Lawrence Livermore National Laboratory

September 2019

Science & Technology REVIEW

MATERIALS UNDER RAMP COMPRESSION

Also in this issue:

- Livermore's Offsite Fellows Program
- Celebrating New Element Discovery
- A Detector for Revealing Neutrinos

About the Cover

For the past decade, a team of scientists at Lawrence Livermore's National Ignition Facility has been using the world's most energetic laser to study solid materials' equations of state at unprecedented pressures. Now, as the article beginning on p. 4 describes, scientists are applying an innovative technique called ramp compression to more gently and slowly put the squeeze on materials. These experiments help researchers better understand the physics of solids compressed to extreme densities under a wide range of pressures. Shown on the cover is a partial view of a ramp compression target as seen through a cone-shaped device attached to the hohlraum wall.

Cover design: Mark Gartland

About *S&TR*

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Beetle Models Biofuel Production

Horned passalid beetles (*Odontotaenius disjunctus*) transform low-nutrient wood into food for their colonies as well as beneficial organic matter for forest soils. Lawrence Livermore bioscientist Jennifer Pett-Ridge, with other members of a team led by Lawrence Berkeley National Laboratory's Javier Ceja-Navarro, have examined the beetles' ability to achieve this chemically challenging goal as a model for renewable fuel production. The research was published in the March 11, 2019, edition of *Nature Microbiology*.

The beetles break down lignin and cellulose in fallen logs and convert the material into simple sugars and organic acids via partnership with microorganisms in their digestive tracts and a compartmentalized gut. Each section of the gut supports a different microenvironment—some acidic, some anaerobic—that sequentially degrades the wood and extracts energy. "We study these beetles because they are a natural biorefinery," says Pett-Ridge. "Understanding how evolution has solved the complex lignocellulose-to-fuel conversion process can help us design better industrial mimics and find novel enzymes or pathways."

Non-food, lignocellulosic feedstocks proposed for biofuel production share a similar composition with the beetles' woody food source, making the insects' digestive process a model for efficient conversion of plants into hydrogen, methane, ethanol, and other bioenergy products. The team defined the digestive microorganisms and identified gut anatomical characteristics contributing to efficient metabolism of lignocellulosic material. Says Pett-Ridge, "Gaining insight into how the gut microbiome populations interact to deconstruct lignocellulosic materials to sugars or potential biofuels could potentially aid in the optimization of industrial cellulosic degradation."

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Researchers Solve a 50-Year-Old Puzzle

An international team, including Lawrence Livermore scientists, has closed a long-standing gap in physicists' understanding of beta decay—a process in which protons inside atomic nuclei convert into neutrons, or vice versa, to form the nuclei of other elements. Their work, published in the March 11, 2019, edition of *Nature Physics*, helps explain why experimental beta decay rates in atomic nuclei are slower than calculated rates.

Historically, nuclear physicists have described the beta decay rate by artificially scaling the interaction of single nucleons with the electroweak force, a process referred to as "quenching." However, predictive methods require accurate calculations of the structure of both the mother and daughter nuclei and how nucleons (individually and as correlated pairs) couple to the electroweak force that drives beta decay. The team simulated decay rates from light to heavy nuclei using high-performance computing resources at Livermore and Oak Ridge National Laboratory, and demonstrated that their approach works consistently across nuclei where ab initio calculations are possible. "By combining modern theoretical tools with advanced computation, we have shown that for a considerable number of nuclei, we can reconcile the discrepancy between experimental measurements and theoretical calculations," says Livermore nuclear physicist and co-author Kyle Wendt. Researchers also demonstrated that the apparent quenching arose from forces within nuclei.

The research effort sets the path toward accurate predictions of beta decay rates for unstable nuclei in violent astrophysical environments, such as supernova explosions or neutron star mergers. Livermore nuclear physicist Sofia Quaglioni, co-author of the paper, says, "The methodology in this work may hold the key to accurate predictions of the elusive neutrinoless double beta decay, a process that, if seen, would revolutionize our understanding of particle physics."

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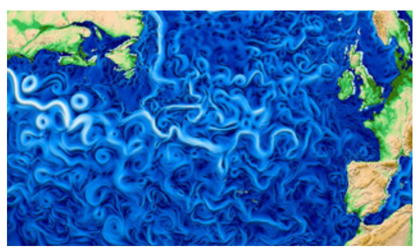

Reducing Climate Model Uncertainty

Earth System Models (ESMs), which are run on advanced computers to simulate aspects of Earth's variability (see image at left), have improved and grown in complexity since their first use in the 1970s, but inconsistencies remain. In a study of the "emergent constraint" (EC) approach for ESM evaluation, Lawrence Livermore scientist Stephen Klein and collaborators investigated EC in the models and found that this method may improve ESMs by focusing on the variables most relevant to climate projections. The research appeared in the March 18, 2019, edition of *Nature Climate Change*.

Trusting climate models requires a mechanistic understanding of the reason for the relationship between the current climate variable and how the variable will change in an evolving climate. The EC approach combines climate simulations with contemporary measurements and seeks variables from the current climate to narrow uncertainties in projections for climate change parameters, such as temperature. "The EC approach offers a promising way to reduce key uncertainties in future climate," says Klein, co-author of the paper. "It could also pave the way for further discoveries about climate system behavior and reduce the uncertainty in critical aspects of climate change."

With support from the Department of Energy's Office of Science, the research team created a framework to assess EC methods and provide indicators that EC is moving toward trusted statistical relationships. According to Klein, future applications of an EC approach include modeling to identify climate system tipping points. More consistent climate change projections could help society better plan for future environmental and economic impacts.

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Studying Matter under Extreme Conditions

HIGH-ENERGY-DENSITY (HED) science is the study of matter under extreme pressure and temperature. Matter subject to these conditions exhibits a wide range of interesting and often unpredictable behavior that transforms atomic bonds and material structures, creating complex chemical reactions, highly ionized materials, and plasmas. HED science exemplifies the dual-purpose research we conduct at Lawrence Livermore—working to support both our core nuclear weapons research and the fundamental science explorations that underpin our mission-focused work.

Today, HED science is a growing research discipline at the Laboratory. It has proven essential to modeling nuclear weapons, advancing the pursuit of controlled fusion energy, and understanding the composition and dynamics of planets and stars. An increasingly multidisciplinary field, HED leverages Livermore strengths in high-performance computing (HPC), materials science, chemistry, physics, and engineering.

A major focus of HED experiments is determining a material's equation of state (EOS), or the relationship between pressure, temperature, and density. As described in the article beginning on p. 4, a useful technique for obtaining an EOS is ramp (or quasi-isentropic) compression. In this technique, refined over the past decade with important contributions from Livermore researchers, a material is pressurized "gradually," over small fractions of a second. As a result, heating is limited to lower temperatures, maintaining a solid crystalline state at higher pressures. In contrast, a standard, nearly instantaneous shock raises temperatures significantly, melting or even ionizing a sample under investigation and limiting the study of its properties.

The 192-beam National Ignition Facility (NIF), the largest and most energetic laser in the world, is superbly equipped for conducting ramp compression experiments. NIF routinely creates temperatures and pressures similar to those that exist in the interiors of stars, the cores of planets inside and outside our solar system, and detonating nuclear weapons. The laser's high energy and power, pulse shape control, and state-of-the-art diagnostics make NIF the premier facility for ramp compression at pressures measured in terapascals (10 million times Earth's ambient air pressure).

Scientists adjust NIF's pulse shape by varying the power of individual lasers over 31 billionths of a second to match the material under investigation and keep it relatively cool and highly compressed. Determination of the pulse shape is guided by high-resolution, predictive simulations performed on Lawrence Livermore's world-class HPC resources. Over the decades, Livermore scientists have pioneered advanced scientific modeling codes on some of the world's most powerful computers.

Ramp compression experiments draw upon our expertise in materials science, precision machining, and metrology (measurement science) to create submillimeter targets comprising intricate assemblies of extremely small components, including a stepped target with thicknesses ranging from 50 to 100 micrometers. Designing, machining, and assembling these parts requires an integrated team of highly skilled physicists, materials scientists, chemists, engineers, technicians, and machinists. The exquisitely manufactured and characterized targets are part of a larger Livermore effort to create advanced—and cost-effective—manufacturing processes that produce structurally and compositionally tailored materials with novel properties, shapes, and interior structures.

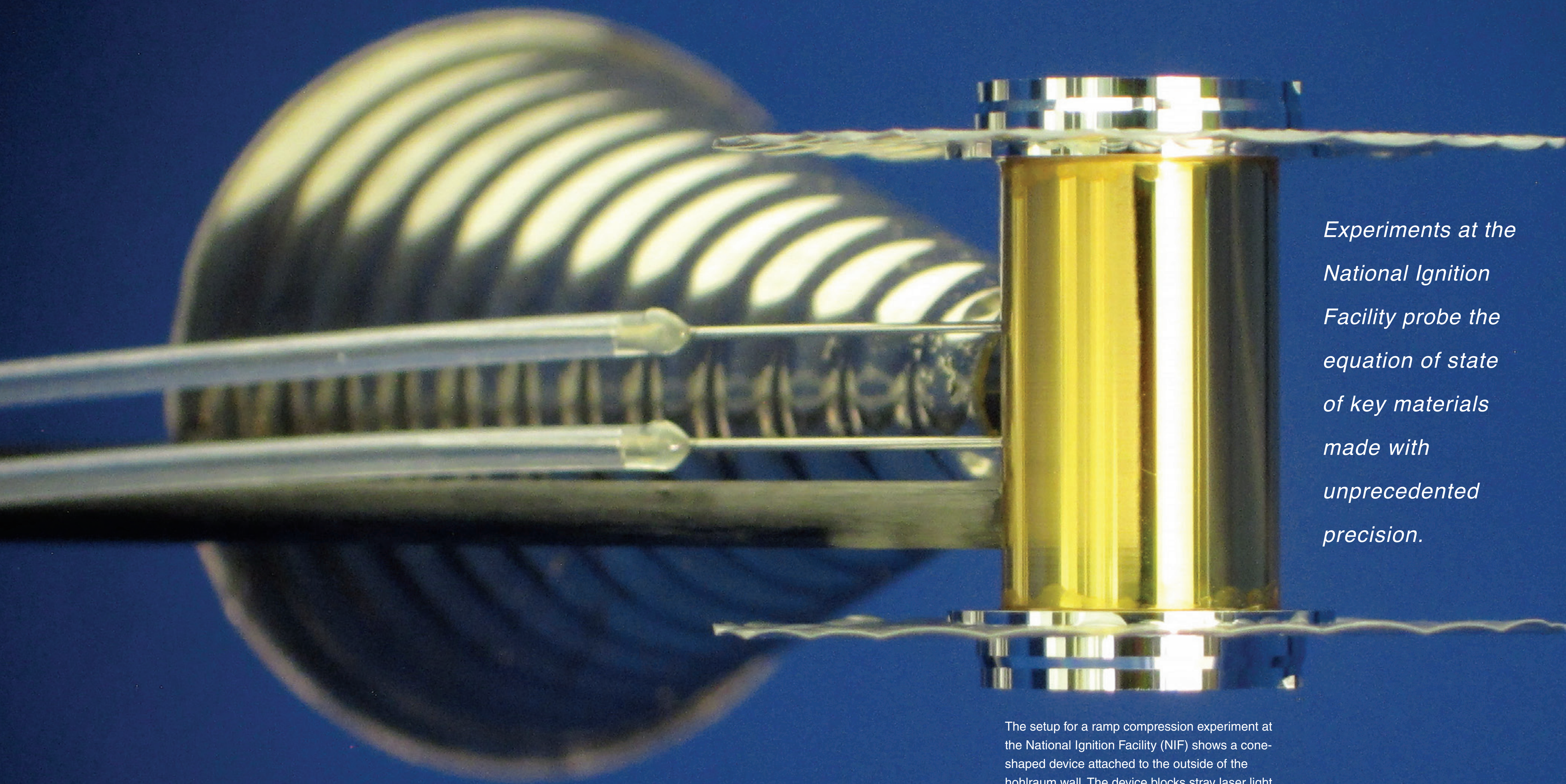
Precise crafting and metrology of targets' dimensional characteristics have significantly reduced uncertainties in the experimental data. Experimental measurements are highly susceptible to manufacturing imperfections, so material samples are diamond turned to astonishing flatness and parallelism, equivalent to trimming a football field to within the thickness variation of a No. 2 pencil lead.

