 1972, "Mössbauer Studies of Exchange Enhancement and Magnetic Properties of PdNi Alloys."

F. Plasil – Institut de Physique Nucléaire, Orsay, France, July 1972, Technische Universität München, Garching, Germany, July 1972, "Limits on Angular Momentum in Heavy-Ion Reactions"; University of Tennessee, November 14, 1972, "Limiting Angular Momentum in Heavy-Ion Reactions."

M. J. Saltmarsh – University of South Carolina, March 9, 1972, "Inner Shell Excitation Induced by Heavy-Ion Bombardment"; Kernfysisch Versneller Instituut, Groningen, Netherlands, May 17, 1972, "Multiple Inner Shell Ionization Induced by Energetic Heavy Ions."

G. R. Satchler – University of Pittsburgh, September 28, 1972, "Excitation of Giant Quadrupole States in Nuclei"; Michigan State University, November 13, 1972, University of Michigan, November 15, 1972, "The Excitation of Giant Resonance States in Nuclei."

H. W. Schmitt – Tulane University, April 13, 1972, "Nuclear Physics with Emphasis on the Physics of Fission"; Texas Christian University, April 14, 1972, "Some New Insights in the Physics of Nuclear Fission"; Florida State University, April 18, 1972, "New Insights in the Physics of Fission."

K. L. Vander Sluis – University of Miami, February 23, 1972, University of South Florida, February 24, 1972, Catholic University of America, March 23, 1972, "Coherent Light and Holography."

A. van der Woude – University of Georgia, May 4, 1972, "X-Ray Excitation by Heavy Ions."

C. L. Viar – University of California, Davis (representatives of Crocker Nuclear Laboratory, the Naval Research Laboratory, and Oak Ridge National Laboratory), July 13–14, 1972, "ORIC Operating Experience."

T. A. Welton – Furman University, February 7–8, 1972, "Energy: Conversion and Control"; "Coherent Electron Microscopy."

C. Y. Wong – University of Manitoba, February 3, 1972, "Toroidal and Bubble Nuclei"; Vanderbilt University, October 6, 1972, "Do Toroidal Nuclei Exist?" Georgia Institute of Technology, November 29, 1972, "Toroidal Nuclei, Toroidal Stars, and All That"; University of Virginia, December 19, 1972, "Toroidal Nuclei and Toroidal Stars."

PHYSICS DIVISION SEMINARS

The normal day for weekly Divisional seminars, long a practice of the Physics Division, is Friday at 3:00 PM. Frequently, however, additional talks are scheduled for other days of the week in order to include on the seminar calendar topics of especial timeliness or interest. Advance Laboratory-wide announcement is made of these seminars, which are open to both employees and guests.

Seminar Chairman for the first eight months of 1972 was S. Raman (Nuclear Data Project); in September 1972 the duties of Seminar Chairman were assumed by Edith Halbert (Theoretical Physics). Lectures arranged by these Chairmen during 1972 were as follows:

January 7 – H. W. Bertini, ORNL, "Continuum State Nuclear Reaction Calculations from 18 to 3000 MeV via Intranuclear Cascades"

January 14 – Calvin Burwell, ORNL, "New Directions in Energy Research at ORNL"

January 21 – R. Broglia, State University of New York, Stony Brook, "Influence of the Isovector Quadrupole Mode in the Particle Evaporation Coupling Scheme"

February 4 – Frank Comas, Department of Radiology, University of Tennessee Memorial Research Hospital, "Radiotherapy – The State of the Art"

February 11 – O. A. Wasson, Brookhaven National Laboratory, "Radiative Neutron Capture Measurements at ORELA"

February 18 – B. J. Allen, Australian Atomic Energy Commission, Lucas Heights, "Neutron Capture Cross Sections and Stellar Nucleosynthesis"

February 25 – Robert W. Manweiler, Cornell University, "Non-Local Nucleon-Nucleus Effective Interactions: A Consistent Picture"

March 3 – Samuel Penner, National Bureau of Standards, Washington, D.C., "Nuclear Moment Measurements by Inelastic Electron Scattering"

March 10 – Duane Larson, Michigan State University, "High-Resolution Inelastic Proton Scattering from $N = 82$ Nuclei"

March 17 – T. A. Welton, ORNL, "High Coherence Electron Microscopy"

March 20 – J. C. Hafele, Washington University, "Time, Relativity, and Around-the-World Atomic Clocks"

