LANSCE Focus

PARTICLES IN MOTION

Nuclear science observations and opportunities at the Los Alamos Neutron Science Center

Los Alamos
NATIONAL LABORATORY
EST. 1943

Nuclear science and technology research at the Los Alamos Neutron Science Center

Colleagues,

This special *Focus* issue highlights a set of nuclear physics capabilities at the Los Alamos Neutron Science Center (LANSCE) serving Los Alamos National Laboratory's national security mission and the global scientific user community.

With a total of 10 flight paths, LANSCE provides the opportunity to perform experiments with low- to high-energy neutron sources and high-energy proton irradiations. As a designated Department of Energy national user facility, LANSCE hosts a considerable number of internal and external users, including large international collaborative research teams.

The result is research critical to meeting the nation's nuclear deterrence, global security, and energy security needs as well as aiding fundamental scientific understanding. This is another excellent example of LANSCE's dual role in serving national security needs and the overall scientific community.

The Weapons Neutron Research facility (WNR) nuclear science research program, which is described in this issue, clearly articulates the vital role WNR plays in delivering competitive science and operating an internationally recognized user program. On average, WNR receives more than 60 nonproprietary and 16 proprietary proposals for beam time, demonstrating the demand, interest, and value provided by WNR to the nuclear physics community.

LANSCE's pioneering work and capabilities related to irradiation of chips and electronics continues to attract a great deal of interest from industries around the world. This high-energy neutron irradiation capability is unique in the United States and also serves the international semiconductor and avionics industries, which come to LANSCE for the beam's unparalleled accuracy for electronics testing. Thanks to a recent infrastructure investment by the Los Alamos National Security Board of Governors, a new experimental area at WNR enables experiments of great relevance to the Laboratory's mission and doubles the capacity for industrial users.

The educational component of the nuclear particle physics capabilities at LANSCE is of great importance to the nation. In tandem with United States universities, LANSCE's nuclear particle physics expertise plays a pivotal role in educating the next generation of highly trained experimental nuclear physicists. LANSCE offers hands-on experience with unique tools and equipment and exposure to a highly motivated and talented Laboratory team as well as international collaborators.

I hope you enjoy reading about and appreciate the leadership in basic and applied nuclear particle physics WNR enables at Los Alamos.

LANSCE Deputy Division Leader Alex H. Lacerda

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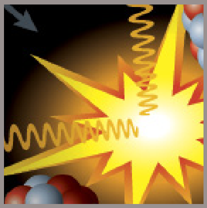

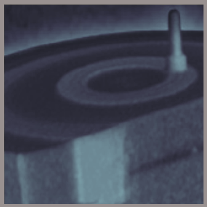

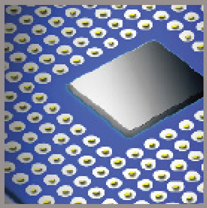

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Cover: A conceptual representation of nuclear scattering upon interaction with a particle beam.

The evolution of nuclear science at Los Alamos

From pions to protons and neutrons

Nuclear science—from fundamental understanding of nuclear structure and reactions to applications of radioactivity for medical and industrial applications—is intimately connected with Los Alamos National Laboratory's mission to solve national security challenges through scientific excellence.

Research using pions at the Los Alamos Meson Physics Facility (LAMPF) in the 1970s to probe the fundamental strong interactions in nuclei has transitioned to studies today using protons and neutrons generated at the Los Alamos Neutron Science Center (LANSCE). The result is a robust program encompassing fundamental nuclear science, defense program applications, and civilian research.

The need to refine nuclear reaction measurements for the purpose of maintaining the nation's nuclear weapons stockpile was one of the primary motivations for creating the Weapons Neutron Research facility (WNR). With Congress supporting the addition of a facility for defense science, WNR opened at LAMPF in 1977.

With time, research at Target-1, the existing neutron production target, transitioned to neutron scattering for materials science studies—and the Lujan Neutron Scattering Center was created. Target-2, known as the Blue Room, and Target-4, the high-energy neutron source, were constructed and began operation in 1986.

Through the use of innovative techniques and instruments, WNR scientists continue expanding the range of measurements available for a variety of applications important to program sponsors, Laboratory researchers, and visiting scientists.

Using the high flux of neutrons provided by the LANSCE proton beam and the unique instrument suite at WNR, Los Alamos researchers perform nuclear reaction studies vital to the Laboratory's nuclear deterrence, global security, and energy security missions. All these Laboratory missions benefit from more accurate neutron cross-section and other data from LANSCE. The studies at WNR also contribute to the Laboratory's leadership role in basic nuclear and particle physics.

The nuclear science program at LANSCE aims to address the Laboratory's defense program mission and perform applied civilian and basic nuclear science research. To accomplish these goals, the program operates three nuclear science research facilities:

- **Weapons Neutron Research Target-4**, with six flight paths for high-energy neutron research;
- **The Lujan Neutron Scattering Center**, with three flights devoted to low-energy neutron science research; and
- **Weapons Neutron Research Target-2** for proton irradiations.

The Lujan Center and WNR Target-4 use LANSCE's 800-MeV proton linear accelerator to produce neutrons either directly or with higher intensity using the proton storage ring. Neutrons are produced at both experimental areas using spallation reactions on tungsten targets. Target-4 is not moderated, and produces neutron beams with energies from approximately 0.2-600 MeV. At the Lujan Center the neutrons are fully moderated, producing neutrons from sub-thermal to several 100 keV. Together, these two neutron sources cover the research needs for most applications. Target-2 is a unique and versatile area for proton irradiations, such as materials testing, and is the driver for the Laboratory's Lead Slowing Down Spectrometer (See LSDS, page 14), an instrument providing an extremely effective high neutron flux.

The nuclear science research program is operated as a user facility, with approval from the Department of Energy. As such, proposals are solicited annually, reviewed, and, based on scientific merit, scheduled for beam time. In 2013, the nuclear science program had more than 550 total user visits by more than 250 researchers from across the United States and around the world. Close collaborations with Lawrence Livermore National Laboratory, CEA Bruyères-le-Châtel, France, universities, and other laboratories and industry are crucial to research at LANSCE.

This issue of *LANSCE Focus* features examples of topical areas emphasizing the depth and breadth of the LANSCE nuclear science research program. These areas include fission, neutron radiography, unstable nuclei and nuclear astrophysics, radiation effects in semiconductor devices and materials, and nuclear reactions.

Nuclear science contributions to weapons physics

Science Campaigns have been supporting a thrust in nuclear cross section measurements related to fission, as well as neutron capture. In collaboration with Lawrence Livermore National Laboratory, and also with the CEA through an NNSA-CEA fundamental science collaborative agreement, scientists at the Los Alamos Neutron Science Center (LANSCE) have embarked on a program to measure plutonium and uranium cross sections to unprecedented accuracy. We need these high-fidelity data as input to our Evaluated Nuclear Data File (ENDF) cross sections for increased accuracy in neutronics simulations of criticality and interpretation of nuclear test diagnostics.

The experiments are very challenging. LANSCE researchers have devised innovative new experimental methods to reduce the uncertainties as compared with historic measurements. For the fission cross section, the teams have designed and built a time projection chamber based on methods and expertise developed in the particle physics community. The prompt fission neutron spectrum is being measured in the Chi-Nu experiment, which is being designed with the help of MCNP6 code simulations to address systematic uncertainties to an extent that is unprecedented in low-energy nuclear science. This simulation work has also helped to identify systematic errors that were present in previous experiments across the world—errors that were not appreciated at the time. The SPIDER experiment is measuring the fission product yield as a function of neutron energy, complementing some recent work that Los Alamos has done with Lawrence Livermore and the Triangle Universities Nuclear Laboratory (TUNL) in Durham, North Carolina through an NNSA-sponsored collaboration under the Stockpile Stewardship Academic Alliance. These data, analyzed and interpreted in collaboration with the theory community, will both advance our fundamental understanding of fission and provide important data to confirm (or contradict!) our present understanding of energy-dependencies in these important nuclear diagnostics.

Advances in the application of the DANCE detector are providing neutron capture cross section measurements that are challenging our current understanding. Recent work on uranium-235 capture has been published in *Phys. Rev. Lett.* (*PRL* 109, 202506 [2012]) and is having a large impact in the nuclear data community. We await, with great interest, the extension of this approach to measure plutonium-239 capture, where few data exist beyond the seminal Los Alamos measurements in the 1950-60s by Ben Diven and John Hopkins.

It is an exciting time in nuclear science at LANSCE, and the data that will come from these experiments will have an enduring impact on both our basic understanding of actinide nuclear science and on a variety of nuclear technologies in defense, energy, and nonproliferation.

Mark B. Chadwick
Program Director for Science Campaigns

Stephen M. Sterbenz
Program Manager for Campaign 1

Fission

New capabilities for a research renaissance

Los Alamos nuclear fission research, which has a rich history dating back to the Manhattan Project, has recently undergone a renaissance with major theoretical advances and development of several new experimental capabilities at the Los Alamos Neutron Science Center (LANSCE). New experimental instruments such as the Time Projection Chamber, the SPectrometer for Ion DEtermination in fission Research (SPIDER), and the Chi-Nu detector array all benefit from the unique neutron sources available at LANSCE, as well as advances in nuclear detector technology and digital systems.

Fission is a highly complex process fundamental to nuclear weapons and nuclear energy technologies. While these fission-based technologies have been explored for decades, only recently has the role of advanced modeling and simulations increased in importance. This is partly due to the end of nuclear testing in the 1990s in the United States. These simulations and their predictive capabilities, however, are only as accurate as the underlying nuclear data. To realistically model the behavior of nuclear reactors and defense applications, accurate measurements of the underlying nuclear fission process are necessary.

Studying the fission process at LANSCE

Modeling applications that involve nuclear chain reactions, such as reactors and weapons, requires accounting for the fission process and other nuclear reactions. While most models previously considered only certain average properties of fission, recent sensitivity studies have identified the need to include higher fidelity information about the fission process. Information about the energy differential cross section, the distribution of energy of the secondary neutrons, and properties of the fission products is important to accurately simulate performance of nuclear devices. LANSCE's fission measurement program addresses these programmatic needs, as well as provides information illuminating the underlying science of the fission process.

The cross section—a measure of the probability for a reaction to occur between a projectile and a target nucleus—is a basic property of any nuclear reaction. In neutron-induced fission the projectile is a neutron, and the target is an actinide such as uranium or plutonium. The cross section varies for different reactions, elements, and incident neutron energies.

To measure fission cross sections at LANSCE, thin, highly enriched samples of the isotope of interest are prepared, and then irradiated in the neutron beam while residing in an instrument that detects fission, thus allowing researchers to analyze the resulting events. The number of incident neutrons is determined using a neutron flux monitor ionization chamber. The number of target atoms in the sample is calculated from the known mass of the deposit. By counting the number of fission events, the reaction cross section can be determined. The uncertainty of the measured cross section in these types of measurements is typically 3-5%, and is dominated by uncertainties associated with the sample and beam properties. The fission Time Projection Chamber (see Time Projection Chamber, page 6), a new detector developed by Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Idaho National Laboratory, and six universities, significantly improves the measurement accuracy and is expected to reach an unprecedented 1% accuracy.

While the cross section is a basic property of all nuclear reactions, fission is different from most other nuclear reactions in that it produces two new nuclei, the fission products, as the target nucleus splits. When most actinides undergo fission the resulting fission products are rarely of equal mass and charge. There are several reasons to study mass distributions—from both basic science and application points-of-view.

A program to study fission fragment properties has been developed at LANSCE. This program takes advantage of the large range of neutron energies available to investigate the changes in mass distributions at different incident neutron energies for many different isotopes. The LANSCE program employs different detectors to create a complete picture: ionization

SPIDER

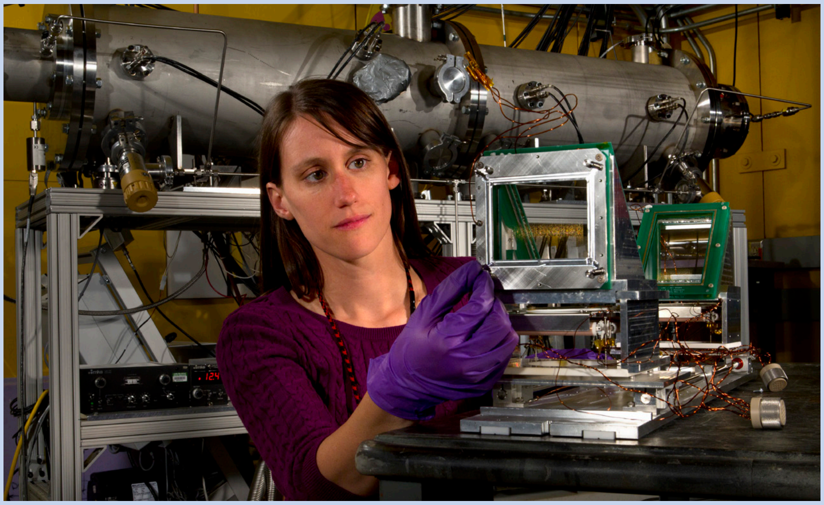
Studying fission fragment properties nanoseconds after fission

The mass and charge distributions of fission fragments have been extensively studied in the past; however, many measurements traditionally used radiochemical methods or mass spectrometry that provided information on fission products after the fragments decayed. Although these techniques are accurate, they do not provide much information about the initial conditions in fission.