Ramp compression experiments on high-*Z* (high atomic number) materials support stockpile stewardship, the effort to assure the safety, security, and effectiveness of our aging nuclear weapons stockpile without relying on nuclear testing. At the same time, NIF operates as the premier national user facility for HED science. The Laboratory's Discovery Science program enables a broad national user community to perform ramp compression experiments that in essence create a microphysics observatory for studying materials under the extreme conditions of astrophysical environments.

Matter at HED conditions is found throughout the universe, especially the interiors of planets and stars. Results from discovery science ramp compression experiments have been published in leading scientific journals. For example, experiments have provided insights into the possible interior structure composition of large rocky exoplanets known as "super Earths." HED science has entered a particularly exciting era, and the Laboratory is proud to be playing a leading role.

■ Glenn A. Fox is the associate director for Physical and Life Sciences.

GENTLY COMPRESSING MATERIALS TO RECORD LEVELS



The setup for a ramp compression experiment at the National Ignition Facility (NIF) shows a cone-shaped device attached to the outside of the hohlraum wall. The device blocks stray laser light that can interfere with diagnostic measurements.

Experiments at the National Ignition Facility probe the equation of state of key materials made with unprecedented precision.

FROM the instantaneous detonation of a nuclear weapon or high explosive to the evolution of a planet's core over millions of years, a material's equation of state (EOS) is required to fully understand the relationship between its pressure, temperature, and density. Lawrence Livermore researchers must determine accurate EOS data of key elements to inform the computational models of material behavior that support National Nuclear Security Administration (NNSA) applications. These models drive simulations that demonstrate how materials respond to enormous pressures and high temperatures and help to assure that the nation's nuclear weapons remain safe, secure, and effective.

For the past decade, a team of scientists has been using Lawrence Livermore's National Ignition Facility (NIF), the world's largest and most energetic laser, to determine EOS data for solid materials at pressures never before achieved, up to 5 terapascals (TPa), or 50 million times Earth's ambient air pressure. Approximately 400 experiments are conducted at NIF annually, many of which support NNSA's Stockpile Stewardship Program, including inertial confinement fusion (ICF) experiments. For a few billionths of a second during an ICF experiment, NIF's 192 lasers duplicate the same temperatures, densities, and pressures found within the interiors of stars and planets and detonating nuclear explosives. About 15 experiments per year are aimed at researching materials' equations of state. In addition, about four shots a year are devoted to discovery science EOS experiments that help

A partial view of the physics package used in ramp compression experiments, as seen through the cone-shaped device attached to the hohlraum's outer wall, shows the stepped surface of the target material (inset). Using the cone to block out stray light, the VISAR (Velocity Interferometer System for Any Reflector) diagnostic (not shown) measures the speed at which each of the four steps move as the compression wave passes through them.

reveal the likely composition of stars and planets. (See the box on p. 9.)

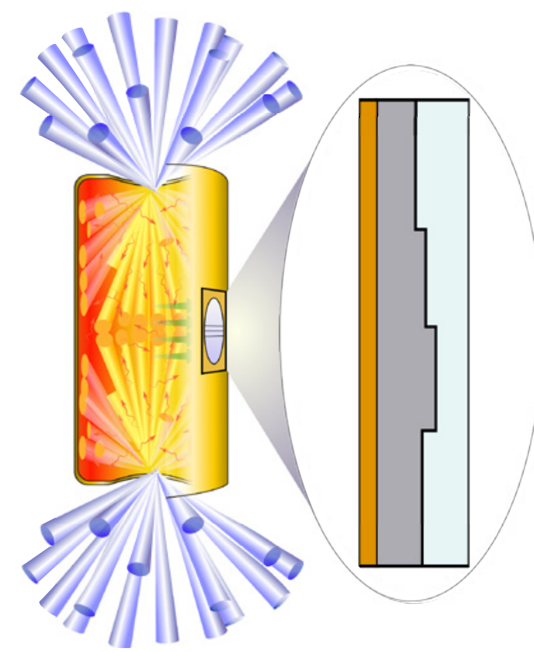
For decades, the traditional method for determining a material's EOS was to send a sudden shock through a material and measure its response. This shock compression method relies on lasers, gas guns, and other tools to launch a virtually instantaneous shock wave through a sample, rapidly melting it. However, shock compression limits the combination of pressures, temperatures, and densities that may be reached to a narrow portion of the material's EOS. To reach a broader set of conditions, an alternative route—ramp compression—is proving immensely useful.

Creating a Gentler Compression

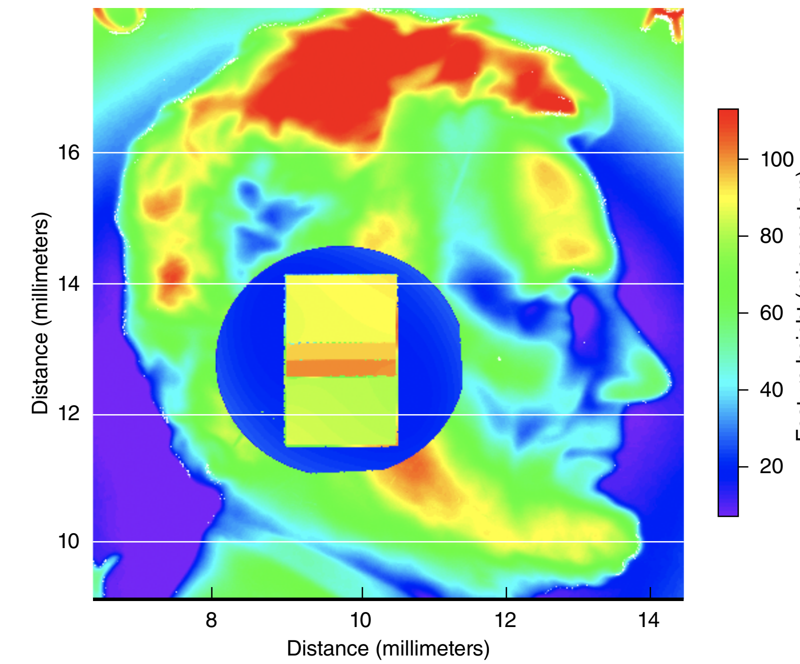
Ramp compression experiments on NIF apply a carefully tailored laser pulse shape that more "softly" compresses a material without forming a shock. Jon Eggert, group leader for Dynamic Materials Properties, explains, "NIF allows us to control the energy of the beams as a function of time so we can compress the sample more slowly. NIF is fantastic for ramp compression." The technique is helping scientists better understand the physics of solids compressed to extreme densities under a wider range of pressures and much lower temperatures.

By controlling the laser's energy (up to 750 kilojoules) and power (up to 10 terawatts) over 31 nanoseconds (billionths of a second), scientists can customize the pulse shape precisely to match the material under investigation. "The quality of the pulse shape largely determines the quality of the EOS data," says Tom Arsenlis, associate program director for Focused Materials Science. Simulations conducted by physicist Dave Braun are used to optimize the shape of the laser pulse. The simulations use a radiation hydrodynamics code that models the full geometry of the laser and its target. Together, the laser's pulse-shape control, high energy and power, and state-of-the-art diagnostics make NIF the premier facility for ramp compression at pressures measured in TPa.

Ramp compression keeps the compressed target material relatively cool—less than 10,000 kelvin (about 9,700°C)—compared with 30 million kelvin in shock compression experiments. "We end up cool and extremely compressed," says Livermore senior scientist Jim McNaney. During shock experiments, in contrast, most of the energy goes into heat, limiting the degree of compression to about four times the starting density. "With ramp compression, we're operating in regions where we have no existing data," says McNaney.



During ramp compression experiments, laser light enters the top and bottom of a hohlraum. The light is then converted to x rays, which heat and ablate the back side of a multilayered physics package placed over a tiny hole in the hohlraum's wall. (inset) The physics package consists of an underlying copper ablator (left), a four-step target material (middle), and a layer of lithium fluoride (right).

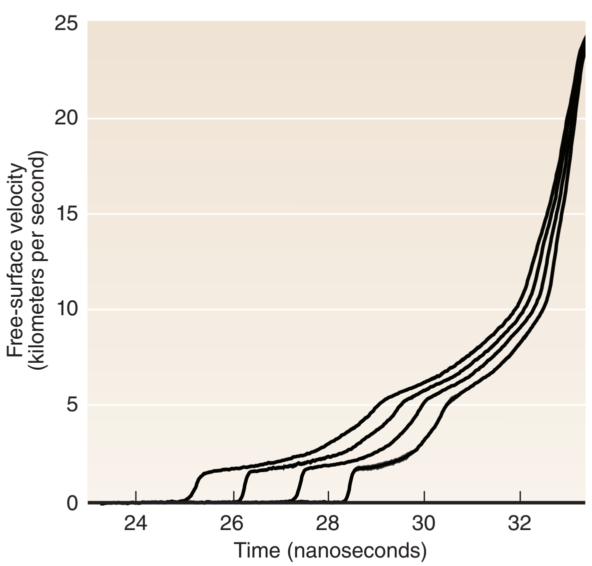


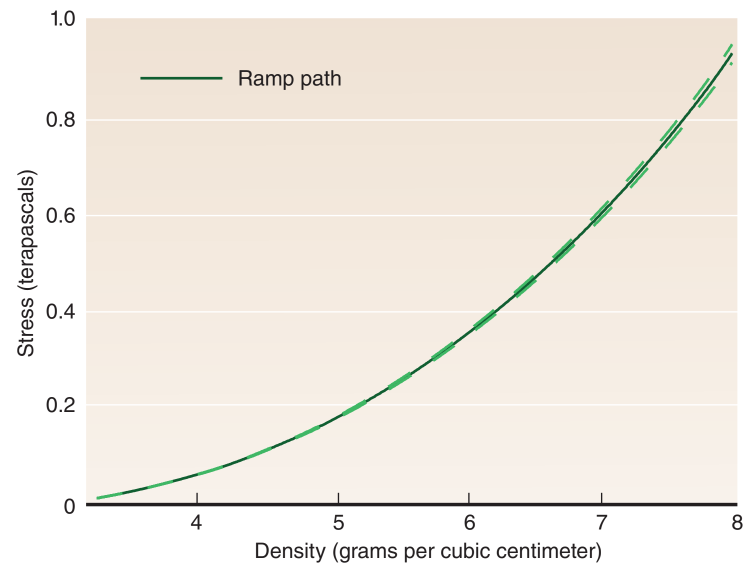
Superimposed onto a penny is the miniscule stepped target attached to the underlying copper ablator (dark blue). The target is machined from one block into four different thicknesses ranging from approximately 50 to 100 micrometers. Colors represent the heights of the four steps as compared to those of the penny's features.

Ramp Compression Up Close

EOS ramp compression experiments at NIF typically use 168 of the facility's 192 beams. The light converges in the target chamber onto a tiny millimeter-sized, vertically aligned cylinder called a hohlraum. The hohlraum is filled with neopentane gas, which holds off collapse of the cylinder's gold-coated walls when they are hit by laser light. Thin windows at the top and bottom, where the laser light pours in, contain the gas until the initial, 2-nanosecond laser pulse blows out the windows. Subsequently, the pulse declines in energy, and then slowly increases (or ramps) over the next 29 nanoseconds as it crushes the target.

