# LASER EXPERIMENTS ILLUMINATE THE COSMOS

*At the National Ignition Facility, scientists are creating extreme pressures and temperatures that mimic conditions on alien worlds.*

THE most extreme conditions that can be created in the laboratory are in the high-energy-density (HED) regime, where materials often behave in unexpected ways. HED research involves examining materials under pressures and densities found until recently only in the cosmos—in stars and the cores of giant planets—or on Earth only in detonating nuclear weapons. The advent of Lawrence Livermore's 192-beam National Ignition Facility (NIF), the world's largest and most energetic laser, now makes it possible to test materials in HED regimes that are inaccessible to scientists by any other means.

Inside NIF's 10-meter-diameter target chamber, laser beams converge on meticulously engineered targets to obtain extremely accurate data on the HED conditions created. The pulses in a NIF beam typically last only a few nanoseconds (billionths of a second) and are spaced at intervals of less than 20 picoseconds (trillionths of a second). Together, the beams can deliver a combined energy of up to 1.8 megajoules and a peak power of 500 terawatts (trillions of watts), creating pressures greater than 100 terapascals (1 billion times Earth's atmospheric pressure), temperatures of up to 100 million kelvins, and densities up to 500 grams per cubic centimeter. Not only can scientists define total laser energy and power by selecting the number of laser beams to use and the energy of each individual beam, but NIF's pulse-shaping ability allows them to vary the power of an individual pulse over time. Furthermore, some beams can be separately targeted at thin foils or other secondary targets to generate diagnostic streams of x rays, protons, or other particles that assess what is occurring in the primary target.

NIF has assembled a specialized team to carry out these HED materials experiments, which fall broadly into three categories: equation of state (EOS), or the relationship between pressure, temperature, and density; strength, that is, the speed and extent of the deformation of a solid; and phase changes, such as from a solid to a liquid. Livermore scientist Tom Arsenlis, who heads the team, explains, "No previous data exist for these very difficult regimes we are accessing."

Physicist Damian Swift notes that although NIF creates HED conditions of extremely short duration, the same physics apply to the long-lasting conditions found in stars and planets. Indeed, NIF provides the ability to reproduce the extreme conditions in myriad celestial phenomena, such as magnetic fields that stretch hundreds of light years, the interiors of stars, and the cores of planets inside and outside our solar system.

## Program Key to Collaborations

Such fundamental HED experiments on NIF are conducted as part of the Discovery Science Program, which provides academic users access to NIF's HED regimes and enhances collaborations between Livermore scientists and academia. The program constitutes about 8 percent of NIF's more than 400 annual shots. A review committee of outside experts from different branches of physics advises NIF managers on the relative scientific merit of proposals submitted by investigators.

Discovery Science participants include researchers from other national laboratories and from leading universities worldwide. They include graduate students and postdoctoral researchers. Many prepare for years to conduct experiments at NIF. Discovery Science teams typically are allocated a few days of access each year, with two to three laser shots conducted in a 24-hour day. "The entire facility is theirs, so they can, within safety limits, fire any kind of laser energy and pulse shape and power they would like," says Bruce Remington, head of the Discovery Science Program. The program encourages Livermore HED researchers to engage the broader academic community in planning and executing Discovery Science experiments, publish their research in the open literature, and elicit comments from their peers. Collaborations also serve to attract the next generation of HED scientists to Livermore.

Discovery Science experiments are conducted on such materials as hydrogen, carbon, iron, copper, magnesium, and various silica compounds. (See *S&TR* December 2015, pp. 4–12.) Physicist Jon Eggert says, "It is important that we do experiments on a wide variety of materials to make sure our results are consistent." An experiment is conducted on a "platform," which comprises the laser configuration (energy, power, and duration), an extraordinarily precise target measuring a few centimeters in size, and ultrahigh-resolution diagnostic instruments, all tailored to an experiment's needs.