To study properties of fragments immediately after fission has occurred, Los Alamos Neutron Science Center researchers developed the SPectrometer for Ion DEtermination in fission Research (SPIDER). This high-resolution spectrometer measures the velocity and kinetic energy of the fragments extremely accurately, allowing an unambiguous determination of their mass. The instrument's development was initially supported by the Laboratory Directed Research and Development program.

In developing SPIDER, researchers addressed several major technical challenges. To measure the velocity of the fragments, they placed fast start and stop detectors 50-70 cm apart and recorded the fragments' time-of-flight. To reach the desired mass resolution of 1%, the detectors' timing resolution needed to be 200 ps. This was achieved by using ultrafast micro-channel plates and specialized read-out electronics. Meeting the instrument's 1% energy resolution goal calls for optimized energy detectors and extremely thin windows to reduce energy straggling. The most promising material for the windows is silicon nitride, which can be obtained with a thickness of 200 nm, thus keeping energy straggling for typical fission fragments below 0.5%. The need for a high-energy resolution fragment detector was solved by building an ionization chamber optimized for resolution. The performance of the ionization chamber was benchmarked using radiation sources, and was shown to reach the required accuracy.

SPIDER's first measurements, which were performed at the Lujan Neutron Scattering Center in 2013, determined the mass yield from fission of the uranium-235 isotope. This isotope is the main fuel in most reactors, and the fission yield is therefore of particular interest. The neutron beams available at the Lujan Center are low energy, allowing the fission fragment mass yield to be measured for thermal neutrons. This measurement campaign will be extended to fast neutrons in 2014, by moving the experiment to the Weapons Neutron Research facility. The fast neutron-induced fission process is of strong interest to defense programs, and the move will therefore make it possible to study this neutron energy region.



A Laboratory researcher inspects the fission fragment timing detectors of the SPectrometer for Ion DEtermination in fission Research detector prototype (background). SPIDER is designed to measure fission fragment mass distributions with a resolution of a single atomic mass unit–a difficult challenge. Detailed fission fragment mass distributions provide a better understanding of the process by which nuclei split and valuable information for better understanding nuclear systems.

chambers provide low mass resolution, but high efficiency; while a specialized fragment spectrometer provides high mass resolution at the cost of efficiency. The ionization chamber allows researchers at LANSCE to measure the gross trends of fission fragments—the shift in mass peaks that is observed when moving from room-temperature neutrons to much higher energies, and the variations in mass peak positions and widths for different isotopes. The newly developed SPIDER detector (see SPIDER, page 5) will eventually complement these measurements with high-resolution mass distributions, where each individual mass is resolved.

Neutron and gamma-ray emission following fission is another important set of physical processes studied at LANSCE that is important for applications as well as of basic science interest. The de-excitation of neutron-rich isotopes provides insight into nuclear structure far from stability, which helps in developing nuclear structure theory and provides valuable information for nuclear astrophysics.

The Chi-Nu instrument (see Chi-Nu, page 7) was specifically designed to measure the energy spectrum of neutrons emitted in fission. Precise knowledge of this energy spectrum is important for accurately modeling fission chain reactions because of the exponential growth of the neutron population. Large uncertainties exist for neutron emission at lower (less than 1 MeV) and higher (above about 8 MeV) energies that Chi-Nu's two detector arrays are designed to measure. Conducted in collaboration with Lawrence Livermore National Laboratory with contributions from university researchers, this work is an important part of the NNSA Defense Program Science Campaigns.

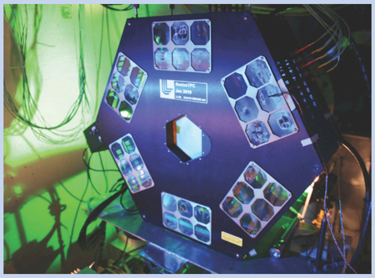
Although primarily designed to investigate neutron capture reactions by recording gamma rays emitted by the excited system created when a nucleus captures a neutron, the Detector for Advanced Neutron Capture Experiments (DANCE) has, in recent years, been used to study gamma rays emitted in fission. By adding a fission detector identifying when fission occurs and by measuring the subsequent gamma decay, DANCE makes it possible to measure not only the total energy release as gamma rays, but also the gamma-ray multiplicity of fission.

Time Projection Chamber

Measuring fission cross sections with unprecedented accuracy

A time projection chamber (TPC) is a type of nuclear particle detector that provides tracking information, most commonly for particles created in high-energy nuclear collisions. Typically, TPCs are large. For example, the STAR TPC at Brookhaven National Laboratory is 4.2 m long and 4 m in diameter.

In a collaboration between Los Alamos, Lawrence Livermore, Pacific Northwest and Idaho national laboratories and six universities (California Polytechnic Institute, Colorado School of Mines, Georgia Institute of Technology, Idaho State University, Oregon State University, and Texas Christian University), a much smaller version of a TPC was recently developed to measure fission cross sections with unprecedented accuracy. The fission TPC is funded by the weapons program Science Campaigns. Instead of being the size of a room, the fission TPC is less than 1 m in diameter and only 30 cm long. Scaling down the detector's size was a challenge due to the large amount of electronics needed to read signals produced in the detector. Making use of advances in digital technology driven in part by the cell phone industry, custom electronics were developed for the TPC that perform, on credit card-sized elements, both the signal digitization and processing. A total of 192 such cards were needed, attached directly to the detector.



The fission Time Projection Chamber is less than 1 m in diameter and only 30 cm long.

To perform an experiment on the fission TPC, a sample of fissile material being investigated is placed in the TPC's active volume, a chamber roughly the size of a coffee can. As incident neutrons from the Weapons Neutron Research facility target induce fission in the sample, energetic fission fragments are emitted from the surface and into the active volume that is filled with gas. As the fragments travel through the volume, they lose energy through ionizing collisions with gas molecules, until they finally stop. The fragment tracks can then be observed by the cloud of ionization left behind. The TPC creates a three-dimensional representation of those tracks using pixilated charge sensitive pads that, essentially, take pictures of the charge cloud. As the charge drifts in the electric field inside the instrument, several such pictures are taken, allowing a computer to combine the information into a full three-dimensional image of the fission fragment tracks.

The next-generation of fission research

Rich in complexity, the fission process requires knowledge of basic reaction theory, as well as a deep understanding of nuclear structure in order to fully understand and model it. State-of-the-art nuclear instruments, together with the LANSCE neutron facility, allow researchers to study virtually every aspect of neutron-induced fission.

The ultimate goal of fission research is a truly predictive model of the process. Recent groundbreaking work by Los Alamos theoretical physicists has revolutionized understanding of the potential energy landscape formed as a nucleus undergoes fission. By combining this work with a dynamic calculation realistically describing the evolution of nuclei through these landscapes, scientists may attain this long sought-after goal. Just such calculations are currently being pursued at Los Alamos.

Given the promising steps in this direction, an expanded experimental program will further support these efforts. This might require studying highly unstable isotopes far from stability and using projectiles other than neutrons, such as heavy ions or highly energetic gamma rays. Given its preeminent fission research stature, Los Alamos National Laboratory can be expected to play an important role in developing the next generation of experiments and theory.

Chi-Nu

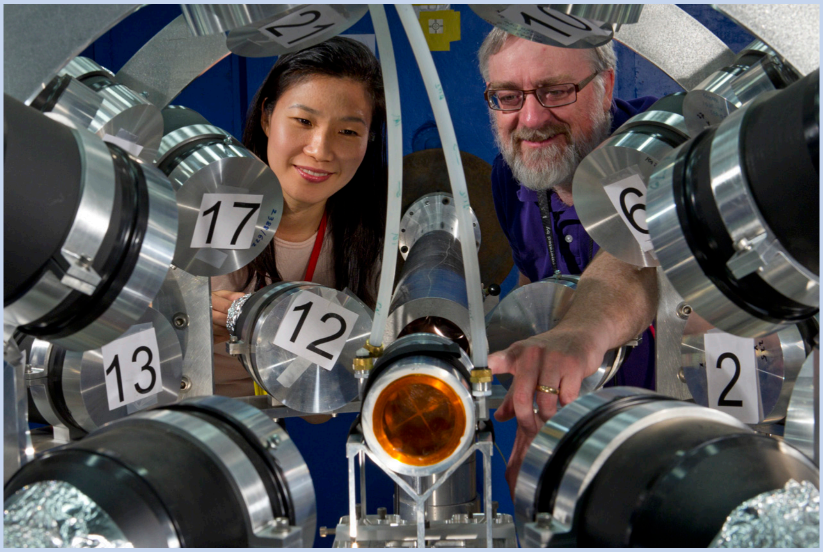
Measuring the plutonium-239 fission neutron spectrum

The neutrons emitted in fission have a range of energies that generally follows a Maxwellian distribution. Since the nuclear chain reaction is highly sensitive to the exact spectrum there are important reasons to precisely measure the neutron output spectrum. Previous measurements had large uncertainties, particularly at the distribution extremes, which are strongly affected by background corrections and low statistics.

A new detector array, Chi-Nu, has been developed at the Los Alamos Neutron Science Center especially to improve the confidence in the outgoing fission neutron spectrum as a function of incident neutron energy. The instrument's development and use is funded by the weapons program Science Campaigns. The array's name originates from the Greek letters used to denote the matrix that relates incident neutron energies to an outgoing neutron spectrum. Chi-Nu's main objective is to measure the fission neutron spectrum of the plutonium-239 isotope due to its high importance for defense applications. This is a major effort due to the challenges involved in making accurate measurements in the neutron energy regions of interest.

The Chi-Nu instrument consists of a central fission tagger detector that holds the actinide samples being investigated. Several neutron detectors are located around the fission tagger at a distance of approximately 1 m. As a neutron from the Weapons Neutron Research facility source hits the actinide sample, the detector records the event and measures the time-of-flight of the incident neutron, which determines its energy. The neutrons emitted in the fission process hit the surrounding neutron detectors, and a second time-of-flight (and hence energy) is recorded—this time of the outgoing neutron. In this way the correlation between incident and outgoing neutrons in fission is determined.

One complication in this experiment is that every time fission occurs, emitted with the neutrons are gamma rays, adding a background component that needs resolving. Much care was taken to optimize the Chi-Nu array to reduce sensitivity to gamma backgrounds. Shape information of the detector pulses is used to distinguish neutrons from gamma rays, and the time-of-flight information obtained from the fission tagger and neutron detectors separates fission gamma rays and neutrons. The result is a much-improved accuracy compared to previous experimental work.



Los Alamos researchers check the low-energy neutron detectors of the Chi-Nu array. The Chi-Nu project is measuring the spectra of neutrons emitted from the neutron-induced fission of plutonium and uranium with emphasis on the low-energy and high-energy portions of the spectrum.

Neutron radiography and computed tomography

Developing new techniques and capabilities for advanced imaging

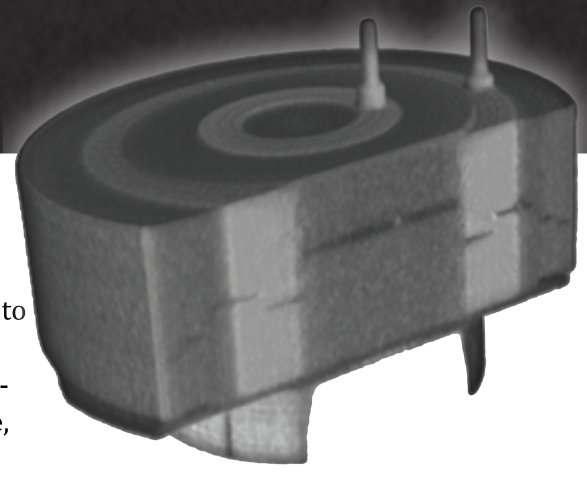
Los Alamos National Laboratory has a distinguished record of developing and using imaging techniques to support its defense, global security, and science missions—from performing radiographic imaging during the Manhattan Project, to inventing proton radiography in the 1990s, and leveraging new advanced neutron imaging detectors today. Using these new detectors, advanced neutron imaging techniques at the Los Alamos Neutron Science Center (LANSCE) have demonstrated a previously unattainable ability to look inside materials to study the spatial distribution of chemical elements and isotopes in thick objects.