Upon illuminating the hohlraum walls, NIF laser light produces x rays that heat and ablate the back side of a multilayered physics package mounted over a 3-millimeter-diameter hole in the hohlraum's wall. The physics package consists of a circular underlying copper ablator (measuring 35 micrometers thick), a stepped target material—one block machined to four different thicknesses ranging from about 50 to 100 micrometers—and, frequently, a layer of transparent lithium fluoride. The copper ablator, irradiated by the x rays, drives a compression wave through the stepped target. The 300-micrometer-thick layer of lithium fluoride helps seal the material under investigation and prevents it from breaking up during a phase transition. The lithium fluoride window is transparent so that it will not interfere with the red laser used by the principal diagnostic called VISAR (Velocity





(left) Velocity profiles measured at the surface of the metal-coated lithium-fluoride sample show that thicker steps launch at a later time and display steeper rises from nonlinear compression. (right) A graph showing the final stress (pressure) versus density of the sample, with the curvature of the plot illustrating the nonlinear compression of the material. The dashed green lines represent the experimental uncertainty in the results.

Interferometer System for Any Reflector). “Lithium fluoride is nature’s clearest crystal,” says postdoctoral researcher Leo Kirsch.

VISAR Sees All

No instrument exists for directly measuring a material’s EOS. Instead, the team uses the VISAR diagnostic to record velocity versus time at various points on the surface of the stepped target during the experiment. VISAR measures the speed (typically to tens of kilometers per second) at which each of the four material steps move as the compression wave passes through them. Surrounded by a metal cone that keeps out stray laser light, VISAR captures the Doppler shift in wavelength (the phase change) of reflected light over time caused by the compression wave. As the wave pushes through the material, the material’s density increases and so does its sound speed.

Analysis of VISAR data then reveals the sound speed, pressure, and density of the target material being compressed, from which the EOS is derived. “The experiments provide precise measurements of material properties to people who work on the codes, and the data helps to improve the predictions of the codes,” says Kirsch. In addition, post-shot simulations help prepare for follow-on experiments.

Methodical Platform Evolution

Eggert says that prior to the year 2000, ramp compression experiments were limited to about 0.01 TPa. Soon after, several additional tenths of a TPa were achieved. (As a point of reference, the center of the Earth is considered to be about 0.35 TPa). The EOS ramp compression platform for NIF was developed following experiments on Livermore’s Janus laser and then on the Omega laser at the University of Rochester’s Laboratory for Laser Energetics.

The first EOS ramp compression experiments at NIF focused on well-characterized materials such as copper, aluminum, and gold, to validate the experimental platform. Many experiments were conducted on gold because the material is a standard in the high-pressure community. Says physicist Amalia Fernandez-Panella, “We wanted to start with simple materials and develop analytical techniques with the goal of using much more complex elements comprising the actinides.” According to Livermore physicist Ray Smith, researchers have since demonstrated smooth EOS ramp loading pressures into the TPa regime on iron, platinum, lithium fluoride, diamond, tungsten, tantalum, iridium, lead, and tin. The campaign was initially headed by physicist Dayne Fratanduono and is now led by Smith.

Eggert notes that another method to determine EOS without imparting a violent shock uses small diamond anvil cells (DACs), a “static” technique Livermore researchers have helped to pioneer (*S&TR,* July/August 2019, pp. 20–23). DACs compress micrometer-sized samples between two brilliant-cut diamonds, generating pressures of several tenths of a TPa. DAC experiments last much longer than NIF shots—from milliseconds to minutes to even days—generating temperatures much lower than NIF’s.

Another vehicle for EOS ramp compression experiments is Sandia National Laboratories’ Z Pulsed Power Facility, located in Albuquerque, New Mexico. At this facility, a series of large capacitors delivers up to 26 million amps to a centimeter-size target over a period of 100 to 200 nanoseconds. The facility produces pressures of 0.4 to 0.5 TPa and material temperatures similar to those in NIF EOS ramp compression experiments.

Three Different Campaigns

EOS experiments constitute one of three campaigns on high-energy-density materials involving ramp compression that provide important information for stockpile stewardship. McNaney leads the materials integrated experimental team, a group of 12 to 15 physicists who work on the three campaigns. He notes that while the two other campaigns—x-ray diffraction experiments called TARDIS (Target Diffraction In-Situ) and strength experiments—on their own generate vital data, they also “help us to interpret EOS data.”

In TARDIS experiments, ramp-compressed samples are probed with diffracted x rays from an x-ray source foil. The resulting diffraction lines provide insight into phase changes, or structural transitions, which can occur in materials under extreme pressure. In strength experiments, ripples imprinted in a material grow in response to the pressure wave as it pushes against the target. The ripples’ rate of growth is inversely related to the material’s strength. Physicist Suzanne Ali explains, “We measure different aspects of material response and then put everything together to obtain a more complete picture.”

Nearly Impossible Specifications

The tiny target sizes and demanding experimental requirements make data highly susceptible to manufacturing imperfections. As a result, multilayered EOS targets must meet precise specifications for dimensions, surface finish, and alignment. As experimental diagnostics improve, an even greater demand for precision in target fabrication is sure to arise.

A team of about 15 machinists, engineers, assemblers, and mechanical designers is responsible for producing exquisitely machined targets that meet

Discovery Science Looks at Exoplanets

About 8 percent of overall shot time at the National Ignition Facility (NIF) is set aside for discovery science experiments that study the makeup of stars, planets, plasmas, and materials under extreme conditions. Physicist Ray Smith has been guiding many equation-of-state (EOS) experiments for the Discovery Science Program, which is open to researchers from outside the Laboratory.

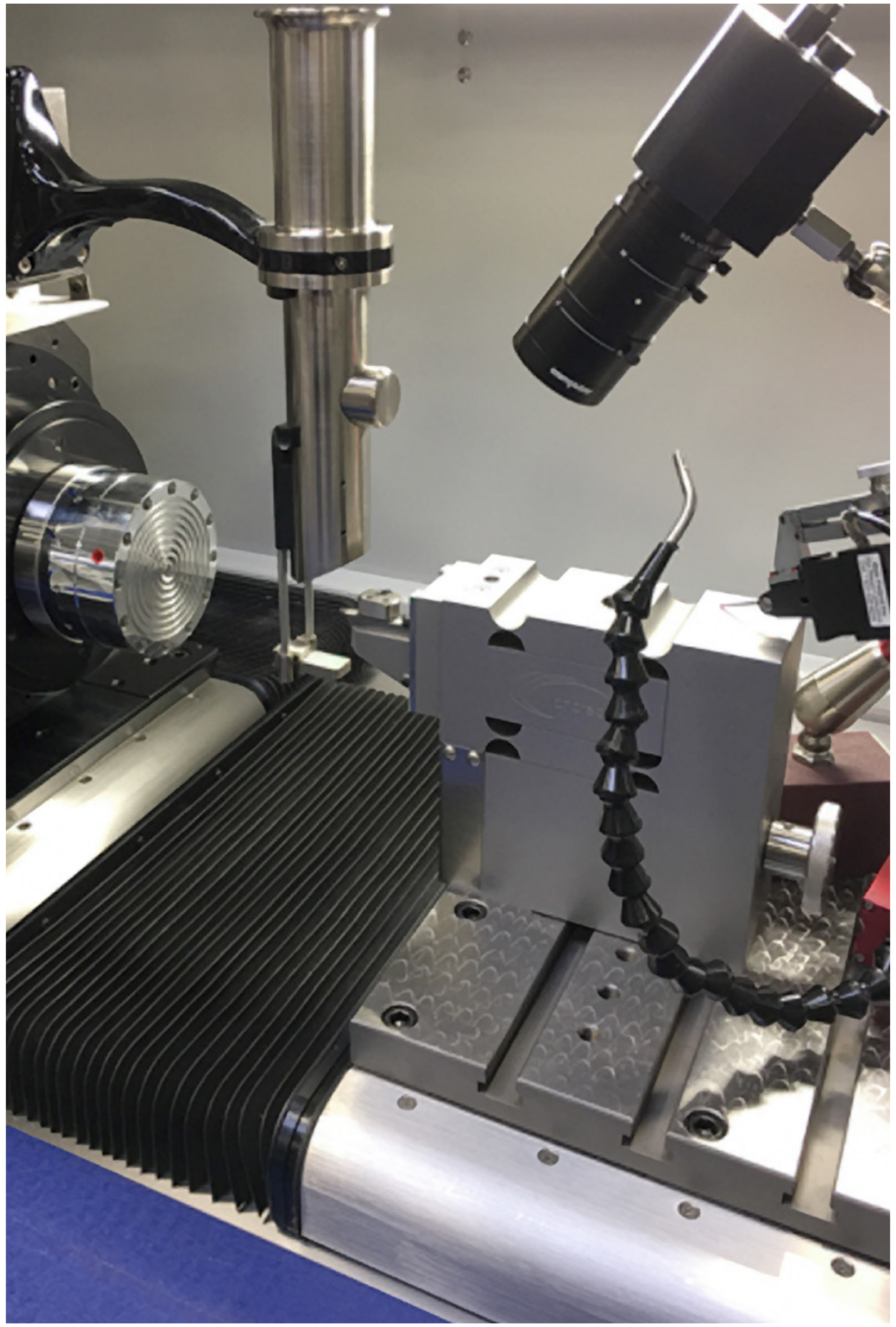
The reduced temperature generated by EOS ramp compression experiments at NIF makes these tests highly relevant to the study of high-pressure physics considered to underlie the structures of stars and, especially, planets both in our solar system and beyond. Thousands of extrasolar planets have been identified, some smaller than Earth and others more massive than Jupiter. NIF allows scientists to duplicate the extreme conditions considered to exist in their interiors.

Scientists are particularly interested in exoplanets known as “super Earths”—extrasolar bodies 3 to 20 times more massive than Earth, with pressures at their cores from 3 to 5 terapascals (TPa). EOS experiments at NIF provide clues to how these exoplanets might have formed billions of years ago, their interior makeup, and whether they could support an atmosphere or even sustain surface conditions suitable for some form of life.

Such planets are thought to contain an iron-alloy core, similar to Earth. A model of a planet’s interior cannot be directly based on EOS data gathered at high temperatures through shock compression experiments. Ramp compression experiments are more suitable because of the lower temperatures they produce. The standard technique for studying conditions relevant to the inside of planets used to be extrapolating data obtained with a diamond anvil cell (DAC). However, a DAC cannot produce the peak pressure of extrasolar super Earths (about 0.35 TPa), Saturn (4 TPa), Jupiter (7 TPa), and Neptune (0.8 TPa). Neither can DAC experiments produce the higher temperatures thought to exist in many planets’ cores. “The only way to recreate the interior conditions of large planets is through ramp compression on NIF,” says Smith.

Discovery science shots have used NIF to subject multiple thicknesses of diamond to ramp compression. (Carbon, from which diamond is formed, is important in planetary science.) Ice giant planets such as Neptune and Uranus may have diamond-rich layers in their interiors, as may exoplanets many times more massive than Earth. The team’s ramp compression experiments, conducted in 2011 and 2012, reached peak pressures of 5 TPa, 20 times higher than the pressure in previous DAC results.

NIF discovery science experiments on iron have aided the modeling of rocky planets including many super Earths. In 2018, a team from Lawrence Livermore, Sandia National Laboratories, Princeton University, the University of California at Berkeley, Johns Hopkins University, and the University of Rochester conducted EOS ramp compression experiments at NIF, generating pressures of 1.4 TPa. The team’s work was featured on the cover of the journal *Nature Astronomy* in 2018. The research is important because Earth’s magnetosphere, which helps to protect life from the Sun’s solar wind, magnetic storms, and harmful cosmic rays, may be generated by the circulating molten iron in Earth’s core.