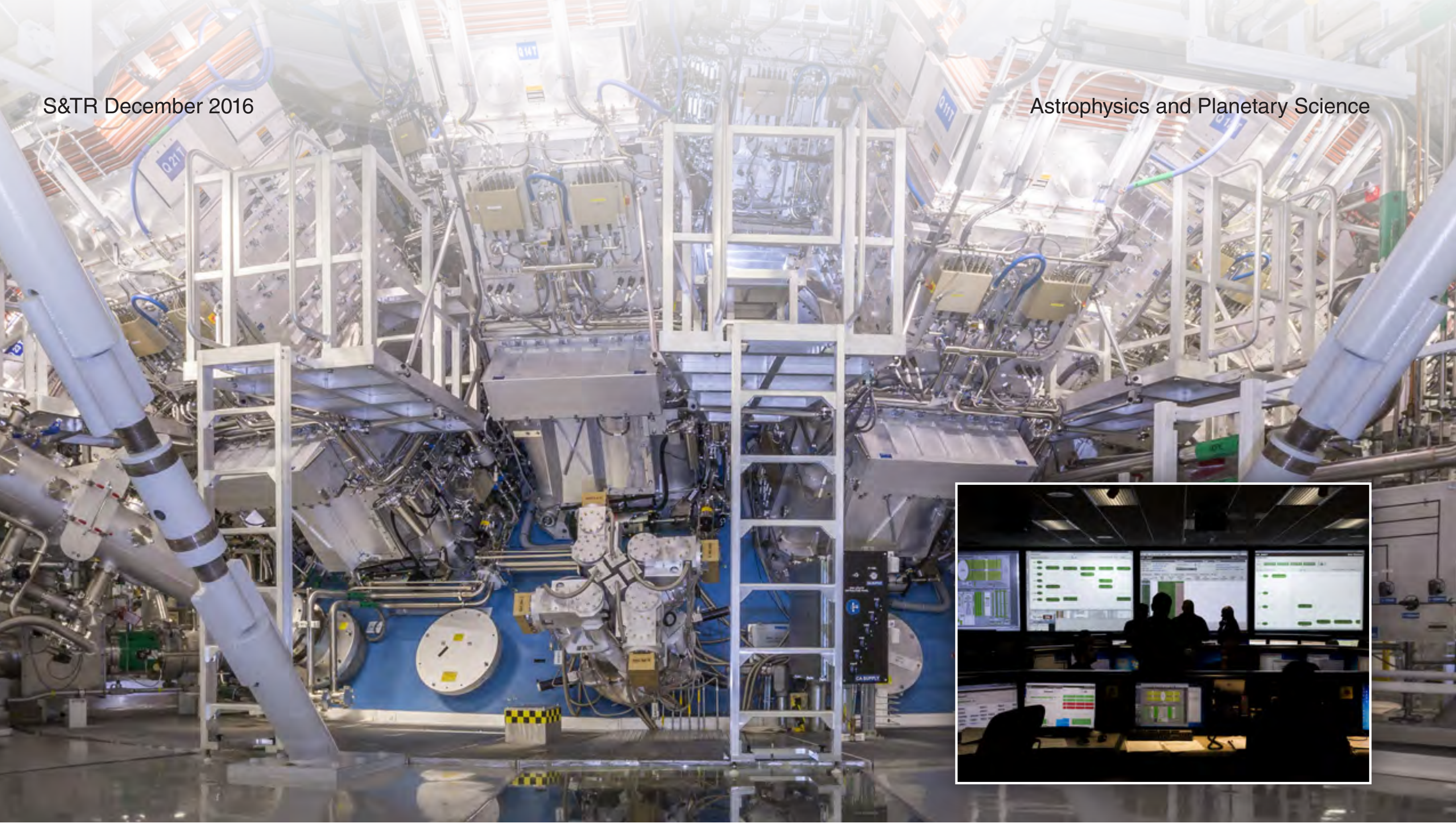
Preliminary experiments are often conducted at lower energy research centers such as the Omega Laser Facility at the University of Rochester and the Z Pulsed Power Facility at Sandia National Laboratories in Albuquerque, New Mexico. "Omega allows us to conduct many experiments in one day," explains Arsenlis. "We can test an idea there before graduating to NIF. Despite fielding more than 400 shots per year, demand for NIF shots always exceeds supply." The Z facility uses high magnetic fields associated with high electrical currents to produce powerful x rays and extreme temperatures and pressures that last 100 times longer than NIF's. Arsenlis explains, "NIF experiments are over in tens of nanoseconds. Z offers a valuable window into a longer timescale, although at somewhat lower energy densities."