Providing a complementary technique to x-rays and protons, both low- and high-energy neutron imaging has been performed in the past at LANSCE. These new capabilities, however, deliver good (greater than 200 μm) spatial resolution of the elemental and isotopic components of objects using the low-energy beams and can image features inside thick and dense materials using the high-energy beams. These improvements rely on features of LANSCE neutron sources that are superior to most other facilities: the Lujan Neutron Scattering Center's high-intensity neutron beams; good (less than 150 ns, FWHM) timing characteristics; and the Weapons Neutron Research facility's (WNR) high-energy beams and suitable flight path lengths and collimation. The ability to use different energy neutrons enhances the contrast of the radiographic image.

Energy-resolved neutron radiography and computed tomography

X-ray imaging provides a means to nondestructively view the interior of objects. By combining modern computer image processing with multiple x-ray images—the process of computed tomography—a three-dimensional view of the structure of an object is created. X-rays, being sensitive to atomic electrons, serve best to image heavier elements inside lighter elements; for example, steel pins in bone inside the human body. In contrast, neutrons, being sensitive to scattering from nuclei, are able to image lightweight, hydrogen-containing objects inside dense, high atomic number materials. A classic example is an image of a flower inside a steel or lead box, an imaging condition that is intractable with x-rays.

Another feature of nuclear scattering is the existence of nuclear resonances, which increase or decrease the chance for a neutron to scatter from a nucleus at



A tomograph of an object consisting of tungsten, polyethylene, graphite, and other materials with internal gaps, and beads.

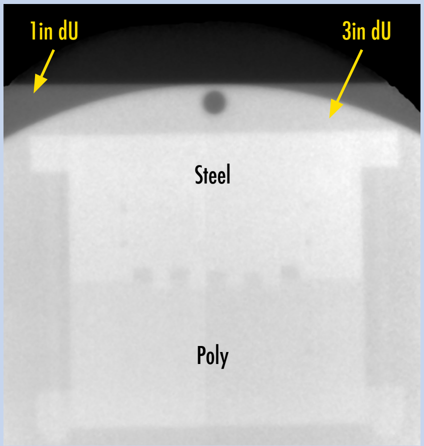
particular incident neutron energies. The energies at which resonances occur are specific to each chemical element and isotope. By producing neutron beams using short proton pulses, such as done at LANSCE, neutrons of different energies can be selected based on their time of arrival at an imaging detector. If the detector can resolve neutrons that are closely spaced in time (hence in energy), then observing individual resonances is possible. By selecting images taken at certain times with respect to the proton beam pulse, an image showing the location of a particular element or isotope can be created. This is referred to as energy-resolved neutron imaging.

LANSCE researchers are in the process of improving energy-resolved neutron imaging and developing applications in collaboration with researchers from the University of California, Berkeley and Nova Scientific Inc., which created micro-channel plate-based detectors for low-energy neutrons that provide excellent spatial and time resolution. These detectors are ideally suited for energy-resolved neutron imaging. Using the low-energy beam at LANSCE, images of tungsten inclusions in simulated reactor fuel pellets made of uranium show that the technique can work quite well. Applications range from nondestructive examination of fission reactor fuel rods for damage and location of fission products, to understanding manufacturing processes and observing the migration of specific materials in fuel cells.

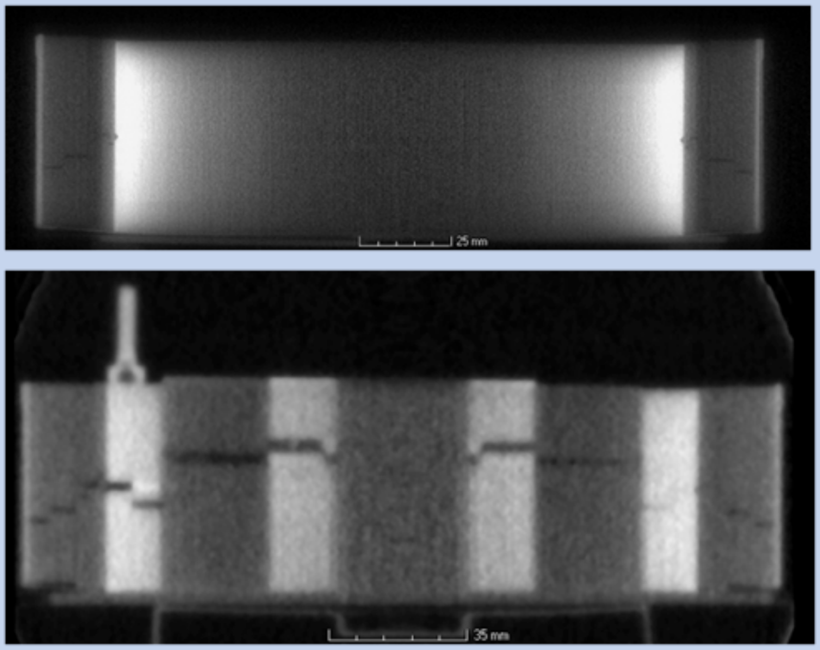
High-energy neutron imaging

Imaging through dense high atomic number materials

The power of high-energy neutron radiography for imaging through dense high atomic number materials is shown by two cases below, which made use of Target-4 neutron beams at the Los Alamos Neutron Science Center in 2013 and 2014. Figure 1 shows a radiograph of a test object composed of steel, polyethylene, and foam behind 76 mm of depleted uranium that has a density of almost 19 g/cc and an atomic number of 92. The test object's features are clearly visible. Figure 2 is a tomographic reconstruction from a set of 800 images of a tungsten and polyethylene test object taken using the Weapons Neutron Research facility neutron source. Each view was acquired in less than 1 min. Slices taken from that reconstruction can be directly compared with a high-energy (15 MeV) x-ray computed tomography slice of the same object. The high-energy neutron image clearly shows the internal structure of the object while, despite the use of deeply penetrating high-energy x-rays, the x-ray image does not show the same detail. This work is funded by the Enhanced Surveillance Campaign.



A steel (top half), high-density polyethylene (bottom half) and foam (center teeth) phantom viewed through 76 mm of depleted uranium. Some ~3-mm diameter holes in the steel are visible.



A tomograph of an object consisting of tungsten, polyethylene, graphite, and other materials with internal gaps, and beads (page 8). Top, the same object imaged with 15-MeV high-energy x-rays where few features are visible, and (bottom) the image using high-energy neutrons where the many gaps are easily seen.

High-energy neutron radiography and tomography

In the mid-1990s, the first high-energy neutron images were obtained by Los Alamos researchers at WNR and by Lawrence Livermore National Laboratory researchers at Ohio State University's 14-MeV neutron source. These efforts required imaging times on the order of 30-60 min exposures per frame. While some important work was carried out at LANSCE at the time, these efforts did not lead to the establishment of a long-term capability.

In early 2014, a new high-energy neutron imaging capability was demonstrated at LANSCE on a flight path at the WNR high-energy neutron source. Using commercially available amorphous silicon medical image plates and specially selected scintillator panels to convert the neutron signals to visible light, high-energy neutron radiographs were acquired in about a minute, and good-resolution, 800-image tomographs were acquired in less than a day. This work showed LANSCE's ability to image features as small as 2 mm in dense composite objects of tungsten, uranium, polyethylene, graphite, steel, and other materials.

This demonstration confirms that LANSCE now has a high-energy neutron imaging capability that can be deployed on WNR flight paths for both unclassified and classified objects. Ongoing research seeks to improve the speed and resolution of this capability. Members of the Laboratory's Non-Destructive Testing and Evaluation and Nuclear Science groups and researchers from Lawrence Livermore are collaborating on this work.

The need to look inside the heaviest metals was the driving force behind this new capability. A major limitation of x-ray imaging is that x-rays are heavily attenuated in thick materials. X-ray absorption increases rapidly with increasing atomic number (Z). This limits the use of x-rays in viewing low-Z materials, such as aluminum or plastic, which are obscured by higher-Z materials, like iron or lead. In addition, x-ray scattering and detection characteristics at higher x-ray energies make difficult the measurement of important quantities like material density profiles and the detection of "buried features," such as a small void or gap deep inside an object.

For thin objects, well-established low-energy neutron imaging capabilities are maintained at user facilities like the ones at the National Institute for Standards and Technology in the United States and the Paul Scherrer Institute in Switzerland. Just as with x-rays, however, a point is reached where higher-energy neutrons are required to penetrate and radiograph thicker objects.

Future

These neutron-imaging advances open new opportunities for research that will benefit Los Alamos National Laboratory programs, as well as international scientific user community studies. State-of-the-art detectors and image reconstruction techniques, combined with the unique neutron beam facilities at LANSCE, make these capabilities possible. Further development will help expand the role of specialized neutron imaging and increase the research areas that will benefit from it.

Energy-resolved neutron imaging

A technique for excellent spatial resolution and element selection

Over the last two-years, energy-resolved neutron radiography and computed tomography were tested at the Los Alamos Neutron Science Center (LANSCE). A first demonstration of the technique using the LANSCE neutron beam showed that excellent spatial resolution and element selection are possible. The work was a collaboration with the University of California, Berkeley, which developed the micro-channel plate detector and readout system. Images acquired with the micro-channel plate detector of simulated nuclear reactor fuel pellets demonstrate the ability to display tungsten pieces that are embedded in depleted uranium.

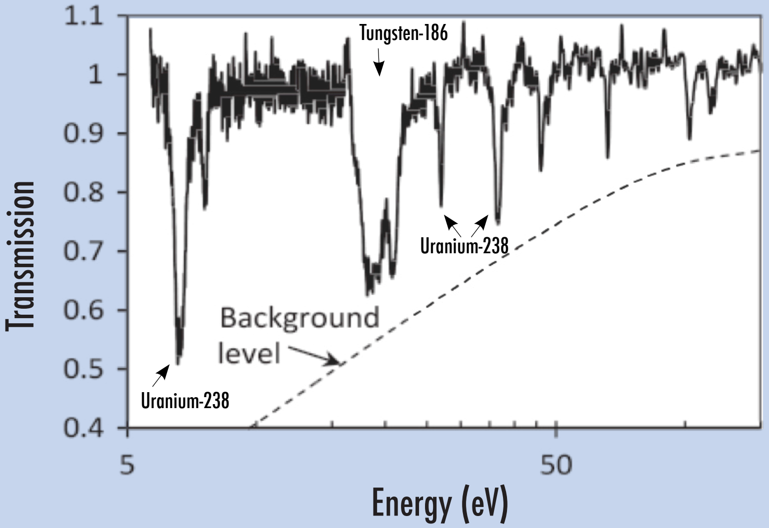
Figure 1 shows the fuel pellets selectively gated on uranium-238 resonances.

Figure 2 shows the same view gated on tungsten resonances. An embedded tungsten piece at the top, center position, and smaller bits of tungsten distributed throughout the two sets of uranium pellets on the left are clearly seen.

Figure 3 is a thermal neutron radiograph view. Here, the image quality is better due to the large number of neutrons available. Data for all of the views were acquired in the same exposure.

Figure 4 shows a neutron transmission spectrum taken with the micro-channel plate detector. Resonance dips due to uranium and tungsten are indicated on the figure.