During target fabrication, a camera projects onto a monitor a magnified image of the part being machined to capture its tiny dimensions.

increasingly exacting standards for thinness and uniformity. Any surface roughness (variation in thickness), for example, causes instabilities that distort the pressure wave and make data unreliable. As Livermore's Target Fabrication Manager Abbas Nikroo notes, many of the precision machining and target assembly techniques used daily at NIF were developed both in-house and in conjunction with vendors. Nikroo points to a long Livermore history of precision machining and metrology (measurement science).

Most components are machined in a Lawrence Livermore facility equipped with high-precision diamond turning lathes capable of nanometer precision and mirror-like surface finishes. The machines are temperature controlled and isolated from vibration, including minute Earth tremors. To capture the targets' tiny dimensions, a camera projects onto a monitor just above the machine a magnified picture of the part being machined.

Over a two-week period, the copper ablator, stepped target, and overlaying lithium fluoride window are slowly machined so that the thickness variation does not exceed 50 nanometers per millimeter and the stepped target has a surface finish comparable to a nearly perfect mirror. Parts are attached with a soluble adhesive to a 100-millimeter-diameter diamond-turned disk held by vacuum on a lathe spindle turning about 1,700 revolutions per minute. The adhesive accumulates in tiny grooves machined into the disk to ensure a smooth rear surface. Stepped targets are machined to the specified micrometer thicknesses and profile that are verified with double-sided white light interferometry to ensure uniformity and parallelism. Adding to the machining challenge is the requirement that the four miniscule steps be cut from a single block of material.

Approximately two weeks are required to assemble the physics package. Parts are secured by a uniform thickness of epoxy glue, which requires 16 hours to cure. All physics package components must be uniformly parallel as well as flat to ensure the pressure wave is planar during experiments.

Many Homegrown Machinists

Former Livermore target fabrication engineer Lila Ahrendes says, "An extremely skilled machinist is needed to make an EOS target to specifications." Many machinists are from the optics industry, which often requires similar tolerances for military and space exploration components. About half of the machinists are graduates of Livermore's own machinist apprenticeship program.

Ahrendes notes that, in 2018, NIF physicists asked the target fabrication team if it could halve the surface variation of the stepped targets. Achieving this extraordinary specification would reduce the uncertainty of the data obtained from each experiment by a factor of two, which in turn would reduce the number of EOS shots required for each material by a factor of four, saving three shots for each data point. Pascale Di Nicola, NIF deputy target production manager, credits senior engineering associate Carlos Castro for leading the successful effort to meet the stringent new specification. The 50-nanometer specification goal can be appreciated with this comparison: If the stepped target were scaled to the size of a football field and had the same flatness specification, the top of every blade of grass would have to be cut within the thickness of a No. 2 pencil lead, across the field's 100 yards.

Castro also developed procedures for machining materials such as tantalum, which have not traditionally been considered for diamond turning because of their hardness or other qualities. One technique combines artificial polycrystalline diamond, natural single-crystal diamond, and specialized cutting fluids to achieve the required specifications and mirror finish. The team also developed techniques for diamond-turning iridium, platinum, lead, and tin.

Plutonium Experiments Begin

For the past decade, the end goal of the NIF ramp compression EOS experiments has been the actinides, a group of 15 high-*Z* (atomic number) elements of the periodic table. One actinide of great interest is plutonium. NIF EOS experiments use isotopically pure plutonium-242 (^{242}Pu), the second longest-lived isotope (half-life of 373,300 years) of the element's 20 isotopes. (NIF does not test weapons-grade plutonium.) In April 2019, the first ^{242}Pu ramp compression experiment was conducted on NIF, marking the start of an experimental campaign to better understand how the element compresses under extreme pressure.

The first ^{242}Pu shot exercised various aspects of forthcoming experiments on NIF, including special procedures for recovering ^{242}Pu debris. For example, VISAR was fitted with a device at one end to capture debris resulting from the extreme compression. This first experiment used an unstepped, flat surface of the isotope. However, the Laboratory is currently standing up a diamond-turning capability for making stepped targets from plutonium.

Platform Reaching Maturity

"We've made tremendous progress over the past few years," says McNaney. "We're right on target." The EOS ramp compression platform—predictive codes, target fabrication, and pulse shaping—continues to advance. As the team prepares to continue the experimental series on ^{242}Pu, some researchers are working to find a way to measure temperature in EOS ramp compression experiments. "Temperature is a very difficult thing to get a handle on, especially in ramp compression," says Eggert. Physicists today must rely on models to derive temperature. However, Smith reports Livermore researchers are investigating two different methods to determine temperature and to incorporate the most promising technology.

Although materials do not give up their EOS secrets easily, NIF researchers have shown this gentle ramp compression method works extremely well for obtaining critical information. Thanks to an extraordinary facility and world-class target-machining capabilities, the next few years are sure to shed new light on materials under extreme pressure.

—Arnie Heller

Target components are primarily machined in a Lawrence Livermore facility equipped with high-precision diamond turning lathes that are temperature controlled and isolated from vibration.

Key Words: diamond anvil cell (DAC), discovery science, equation of state (EOS), exoplanet, National Ignition Facility (NIF), plutonium-242 (^{242}Pu) isotope, ramp compression, Stockpile Stewardship Program, super Earth, Z Pulsed Power Facility.

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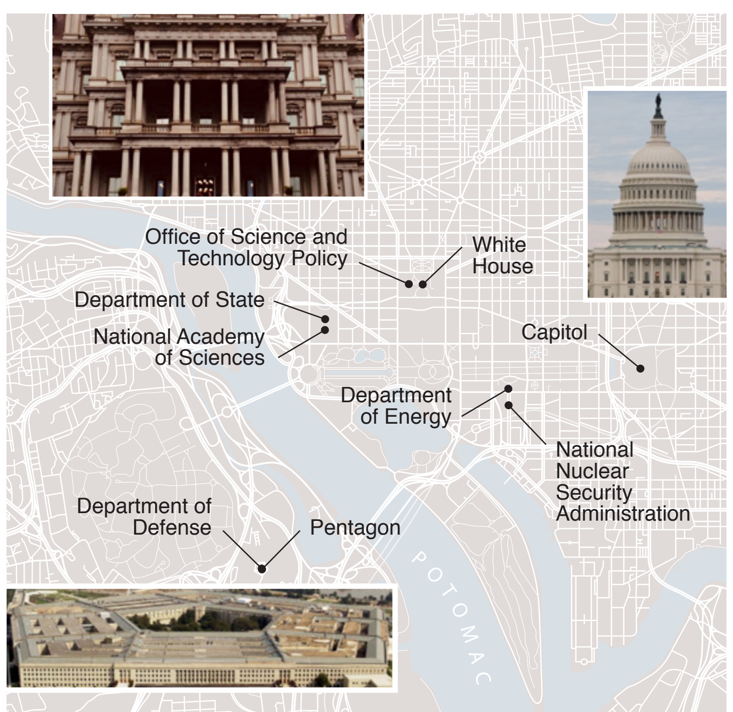
LABORATORY FELLOWS LEND THEIR EXPERTISE

ALMOST since the Laboratory's beginning, Lawrence Livermore employees have provided technical expertise to government agencies and other institutions as part of temporary off-site assignments. Now, Livermore's Office of Defense Coordination (ODC) has formalized this effort into the Offsite Fellows Program (OFP) to help efficiently recruit and support Laboratory staff in these roles. "The program helps develop future leaders of the Laboratory," says OFP manager Ric Schumacher. "They grow and learn by meeting the Laboratory's customers face-to-face."

Off-site fellows serve in such institutions as the Departments of Energy (DOE), State, and Defense (DOD), DOE's National Nuclear Security Administration (NNSA), the White House, and in Congressional committees. "The purpose of the program is to help align the Laboratory's strategic priorities to those of our funding agencies, to formulate relationships outside Lawrence Livermore, and to develop our staff," says Deborah W. May, who serves as chair of the Offsite Assignment Board.

Fellows are assigned to their positions either through Intergovernmental Personnel Act (IPA) agreements or as detailees. Employees who have IPA agreements remain Lawrence Livermore paid employees and are permitted to speak and act on behalf of the U.S. government. However, in these roles, personnel cannot act as advocates for the Laboratory. Detailees, on the other hand, are considered Lawrence Livermore representatives in the organizations they join. They cannot act as federal employees, but they provide technical advice as well as connections to Laboratory expertise. The program considers two to four years an ideal assignment length but does accommodate the growing need for briefer terms. For employees with young families, for example, short-term positions can also be developed.



Advising the White House

Arriving at the White House's Office of Science and Technology Policy (OSTP) in June 2012, Livermore's Cindy Atkins-Duffin quickly became immersed in several matters of national concern. As an IPA employee at OSTP, Atkins-Duffin lent her expertise to decision makers as they developed policy responses to complex scientific and technical issues. For example, at the request of then-OSTP Director John Holdren, Atkins-Duffin convened an interagency task force that examined the overall response to the Fukushima Daiichi Nuclear Power Plant accident, which had taken place the previous year, and developed a protocol for addressing potential similar incidents in the future.

Over her two and a half years in OSTP's National Security and International Affairs division, Atkins-Duffin also participated in a government–industry working group on medical isotope production and contributed to whole-of-government meetings evaluating the use of chemical weapons in Syria. Her technical advice influenced presidential directives on such issues as chemical facility safety and security. Since her return to Livermore in 2015, Atkins-Duffin has served as the principal deputy associate director for the Global Security Principal Directorate. Of her time in Washington, DC, she says, "I call it my science sabbatical. It was a fantastic experience. Personnel in these off-site assignments can see how government works, how science informs policy, and what the possibilities are, as well as the limitations."

(left) Off-site fellows serve in various institutions in Washington, DC, including the White House, Pentagon, and National Nuclear Security Administration (NNSA), among others. (right) Livermore's Aaron Miles (second from left), who serves in the White House's Office of Science and Technology Policy, sits on the panel at a meeting of the National Space Council in August 2019. (Image courtesy of NASA/Aubrey Gemignani.)

During their off-site assignments, Livermore personnel have contributed to various federal reports that help inform decision makers about technical issues related to policy.

Today, Livermore provides technical expertise to OSTP via Aaron Miles, who through an IPA agreement serves as the principal assistant director for National Security and International Affairs, a one-year renewable position. "OSTP provides advice to the president and senior White House staff on policy matters with a significant technical element," he says. "We participate in formulating national science and technology policy, and we coordinate across federal departments and agencies."

In this role, Miles helps address challenges at the intersection of national security and science and technology—for example, the security implications of artificial intelligence, quantum information science, synthetic biology, and unmanned autonomous vehicles. Miles explains that staff members contribute to the process by applying their analytical skills and scientific rigor to policy considerations and processes. Miles notes that the work "gives me insight into how the federal government operates. I have learned how to express technical issues to decision makers."

Supporting Stockpile Stewardship

In 2018, Ashley Bahney spent six months as a detailee in DOD's Office of Nuclear and Missile Defense Policy supporting the draft process for the 2018 Nuclear Posture Review (NPR)—a position previously filled by Miles. When Miles left to join OSTP, Bahney stepped in to continue the Laboratory's support of completing the NPR process, which helps determine the role of the U.S. nuclear stockpile in the nation's security strategy. NPRs are comprehensive reviews of U.S. nuclear weapons policy that have been conducted by each presidential administration since the time of President Bill Clinton. "The Nuclear Posture Review underpins much of what we do at Livermore, as well as my work," says Bahney. "My experience at DOD was extremely valuable. It helped me understand the needs of our sponsors; the importance of Livermore's contributions in Washington, DC; and how to better support the federal government's national security strategy."