Discovery Science experiments probe such mysteries as the source of ultrahigh-energy cosmic rays; the formation and evolution of collisonless astrophysical shocks; the creation mechanisms for the magnetic fields that thread the universe; nuclear reactions in HED plasmas; how the elements of the universe are forged in the interiors of stars; how stars form in molecular hydrogen clouds, such as the famous "Pillars of Creation" in the Eagle Nebula; and the likely composition of the cores of exoplanets, those planets located outside our solar system.

## Duplicating Cosmic Rays in the Lab

One series of experiments is devoted to understanding ultrahigh-energy cosmic rays. Most cosmic rays are protons or helium nuclei—two protons bound to two neutrons—originating mainly from outside the solar system. Scientists do not know the origin of these rays or how they gain their incredible energy, which is largely dissipated when they enter Earth's atmosphere. In the experiments, conducted by an international collaboration called Astrophysical Collisionless Shock Experiments with Lasers (ACSEL), researchers are investigating the possible role of collisionless shocks and related magnetic fields in the acceleration of cosmic rays.

In collisionless shocks, clouds of rapidly moving plasma particles pass through each other largely without colliding but create shocks by means of collective plasma instabilities, such as the Weibel instability. Collisionless shocks appear in violent solar flares, outbursts from galaxies, supernova remnants, protostellar jets, and gamma-ray bursts. NIF is the only facility capable of creating plasma streams with sufficiently high density (greater than $10^{20}$ particles per cubic centimeter), velocity (greater than 1,000 kilometers per second), and temperature (greater than 1,000 electronvolts) to approximate these energetic astrophysical conditions. "We are seeing that magnetic fields can be generated from these high-velocity interacting plasmas. The magnetic fields definitely play an important role in the acceleration of cosmic-ray particles," says Hye-Sook Park, leader of the ACSEL experimental team. The NIF targets used in the experiments consist of two opposing plastic foil discs spaced 10 millimeters apart. When struck by NIF laser beams, the foils emit high-velocity plasma flows that generate shock, largely without ion–ion collisions. The associated magnetic fields produced by the interpenetrating plasmas are probed with protons created



The Discovery Science Program at Livermore's National Ignition Facility (NIF) provides academic users access to the high-energy-density regime found in stars and the cores of giant planets. (top) NIF's target bay houses the 10-meter-diameter target chamber (partially obscured blue sphere), inside which up to 192 beams converge on a precisely engineered target. (inset) Researchers in the NIF control room monitor preparations for an experiment.

by other NIF beams imploding a tiny capsule known as an "exploding pusher," which is filled with a mixture of helium-3 and deuterium (a hydrogen isotope with one neutron).

A related series of experiments, called Turbulent Dynamo, or TDyno, is aimed at understanding how magnetic fields created in the early universe grew to their current size and strength. Led by a team from the University of Oxford in the United Kingdom, the TDyno researchers are studying how small "seed" magnetic fields are amplified by a turbulent dynamo—a kind of plasma characterized by turbulent eddies. Collisionless shocks are thought to be one of the mechanisms that create seed magnetic fields, which a turbulent dynamo then amplifies. The NIF experiments are re-creating the dynamos on a much smaller scale by striking two parallel plastic foils in a fashion that produces highly turbulent plasmas. As with the collisionless shock experiments, an exploding pusher creates a proton source to diagnose the magnetic fields as they are amplified by the turbulent plasma.