Figure 4



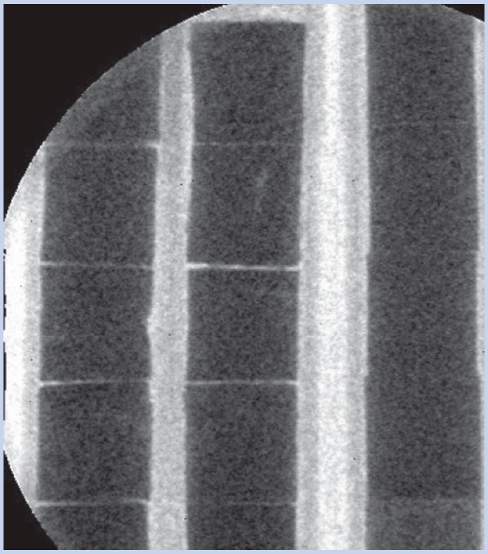


Figure 1

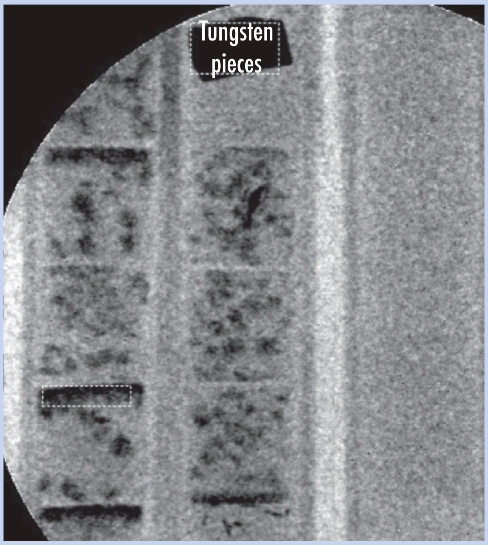


Figure 2

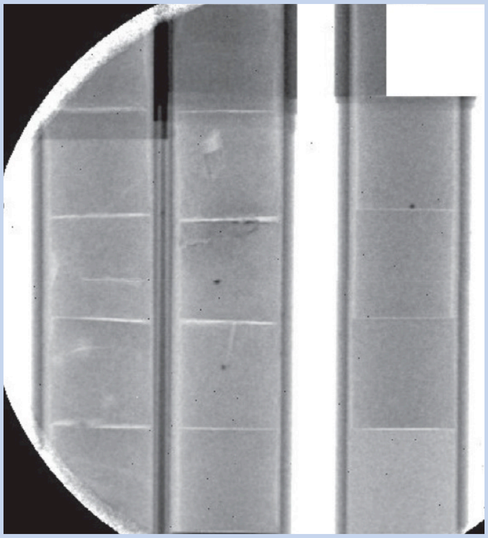


Figure 3

Nuclear astrophysics

Revealing the universe through unstable nuclei

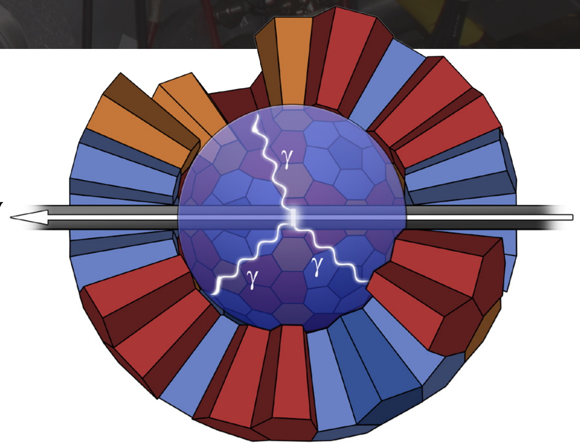
As stars die they produce heavy elements that are dispersed into the cosmos and form the next generation of stars and planets. At the Los Alamos Neutron Science Center (LANSCE), Laboratory researchers use high-intensity neutron beams, radioisotope production, and advanced detector systems to directly measure the underlying reactions driving these elemental evolutions. With these data researchers can develop new nuclear reaction models to predict reactions in cases that cannot be measured, design stellar models to track the evolution and elemental genesis of a star through its many phases of life, and combine these elements with astronomical observations, further refining understanding of the natural world.

Nuclear astrophysics has long been of interest to Los Alamos researchers, given that many of the physical processes involved are also relevant to understanding weapon performance and effects. For example, the s-process (see below)—where sequential neutron capture builds heavy elements—is similar to radiochemical weapons networks used to calculate weapons performance in past nuclear tests. At LANSCE, researchers seek to understand the origins of the elements and cosmological environments through the lens of unstable nuclei and elemental production. Improved techniques and technical capabilities have advanced modeling and simulation of astrophysical environments giving rise to turbulent, dynamic environments that demand improved understanding of the relevant nuclear physics.

The role of neutrons

Neutrons are responsible for the creation of all elements heavier than iron—including such wide-ranging species as copper, krypton, silver, gadolinium, platinum, gold, and lead—through a process known as neutron capture. In this process, a neutron is absorbed into an atom, making it heavier and increasing its ratio of neutrons to protons, continuing until the nucleus become so neutron-rich that it decays to a different, less neutron-rich isotope.

Part of the challenge of astrophysical research is that neutrons themselves are unstable—decaying to protons with a lifetime of approximately 15 min—making the conditions found in a star difficult to recreate on the earth. Neutrons play an important role in primarily two environments: near the end of the lives of stars slightly heavier than the sun, where neutron-generating pulsations create many of the heavy elements; and in the cataclysmic collapse and explosion of stars 10 times heavier than the sun, briefly generating an intense neutron environment that is thought to form the remainder of the heavy elements. The explosion efficiently drives this newly generated material into the cosmos.



An illustration of the Detector for Advanced Neutron Capture Experiment, a 160-element, barium-fluoride device designed to detect the complete cascade of gamma rays emitted following capture.

For many of these astrophysical environments, the most discriminating and least studied reactions are on unstable isotopes. These elements that either have so many or so few neutrons that the forces holding their nuclei together drive them, on timescales ranging from hundredths of a second to hundreds of millions of years, to change into another species.

Through several distinctive capabilities, LANSCE enables critical studies on these isotopes. The LANSCE accelerator provides high-energy protons, which are used to generate some of the most intense neutron beams in the world for nuclear physics studies. These beams cover 11 orders of magnitude in neutron energy, exactly the conditions needed to advance scientists' understanding of the genesis of the heavy elements. At LANSCE's Isotope Production Facility (IPF), samples are irradiated in the direct proton beam to create exactly those unstable isotopes needed for neutron-capture studies.

A good nuclear physics experiment requires four necessary components:

- A good beam: LANSCE provides those neutrons.
- A good sample: IPF delivers unstable isotope samples not available anywhere else.
- Great detectors to study the reactions that take place: LANSCE is well equipped with several instruments.
- Inquisitive researchers to analyze the measurements, interpret the results, and determine how to meet the next challenge, perhaps by improving the beams, samples, and detectors.

The Detector for Advanced Neutron Capture Experiments (DANCE) is designed for maxi-

DANCE

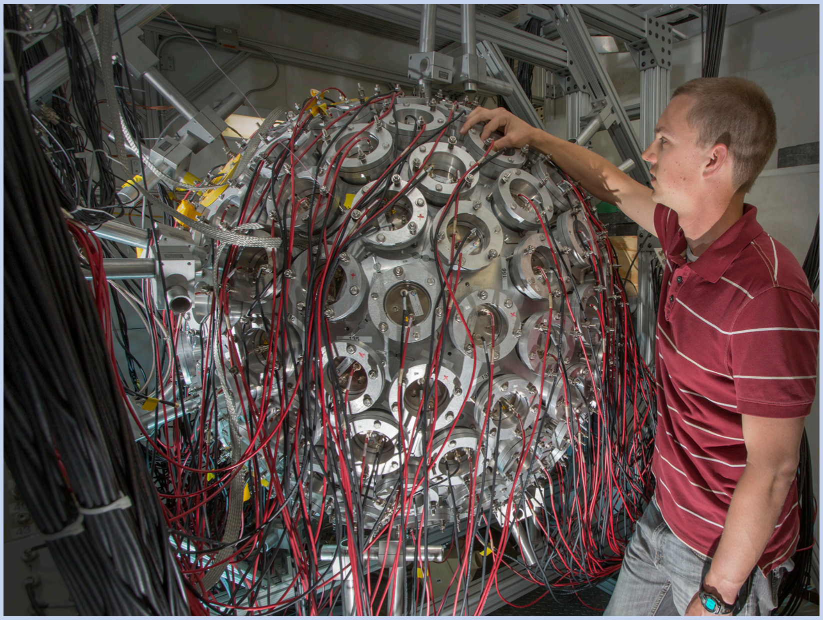
Measuring neutron capture reactions with great sensitivity

Combined with the intense neutron flux provided by the Los Alamos Neutron Science Center beam, the Detector for Advanced Neutron Capture Experiments (DANCE) is ideal for measuring neutron capture cross sections on small, highly radioactive samples. While historical measurements have required samples of hundreds of milligrams to several grams, with DANCE, measurements of a few milligrams are routine, and even measurements with as little as 10 mg of material have been successful.

Traditionally, photons emitted following the neutron capture reaction have been the signature used for its detection. DANCE is a 160-element, barium-fluoride device designed to detect the complete cascade of gamma rays emitted following capture. This array is a high-efficiency, high-segmentation "calorimeter," meaning it can measure the total energy emitted as photons. This total energy signature is characteristic of the isotope on which the neutron capture took place. As each isotope has a unique total energy from capture, this signature can be used to disentangle true capture from background. DANCE's efficiency is greater than 85% for a single cascade gamma ray.

While a powerful capability, this efficiency also means DANCE is sensitive to the decay of an unstable sample, as these decays frequently include gamma rays. Using the total-energy signature, researchers can separate radioactive decays from neutron capture, provided the raw photon rate does not completely overwhelm the instrument. DANCE has been used in photon fields in excess of 10 million gamma rays per second. In contrast, many previous instruments had no sensitivity to the total capture energy, making them unsuitable for the studies on unstable isotopes that have become so critical for astrophysics.

DANCE is truly a one-of-a-kind capability for performing neutron capture studies on unstable isotopes. Projects at DANCE are funded by the Laboratory Directed Research and Development program, universities, and the weapons program Science Campaigns. Should the Nuclear Science Complex be constructed at Los Alamos National Laboratory (see main article, page 14), DANCE will only increase its competitive advantage over other neutron facilities.



The Detector for Advanced Neutron Capture Experiments is designed to study neutron capture reactions on small quantities, of order 1 mg, of radioactive or rare stable nuclei.

mum efficiency, which allows measurements on small and rare samples. By making the most of resolving power, DANCE permits measurement on impure, mixed, and highly radioactive samples, which is important as all unstable samples are radioactive.

While DANCE has been the most heavily utilized instrument at LANSCE for research in nuclear astrophysics (see DANCE, page 13), opportunities abound for research on unstable isotopes with many of the LANSCE instruments discussed elsewhere in this issue, including the Time Projection Chamber, the Low Energy Neutron-induced Charged-particle (Z) Chamber, and the Germanium Array for Neutron Induced Excitations.

The LANSCE nuclear science team includes researchers from top institutions around the world, including Michigan State University, North Carolina State University, and the University of Notre Dame. Active collaboration with faculty and students at these institutions, as well as at American institutions such as Lawrence Livermore National Laboratory, Argonne National Laboratory, Rutgers University, Colorado School of Mines, and Washington University in St. Louis, and international ones such as CEA/Bruyères-le-Châtel, in France, Göthe Universität Frankfurt, in Germany, and the neutron time-of-flight collaboration at CERN, a multinational European laboratory in Switzerland, keep LANSCE scientists engaged at the frontier of nuclear research and in a position to recruit the best and the brightest of the next generation of nuclear scientists.

Challenging environment

Despite the formidable capability LANSCE brings to bear on unstable isotopes studies, the extremes of astrophysical environments demand knowledge in ever-more challenging conditions.

The LANSCE nuclear science team, in collaboration with Los Alamos radiochemistry colleagues, has developed a facility vision that would dramatically enhance the neutron beam intensity in the energy regime of interest for fundamental nuclear astrophysics, as well as for applied defense-related research and nuclear energy nuclear data needs. The Nuclear Science Complex is a proposal that would increase the neutron flux for neutron capture measurement—like those performed with DANCE—by up to a thousand fold in critical regions of interest. This would drastically improve the fidelity of measurements scientists can perform today and would enable new measurements on unstable isotopes, with the possibility of making measurements on species that live for as little as 10 days.

Unfortunately, no matter how intense the neutron beams can be made, eventually the isotope of interest becomes so short-lived that no sample can be made for study. Recognizing this limitation, members of the national nuclear physics community have come together to create the Facility of Rare Isotope Beams (FRIB), which as its basic concept accepts the limitation on samples and instead generates a high-intensity beam of unstable isotope for study. The scientific goals of the construction of this Department of Energy-sponsored $700 million experimental facility at Michigan State University go well beyond the challenges discussed above. Yet FRIB will address many astrophysics questions. Recognizing this possibility, LANSCE scientists are engaged with this external community to build a program to address questions about neutron-induced reactions on these unstable species (see Apollo, page 15).