At NNSA, Livermore's Joseph Wasem took a three-month assignment during the start-up of the Stockpile Responsiveness Program, which was mandated by Congress to develop concepts for nuclear weapons systems anticipating future needs, and to help train a new generation of nuclear stockpile experts. Wasem found himself in demand to help others understand technological capabilities, review implementation plans, and convene workshops examining such issues as the survivability of the nuclear stockpile. Says Wasem, "The benefit to NNSA was having someone on hand who works with those technologies every day to explain technical issues."

Cultivating Leadership Potential

The Laboratory benefits from its returning off-site fellows because they bring knowledge about how to provide better value to its agency sponsors and stakeholders, as well as a wealth of connections. "I strongly believe that the off-site fellows are an increasingly important part of the Laboratory's leadership cadre," says Kim Budil, principal associate director for the Laboratory's Weapons and Complex Integration (WCI) Principal Directorate. "We need people who understand how the government works, and our off-site fellows have great insight into this process."

Budil worked in two off-site positions in Washington, DC. She was a detailee in NNSA's Office of Defense Programs, where she led a government and multilaboratory task force to study how the aging of plutonium pits used in the nuclear stockpile was affecting its viability. As a detailee at DOE's Office of the Under Secretary for Science, her technical advice informed plans for modernizing the nuclear stockpile, as well as a National Academy of Sciences study on the future of inertial confinement fusion.

While on assignment with NNSA, Kim Budil (center) received the NNSA Administrator's Award for Excellence medal from then NNSA Administrator Tom D'Agostino (left) and Department of Energy Under Secretary for Science Steve Koonin (right).

Budil also worked for five years at the University of California (UC) Office of the President as the vice president for national laboratories. In this role, as a UC employee, she provided oversight for the three UC-affiliated national laboratories (Lawrence Livermore, Los Alamos, and Lawrence Berkeley), serving as a member of the Lawrence Livermore National Security, LLC, Board of Governors, and strengthening relationships between UC and the national laboratories.

Valuable Insights—And Fun

When it comes to their terms in off-site assignments, many IPA personnel and detailees recall them as positive experiences that provide many benefits. For Brad Wallin, now the program director for Weapons Physics and Design in WCI, his two-year assignment at DOE headquarters allowed him to oversee a program on the dynamic behavior of materials relevant to the stockpile. "This experience provided insight into the scale and complexity of the nuclear enterprise," says Wallin. "I met with many people at other government agencies and laboratories." He adds, "Although my assignment was 10 years ago, I still work with people I met during that time. I am more effective in my current role because of that network."

These assignments are also dynamic. Craig Wuest, who leads the ODC's Systems Analysis Group, says, "People might be shocked to find out the extremely fast-paced nature of these off-site positions." Wuest spent three years as special scientific advisor to DOD's assistant secretary of defense for Nuclear, Chemical, and Biological Defense Programs.

"I strongly urge Livermore staff who are interested in off-site positions to seek out these opportunities," says Budil. "They are fun, and they allow people to operate at a larger scale and scope than what is typically available at the Laboratory—it stretches employees' skills and helps them understand the agencies the Laboratory supports."

—Allan Chen

Key Words: Department of Defense (DOD), Department of Energy (DOE), inertial confinement fusion, National Academy of Science, National Nuclear Security Administration (NNSA), Nuclear Posture Review (NPR), Office of Science and Technology Policy (OSTP), Offsite Fellows Program, stockpile stewardship, University of California Office of the President.

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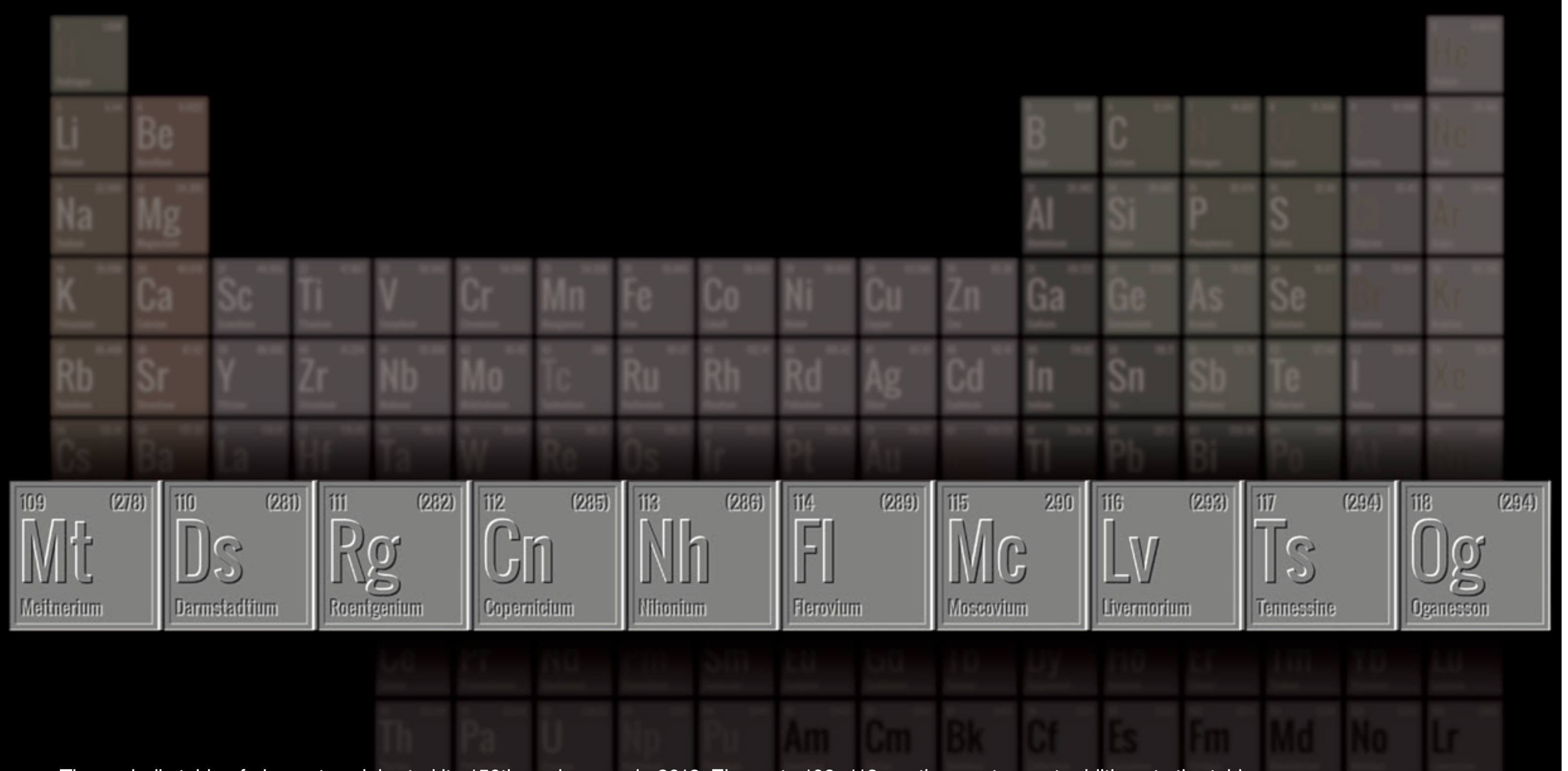
LIVERMORE A KEY ELEMENT IN EXPANDING THE PERIODIC TABLE



The periodic table of elements celebrated its 150th anniversary in 2019. Elements 109–118 are the most recent additions to the table. Several of these superheavy elements were discovered by multi-institutional teams that include researchers from Lawrence Livermore.

THIS year, scientists across the world are celebrating the 150th anniversary of the periodic table. Invented by the Russian chemistry professor Dmitri Mendeleev in 1869, this chart organized the 63 known elements by their atomic mass and chemical characteristics and interactions. In doing so, Mendeleev illustrated that the elements exhibited similar properties at regular intervals (periods) when organized by weight, and that this information could be used to predict the existence and properties of as-yet-undiscovered elements. To honor Mendeleev's achievement, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) proclaimed 2019 the international year of the periodic table.

Since the Laboratory's inception in 1952, Lawrence Livermore researchers have participated in the quest to understand—and discover—new elements, both as a fundamental science challenge and to hone skills for work related to its core national security mission. "The study of superheavy elements (those with high atomic numbers and correspondingly large proton counts) allows us to understand the complex interactions between neutrons and protons in the nucleus and the forces that hold a nucleus together and force it apart," notes nuclear chemist Mark Stoyer. "The heaviest nuclei provide a unique laboratory for testing and probing the nature of matter—what makes some matter stable and other matter unstable." Of the 118 elements found on the most recent periodic table, 90 exist naturally on Earth. The remaining 28 elements—which are characterized as either heavy or superheavy—must be synthesized.

Element discovery is a team enterprise, given the immensity of the task and the specialized tools and materials required, such as accelerators and difficult-to-obtain targets. Often, dozens of scientists across multiple institutions and countries are involved. For Lawrence Livermore researchers, these collaborations have proven both enduring and rewarding. Sonia Létant, deputy associate director for Science and Technology in the Physical and Life Sciences Directorate, says, "More than anything else, teamwork is at the heart of heavy element discoveries and deeply ingrained in our Laboratory's culture." Exploration of superheavy elements continues at Livermore today, largely with support from the Laboratory Directed Research and Development (LDRD) Program.

A Surprising Pairing

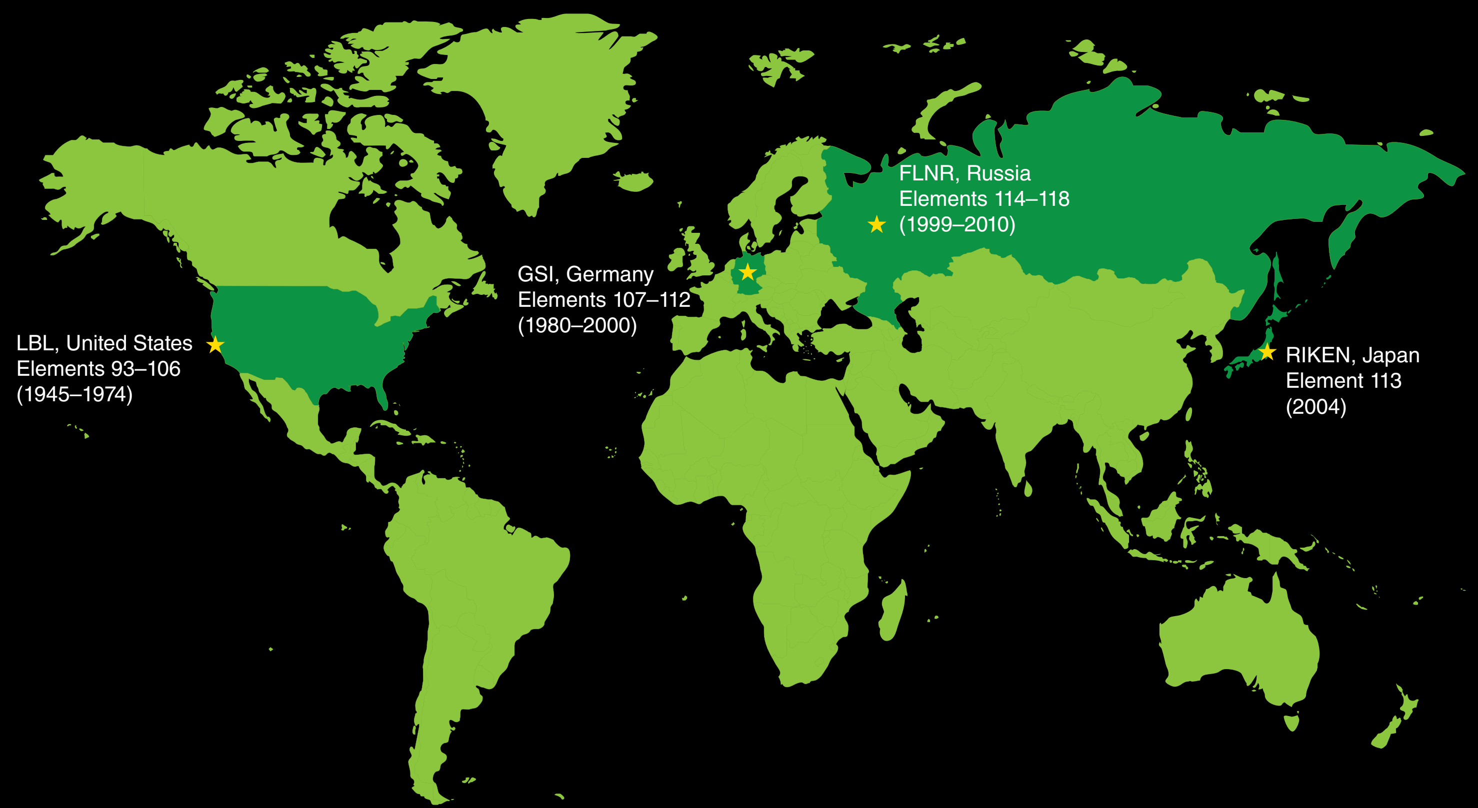
Following a fruitful three-decade collaboration with Lawrence Berkeley Laboratory (now Lawrence Berkeley National Laboratory) to discover new elements, Livermore embarked on a more unexpected alliance with the Flerov Laboratory of Nuclear Reactions (FLNR) in Dubna, Russia, in 1989. Previously stymied by Cold War politics, the collaboration was a turning point, built on complementary assets—FLNR's particle accelerator and Livermore's detector technology and data collection and analysis expertise—plus a mutual interest in finding more stable and longer-lived (and thus easier to study) superheavy elements. Until then, the field had been highly competitive, with Russian and U.S. researchers both staking claim to elements 104 and 105, a dispute ultimately settled in the 1990s.

