PHYSICS

Director's R&D Fund

Detector Development for Fundamental Neutron Physics at the Spallation Neutron Source

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Low-energy, cold neutrons have been employed in a wide variety of investigations that shed light on important questions in particle and nuclear physics. Among the most important experiments in this field are those related to the precise measurement of the parameters that describe the beta decay of the free neutron. This includes the determination of the correlations between the decay particle momenta and between the decay particle momenta and the neutron spin. The purpose of this project is the development of a detector that can be used to provide a highly accurate determination of these decay correlation coefficients. Such measurements would provide a detailed test of the standard model and new information that could address a current discrepancy among data from nuclear beta decay and high-energy physics experiments. The work supported here concerns the development of the silicon detectors, front-end electronics, and electromagnetic fields that comprise the neutron decay detector.

The challenge in the measurement of the neutron beta decay correlations lies in the development of a detector that can measure the complete kinematics of the decay products that result from the decay of a polarized neutron. This includes the determination of the direction of emission of the decay proton and electron and their energies. We are pursuing a novel approach that will allow the measurement of the electron and proton in the same detector as well as provide accurate timing of delay between the detection of each particle. The detector will consist of segmented silicon surface barrier detectors, high-speed digital signal processing front-end electronics, and a combination of electric and magnetic fields that carefully define the particle trajectories. We have made substantial progress in the development of each of these components.

Silicon Detectors. The silicon detectors must satisfy the following three criteria: (1) a sensitivity of <30keV, (2) an energy resolution of ≤10keV up to ~1MeV, and (3) a capability of few-nanosecond timing. We tested a series of thick (~2-mm) silicon surface barrier detectors and demonstrated charged-particle detection with sensitivities and timing resolution that satisfy conditions (2) and (3). In a separate experiment, we demonstrated that the thin (~200-μm) silicon detectors with very thin entrance windows provide energy sensitivity as required for condition (1). This work demonstrates that a thick detector with a thin window should be able to meet all the criteria. We have identified manufacturers who are able to provide such detectors.

Digital Signal Processing Electronics. In a series of tests with radioactive sources, we demonstrated an ability to reach noise-limited timing resolution with a 40-MHz digital signal processor based data acquisition system. While the performance of such a 40-MHz system is somewhat marginal for our needs, this work has given us confidence that a 100-MHz system will be well suited. As a result we have begun the development of such a system in collaboration with a commercial vendor. A prototype board has been designed, and fabrication is under way. This system has the feature that it is fully scaleable to the approximately 200 channels required for a final experiment with a segmented detector.

Electric and Magnetic Field Design. Using a number of simulation techniques including the particle trajectory calculation programs Simian© and Giant as well as custom analytical software, we have developed a system of electric and magnetic fields that define the decay particle trajectories and provide suitable particle timing. The system developed is unique in its ability to utilize the proton time of flight to provide complete kinematic information of the decay particle. It was further demonstrated that the field geometry is sufficiently homogeneous to provide immunity from all identified systematic effects.

The measurements and simulations have provided an initial design for a neutron decay correlation coefficient detector that satisfies the technical requirements of the next generation of experiments anticipated at the Spallation Neutron Source. Because the design is based on a straightforward extension of existing commercial technologies, there should be no fundamental problems in its realization.

Three-Dimensional Neutron Structural Microscopy: Design and Demonstration

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We have designed and tested achromatic neutron-beam focusing mirrors and spatially resolved neutron Laue-diffraction techniques as steps toward enabling nondestructive, spatially resolved, three-dimensional (3D), structural microscopy investigations of coarse-grained polycrystalline materials. Kirkpatrick-Baez neutron super-mirrors tested at the pulsed-neutron LANSCE facility showed that ~1×3 mm^2 neutron beams could be focused to ~0.1×0.2 mm^2 diameters, a flux gain of ~75 assuming a reflectivity of 0.7 for each mirror. Depth-resolved, unfocused-white-beam Laue diffraction measurements performed at the IPNS facility using assembled polycrystals demonstrated that our traveling-aperture technique provides both the crystal structure and the lattice orientation with <1 mm spatial resolution. Similar measurements on cylindrically indented copper showed that plastic deformation induced lattice rotations could be spatially resolved in 3D. Arrangements have been made to demonstrate focused, 3D, depth-resolved neutron microscopy at the Chalk River steady-state reactor.