LSDS

Generating a high effective neutron flux for measurements of small and radioactive samples

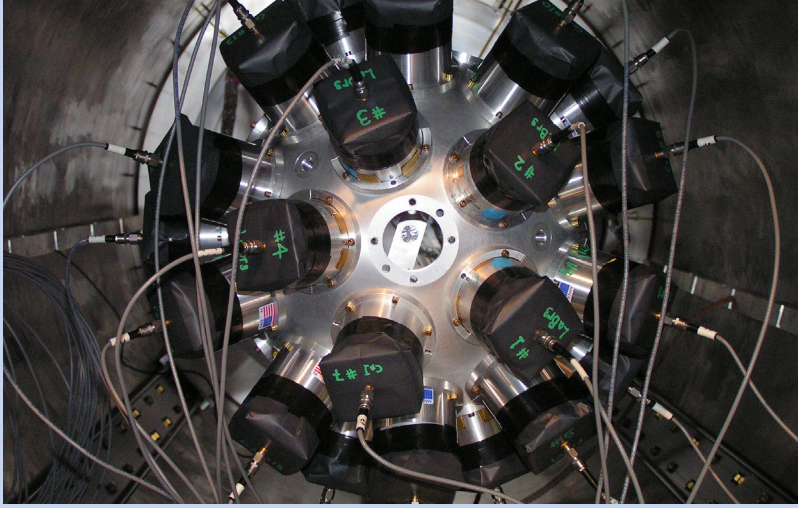
The Lead Slowing Down Spectrometer (LSDS) relies on elastic scattering to "recycle" neutrons produced by spallation of 800-MeV protons hitting a tungsten target at its center. Because the absorption of neutrons in pure lead is very little, neutrons can pass through the volume of the LSDS many times. The resulting high effective flux enables measurements on very small and radioactive samples. At LANSCE, fission measurements have been performed on samples as small as 10 ng, and samples with very small reaction probabilities have been measured for astrophysics applications.

Apollo

An instrument leading to improved rare isotope science

No matter how brilliant the neutron source or how efficient the detector, at some point a radioisotope desired for study becomes so short-lived that fabricating a sample is impossible. And yet, exotic, short-lived isotopes remain both interesting and important, whether for understanding how the elements are created in explosive environments, developing a truly physics-driven predictive model of how nuclei hold together and evolve, or understanding the history of device performance through the evolution of a radiochemical chain of nuclei.

To further these studies of short-lived nuclei, a team of Los Alamos Neutron Science Center nuclear scientists developed Apollo, a scintillator array for studying decay from excited states created when a rare-isotope beam interacts with a deuteron target. The Laboratory Directed Research and Development program supported their work on this project. Apollo was inspired by successful investigations of global nuclear decay properties with Detector for Advanced Neutron Capture Experiments (DANCE).



Apollo was developed to further studies of exotic, short-lived isotopes.

Apollo is presently coupled to the Helical Orbit Spectrometer (HELIOS) at Illinois's Argonne Tandem Linear Accelerator System (ATLAS). ATLAS produces the beam, HELIOS determines the excitation, and Apollo studies the gamma decays. These measurements will be used to improve predictions of neutron capture rates for a wide range of isotopes that cannot be studied at DANCE. Further, this will lead to a program at the future Facility for Rare Isotope Beams (FRIB) in Michigan, which will deliver enhanced intensities of a much wider range of unstable isotopes than can be produced at ATLAS. These studies with Apollo will be extended to take full advantage of FRIB's capabilities.

Radiochemical diagnostics

Monitoring neutron spectra for applications

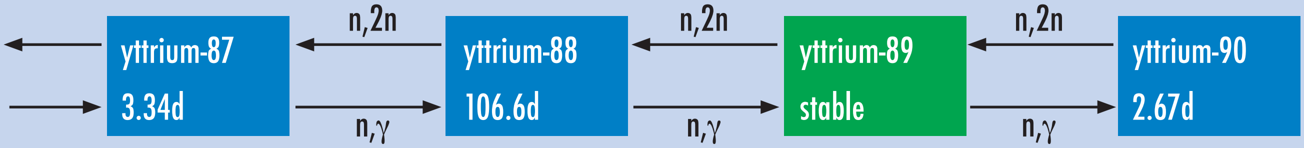
Many nuclear science applications require measuring the total number of neutrons present (known as the fluence) in an environment where standard techniques cannot be used; for example, in nuclear reactors or nuclear explosions. In these cases, measurements can be made by "activation," a technique where the number of nuclei made in a monitor reaction is measured. These measurements often involve radioactive nuclei and chemical separations, hence the name radiochemical or "rad-chem" diagnostics. In this technique, a carefully measured sample of a mono-isotopic element is inserted in the environment under study and exposed for a known amount of time. The analysis of the rad-chem data requires knowing the reaction probability, or cross section, for making the residual isotope of interest over the entire range of neutron energies present.

Understanding archived data from past underground nuclear tests is an important application of rad-chem diagnostics. For this, trace amounts of various elements were inserted in the test package and activated during the explosion. The resulting nuclei were retrieved by drilling into the explosion site and obtaining debris samples. In the extreme environment of a nuclear explosion, multiple neutron-induced reactions took place, including reactions on the radioactive isotopes produced by an earlier reaction.

As estimates of cross sections for many of the elements are available only from theoretical calculations, large uncertainties often are associated with the calculations, and measurements are needed for more accurate results. The reaction probabilities for many of the reactions on stable isotopes have been measured; however, surprising gaps exist in the measurements, especially for isotopes where the reaction probability is small. There are few measurements on radioactive isotopes.

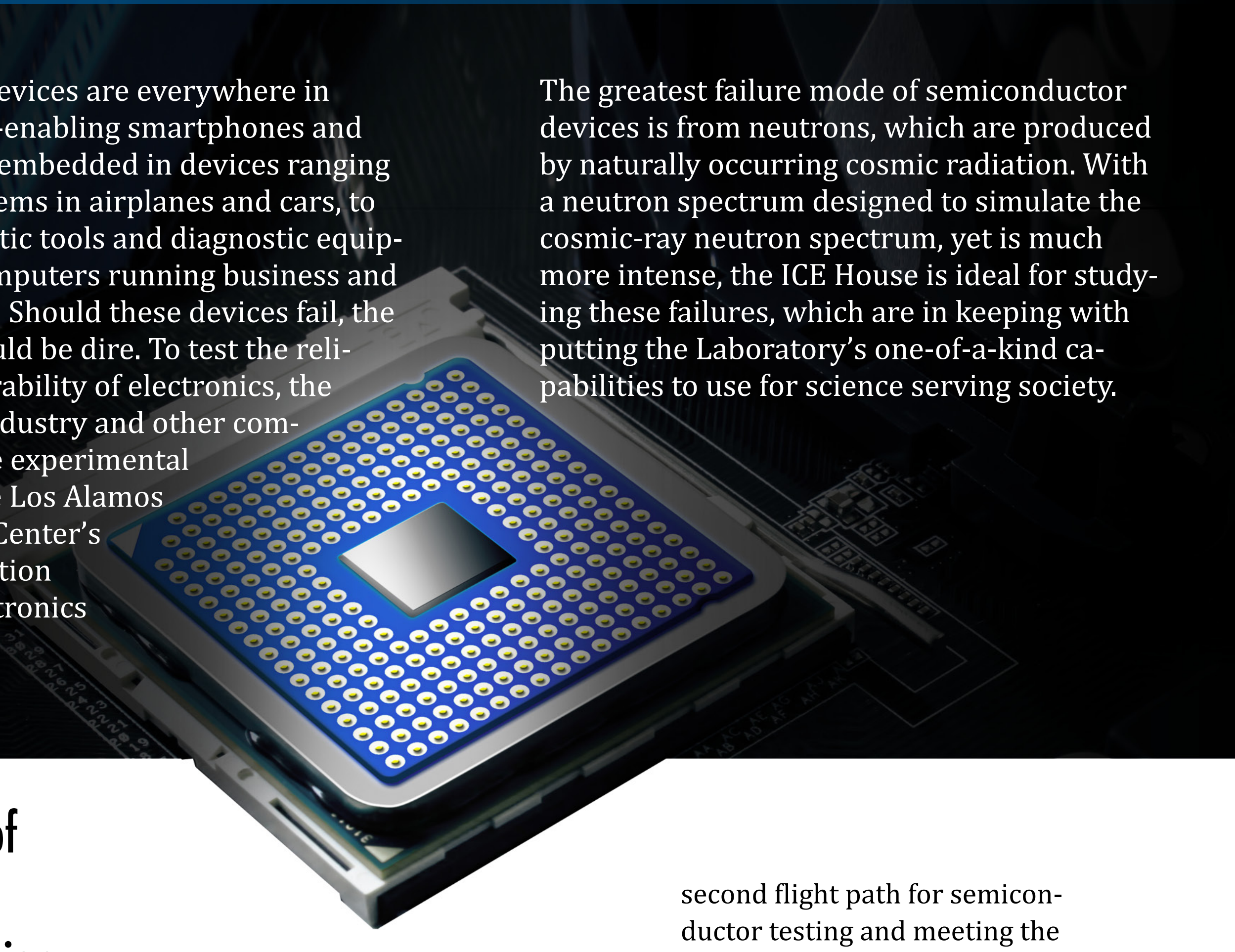
The Detector for Advanced Neutron Capture Experiments (DANCE) is ideal for making many of these measurements because of its high efficiency, its high count-rate capability, and the high neutron flux available at the Lujan Neutron Scattering Center. Using DANCE, measurements can be made on isotopes with small reaction cross sections, such as yttrium-89. More importantly, measurements can be made on small samples–those less than a milligram. This is crucial for measuring radioactive isotopes, where the amount of radiation must be kept small. A program to measure reactions on stable yttrium-89 and iridium-191 and iridium-193 is underway. Measurements on radioactive isotopes, such as thulium-171, are anticipated, but sample preparation is more challenging.

Reaction network for two major nuclear reactions on yttrium-89. The isotope yttrium-90 is made by (n,γ) reactions at lower neutron energies, and yttrium-88 is made by (n,2n) reactions at higher energies. The reaction yttrium-88(n,γ) is important when the number of neutrons is high enough for multiple reactions to take place.



Radiation effects in semiconductors

Putting electronic devices through their paces at the ICE House



Semiconductor devices are everywhere in modern society—enabling smartphones and the Internet, and embedded in devices ranging from control systems in airplanes and cars, to medical therapeutic tools and diagnostic equipment, and the computers running business and financial systems. Should these devices fail, the consequences could be dire. To test the reliability and vulnerability of electronics, the semiconductor industry and other companies rely on the experimental capabilities of the Los Alamos Neutron Science Center's (LANSCE) Irradiation of Chips and Electronics (ICE) House.

The greatest failure mode of semiconductor devices is from neutrons, which are produced by naturally occurring cosmic radiation. With a neutron spectrum designed to simulate the cosmic-ray neutron spectrum, yet is much more intense, the ICE House is ideal for studying these failures, which are in keeping with putting the Laboratory's one-of-a-kind capabilities to use for science serving society.

Vulnerability of electronics to neutron radiation

It would be hard to imagine life without transistors and integrated circuits—even washers, dryers, and dishwashers use semiconductor devices. By 2015, there will be an estimated 170 billion transistors for every man, woman, and child on the planet. As reliance on these devices increases, so does concern about their reliability.

LANSCE has been involved in testing the vulnerability of electronics to neutron radiation since the early 1990s, when the Boeing Company, as part of certifying the 777 airplane, the first commercial fly-by-wire airplane, sought out the Weapons Neutron Research facility's (WNR) high-energy neutron source because of its ability to emulate conditions triggering semiconductor failure modes. Due to demand from the electronics industry, a dedicated facility was created–the ICE House. In 2010, a new building was constructed, allowing a second flight path for semiconductor testing and meeting the demands of the community.

Semiconductor failure modes, or "single-event effects" (SEE), are so-called because a single neutron causes them. These neutrons are created when cosmic rays strike the atmosphere, trigger nuclear reactions with the nitrogen and oxygen, and produce an array of energetic particles. The air absorbs the charged particles, but neutrons, being uncharged, can travel long distances to reach places where people and semiconductor devices exist. These cosmic-ray neutrons interact with the silicon in the semiconductor devices to produce charged particles, which then deposit charge near the sensitive volumes of transistors and can cause failures.

There are several types of SEE. A single-event upset (SEU) occurs when a single memory bit changes state and the device continues to function normally, but with corrupted data. Multiple-bit upset (MBU) occurs when several bits are changed. An SEU can often be mitigated with error-correcting techniques, while error correction is much more difficult with MBU. Single-event latch up occurs when the device completely stops operating and may have to be powered down to be reset or replaced.

In addition to SEE failure modes, transistors can be affected by radiation that causes lattice displacement damage (LDD). In this case, the high radiation dose destroys the crystal lattice structure of the device, leading to loss of transistor gain, higher leakage currents, and other changes to the device's characteristics. When changes to the electrical characteristics of the device exceed the design parameters, the semiconductor device may fail. This type of damage depends on the cumulative effect of the radiation dose and worsens as radiation exposure increases.

The Q-Machine

Diagnosis: Single-event effect

When the Q-Machine, a Los Alamos National Laboratory supercomputer, and then one of the world's fastest supercomputers, began operating in 2002, it would fail approximately three times a day. To determine if the failures were due to single–event effects, Laboratory researchers placed a module of the computer in the Irradiation of Chips and Electronics House neutron beam and measured the failure rate. By analyzing the results of the tests, they determined that essentially all of the computer failures could be attributed to single-event effects—failures caused by a single neutron interacting with the silicon in the computer's semiconductors. With this knowledge, designers modified the software to mitigate this problem. This work was funded by the Accelerated Strategic Computing Initiative.