Scientists create new elements through high-energy collisions that force positively charged atomic nuclei to fuse. In these experiments, large quantities of an element with a low atomic number are accelerated to roughly 10 percent of light speed and directed at a heavy element target. For example, in 1974, researchers from Lawrence Livermore and Lawrence Berkeley made seaborgium (element 106) by bombarding a californium target with a beam of "lighter" oxygen ions. Determining optimal collision speed is crucial: nuclei spring apart with too little energy and destroy each other with too much.

Livermore's use of independent data analysis to verify each claim—essential in high-stakes, high-profile research—was key to the collaboration. FLNR and Livermore analysts each developed their own search algorithms and reviewed data separately during experiments, sharing findings at regular intervals. (See *S&TR,* September 2016, pp. 12–15; and January/February 2002, pp. 16–23.) Regarding the scale of data analysis, Livermore nuclear chemist Roger Henderson explains, "The process is comparable to looking for one grain of sand on an entire beach. We end up collecting a terabyte or so of data, but we only see a handful of 'real' events."

The researchers employed several strategies to narrow down results for evidence of a new element. They looked backward from fission events, as fission (when an atom splits into two stable parts) is the most common way for nuclear decay chains to end. Scientists could focus on identifying spatially constrained decay chains ending in fission because detectors record event location and time, and because many daughter products of heavy elements are too heavy to travel far between decays. (See *S&TR,* April 2007, pp. 22–24.) In cases where they could not determine where the decay chain might end before new signals obscured the results, the researchers instead had to examine each signal that was detected to see if it had the characteristics they were looking for, which meant combing through many more results.

Scientists from Lawrence Livermore and the Flerov Laboratory of Nuclear Reactions (FLNR) conducted research together for the first time in the late 1980s. (clockwise, from back left) FLNR's Vladimir Utyonkov and Yuri Oganessian are shown meeting with Livermore's Ken Moody and Ron Lougheed in 1989.



Over the last several decades, experiments to discover new elements have typically been conducted at four main research institutions across the globe: Lawrence Berkeley Laboratory (LBL, now Lawrence Berkeley National Laboratory), the GSI Helmholtz Centre, FLNR, and RIKEN.

The Livermore–FLNR team and collaborators have officially completed the periodic table's seventh row, by co-discovering flerovium (element 114), moscovium (115), livermorium (116), tennessine (117), and oganesson (118). Each element's name reflects people and places important to the research. Although Lawrence Livermore has begun new collaborations with Lawrence Berkeley, Germany's GSI Helmholtz Centre, and other institutions, Livermore's connection with FLNR remains strong. "The friendships developed with our Russian colleagues were surprising and welcome—friendships that still exist," says Stoyer. "Our work together has been going strong for 30 years, which is highly unusual in scientific collaborations."

A New Period Begins

Although the thirst for new element discovery has not waned, the challenge has grown. Technological advancements may be needed for further discoveries, including more intense accelerators, new light-element beams, and faster detectors and electronics. To find ever-heavier new elements, scientists must force more protons into the nucleus, increasing the risk of failure. Researchers compensate by choosing isotopes with many more neutrons than protons so the newly fused nucleus can stabilize by shedding extra neutrons. Notes Henderson, "We used calcium-48 (a rare isotope containing 20 protons and 28 neutrons) beams for many of the element-creation experiments in the 1990s and early 2000s. It is a 'doubly magic' projectile—that is, the shells of both the protons and neutrons in the nucleus are filled, so the nucleus is inherently more stable than nearby isotopes." However, a stream of 10^{18} calcium nuclei has only netted scientists between 0 and 20 atoms of the desired element.

Livermore researchers have participated in two attempts to make element 120: one with GSI involving curium and chromium, and the other with FLNR to refine a new iron-beam technique because no target element would pair with calcium. "Unlike calcium-48, iron-58 has no magic numbers, so the projectile is 'hotter.' The extra energy shows up as extra excitation in the compound nucleus, so the probability of the nucleus falling apart is much higher," says Henderson.

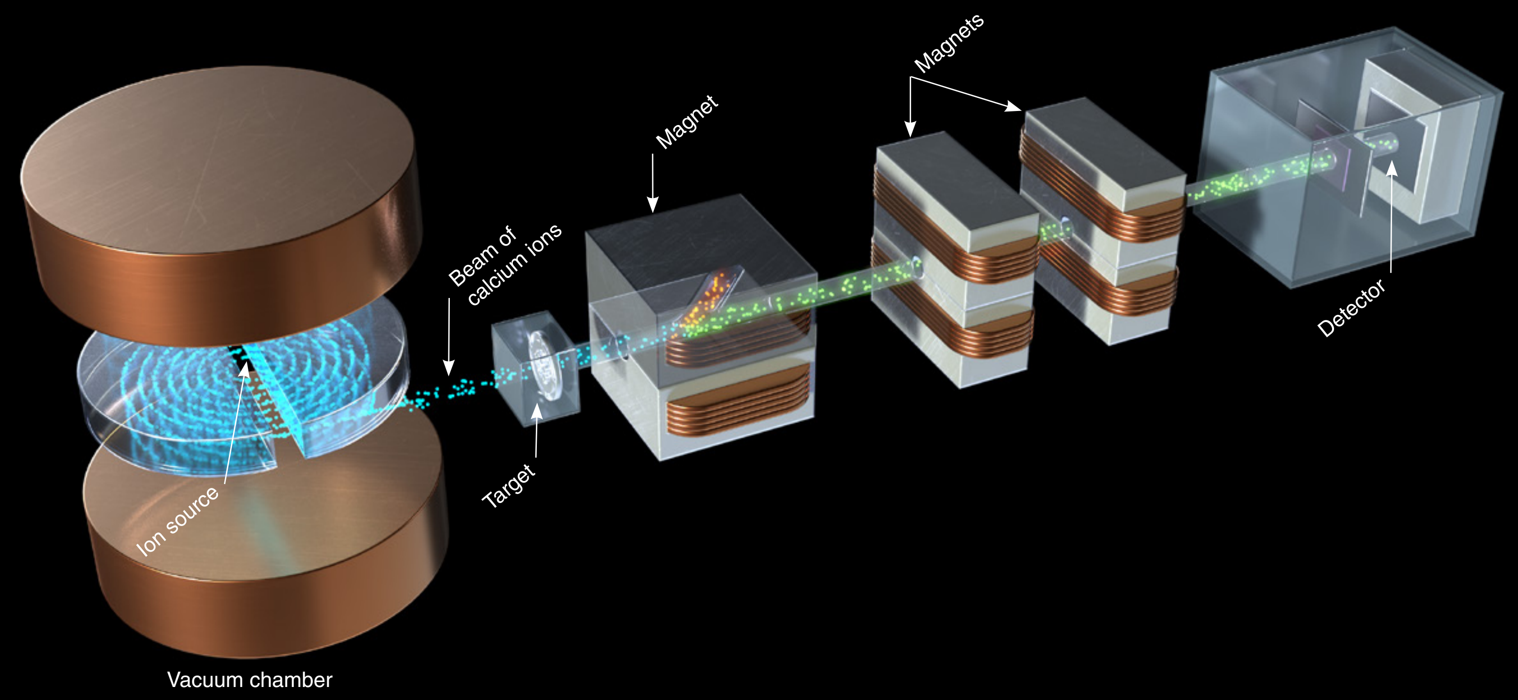
Understanding the chemical properties of the newest elements, and where they ought to be placed in the periodic table, is an ongoing area of interest for Livermore researchers. As they examine single atoms that decay within seconds or fractions of a second, they need extremely rapid, reliable, and precise experimental approaches—an area nuclear chemist John Despotopulos has been exploring, with LDRD funding. Chemical automation methods, such as those being developed by Despotopulos and colleagues, could support heavy element research along with other rapid chemical analysis needs, such as field-based nuclear forensics. For now, scientists must infer an element's chemical behavior from homologs—related elements that are longer lived and more common.

The next new element discovery will begin the eighth row on the periodic table. Electrons for these elements will travel at nearly light speed, so fast that elements may no longer follow period trends because of the electrons' effects on physical and chemical properties. This phenomenon may already be happening with some seventh-period elements. Flerovium, for example, should share properties with lead, based on its periodic table placement, but studies suggest that the short-lived element may behave more like a gas than a metal. (See *S&TR*, March 2014, pp. 4–11.)

Dedication and Inspiration

The dedicated scientists of Livermore's heavy element research program are stewards of core Laboratory expertise. "Few trained radiochemists exist in the world and fewer university programs are offered, but this research area is essential to our mission work," says nuclear chemist Dawn Shaughnessy. Heavy element discovery is also a viable route for attracting talented researchers and training them in skills with broader application. Létant explains, "Preparing targets, designing complex flow-through chemical systems, and fielding experiments at accelerator facilities are foundational skills for heavy element chemistry that are also central to nuclear chemistry and physics experiments needed for stockpile stewardship and nuclear threat reduction."

S&TR September 2019



To make new elements, the Livermore–FLNR team accelerated large quantities of an element with a low atomic number in a cyclotron—a spiral-shaped accelerator—and then directed the stream of energetic particles at a heavy element target. Particles of interest were separated from unreacted or waste particles using a series of magnets. Their radioactive decays were then recorded by a detector for analysis. (Illustration by Jacob Long.)

Livermore's contributions to the periodic table could help inspire young people to explore careers in chemistry. "The discovery of a new element has the potential to capture the public's imagination, just like walking on the moon or driving probes on Mars," says Stoyer. "The periodic table is something everyone studies in school and can potentially relate to, as it describes the fundamental building blocks of our universe."

—*Rose Hansen*

Key Words: accelerator, chemistry, decay chain, fission, Flerov Laboratory of Nuclear Reactions (FLNR), flerovium, homolog, isotope, Laboratory Directed Research and Development (LDRD) Program, nucleus, periodic table, superheavy element.