March 24 – A. M. Koehler, Harvard University, "Radiological Applications of High-Energy Protons"

April 7 – H. W. Schmitt, ORNL, "Some Recent Advances in Nuclear Fission"

April 11 – J. P. F. Sellschop, University of Witwatersrand, Johannesburg, S. Africa, "Cosmic Ray Experiments at 10,500 Feet Below the Surface of the Earth"

April 14 – G. R. Satchler, ORNL, "Towards a Microscopic Description of Scattering from Nuclei"

April 21 – A. J. Sierk, California Institute of Technology, "Super Conducting (?) Heavy-Ion Linacs"

April 28 – J. P. Svenne, University of Manitoba, "Hartree-Fock Calculations with Density-Dependent Effective Interactions"

May 5 – Walter Benenson, Michigan State University, "(^{3}He,^{6}He) for the Masses"

May 12 – Cleland H. Johnson, ORNL, "Single-Particle Fragments in ^{17}O from Neutron Total Cross Sections"

May 19 – Akito Arima, State University of New York, Stony Brook, "Spectroscopic Information from Heavy-Ion Reactions"

May 26 – S. Wagner, Ortec, Inc., "The Efficiency Instability of Ge Detectors and the Related Short-Term Effects"

June 8 – C. W. Wong, U.C.L.A., "Generator-Coordinate Theory of Collective Motion"

June 16 – J. A. Biggerstaff, ORNL, "Gullible's Travels"

June 26 – P. Todd, Pennsylvania State University, "Possibilities for Radiobiological and Biomedical Research with Fast Heavy Ions"

July 10 – E. Konecny, Technische Universität München, "Electromagnetic Transitions in the Second Minimum in ^{240}Pu"

July 19 – K. Amos, University of Melbourne, Australia, "Inelastic Scattering and the *s-d* Shell"

July 21 – Freeman J. Dyson, Institute for Advanced Study, Princeton, "Do the Constants of Nature Stay Constant?"

July 31 – J. Halbritter, Institut für Experimentelle Kernphysik, Karlsruhe, W. Germany, "RF Superconductivity in Niobium"

August 4 – K. H. Bhatt, Physical Research Laboratory, Ahmedabad, India, "Studies of the Structure of Shell Model Wave Functions"

August 11 – "Apollo 16 – Nothing So Hidden" (color film)

August 18 — E. E. Gross, ORNL, "Danish Pastry"

August 25 — C. M. Jones, ORNL, "Status of the Super-Conducting Linear Accelerator at Karlsruhe"

September 8 — F. Plasil, ORNL, "Predicted Limits on Angular Momentum in Heavy-Ion Reactions"

September 15 — J. B. McGrory, ORNL, "A Funny Thing Happened on the Way to Europe"

September 18 — A. H. Wapstra, Institute of Nuclear Physics Research, Amsterdam, The Netherlands, "Atomic Effects in Determinations of Nuclear Masses (with a short introduction on The Multi-Particle Detector BOL)"

September 22 — S. J. Krieger, University of Illinois, Chicago Circle, "Some Recent Results of Deformed Hartree-Fock Calculations"

October 3 — Ulrich Mosel, University of Washington and Justus Liebig University, Giessen, Germany, "Finite-Size Effects in Heavy-Ion Scattering"

October 12 — P. J. Ellis, Oxford University, England, and Argonne National Laboratory, "The Effective Charge and Interaction in Nuclei"

October 16 — J. L. Fricke and J. E. Vetter, Institut für Experimentelle Kernphysik, Karlsruhe, Germany, "Current Status of the Karlsruhe Superconducting Linac, and Experimental Studies of r-f Superconductivity in Nb at Low Frequencies"

October 25 — H. C. Lee, Atomic Energy of Canada Limited, Chalk River Ontario, Canada, "Coulomb Induced Mirror Asymmetry in Allowed β-Decays in the Hartree-Fock Approximation"

November 10 — H. Nifenecker, Lawrence Berkeley Laboratory, "New Features of Gamma-Ray and Neutron Emission from ^{252}Cf Fission Fragments"

November 17 — B. H. Wildenthal, Michigan State University, "Five Years of Interaction between Shell-Model Theory and Experiment in the *sd* Shell"

November 22 — B. B. Back, Los Alamos Scientific Laboratory and the Niels Bohr Institute, Copenhagen, Denmark, "Fission of Actinide Nuclei Induced by Direct Reactions"