Although advanced materials processing relies almost entirely on controlling microstructural features such as grain boundaries, nondestructive 3D probes of the local lattice structure, strain and orientation are not currently available. This project aims at developing 3D neutron structural microscopy with submillimeter resolution. Our approach employs high-resolution neutron beam focusing and depth-resolved Laue diffraction measurements. The scientific motivation is the investigation of the local 3D inter- and intra-grain interactions using both spallation and reactor white-beam sources. Three-dimensional studies are needed to link materials theory and computer modeling with experimental microstructures.

Our analysis of non-dispersive (achromatic) Kirkpatrick-Baez (KB) neutron optics showed that mirror focusing will provide increased neutron intensity with smaller beam diameter than simple apertures for beams focused to 0.5 mm or less. Guided by the modeling, components of a neutron KB mirror pair were designed and assembled into a working independent unit, as shown in Fig. 1. Each mirror consists of a SiO_2 substrate with M3 multilayer coatings, and mechanical bending generates an elliptical reflecting surface. Laser testing of the focus was completed, and the first neutron test of the KB mirror was carried out at the Los Alamos Neutron Science Center (LANSCE) pulsed neutron source. The mirror assembly successfully focused a monochromatic 1- $\times$ 3-mm^2 beam to half-intensity widths of ~0.1×0.2 mm^2, demonstrating a flux gain of ~75 assuming a reflectivity of 0.7 for each mirror, consistent with the original objectives.

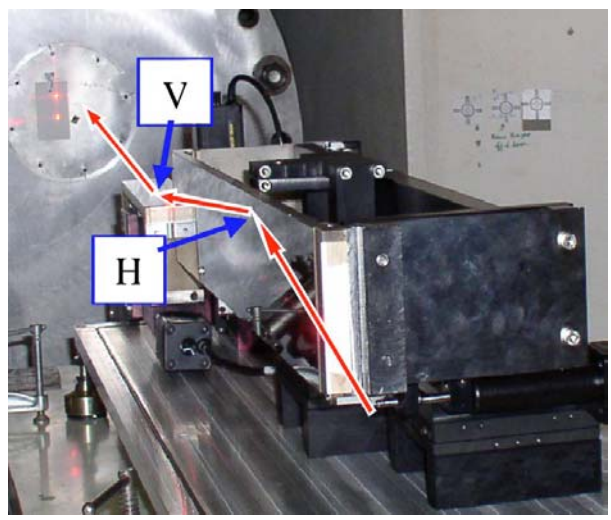

Fig. 1 Neutron-optics apparatus used to experimentally evaluate KB mirror focusing performance at LANSCE. H and V indicate the horizontally and vertically focusing mirrors. The red arrows show the neutron path as the beam reflects first from the H mirror and then the V mirror.

Depth-profiling of neutron Laue diffraction and data analysis techniques were adapted from our recently developed synchrotron X-ray profiling procedures[1] and were tested in two experiments carried out using the Single Crystal Diffraction (SCD) beamline at the relatively low-intensity Intense Pulsed Neutron Source (IPNS) at Argonne. The first experiment demonstrated the ability of 3D Laue diffraction microscopy to spatially resolve

lattice symmetry, chemical structure, and crystal orientation as a function of depth along an incident unfocused 1-mm-diameter neutron beam. As shown schematically at the bottom of Fig. 2, a series of copper or niobium single-crystal plates of 0.5-, 1.0-, or 2-mm thickness were stacked perpendicular to the neutron beam direction. Analysis of Laue images from this "synthetic polycrystal" revealed the depth-resolved crystal orientations and the niobium-versus-copper structure of individual plates with 1-mm spatial resolution. A second neutron microscopy experiment was performed on the same beam line to demonstrate the ability of the technique to determine lattice rotations in a large copper crystal that was cylindrically indented to a depth of 0.5 mm using a 5-mm-diameter steel rod. Measurements made as a function of depth along a direction perpendicular to the indent axis and as a function of distance below the indent yielded a spatially resolved map of the local lattice rotations (range ~0–5°) inside the deformed sample, successfully demonstrating our ability to nondestructively map 3D microstructures.