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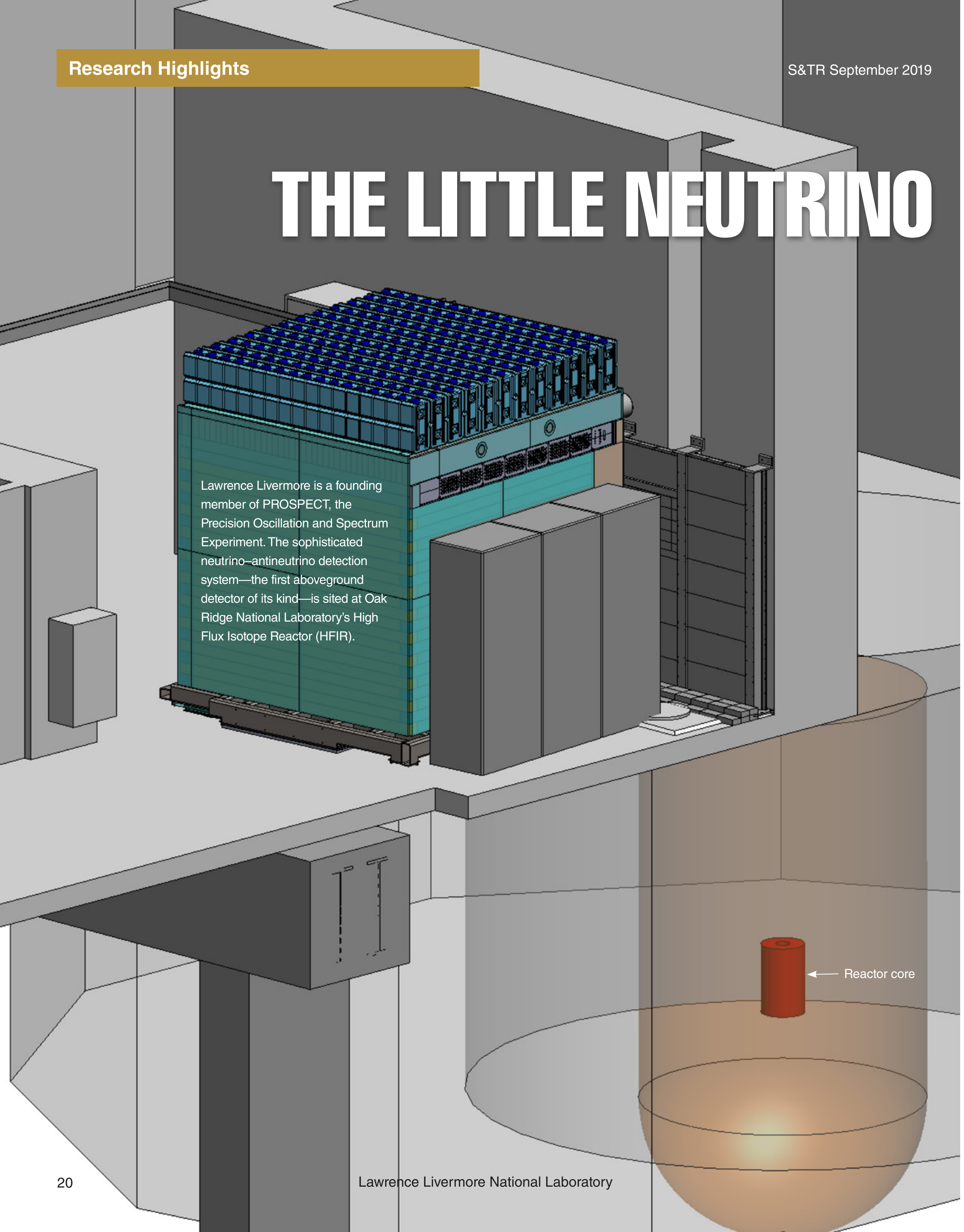
THE LITTLE NEUTRINO EXPERIMENT THAT COULD



Lawrence Livermore is a founding member of PROSPECT, the Precision Oscillation and Spectrum Experiment. The sophisticated neutrino–antineutrino detection system—the first aboveground detector of its kind—is sited at Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR).

MANY experiments conducted by Lawrence Livermore researchers are designed to explore questions of fundamental science. Others are intended to test-drive new mission-critical technologies. Perhaps the most exciting experiments are those that undertake both objectives. PROSPECT, the Precision Oscillation and Spectrum Experiment, is a unique neutrino–antineutrino detection project aimed at investigating fundamental particle physics and improving detection sensitivity for nuclear fission reactions.

The PROSPECT collaboration began in 2013, and includes Livermore physicists Nathaniel Bowden, Jason Brodsky, Tim Classen, and Michael Mendenhall, as well as colleagues from the National Institute of Standards and Technology (NIST), Brookhaven and Oak Ridge national laboratories, and 10 universities. Over the last six years, the detector was designed, then assembled at Yale University, and later installed at Oak Ridge's High Flux Isotope Reactor (HFIR)—a user facility that provides a high-intensity neutron source for materials science and isotope production experiments. The PROSPECT detector began collecting data in 2018.

Compared to other detectors, which can weigh up to 50,000 tons, the 4-ton PROSPECT detector is more moderate in size. In 2016, the PROSPECT team won the Department of Energy's Office of Science funding competition for neutrino research projects that were, among other criteria, "modest in cost and timescale." Bowden, who serves as the project's co-spokesperson, says, "Many researchers are excited about small experiments in neutrino detection, and our collaboration is at the forefront with the first published results. PROSPECT is also the first full-scale detector operating aboveground, which opens up possibilities for mobile reactor monitoring technology." Additional funding comes from Livermore's Laboratory Directed Research and Development Program, the Heising–Simons Foundation, and other partners.

The Mysterious Neutrino

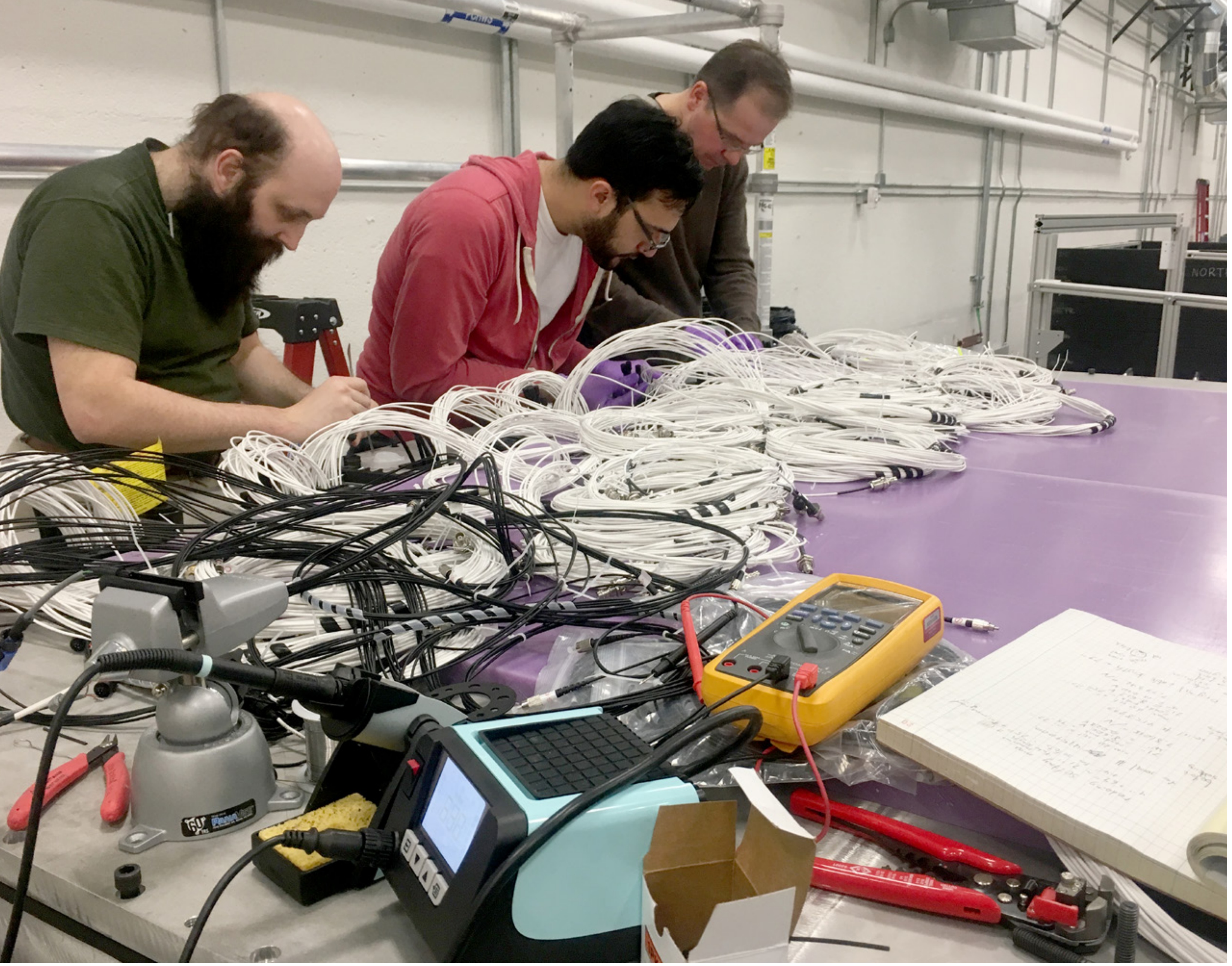
Since its discovery 60 years ago, the neutrino has continually intrigued the physics community. (See *S&TR*, December 2012, pp. 4–11; and July/August 2016, pp. 20–23.) Just when the elementary particle's three "flavors" (electron, muon, and tau) were finally understood, along came the possibility of a fourth—the sterile neutrino—whose existence would pose new questions about the Standard Model of physics.

Neutrinos are electrically neutral, have a smaller mass than other elementary particles, and usually pass through matter undetected. Successful neutrino detection at a nuclear reactor hinges on exploiting the inverse beta decay (IBD) process, in which the neutrino's antiparticle—the antineutrino—collides with a proton, leaving behind a positron and a neutron. PROSPECT measures the time delay between the proton–antineutrino collision and subsequent capture of the neutron, thus identifying IBD events. In other words, Mendenhall explains, "The positron carries away the antineutrino's incoming energy, which allows us to measure that quantity."

In recent years, experiments at nuclear reactors have detected fewer antineutrinos than predicted, leading physicists to hypothesize that the missing particles were transforming into unobservable sterile neutrinos as they traveled. PROSPECT probes this anomaly by searching for a particular signature: neutrino oscillation.

When a neutrino is created, it starts in a quantum superposition of three underlying mass states that represent the three flavors. As the neutrino travels away from its point of creation, the differing mass of those underlying states causes oscillation—wherein the neutrino transforms from one flavor to another. Each flavor state generates a unique oscillation signature, represented by a variation in the neutrino detection rate with the distance traveled (the baseline). For electron antineutrinos from a nuclear reactor, the baseline at which oscillation first becomes noticeable is at about a 1-kilometer distance from the reactor. Bowden states, "The oscillation signature is the key to understanding the differences between prediction and observation. If a fourth type of neutrino exists, its oscillation baseline would have to be much shorter than a kilometer to bring prediction and observation into agreement."

Weighing in at approximately 4 tons, the PROSPECT detection system arrived at HFIR in early 2018. (Photo courtesy of the PROSPECT collaboration.)



Livermore physicist Michael Mendenhall (left) and PROSPECT colleagues assemble components of the segmented detector array during its construction at Yale University. (Photo courtesy of the PROSPECT collaboration.)