## Thousands of Exoplanets

Other Discovery Science experiments are aimed at understanding the upwards of 4,000 exoplanets discovered to date orbiting more than 2,600 stars. Scientists aim to determine exoplanets' internal structure, including whether they could have plate tectonics and a magnetodynamo, both considered essential to supporting some form of life. Indeed, identifying habitable planets has been deemed one of the top three scientific goals for both astrophysics and planetary science. Livermore physicist Robert Rudd states that the search aims to find a "Goldilocks" exoplanet that is not too hot or cold, has some water, and possesses a magnetosphere—a magnetic field generated by a magnetodynamo, shielding potential life forms from damaging cosmic radiation. Scientists may have found one such exoplanet in August 2016—a roughly Earth-sized planet orbiting Proxima Centauri, the star nearest to our solar system. The planet, Proxima b, is located at a distance from its parent star that allows temperatures mild enough for liquid water to exist on its surface.

Exoplanet-related experiments on NIF are designed to replicate the conditions believed to exist in exoplanetary cores, where estimated pressures range from 350 gigapascals to 7 terapascals—the pressures found inside Earth and Jupiter, respectively. "Deep inside a planet, the properties of the constituent materials are strongly modified by extreme density, pressure, and temperature," explains Livermore physicist Marius Millot. Even those conditions can be re-created using NIF.

The experiments also seek to accurately determine an exoplanet's composition, which is largely a matter of comparing its mass and radius—deduced from dips in the parent star's light as the planet crosses in front—to the composition suggested by the planet's distance from its star. The mass–radius relationship relies heavily on the EOS, which in turn is determined experimentally from a material's compressibility under HED conditions. Squeezed to extreme pressures by a single shock wave or a sequence of staged shocks, the material changes to a new state at higher density, temperature, and pressure. The resulting EOS data refines computational models. "We need data from NIF experiments to validate our calculations," says Swift.

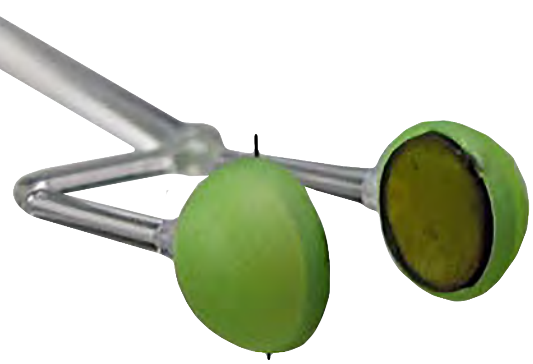
An extremely useful technique for obtaining EOS and material strength data is ramp compression, in which a material is pressurized gradually, so that it heats to lower temperatures and thereby retains its structural integrity. In contrast, a standard, nearly instantaneous shock raises temperatures significantly, limiting the study of fluid properties to those beyond 200 gigapascals. A realistic model of a planet's interior cannot be based on an EOS ascertained at high temperatures because compression in these planets is caused by shock-free gravitational forces acting over millions of years, leading to high densities at relatively low temperatures.

### Iron a Major Focus

Because iron is a major component of Earth and other planets, understanding the phases and melt curve of the metal at high pressure advances our understanding of Earth and Earthlike exoplanets. Studying iron at Earth-core conditions requires pressures of 130 to 360 gigapascals and temperatures of over 6,000 kelvins. These conditions are near melting, and in fact Earth's core is separated into a solid iron inner core surrounded by a rapidly convecting liquid iron outer core. The magnetosphere that protects life on Earth from cosmic radiation is generated by a magnetodynamo driven by this convective flow of electrically conducting molten iron. Iron's melting transition is therefore extremely important for determining the habitability of large terrestrial exoplanets, the so-called "super-Earths" that have up to 10 times the mass of our planet. (Beyond this mass, planets tend to be gas giants such as Jupiter.) Super-Earths are calculated to have core pressures of up to 3.6 terapascals, but researchers presently have no idea whether such exoplanets will also have a liquid outer core and a magnetosphere.