Combining the developments described above, the final test of the neutron microscopy concept is planned for early 2004 at the Neutron Reactor Universal (NRU)—a steady-state neutron source at Chalk River Laboratories. A white beam will be deflected from the main beam by a mirror contained within the monochromator drum of the L2 diffractometer. This beam will be focused by our KB mirror to a submillimeter diameter, and the scattering gauge-volume will be scanned through large-grained polycrystalline specimens. A high-resolution image-plate area detector will record the Laue patterns. Important objectives in these experiments will be (1) evaluation of the resolution achievable in lattice strain measurements and (2) a relative comparison of steady-state versus pulsed-neutron (time-of-flight) microscopy techniques.

In summary, ray-trace modeling has shown show the capabilities of KB mirrors for focusing to submillimeter dimensions. A neutron-optics apparatus was constructed and tested, achieving focusing to a beam width of 0.1–0.2 mm. Depth-resolved Laue diffraction experiments at the IPNS demonstrated the ability to nondestructively map microstructures inside bulk specimens. We believe that combining neutron-beam focusing, depth-profiling, and high-resolution area detectors will enable important new 3D micro- and macro-neutron materials investigation capabilities. The advent of more powerful neutron sources such as the SNS will be ideally suited to exploit these capabilities. In engineering technology, the determination of the stress state within large-grained materials will become possible for the first time. Individual grain morphologies and microstructures could be monitored during thermal or deformation processing. In biology, the application of focused beams to macromolecular crystallography has the potential to significantly reduce the size of the required specimens. The construction of high-pressure cells for smaller samples in a focused beam could also be greatly simplified. These examples represent but a few areas where focusing optics and 3D structural microscopy can have a major impact on neutron science and materials investigations.

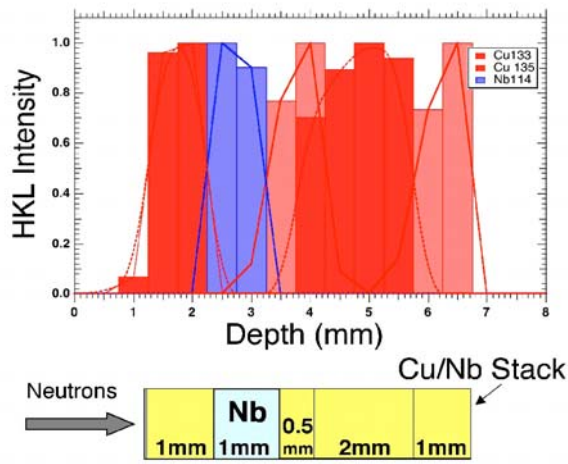

Fig. 2 Experimental demonstration of depth-resolved and BCC/FCC lattice-structure-resolved neutron microscopy from a stack of copper (FCC) and niobium (BCC) single-crystals simulating a two-phase polycrystalline material.

Reference

[1]B.C. Larson, W. Yang, G. E. Ice, J. D. Budai, and J. Z. Tischler, "Three-Dimensional X-Ray Structural Microscopy with Submicrometre Resolution," *Nature* **415**, 887 (2002).

Neutron-Rich Radioactive Ion Beam Production with High-Power Electron Beams

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We are investigating the production of neutron-rich radioactive ion beams (RIBs) using high-power electron beams. This concept has never been employed at an operational facility, but numerical investigations and preliminary experiments indicate that there is potential for very high intensities of particularly interesting RIB species at a cost much lower than that of a comparable-performance conventional facility. We propose to measure RIB yields of key species, in a well-understood environment such that relative production rates and approximate absolute rates can be deduced out to very neutron-rich species. These measurements will provide a first quantitative experimental evaluation of electron-beam RIB production.

Introduction

Much of the scientific focus in nuclear physics for the next decade will be on the use of neutron-rich radioactive ion beams (RIB) to explore novel nuclear structure effects associated with weak nucleon binding, to address important questions in nuclear astrophysics, and to provide the opportunity for certain critical cross section measurements of importance to the nuclear safeguards and stockpile stewardship community. ORNL is the site of the Holifield Radioactive Ion Beam Facility (HRIBF), which will provide the nucleus on which a RIB physics research community will be developed and nurtured in anticipation of a next-generation U.S. facility. The science that has been done over the last several years at HRIBF is remarkable. However the HRIBF in its current form cannot meet the level of performance that will be required of it over the next decade. We have developed a phased approach to upgrading our facility that fits well with our understanding of possible funding profiles that are acceptable to the DOE Office of Nuclear Physics (DOE-NP). As part of this phased approach, we have identified an entirely new direction[1] for RIB production using a high-power electron beam which could improve the capabilities of the HRIBF by two orders of magnitude in critical areas, at modest cost.