One module of Los Alamos National Laboratory's Q-Machine supercomputer being tested in the Weapons Neutron Research facility's neutron beam.

Semiconductor studies benefit LHC

LANSCE used to develop next generation of detectors

The results of semiconductor testing using the Weapons Neutron Research facility proton beam will be used to develop the next generation of detectors for use at CERN's Large Hadron Collider (LHC), which recently was used to discover the Higgs Boson particle. The collider is planned to undergo several upgrades to increase its beam intensity. To take advantage of these upgrades, new detector materials must be developed and certified to show they can survive the intense radiation fields in the vicinity of the interaction region. To test the effects of radiation on these materials, members of the University of New Mexico Collider Physics group and collaborators from around the country are using the Los Alamos Neutron Science Center (LANSCE) proton beam. The LANSCE accelerator produces 5 x 10^{11} protons/sec at 800 MeV and has delivered doses of up to 2 x 10^{16} protons.

A University of New Mexico researcher assembles a stack of semiconductor devices for testing in the Weapons Neutron Research facility's proton beam.

LANSCE experimental facilities are used to study both SEE and LDD failure modes.

The ICE House source, which is positioned at 30 deg to the left of the proton beam closely mimics the cosmic-ray neutron energy spectrum. This permits researchers to test semiconductor devices by placing them in the neutron beam and determining the failure rate. The failure rate in any environment can be obtained by scaling the neutron intensities. With an intensity of approximately 10^8 times that of the cosmic-ray neutron spectrum, the source allows testing of semiconductor devices at an accelerated rate. For example, placing a device in the ICE House neutron beam for 1 h equals exposure to neutron flux at aircraft altitudes of more than 100 years.

As an example of SEE radiation testing, researchers in the Laboratory's radio frequency group measured the response of insulated gate bipolar transistors (IGBT) to the cosmic-ray neutron spectrum. Often used in power systems, IGBTs carry thousands of amps at thousands of volts. Figure 2 shows a plot of the device's lifetime in the beam as a function of applied voltage for a 3,300 V IGBT. The IGBTs were placed in the neutron beam for 60 min. The different curves represent different devices fabricated by different manufacturers. As seen in Figure 2, below a critical voltage (approximately 1,600–2,300 V), the part lasted the full 60 min—meaning, it did not fail. Above the critical voltage, the IGBT failed rapidly. This critical voltage is significantly below the rated voltage of 3,300 V. This result shows that, for reliable operation, circuit designers must know the critical voltage for the part and operate the IGBT below that value.

In many ways LDD is similar to the damage seen in materials where radiation causes swelling, cracking, and embrittlement. In this case, the damage depends on the total integrated radiation dose to the semiconductor. These high radiation doses typically are found near nuclear reactors or detectors. Using the direct proton beam at LANSCE, University of New Mexico scientists are developing detectors for the Large Hadron Collider at CERN. The detectors and materials close to the interaction region of the CERN beam are subject to extremely large radiation fields. With LANSCE, the researchers are able to simulate this damage.

Future

Los Alamos National Laboratory expects demand for semiconductor testing to continue to increase. Industries will likely develop radiation effect standards and specifications that will increase demand at the LANSCE facility. Several ICE House upgrades are planned in the near future. With the completion of the LINAC Risk Mitigation Project, a refurbishing of LANSCE's high-intensity proton accelerator, the neutron beam's intensity will increase by a factor of 2.5, allowing much faster testing and increased sensitivity to smaller radiation-induced effects. In addition, LANSCE is developing the capability for large area irradiations, allowing irradiation of complete systems in order to determine their failure rates and test high-level mitigation schemes.

As users frequently stack several circuit boards one after the other in the neutron beam, a continuing question is the attenuation of the neutron beam after passing through several boards. As several users have requested this information, Los Alamos is developing approaches to measure the energy-dependent attenuation of the neutron beam as it passes through several circuit boards. The ability to quickly obtain a digital picture of the beam spot shape is also being installed at the ICE House, which will enhance the alignment process.

Los Alamos National Laboratory is confident that the semiconductor irradiation facility at WNR will continue to provide an important resource to the semiconductor industry for the foreseeable future.

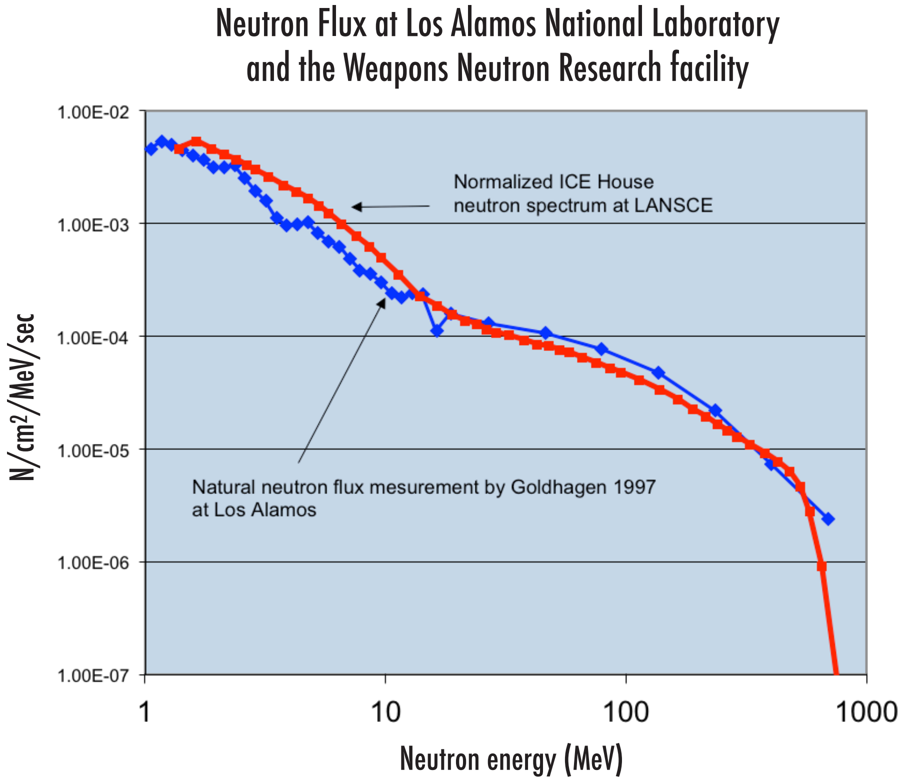


Figure 1. A comparison of the measured cosmic-ray induced neutron flux (blue line) with the neutron spectrum at the Los Alamos Neutron Science Center's (LANSCE) Weapons Neutron Research facility.

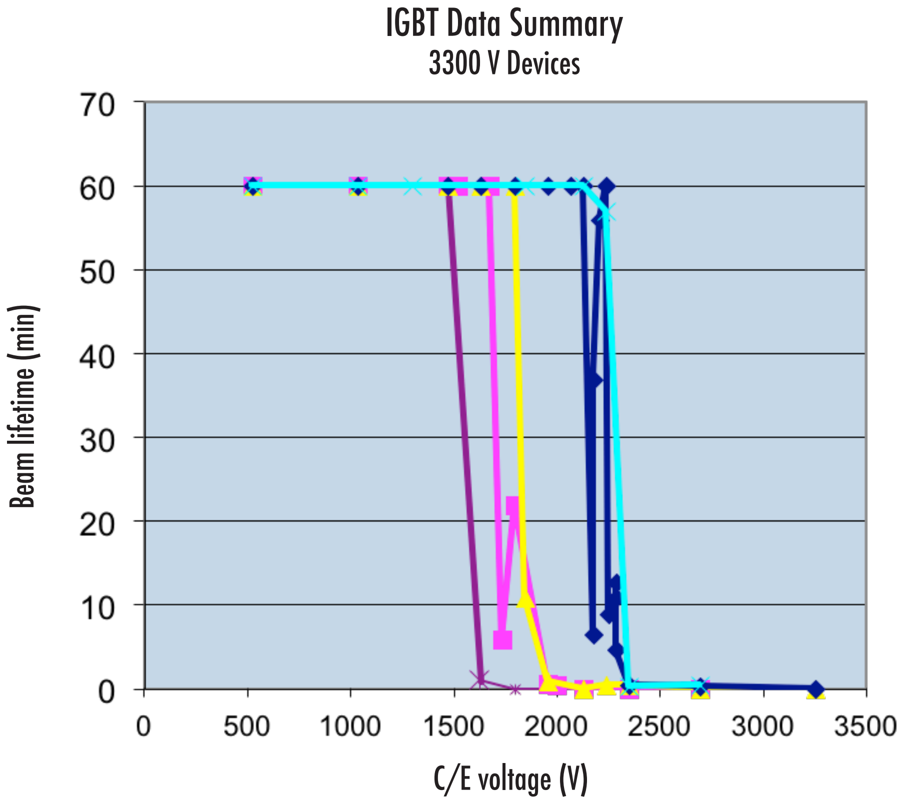
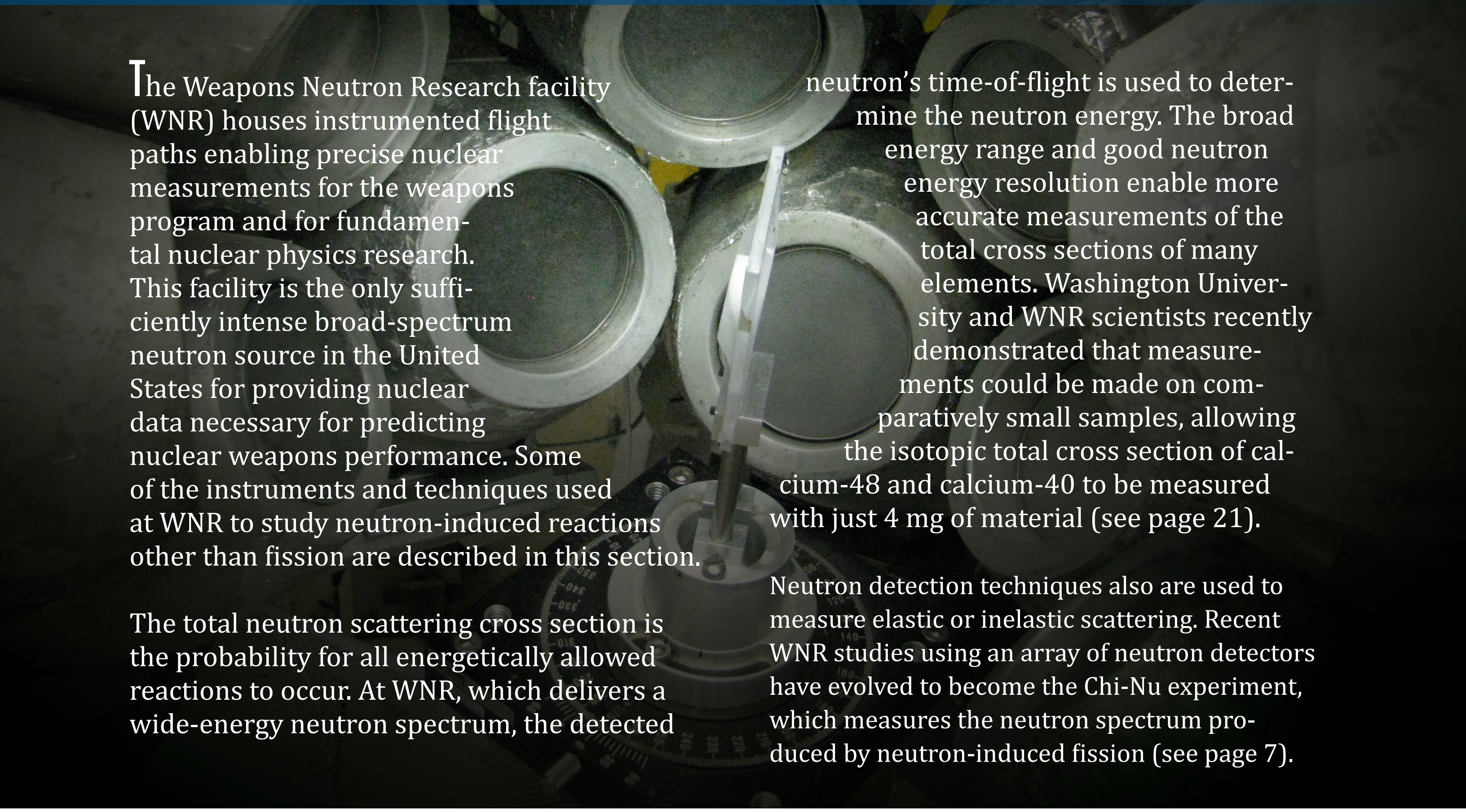


Figure 2. A plot of the device lifetime of an insulated-gate bipolar transistor (IGBT) in the Weapons Neutron Research facility neutron beam as a function of applied voltage. The IGBTs were tested for 1 h. As seen in the plot, the time to failure decreases dramatically when operated above a critical voltage, which is roughly half the rated voltage for these particular devices.