A team of scientists led by Livermore physicist Richard Kraus is conducting experiments to measure iron's melting curve at pressures from 500 gigapascals to 2 terapascals, an area where no experimental data currently exist. If the iron core of a super-Earth is completely solid, it may not generate a magnetosphere, making it more difficult for life to evolve on the planet's surface. Kraus explains, "We need to know more about the liquid–solid transition in iron cores to determine whether rocky planets larger than Earth could have a protective magnetosphere."

NIF has also advanced investigations of the phase changes of materials under HED conditions. Kraus and his team are using a novel experimental technique, developed at Omega, in which a sample is initially shocked into the liquid phase with high heat and low pressure and then subsequently ramp-compressed back into the solid phase at high pressure, with



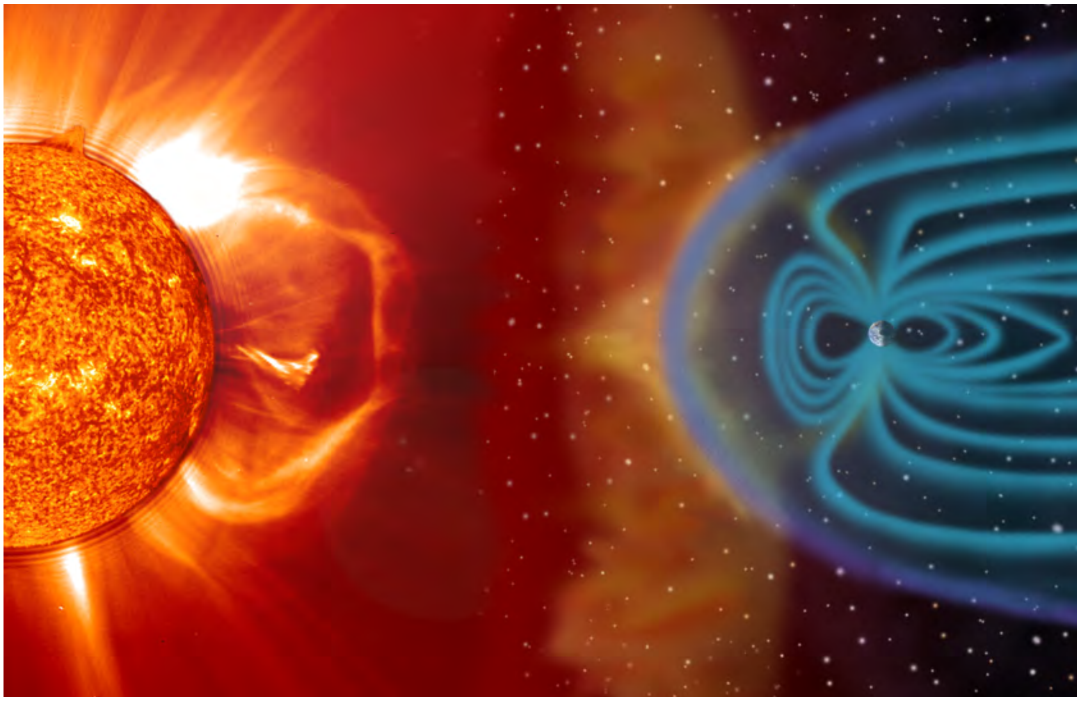
(left) This target used in collisionless shock experiments conducted at NIF under the Discovery Science Program consists of two nickel- and iron-doped plastic foil discs 10 millimeters apart. The green plastic caps are light shields. Laser beams striking the discs create plasmas that interpenetrate at high velocity, thereby generating on a small scale the collisionless shocks that are believed to govern many large-scale astrophysical phenomena.