Unique Detector Design

Measuring the position and timing of IBD events relative the the HFIR facility's reactor core requires sensitive instrumentation to operate in what Bowden calls "an extremely challenging environment." To get close enough to the reactor core to detect short baseline oscillations, the PROSPECT detector must be located aboveground. However, in this location, cosmogenic neutrons, the high-intensity conditions created by HFIR's 85-megawatt reactor core, along with site-specific factors such as the reactor's steel-reinforced concrete floor, all affect the experiment. Notes Mendenhall, "This background interference can swamp the data, which is why detectors are usually positioned underground."

The PROSPECT team mitigates the effect of background events with multilayered shielding around the detector and by conducting tests, in which the reactor is turned on and off, to measure background levels. Bowden explains, "By combining the ability to measure particle type, position, and energy in a space-efficient system, the PROSPECT detector can identify and distinguish antineutrino interactions and background events with high efficiency." Such capabilities have given PROSPECT unprecedented accuracy, despite operating close to a research reactor at the Earth's surface.

PROSPECT's compact architecture comprises 154 individual detector segments arranged in an 11-by-14 array. Each segment measures 119 by 15 by 15 centimeters and contains two photomultiplier tubes (PMTs), reflector panels, three-dimensionally printed support rods, and a mirrored coating. PMTs are arranged within a liquid scintillator doped with lithium-6—a setting conducive to capturing a neutrino's distinctive oscillation signature at short baselines while minimizing background signals. "The detector design strives to collect as much signal from each IBD interaction as possible, thus improving our ability to measure antineutrino energy," says Bowden.

During the design and construction phases, Livermore tested PMTs, set up the data acquisition electronics, and ran Monte Carlo computer simulations to refine aspects of the detector's functionality. Mendenhall says, "We configured off-the-shelf waveform digitizers for data collection and developed the analysis toolchain for simulation data, which became the process for analyzing results from the experiment." Since PROSPECT came online, the Livermore team has maintained the software analysis framework and continues to study the processes that generate background events. PROSPECT data is stored on the Laboratory's high-performance computing systems.

New Uranium Insights

Livermore's nuclear nonproliferation efforts stand to benefit from PROSPECT's results. Measuring antineutrino energy spectra at a nuclear reactor site helps researchers better understand fuel mixture, power level, and other characteristics of the reactor. HFIR's highly enriched core is powered by uranium-235 (^{235}U). In fact, more than 99 percent of neutrinos emitted by HFIR come from ^{235}U fission, a process that enables researchers to establish a reference point for testing predictions associated with a single isotope. (In reactors that consume a mixture of ^{235}U and plutonium-239, the observed neutrinos come from a combination of two different energy spectra, which increases the difficulty of isolating each isotope's independent contributions.)

PROSPECT has recorded more than 31,000 IBD events. Results are compared with a predicted ^{235}U model of antineutrino energy spectra from nuclear reactors. Initial data have shown the best-ever measurement of an energy spectrum in this context. "We are seeing six times more antineutrinos than anyone has previously observed," says Bowden. The research team uses these data to precisely define the ^{235}U antineutrino energy spectrum and, therefore, inform modern physics models. Mendenhall adds, "We expect the statistics to improve as we complete analysis of more data that have already been collected."

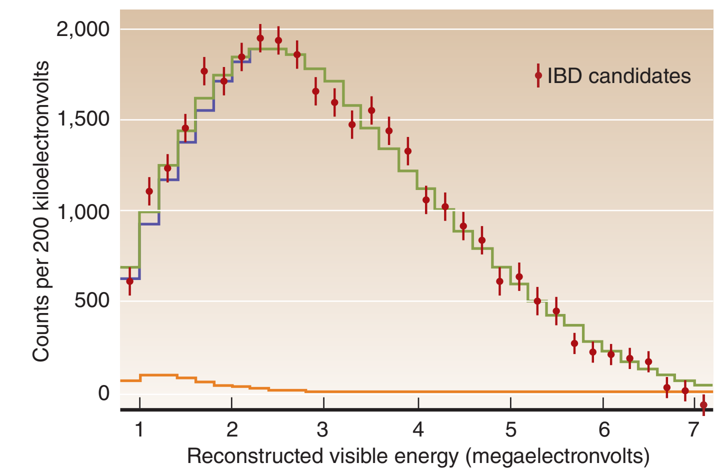
Future Prospects

As the PROSPECT detector continues to operate, the system provides opportunities for detailed study of multiple phenomena, including the evaluation and management of background sources. "We detected neutrinos from day one. The team has been excited to see the project evolve from computer simulations into an operational detector," states Mendenhall, who worked on PROSPECT at NIST and subsequently "followed the project" to Livermore.

The PROSPECT team seeks to improve predictions and detection technologies that will make nuclear reactor monitoring more precise and feasible. One intriguing possibility is the development of mobile detection systems. Bowden explains, "Over time, we can improve detection capabilities for any given reactor site, but unless detection systems can move between reactors, comparisons are difficult to achieve. The PROSPECT detector provides an important capability demonstration for new reactor safeguard applications."

The detector's exceptional sensitivity and ability to gauge short-baseline neutrino oscillations may one day solve the "missing antineutrino" anomaly and lead to the discovery of a fourth neutrino flavor. Meanwhile, the PROSPECT team has developed a plan for a second phase that can extend the experiment's sensitivity to smaller oscillation amplitude values. Bowden asserts, "With this technology, we could possibly make a groundbreaking discovery in neutrino physics."

—Holly Auten



PROSPECT's measurements of inverse beta decay (IBD) events (green line) are compared with a predicted uranium-235 model of antineutrino energy spectra from nuclear reactors (purple line) alongside the spectra of aluminum-28, helium-6, and nonequilibrium isotopes in the reactor core (orange line). The research team uses these data to precisely define the uranium isotope's antineutrino energy spectrum.

Key Words: antineutrino, High Flux Isotope Reactor (HFIR), inverse beta decay (IBD), neutrino, neutrino detection, neutrino flavor, nuclear reactor, oscillation signature, particle physics, photomultiplier tube (PMT), Precision Oscillation and Spectrum Experiment (PROSPECT), Standard Model, sterile neutrino, uranium-235 (^{235}U) isotope.

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Patents and Awards

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory. For the full text of a patent, enter the seven- or eight-digit number in the search box at the U.S. Patent and Trademark Office's website (https://www.uspto.gov).

Patents

Selective High-Affinity Polydentate Ligands and Methods of Making Such
Sally J. DeNardo, Gerald L. DeNardo, Rodney L. Balhourn
U.S. Patent 10,292,992 B2
May 21, 2019

Electrostatic Generator/Motor Electrodes Located on the Inner Surface of an Electromechanical Battery Rotor
Richard F. Post
U.S. Patent 10,298,090 B2
May 21, 2019

Composite 3D-Printed Reactors for Gas Absorption, Purification, and Reaction
Du T. Nguyen, Roger D. Aines, Sarah E. Baker, William L. Bourcier, Eric B. Duoss, James S. Oakdale, Megan M. Smith, William L. Smith, Joshuah K. Stolaroff, Congwang Ye
U.S. Patent 10,300,430 B2
May 28, 2019

Assessment of Tissue or Lesion Depth Using Temporally Resolved Light Scattering Spectroscopy
Stavros G. Demos
U.S. Patent 10,413,188 B2
September 17, 2019

Awards

Livermore physicists **Linda Stuart** and **Hank O'Brien** were recognized with commendations from the **United Kingdom's Ministry of Defence** (MOD). Each year, MOD assesses and gives commendations to their most impactful science, technology, and engineering programs.

The United States and the United Kingdom partner under the 1958 Mutual Defence Agreement on Atomic Weapons Treaty to leverage each country's capabilities to better support their independent nuclear deterrence postures. Stuart and O'Brien were recognized for their efforts in establishing and delivering the Joint Technology Demonstrator program, which reduces technical risk for future life-extension programs.

The Applied Biosystems™ Axiom™ Microbiome Array (ABAMA), the commercialized successor to the Lawrence Livermore Microbial Detection Array (LLMDA), has garnered an **Excellence in Technology Transfer Award** from the **Federal Laboratory Consortium** (FLC). The microarray is the most comprehensive microorganism detection platform built to date and the first high throughput microarray that uses whole genome resolution for identifying all sequenced microbes, including bacteria, viruses, fungi, archaea (primitive bacteria), and protozoa. Started in 1974, the FLC is a chartered, nationwide network that helps accelerate the transfer of technologies from federal laboratories into the marketplace.

Retired Laboratory physicist **William Bookless**, whose distinguished 35-year career includes serving as Lawrence Livermore's deputy associate director of Defense and Nuclear Technologies and the associate director for the Safety and Environmental Protection Directorate, has been selected as the **principal deputy administrator** at the Department of Energy's (DOE's) **National Nuclear Security Administration** (NNSA). In this role, Bookless will support the NNSA administrator in the management and operation of NNSA, as well as in policy matters across DOE and the nuclear security enterprise.

Lawrence Livermore atmospheric scientist **Benjamin Santer** has received the **William Procter Prize for Scientific Achievement** from **Sigma Xi**—the Scientific Research Honor Society. The Procter Prize has been awarded annually since 1950 to a scientist who has made an outstanding contribution to scientific research and has demonstrated an ability to communicate the significance of this research to scientists in other disciplines.

Since 1995, Santer and his colleagues have identified human "fingerprints" in atmospheric temperature and water vapor, ocean heat content, sea surface temperature in hurricane formation regions, and many other climate variables. As a Procter Prize recipient, Santer receives a $5,000 honorarium and is able to designate an early-career colleague in the same field of research to receive a $5,000 award from Sigma Xi's Grants in Aid of Research program.

Abstract

Gently Compressing Materials to Record Levels

A material's equation of state (EOS) is required to fully understand the relationship between its pressure, temperature, and density. Scientists are using Lawrence Livermore's National Ignition Facility (NIF), the world's largest and most energetic laser, to acquire the EOS data of solid materials at pressures never before achieved—up to 50 million times Earth's ambient air pressure. For decades, the traditional method to determine a material's EOS was to send a sudden shock through it and measure its response. A more revealing and "gentler" method called ramp compression uses a carefully tailored laser pulse shape rather than a shock front to compress a material, helping scientists better understand the physics of solids compressed to extreme densities. Together, the laser pulse-shape control, high energy and power, and state-of-the-art diagnostics make NIF the premier facility for ramp compression. The NIF experiments use target samples of unprecedented precision machined in Livermore's own facilities.

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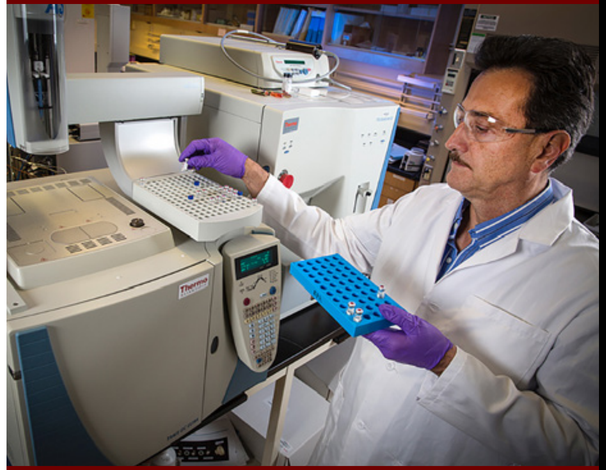
Coming Next Issue

Preventing Chemical Weapons Proliferation



The Forensic Science Center develops novel analytical methods and trains at-risk nations to respond to incidents involving toxic chemicals.

Also in October/November

- *New designs for hohlraums go "outside the box" in the search for greatly increased performance on the path to fusion ignition.*
- *Recent technological advancements have given scientists the unprecedented capability to detect dark matter.*
- *Preparations for an experiment at an upcoming accelerator facility yield a surprising property of a radioactive zirconium isotope.*

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