Nuclear reaction measurements

Diagnostics that capture data for defense and civilian applications



The Weapons Neutron Research facility (WNR) houses instrumented flight paths enabling precise nuclear measurements for the weapons program and for fundamental nuclear physics research. This facility is the only sufficiently intense broad-spectrum neutron source in the United States for providing nuclear data necessary for predicting nuclear weapons performance. Some of the instruments and techniques used at WNR to study neutron-induced reactions other than fission are described in this section.

The total neutron scattering cross section is the probability for all energetically allowed reactions to occur. At WNR, which delivers a wide-energy neutron spectrum, the detected neutron's time-of-flight is used to determine the neutron energy. The broad energy range and good neutron energy resolution enable more accurate measurements of the total cross sections of many elements. Washington University and WNR scientists recently demonstrated that measurements could be made on comparatively small samples, allowing the isotopic total cross section of calcium-48 and calcium-40 to be measured with just 4 mg of material (see page 21).

Neutron detection techniques also are used to measure elastic or inelastic scattering. Recent WNR studies using an array of neutron detectors have evolved to become the Chi-Nu experiment, which measures the neutron spectrum produced by neutron-induced fission (see page 7).

Nuclear reactions

Nuclear reactions typically produce gamma rays. As the reaction product nuclei de-excite to their ground states, these gamma rays and gamma-ray cascades maintain characteristics of the isotope that produced them. This cascade not only allows researchers to study the structure of nuclei made in neutron-induced reactions, but also allows them to identify the reaction products. The incident neutron time-of-flight also reveals the energy of the neutron causing the reaction. With that knowledge, researchers can measure the gamma-ray production cross sections as a function of neutron energy. Since researchers can identify the reaction products by virtue of their emitted gamma rays, they can determine reaction rates for inelastic scattering or for various neutron and charged-particle emitting reactions.

At WNR, the main instrument for detecting gamma rays following neutron-induced reactions is the Germanium Array for Neutron Induced Excitations (GEANIE) (see page 23). This array, which was assembled at the Los Alamos Neutron Science Center specifically to measure the plutonium-239(n,2n)plutonium-238 cross section using the above-described technique, also has been used to identify short-lived nuclear isomers and to measure their half-lives. The plutonium-239(n,2n)plutonium-238 cross section is required to interpret data from past nuclear tests.

Some nuclear reactions produce charged particles. Using standard notation, these are referred to as (n,z) reactions, wherein the incident neutron produces a charged particle—a proton or alpha particle, for example. WNR has had a program to perform such measurements for some time, using an array of four charged-particle detector telescopes. Laboratory researchers have used the array for studying such reactions to learn about nuclear level densities in various nuclei.

In addition, this charged-particle array has been used to measure the rates of gas production in structural materials used in nuclear power plants. In such plants, (n,p) reactions produce hydrogen (protons with an electron) and (n,α) reactions produce helium (α plus two electrons). These elements are gases and as these gases increase, the materials' structural properties are degraded by swelling, cracking, and embrittlement. Therefore, determining the rates at which these gases build up is critical, for example, to assessing a nuclear power plant's longevity, an important issue nationally. To advance these studies a new, improved (n,z) facility is planned (see page 24).

Neutrons from WNR are also available for specific nuclear measurements needed by program sponsors. The measurement of the lithium-6 (n,α) cross section for neutrons in the few-MeV energy range is but one example of nuclear data with applications to defense programs. While the cross section for this exothermic reaction is well measured at thermal neutron energies, with an uncertainty of

Neutron total cross section measurements at LANSCE

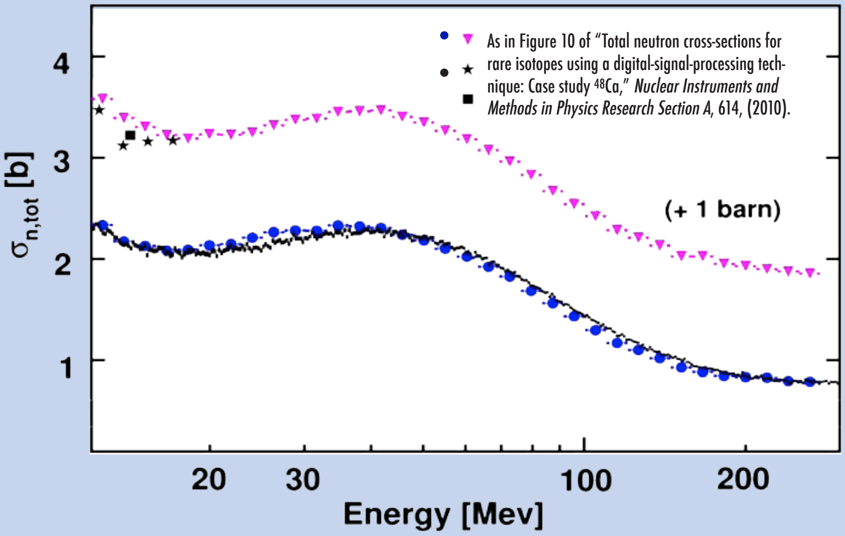
A window into nuclear physics

The Los Alamos Neutron Science Center (LANSCE) contributes to nuclear and defense science by enabling measurements of the various reactions resulting from neutrons interacting with matter. The neutron total cross section—a measure of all of the reactions a neutron can induce—is a basic measure of neutron interactions. LANSCE researchers are performing new and more accurate work on measurements of neutron total cross sections, offering the continued opportunity to discover more about nuclear physics.

More than a decade ago at the Weapons Neutron Research facility, researchers measured neutron total cross sections for a series of elements, covering the periodic table, to high accuracy and over an energy range from 5-600 MeV. To achieve this, tens-of-grams samples of each element were needed.

Today, by applying modern data acquisition techniques in which electronic pulses are digitally analyzed, LANSCE scientists can collect such data at higher rates. This development means the sample size needed to make measurements can be reduced, which creates the possibility of measurements on small isotopic samples, and even radioactive samples, rather than elemental samples. Isotopic samples in large quantities, in many cases, are prohibitively expensive.

Recently, Washington University and Los Alamos scientists performed such a measurement with a 300 mg sample of calcium-48, a rare isotope. Naturally occurring calcium is 97% calcium-40, and only 0.2% calcium-48. This measurement provided valuable information about the stability of nuclei that are very neutron rich or very neutron poor. More measurements of this type are planned.



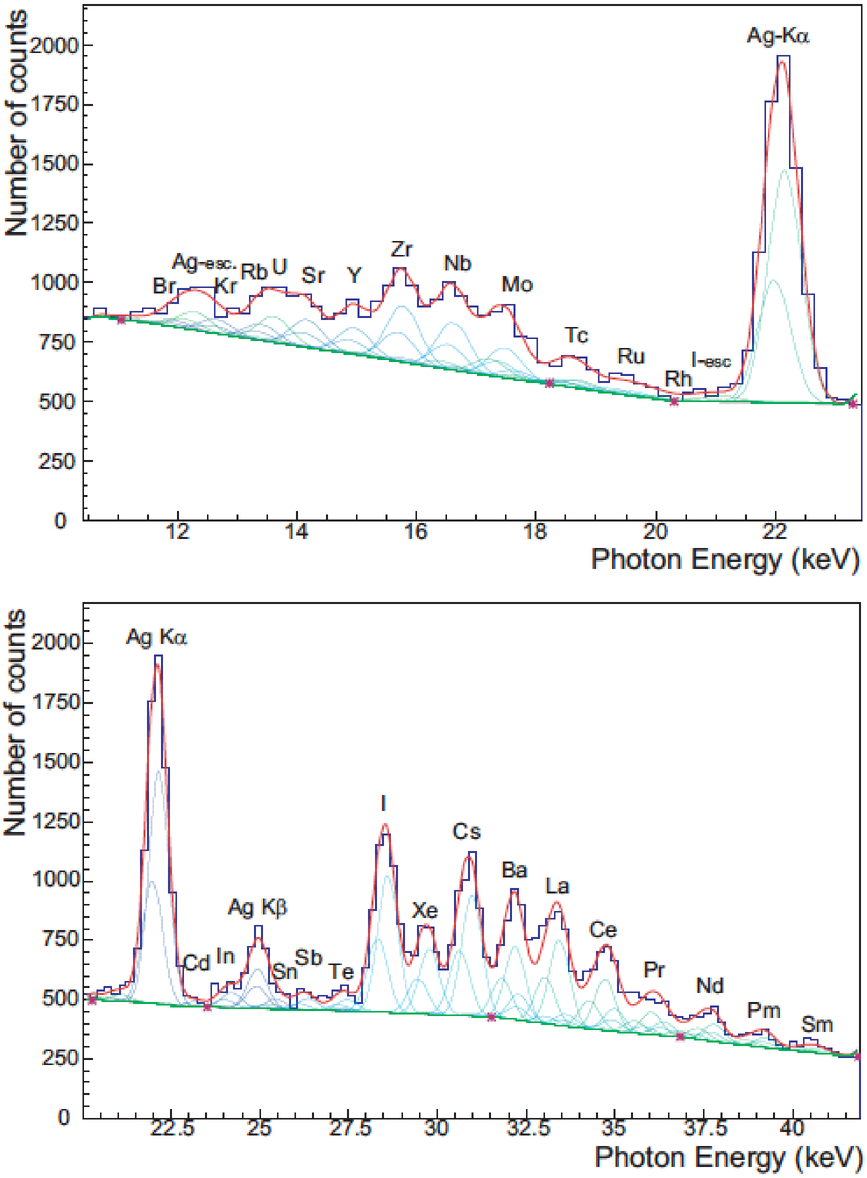
As in Figure 10 of "Total neutron cross-sections for rare isotopes using a digital-signal-processing technique: Case study ^{48}Ca," *Nuclear Instruments and Methods in Physics Research Section A*, 614, (2010).

Total neutron cross-sections ($\sigma_{n,\,tot}$) for calcium-40 and calcium-48. Statistical errors for this work are smaller than the size of markers. For clarity, data for calcium-48 has been shifted up 1 b.

a few percent, it was less well known at MeV energies, with an uncertainty of about 20%. This large uncertainty became an issue for weapons physics simulations of device performance, and it became clear that accurately determining this cross section in this energy range was required. The high-neutron flux available at WNR was used to provide new measurements of this important cross section, reducing its uncertainty to about 5%, and satisfying an important nuclear data need of the weapons community.

Future

LANSCE plans to continue these studies with the expected increase in WNR neutron flux in 2014. Further isotopic total cross section measurements and gamma-ray production data in a variety of cases are a vital part of the plan. The addition of the new Low Energy (n,z) (LENZ) detector array will allow LANSCE to expand its program in (n,z) reaction studies. In addition, LANSCE intends to pursue nuclear data needs in both the weapons and criticality programs for improved elastic and inelastic scattering data and thus evaluated data libraries also.



Example of spectrum deconvolution in terms of x-ray lines. Top: 10-23 keV region. Bottom: 20-41 keV region. The main peaks are labeled. Incident neutron energy is from 0.7-6 MeV corresponding to $\bar{E}$=3 MeV. Although the number of x-ray lines taken into account is large, the number of free parameters in the fitting procedure remains limited to one per element.