December 1 — H. J. Kim, ORNL, "Population of $(f_{7/2})^2$ States via $(^{16}O,xn)$ Reactions on Si Isotopes, and $E2$ Effective Charges for Protons vs Neutrons"

December 8 — L. J. Nugent, ORNL, "Generalized f-Electron Energetics in Lanthanide and Actinide Chemical Phenomenology"

December 11 — R. P. Scharenberg, Purdue University, "Experimental Basis of the Reorientation Effect"

December 15 — Alexander Zucker, ORNL, "Science and Environmental Policy"

Ph.D. THESIS RESEARCH

During 1972, 16 Physics Division staff members served in either an advisory or supervisory capacity for thesis research conducted by 17 candidates for the Doctor of Philosophy degree. For the most part, research by the students was carried out at Oak Ridge National Laboratory through fellowship appointments or through guest assignment arrangements with the Laboratory.

Doctoral degrees were conferred during the year to eight of the graduate students — one by Vanderbilt University and seven by the University of Tennessee. A listing of those concerned follows:

Ph.D. candidate	Staff advisor(s)	Field of research (thesis title listed if known)
W. J. Carter III University of Tennessee	T. A. Carlson	"Electron Spectroscopy Applied to Environmental Problems"
J. C. Carver University of Tennessee	T. A. Carlson	"Photoelectron Multiplet Splitting and Chemical Shifts in Transition-Metal Compounds" (Ph.D. granted March 1972)
K. Dagenhart University of Tennessee	P. H. Stelson	Coulomb excitation of ^{115}Sn
D. O. Galde Tulane University	M. L. Halbert C. A. Ludemann A. van der Woude	Proton-proton bremsstrahlung at 64.4 MeV

J. Gomez del Campo National University of Mexico	J. L. C. Ford, Jr. G. R. Satchler	Heavy-ion reaction
M. B. Greenfield University of Tennessee	E. Newman M. J. Saltmarsh T. A. Welton	"A Study of the (^{3}He,n) Reaction at 25 MeV" (Ph.D. granted fall 1972)
J. P. Judish University of Tennessee	P. H. Stelson C. M. Jones	Superconducting rf cavities
G. E. McGuire University of Tennessee	T. A. Carlson	"Study of Complex Metals Salts by Photoelectron Spectroscopy" (Ph.D. granted June 1972)
Elizabeth C. Miller University of Tennessee	T. A. Welton	Ultrasonic waves in liquids (Ph.D. granted summer 1972)
Joyce A. Monard University of Tennessee	F. E. Obenshain R. L. Becker	"Mössbauer Studies of Electrostatic Hyperfine Interactions in ^{238}U, ^{236}U, and ^{234}U" (Ph.D. granted August 1972)
R. Peterson University of Tennessee	I. Sellin	Atomic physics
C. L. Rao University of Tennessee	G. R. Satchler T. A. Welton R. L. Becker	"Target Excitations and Higher Order Corrections to the Optical Potential for Protons" (Ph.D. granted fall 1972)
W. J. Roberts University of Tennessee	E. E. Gross E. Newman P. H. Stelson	"Test of Isospin Conservation by a Comparison of ^{3}H(^{3}He,^{4}He)^{2}H and ^{3}He(^{3}He,^{4}He)2p at 16.0 MeV c.m."
D. P. Spears University of Oklahoma	T. A. Carlson	"Study of Electron Shake-up in Photoelectron Spectroscopy of Gaseous Atoms and Molecules"
John Springer Vanderbilt University	H. W. Morgan	Infrared spectroscopy of molecular solids (Ph.D. granted 1972)
J. E. Tansil University of Tennessee	F. E. Obenshain R. L. Becker	"The Nickel-61 Mössbauer Effect in Nickel-Palladium Alloys" (Ph.D. granted August 1972)
W. Tuttle III University of Tennessee	P. H. Stelson	"Interference Effects from Coulomb and Nuclear Excitation"
G. Vernon University of Illinois	T. A. Carlson	"Application of Photoelectron Spectroscopy"

M.S. THESIS RESEARCH

Five students were advised or supervised by staff members of the Physics Division during 1972 while conducting thesis research leading to the Master of Science degree; four of these students were awarded the M.S. degree during the year. Students and staff members concerned are as follows:

M.S. candidate	Staff advisor	Field of research (thesis title listed if known)
J. P. Forester University of Tennessee	K. S. Toth	"The Decay of ^{148}Eu" (M.S. granted August 1972)
Lawrence Hess Fisk University	H. W. Morgan	Infrared spectroscopy of solid solutions (M.S. granted in 1972)

Z. T. L. Lukuba University of Tennessee	C. B. Fulmer	Accelerator production of radioisotopes useful in medical diagnostic work
D. U. O'Kain University of Tennessee	K. S. Toth	"Measurement of α-Decay Branching Ratios for Dysprosium and Terbium Isotopes" (M.S. granted August 1972)
R. A. Villecco University of Tennessee	F. E. Obenshain	"Mössbauer Investigation of Weyl's Theory of the Unified Field" (M.S. granted August 1972)

STUDENT GUESTS

Graduate

J. J. Bautista, Los Alamos Scientific Laboratory

R. P. Fogel, University of Virginia

Joachim Maruhn, University of Frankfurt

R. A. Villecco, University of Tennessee

Undergraduate

R. R. Bensch,[1] Oklahoma State University

Agnes L. Blake, Furman University

Kay W. Brown,[1] Clemson University

R. B. Dickinson,[1] University of California, Berkeley

L. W. Mlinarski,[1] University of Chicago

Christine E. Poe,[1] Emory University

H. Tang,[2] Kalamazoo College

Beverley A. Taylor,[1] East Tennessee State University

H. Teichman,[1] Upsala College

D. L. Vassy, Furman University

L. S. Weaver, Eastern Mennonite College

1. ORAU undergraduate research trainee.
2. Great Lakes College Association program.

COOPERATIVE EDUCATION PROGRAM FOR UNDERGRADUATE STUDENTS

Promising students in science and engineering (generally those who have completed at least two quarters of undergraduate study) are selected to participate in the Cooperative Education Program of Oak Ridge National Laboratory. Students alternate between equal periods of time spent in school attendance and in work at the Laboratory. During calendar year 1972, six co-op students were with the Physics Division; of these, four completed their assignments in the program, and two are continuing their work association with the Division. These students, the schools they attend, and the research programs of the Division with which they have been assigned are as listed:

W. K. Bell, University of Tennessee – Theoretical Physics Program (completed assignments in June 1972)

S. D. Blazier, University of Tennessee – Theoretical Physics Program (changed assignment in summer 1972 within Physics Division; formerly with Electron Microscopy Program)

J. L. Brown, University of Tennessee – Electron Microscopy Program (completed assignments in June 1972)

R. M. Feezel, Auburn University – Van de Graaff Program and Oak Ridge Electron Linear Accelerator (ORELA) Time-of-Flight Spectroscopy Program (completed assignments in June 1972)

P. B. Foster, Georgia Institute of Technology – Van de Graaff Program and Oak Ridge Electron Linear Accelerator (ORELA) Time-of-Flight Spectroscopy Program (began assignments in January 1972)

M. A. Stephens, Georgia Institute of Technology – Physics of Fission Program (completed assignments in September 1972)

GUEST ASSIGNEES – STUDENTS NOT ENGAGED IN THESIS RESEARCH AT ORNL

H. J. Hargis, on leave of absence from the Mathematics Division; presently graduate student at the University of Tennessee – High Energy Physics Program (continued indefinite assignment begun in October 1970)

Karen M. Smith, employee of the University of Tennessee – High Energy Physics Program (continued indefinite assignment begun in October 1969)

V. E. Vandergriff, employee of the University of Tennessee – High Energy Physics Program (continued indefinite assignment begun in December 1968)

CONSULTANTS UNDER SUBCONTRACT WITH UNION CARBIDE CORPORATION NUCLEAR DIVISION – ORNL

Faculty members of colleges and universities who served as consultants under subcontract to the Physics Division during the past year are listed below, along with the research program with which they were associated. Numerous other consultants (not under subcontract or not faculty members) have also been associated with the various physics programs of the Division, either as collaborators or as seminar speakers, during this report period.