To assess the potential of this concept, we propose to use a high-power beam of electrons from the Oak Ridge Electron Linear Accelerator (ORELA) to induce photo-fission in a uranium foil target array. Fission products emitted from the uranium foils will be stopped in high-pressure helium gas and captured by NaCl aerosol particles in the gas. The flow of aerosol-laden helium will transport the fission products over a distance ~12–15 m to a skimmer system, where the aerosols will be separated from the helium and injected into an appropriate ion source for subsequent acceleration and mass analysis. Transit times below 1 second are expected, with essentially no chemical-species dependence. Consequently we will be able to make systematic yield measurements of a variety of elements over a wide isotope range extending to very neutron-rich nuclei. This program can be accomplished at very modest cost because of the availability of ORELA, and a diligent canvassing of the North American nuclear physics community for surplus hardware that can be used to assemble our experimental system.

A target suitable for high-power (at least 10 kW) irradiations at ORELA has been designed, fabricated, and pressure tested to 15 atmospheres. The multifoil target contains 20 uranium foils inside of a water-cooled housing made from high-purity copper with input and outlet connections for the transport of salt-loaded helium gas. The transport of fission products from this target has been checked with a ^{252}Cf source and flowing helium at 10 atmospheres. Preliminary analysis indicates that the transport efficiency is around 40% along a 30-m, 0.75-mm-diameter stainless tube.

Substantial effort was devoted to adapting the HRIBF electron beam plasma ion source to function as an ion source/skimmer. We have demonstrated that we cannot achieve the necessary He throughput with this source and decided instead to adapt an existing Bernas-Nier source which was developed at Chalk River Nuclear Laboratories (CRNL) as a He-jet source. A completed source is available for testing as of September 30, 2003.

Design of the system to contain the production target, and insert it into the ORELA target room, has been completed. The device will be inserted in one of the neutron beam flight tubes (Flight Tube # 9) and will

intersect the electron beam between the vacuum window and the neutron target. The design includes vertical and horizontal position adjustment over a large range. The target can be retracted out of the electron beam line during normal ORELA operation. A significant effort has been placed into considerations of remote handling of the target after the experiments are finished. The design is complete and is undergoing final checking in preparation for fabrication. Fabrication of the insertion device will be completed in the second quarter of FY 2004.

All equipment necessary for the completed experimental setup has now been procured or identified. A major savings was achieved by locating a complete helium recirculation system at Los Alamos Nuclear Laboratories (LANL). Arrangements to transfer it to ORNL took far longer than expected and resulted in a substantial delay in the project. Testing and commissioning of the helium recirculation system was well under way by the end of FY 2003. We will begin assembly of the complete experiment system in the first quarter of FY 2004. The setup will be fully operation in the third quarter of 2004. We plan to begin measurements no later than the end of the third quarter and complete them by the end of fiscal year. A postdoctoral fellow has been identified to participate in this work. We have been able to carry out this project in a very cost-effective manner because we have been able to identify and obtain specialized equipment ideally suited to our needs from other laboratories, at essentially zero cost in dollars, but a finite cost in time delay.

The first phase of the HRIBF upgrade plan has just been funded by DOE-NP at a level of $4.7M for FY 2004–2005. This initial project does not involve a production accelerator upgrade and hence is not directly coupled to this LDRD project; however, the existence of this R&D program on an innovative direction for RIB production which might eventually be implemented at a later stage was viewed favorably by both program office staff and project reviewers. If this project is successful, we will have a strong case for adding a modest electron accelerator to the upgraded HRIBF complex. The total additional cost of the electron-accelerator addition to the upgrade program would be about $10M. The total upgrade package for the HRIBF, including the electron accelerator, should approach $20M. We have already been awarded the first-phase funding. A second-phase funded at about $5M has a high probability. The direction we go with the third phase of the upgrade, and the probability for funding, depends on the outcome of this work. The project may also provide results of value to nuclear safeguards and stockpile stewardship programs of DOE and Homeland Security.