GEANIE

Revealing cross sections for weapons physics and basic nuclear physics

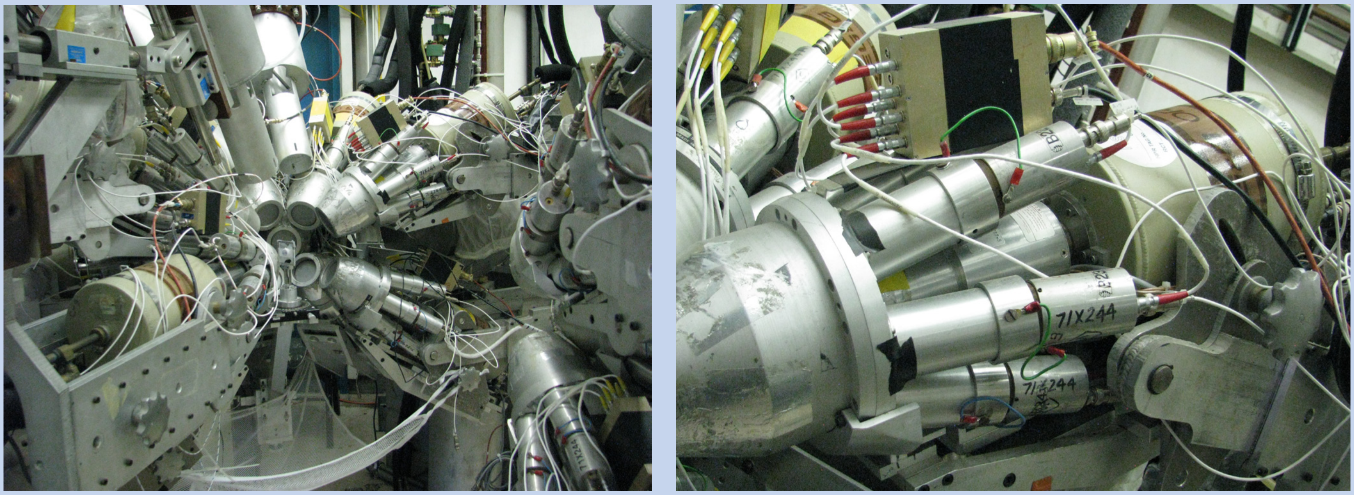
The Germanium Array for Neutron-Induced Excitations (GEANIE) consists of 20 high-purity germanium detectors for gamma-ray spectroscopy. These germanium crystals are cooled to liquid nitrogen temperatures in order to achieve high-energy resolution of the detected gamma rays, and are arranged around a target placed in the neutron beam at the Weapons Neutron Research facility. The result is a powerful instrument for the study of gamma rays produced by energetic neutron-induced reactions.

GEANIE's primary purpose is measuring cross sections of interest to weapons physics, such as isotopes used for radiochemical analysis of past nuclear weapons tests. GEANIE has also branched out to other applications and to basic nuclear physics studies.

In weapons physics, knowing the ratio of plutonium-239 to plutonium-238 in the debris of a nuclear test is an important radiochemical diagnostic. The first experiment performed at GEANIE was the determination of the plutonium-239(n,2n)plutonium-238 cross section. This result was achieved by detecting the gamma rays in the daughter nucleus plutonium-238 as a function of the incoming neutron energy.

In a recent example of a new application, GEANIE produced novel and unique results by measuring x-rays yields following neutron-induced fission, and revealing the x-ray spectrum of fission fragments from the fission of uranium-238. GEANIE also has been used to establish new nuclear levels using (n,n′) and other neutron-induced reactions, and to measure the half-lives of short-lived nuclear isomeric states.

For the next generation of large neutrinoless double beta decay experiments in both the United States and Europe, scientists are using GEANIE measurements to investigate possible backgrounds due to environmental neutrons. These experiments, which involve large international collaborations, seek to observe the rare decay mode and require large detectors with extremely low and well-characterized backgrounds. This capability makes them sensitive to environmental, neutron-induced reactions, and GEANIE and the Weapons Neutron Research facility are ideal for characterizing the sensitivity to these backgrounds.



Left: The Germanium Array for Neutron-Induced Excitations of high-resolution gamma-ray and x-ray detectors is shown with a section of the array pulled back for access to the sample mount. The net is to catch any dropped samples or tools. Right: A bismuth germanate detector shields the germanium detector and allows backgrounds in the gamma-ray spectrum to be significantly reduced.

LENZ

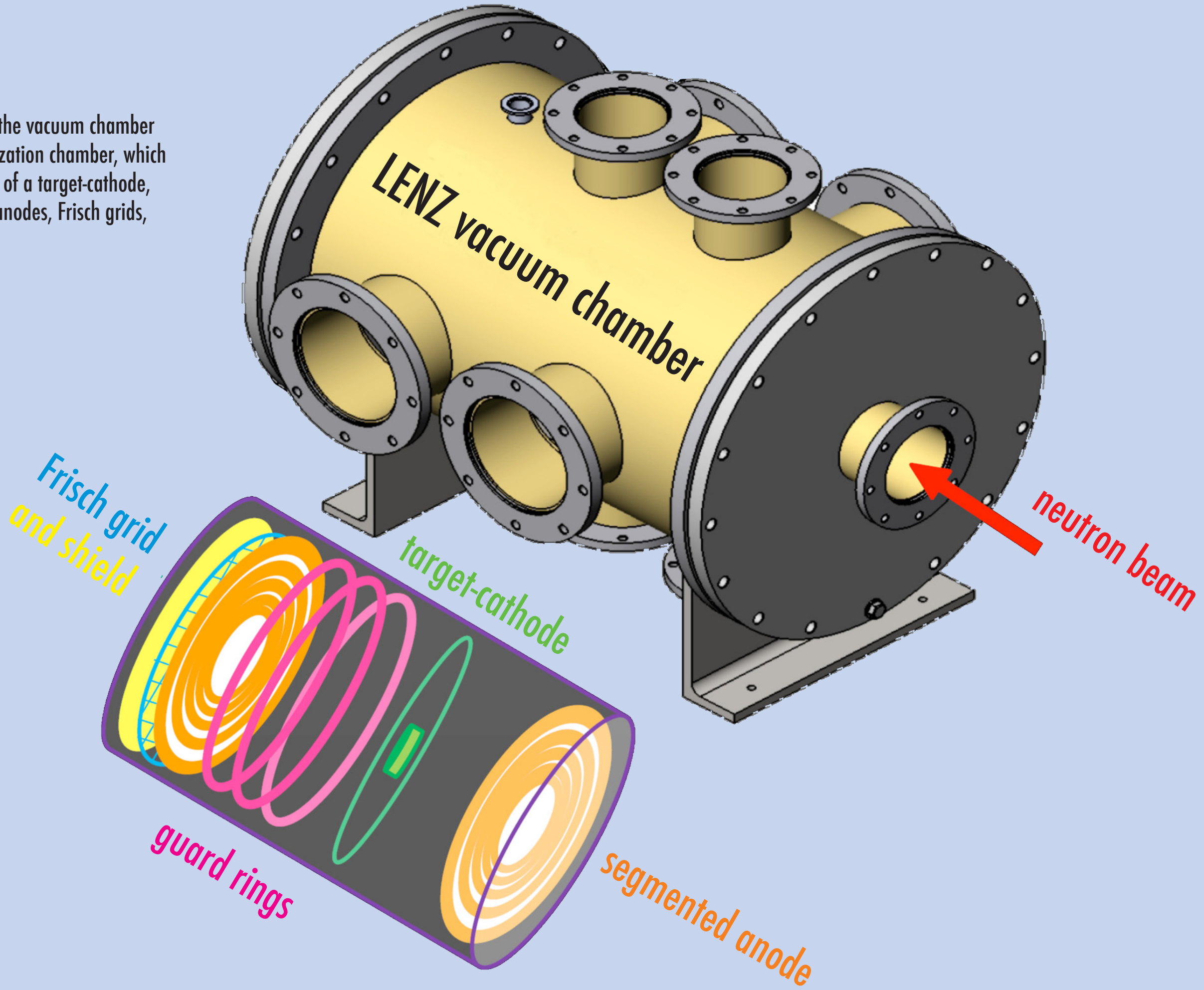
A new device for low energy neutron-induced charged-particle (Z) studies

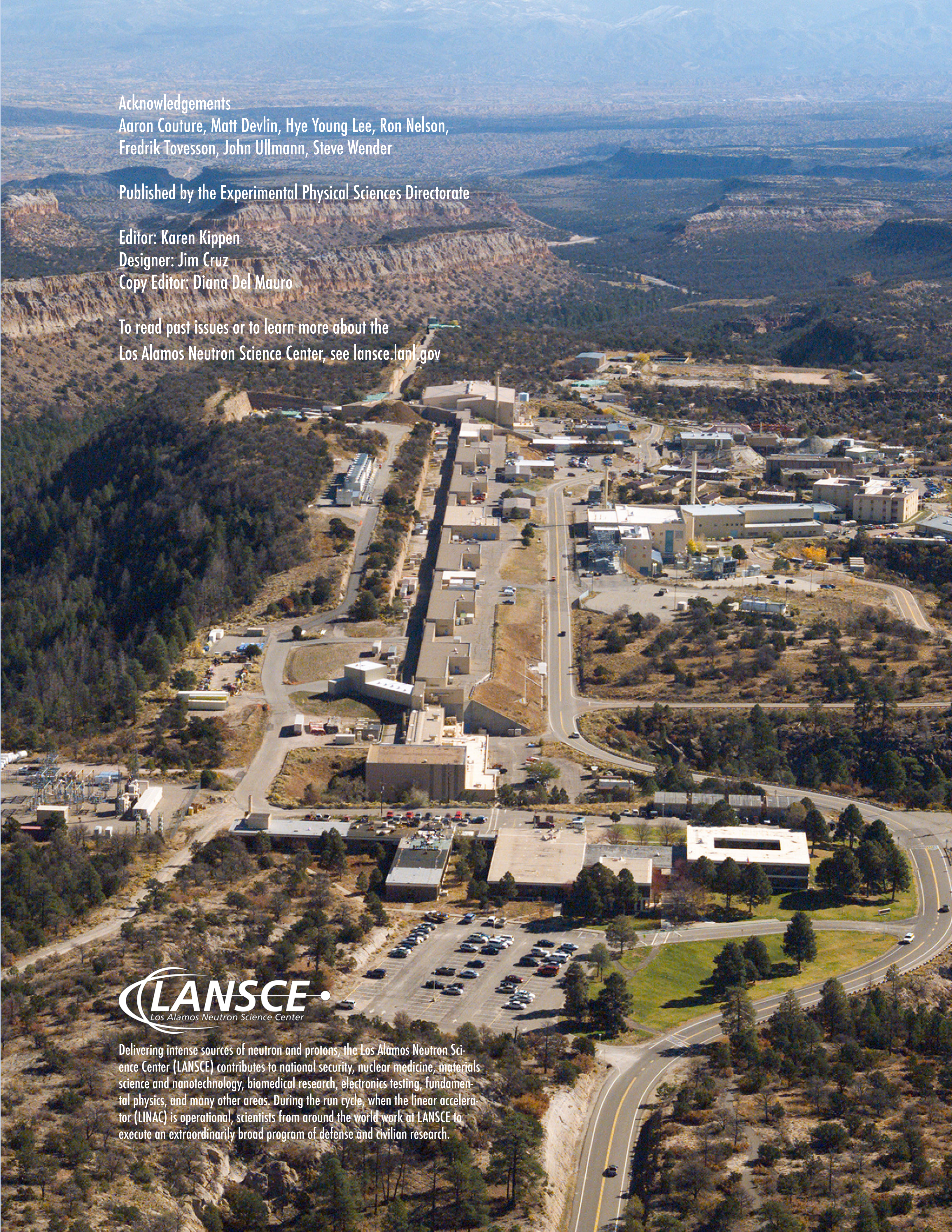
To understand s-process nucleosynthesis in stellar evolution modeling (see Nuclear Astrophysics, page 12), better knowledge of (n,α) and (n,p) nuclear reactions at low and MeV energies is key. For deducing nuclear level density information and optical potentials—data critical for predicting reliable nuclear reaction cross sections using the Hauser-Feshbach formula, neutron-induced reactions at higher neutron energies up to about 50 MeV are used. For applications, these reactions are important for understanding structural materials in reactor design and to the Laboratory's programmatic mission.

Located at the Los Alamos Neutron Science Center, the Low Energy Neutron-induced Charged-particle (Z) Chamber (LENZ) will be used to study neutron-induced charged particle reactions for neutrons from thermal to several-MeV energies. The LENZ chamber is composed of an ionization detector with segmented anodes and Frisch grids for high-efficiency and low-detection thresholds for low-energy measurements.

Upgraded from the previous chamber at the Weapons Neutron Research facility, LENZ will offer vastly improved solid-angle coverage. To collect full-energy deposits from energetic protons for high-energy measurements, LENZ will be coupled with segmented silicon detectors. To take advantage of all possible beam energy ranges, LENZ will run at the Lujan Neutron Scattering Center flight path 12 and Weapons Neutron Research facility flight path 15R. Funded by Los Alamos's Laboratory Directed Research and Development Early Career program, the project is expected to be complete by fiscal year 2015.

Diagram of the vacuum chamber and the ionization chamber, which is composed of a target-cathode, segmented anodes, Frisch grids, and shields.





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LANSCE
Los Alamos Neutron Science Center

Delivering intense sources of neutron and protons, the Los Alamos Neutron Science Center (LANSCE) contributes to national security, nuclear medicine, materials science and nanotechnology, biomedical research, electronics testing, fundamental physics, and many other areas. During the run cycle, when the linear accelerator (LINAC) is operational, scientists from around the world work at LANSCE to execute an extraordinarily broad program of defense and civilian research.

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