Michel Baranger, Massachusetts Institute of Technology – Theoretical Physics Program

C. R. Bingham, University of Tennessee – Nuclear Physics Program

Gregory Breit, State University of New York, Buffalo – Nuclear Physics Program (contract closed in January 1972)

D. A. Bromley, Yale University – Nuclear Physics Program

W. M. Bugg, University of Tennessee – High Energy Physics Program

J. W. Burton, Carson-Newman College – Mössbauer Experimental Program

J. G. Castle, Jr., University of Alabama – Electronuclear Systems Development Program (contract closed in August 1972)

R. W. Childers, University of Tennessee – High Energy Physics Program

G. T. Condo, University of Tennessee – High Energy Physics Program

R. Y. Cusson, Duke University – Theoretical Physics Program and Physics of Fission Program (contract began in September 1972)

R. M. Drisko, University of Pittsburgh – Theoretical Physics Program

J. B. French, University of Rochester – Theoretical Physics Program (contract closed in February 1972)

J. H. Goldstein, Emory University – Atomic and Molecular Spectroscopy Program

L. B. Hubbard, Furman University – Theoretical Physics Program

P. G. Huray, University of Tennessee – Mössbauer Experimental Program (contract began in May 1972)

D. Kolb, Duke University – Physics of Fission Program (contract closed in May 1972)

S. J. Kreiger, University of Illinois, Chicago Circle – Theoretical Physics Program

J. C. Love, Clarkson College of Technology – Mössbauer Experimental Program (contract closed in August 1972)

F. B. Malik, Indiana University – Electron Spectroscopy Program (contract closed in August 1972)

R. J. McCarthy, Carnegie-Mellon University – Theoretical Physics Program

G. H. Nussbaum, University of Tennessee – Van de Graaff Program (contract closed in August 1972)

S. C. Pancholi, University of Delhi, India – Nuclear Data Project (contract closed in December 1972)

P. Z. Peebles, University of Tennessee – Van de Graaff Program

D. J. Pegg, University of Tennessee – Van de Graaff Program (contract began in January 1972)

L. L. Riedinger, University of Tennessee – Van de Graaff Program (contract began in May 1972)

J. T. Sanderson, NSF, Washington (formerly with Harvard University) – Physics of Fission Program (contract closed in December 1972)

R. O. Sayer, Furman University – Van de Graaff Program (contract began in April 1972)

I. A. Sellin, University of Tennessee – Van de Graaff Program

K. K. Seth, Northwestern University – Nuclear Data Project (contract closed in April 1972)

J. O. Thomson, University of Tennessee – Mössbauer Experimental Program

S. T. Thornton, University of Virginia – Van de Graaff Program (contract began in July 1972)

Hendrik Verheul, Free University, Amsterdam, Netherlands – Nuclear Data Project

Lawrence Wilets, University of Washington – Physics of Fission Program

I. R. Williams, Knoxville College (now with Technical Applications Group of Leeds Register of Shipping, London, England) (contract closed in May 1972)

CONSULTANTS UNDER CONTRACT ARRANGEMENT WITH OAK RIDGE ASSOCIATED UNIVERSITIES

Under arrangements with Oak Ridge Associated Universities ("S" contracts and "U" contracts), 62 university or college faculty members visited the Physics Division for consultation and collaboration during the past year. These individuals and the educational institutions with which they were affiliated at the time of their 1972 visits are as follows:

D. A. Atkinson, Tennessee Technological University

F. T. Avignone, University of South Carolina

W. H. Brantley, Furman University

M. D. Brown, Kansas State University

R. F. Carlton, Middle Tennessee State University

H. K. Carter, Furman University

W. E. Collins, Jr., Vanderbilt University

R. Y. Cusson, Duke University

R. H. Davis, Florida State University

B. L. Donnally, Lake Forest College

F. E. Durham, Tulane University

R. W. Fink, Georgia Institute of Technology

H. J. Fischbeck, University of Oklahoma

J. D. Fox, Florida State University

R. M. Gaedke, Trinity University

L. A. Galloway III, Centenary College of Louisiana

M. B. Greenfield, Florida State University

J. C. Haefele, Washington University

J. H. Hamilton, Vanderbilt University

K. J. Hofstetter, University of Kentucky

R. F. Holub, Florida State University

D. L. Humphrey, Western Kentucky University

M. A. Ijaz, Virginia Polytechnic Institute and State University

J. A. Jacobs, Virginia Polytechnic Institute and State University

R. W. Jones, University of South Dakota

K. W. Kemper, Florida State University

B. D. Kern, University of Kentucky

Y. E. Kim, Purdue University

K. Kumar, Vanderbilt University

Juergen Lange, Vanderbilt University

Jung Lin, Tennessee Technological University

J. C. Love, Clarkson College

D. A. McClure, Georgia Institute of Technology

D. L. McShan, Florida State University

R. J. de Meijer, Florida State University

M. G. Menendez, University of Georgia

U. B. Mosel, University of Washington

B. M. Preedom, University of South Carolina

B. P. Pullen, Southeastern Louisiana University

A. E. Quinton, University of Massachusetts

N. F. Ramsey, Harvard University

A. V. Ramayya, Vanderbilt University

P. J. Riley, University of Texas

E. L. Robinson, University of Alabama

P. G. Roos, University of Maryland

R. O. Sayer, Furman University

W. D. Schmidt-Ott, Georgia Institute of Technology

H. L. Scott, University of Georgia

Enrique Silberman, Fisk University

W. W. Smith, University of Connecticut

E. H. Spejewski, Oberlin College

F. L. Talbott, Allentown College

S. T. Thornton, University of Virginia

L. S. Varnell, Yale University

George Vourvopoulos, Florida A & M University

R. F. Walker, Centenary College

T. A. Walkiewicz, Edinboro State College

J. C. Wells, Jr., Tennessee Technological University

M. L. Whiten, Armstrong State College

B. H. Wildenthal, Michigan State University

R. H. Winters, Denison University

E. F. Zganjar, Louisiana State University

ANNUAL INFORMATION MEETING OF THE PHYSICS DIVISION

Advisory committees are attached to the majority of the research divisions of the Laboratory for the purpose of reviewing and offering advice on the cogency and effectiveness of the varied scientific programs.

The Annual Information Meeting of the Physics Division was held at ORNL on May 31 and June 1, 1972.

Members of the 1972 Advisory Committee were:

Professor J. S. Blair, University of Washington

Professor D. A. Bromley, Yale University

Professor Roy Middleton, University of Pennsylvania

Dr. Joseph Weneser, Brookhaven National Laboratory

RADIATION CONTROL AND SAFETY IN THE PHYSICS DIVISION

The Radiation Control and Safety Officers for the Physics Division report that there was one "unusual occurrence" in the Division for the year. This involved an unplanned exposure to x rays during the testing of high-voltage capacitors. The larger of the two doses involved was about one-third of the maximum permissible quarterly limit.

The Oak Ridge Electron Linear Accelerator, a joint Physics Division–Neutron Physics Division facility, has now completed its fourth year of operation and has had no "unusual occurrences" or direct radiation exposures above normal levels.

UNISOR PROGRAM

The UNISOR facility (University Isotope Separator at Oak Ridge) was formally dedicated in ceremonies held at Oak Ridge National Laboratory on June 19, 1972. Attending were administrators and scientists from all of the sponsoring and participating institutions: Georgia Institute of Technology, Louisiana State University, Oak Ridge Associated Universities, University of Kentucky, University of Massachusetts, University of South Carolina, University of Tennessee, Vanderbilt University, Virginia Polytechnic Institute and State University, Emory University, Furman University, and Tennessee Technological University. In addition to these and to ORNL administrators and staff, representatives from a number of other universities and government laboratories were in attendance.

Speakers for the dedication were Joseph H. Hamilton of Vanderbilt University, the Chairman of the UNISOR Executive Committee; Alvin M. Weinberg, Director of ORNL; H. Willard Davis of the University of South Carolina, the President of ORAU; Alexander R. vanDyken, Assistant Director for Chemistry Programs of the AEC; and P. Gregers Hansen, Director of the ISOLDE Project, CERN. William G. Pollard, Executive Director of ORAU, presided. The formal ceremonies were followed by a very informal ribbon-cutting ceremony and tour of the UNISOR facility at the ORIC building.

The UNISOR Executive Committee met on April 28, June 20, and August 22 at the ORIC building for business sessions. The Scientific Programs Committee met on July 11 to consider proposals and recommendations for the experimental program. This was followed by a meeting of the Technical Committee on July 12 to discuss experimental equipment needs based on the recommendations of the Scientific Programs Committee.

A general Users Group meeting was held on June 20 in the ORIC conference room. The UNISOR staff described the facility and the equipment which were under construction, and discussed the developmental program which was to begin once construction was completed. F. T. Avignone presented the report of the Scientific Programs Committee, recommending general directions for the experimental program.