Reference

[1]W. D. Diamond, "A Radioactive ion beam facility using photofission," *Nucl. Instrum. and Methods Phys. Res.* **A432**, 471 (1999).

Probing Explosive Nucleosynthesis Through Measurements at the Holifield Radioactive Ion Beam Facility

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Unstable nuclei play an influential role in many astrophysical processes occurring in exploding stars such as novae, supernovae, and X-ray bursts. To understand these events, we must understand the reactions involving unstable, radioactive nuclei. The best way to probe such reactions is by using beams like those available at the Holifield Radioactive Ion Beam Facility (HRIBF). We are performing studies of proton-induced reactions on radioactive fluorine and phosphorus nuclei and neutron-induced reactions on radioactive neutron-rich nuclei. The large detector arrays and the ion beams at the HRIBF are being used to carry out these measurements.

The understanding of the reactions on and structure of unstable nuclei is critical to understanding cataclysmic stellar explosions such as novae, supernovae, and X-ray bursts. The goal of this project is to measure the properties of and reaction rates on several important radioactive nuclei. The information gained will help address issues such as the gamma-ray emission from novae, which is important to understanding results from new space-based telescopes, and of the composition of meteorites, which sample the universe outside the solar system.

In particular, we will study the rate of the $^{18}F + p \rightarrow {}^{15}O + \alpha$ reaction by measuring the rate directly at a variety of energies and by studying the elastic scattering of $^{18}F + p$. We will also study the proton-capture rates of ^{29}P and ^{30}P. These reactions form compound nuclei ^{30}S and ^{31}S, respectively, which we will study via the $^{32}S + p \rightarrow t + {}^{30}S$ and $^{32}S + p \rightarrow d + {}^{31}S$ reactions at the HRIBF. Finally, the transfer of neutrons to heavy neutron-rich radioactive beams will also be studied. This is important because in supernovae, neutron-rich nuclei are processed to even heavier nuclei by a series of neutron captures and beta decays called the r-process. To understand this processing, we must understand the neutron-captures rates on these nuclei, and we will study these rates via measurements of neutron-transfer reactions on radioactive beams at the HRIBF.

Several requirements of the measurements make them difficult, if not impossible, to be studied at other facilities besides the HRIBF. Only at the HRIBF is a ^{18}F beam available with sufficient quality to perform the high-precision measurements necessary for astrophysics. The $^{32}S + p$ studies require high-energy proton beams coupled with large-area silicon-detector arrays. Such a combination is only available in the United States at the HRIBF. The neutron-transfer studies on r-process nuclei are only possible at the HRIBF. These studies require beams of neutron-rich nuclei accelerated to energies high enough to overcome the electrostatic repulsion of the positively charged nuclei. Such beams are only available at the HRIBF.

Much progress has been made on the preparation and implementation of these studies. The elastic-scattering rate of $^{18}F + p$ has been measured over a large energy range. Properties of important states in the compound nucleus ^{19}Ne have been deduced, and the results presented at scientific meetings. To study the $^{32}S + p$ reactions, special target materials are required. Elemental sulfur is unstable under vacuum conditions, and thus targets made from sulfide compounds are required. Other requirements of the targets resulted in the only suitable compounds being ZnS and FeS, of which commercially made targets are not available. Special production techniques were developed locally and suitable targets have now been produced. Finally, the neutron-transfer reaction $^{82}Ge + d \rightarrow p + {}^{83}Ge$ has been measured at the HRIBF. This is the first neutron-transfer measurement ever made on an r-process nucleus. The techniques developed highlight a roadmap to further studies at future facilities such as the Rare Isotope Accelerator (RIA), a proposed facility endorsed by the Nuclear Science Advisory Committee at the highest priority for future construction.

The DOE Office of Nuclear Physics supports research in low-energy nuclear physics with a new component involving reactions of astrophysical interest. This component is growing due to the recent availability of radioactive ion beams. This project is central to DOE's desire to continue growth in that area and to develop techniques applicable for use at future facilities such as RIA. This project also advances goals of the National Science Foundation (NSF), which supports nuclear measurements of astrophysical interest.