PARTICIPATION IN VARIED INSTITUTES AND SYMPOSIA

Fisk University Twenty-third Annual Infrared Institute, Nashville, Tennessee. H. W. Morgan and P. A. Staats (Atomic and Molecular Spectroscopy Program) served as visiting lecturers at the Fisk University Twenty-third Annual Infrared Institute, held on the Fisk University campus in Nashville, August 14–18 and August 21–25, 1972.

Included in the institute were seminars on basic infrared spectroscopy, gas chromatography, and interpretation of infrared and Raman spectroscopy. P. A. Staats directed laboratory sessions designed to train participants in the construction and renovation of liquid and gas absorption cells, the preparation of solid and liquid samples, qualitative and quantitative analyses, the calibration and operation of standard infrared spectrometers, and the use of newer infrared techniques and accessories for difficult samples. In addition to serving as a faculty member, H. W. Morgan was associated with the planning of the institute and the organization of the lecture program as well as assisting in the laboratory program.

The ORNL participants presented a total of eight lectures on the topics listed below:

H. W. Morgan — "Instrumentation II" (optimum conditions for instrument operation), "Laser Raman Spectroscopy," "Liquid Phase Sampling," and "Future Developments in Infrared and Raman Spectroscopy."

P. A. Staats — "Experimental Infrared Spectroscopy" (four lectures).

ORIENTATION MEETING AT THE ORNL NUCLEAR DATA PROJECT FOR NSF-SPONSORED NUCLEAR INFORMATION RESEARCH ASSOCIATES (NIRA)

All Nuclear Information Research Associates (11) and their sponsors were invited to an Orientation Meeting at ORNL during the week of October 2–7, 1972. The first day was devoted to formal presentations regarding various aspects of the NIRA Program and the philosophy and methods employed by the Nuclear Data Project. The latter were presented by D. Horen, S. Raman, and M. Martin. During the remaining days, informal discussions were held which attempted to give those NIRA's with predominantly nuclear reaction study background an exposure to radioactive decay processes, and vice versa.

In addition to ORNL staff members in attendance at the Orientation Meeting, the following guests were present.

F. Ajzenberg-Selove, University of Pennsylvania

F. M. Bernthal, Michigan State University

H. Feshbach, Massachusetts Institute of Technology

J. Joy, National Science Foundation

Wm. C. McHarris, Michigan State University

J. Nunn, National Academy of Sciences

Sponsors

C. P. Browne, University of Notre Dame

E. G. Fuller, National Bureau of Standards

W. H. Kelly, Michigan State University

J. J. Kraushaar, University of Colorado

M. T. McEllistrem, University of Kentucky

R. A. Meyer, Lawrence Livermore Laboratory

R. Segel, Northwestern University

W. L. Talbert, Jr., Iowa State University

NIRA's

R. L. Bunting University of Colorado

T. W. Burrows, University of Kentucky

G. H. Carlson, Iowa State University

L. R. Greenwood, Northwestern University

E. A. Henry, Lawrence Livermore Laboratory

H. R. Hiddleston, University of Notre Dame

J. F. Lemming, Ohio University

L. Samuelson, Michigan State University

J. R. Shepard, University of California, Davis

R. M. Strang, University of California, Los Angeles

H. Van der Molen, National Bureau of Standards

ORNL HEAVY-ION SUMMER STUDY

Since the use of heavy-ion beams in scientific research is rapidly increasing, ORNL management believed it would be valuable to hold a summer study to review the many recent results in this field and to appraise future possibilities for heavy-ion research. The form, content, and speakers for the summer study were developed through discussions of ORNL staff members of the Physics, Chemistry, and Solid State Divisions. The study lasted three weeks. The first two weeks emphasized heavy-ion nuclear physics and chemistry. The third week was concerned with atomic, solid-state, and biological physics. Scheduled sessions were held each morning with usually two invited speakers. The pace of the summer study was slow enough to allow appreciable time for discussions, both during the sessions and during the afternoons.

Initially the format was planned to be much like the Gordon Conferences, and so the speakers were told that they did not have to bring a prepared text. This format promotes open, frank, and timely talks, but it has the drawback that there is no written record with which to refresh the memory. We therefore decided to tape the talks and discussions and to type the entire summer study in the belief that the proceedings [USAEC CONF-720669, 638 pp. (1973)] would be useful to the participants and in the hope that they would also be of interest to others.

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