(right) The Turbulent Dynamo experiments at NIF produce the same turbulent plasma conditions that generate the vast magnetic fields permeating the universe. As in collisionless-shock experiments, a deuterium-filled exploding pusher (at the end of the L-shaped arm below the target) produces protons that probe the magnetic fields that are generated.

only a small increase in temperature. They use x-ray diffraction to confirm whether a 20-micrometer-thick iron foil was melted by the initial shock and then resolidified by the ramp-compression wave. This technique was proven on Omega at pressures lower than 500 gigapascals, but now researchers need access to higher pressures along the melting curve. Upcoming tests on NIF will provide the crucial data.

The integrated platform used in these experiments features a target and a diagnostic named Target Diffraction In Situ. In this setup, as many as 24 NIF laser beams strike an iron sample, followed nanoseconds later by up to 16 additional beams that illuminate a backlighter metal foil mounted on a stalk. Collimated x rays from the backlighter probe the sample, producing a diffraction pattern that serves as a "fingerprint" revealing the structure (phase) of the iron. (See *S&TR,* January/February 2016, pp. 4–12.) Kraus notes that the experiments are highly sensitive to the laser pulse's temporal shape, that is, how its power varies over time. He reflects that a pulse lasting all of 30 nanoseconds provides reliable data on processes that occur in the cosmos over tens of thousands of years.

In previous experiments on the Z facility, Kraus and colleagues determined the impact conditions needed to vaporize iron in meteors and other objects that collided with an ancient Earth. "We need to model iron during impact events because it is a major component of planets, and its behavior is critical to how we understand planet formation," explains Kraus. The experiments showed that these violent collisions generated significant amounts of iron vapor, and that iron vaporizes at much lower impact speeds than previously thought. As a result, more iron was probably vaporized during Earth's period of formation and spread over the young planet's surface instead of immediately sinking down to Earth's incipient core.



Earth is surrounded by a magnetosphere (blue), which is generated by the planet's molten outer core acting as a dynamo. The magnetosphere protects the planet from the Sun's solar wind (white to light yellow lines) and magnetic storms (yellow cloud). When the solar wind collides with the magnetosphere, a bow shock (purple) forms. The shock is collisionless, forming not from the collision of particles but from collective instabilities of the interpenetrating plasmas. (Image courtesy of NASA.)

## Hydrogen as a Metallic Liquid

Most exoplanets discovered so far are gas giants similar to Jupiter and Saturn, along with even larger "hot Jupiters," so called because of their proximity to the stars they orbit. Gas giants are believed to be composed largely of hydrogen and helium. Hydrogen is the simplest element (one proton orbited by one electron) yet exhibits complex behavior under HED conditions, with at least four different solid phases, perhaps two different liquid phases, and a gas phase.

Some scientists postulate that the hydrogen and helium swirling around together in gas giants could separate when hydrogen becomes metallic under terrific pressures. Such a separation could affect the internal core structure and influence how the planets evolved over the past 4.5 billion years. Previous experiments and models produced conflicting results about hydrogen's sudden transition from an insulating molecular fluid to a metallic atomic fluid at around 100 to 300 gigapascals and at a relatively cool 1,000 to 2,500 kelvins.

Looking for signs of this transition was a goal of Discovery Science experiments on NIF conducted by Marius Millot, Peter Celliers, and other Livermore researchers, together with colleagues from the University of California (UC) at Berkeley, the Carnegie Institution, France's Alternative Energies and Atomic Energy Commission, and the United Kingdom's Edinburgh University. A series of small shocks of increasing strength was fired at cryogenic liquid deuterium positioned between a copper plate and a lithium fluoride window. This technique kept the temperature lower than would be possible with one large shock, allowing access to unprecedentedly high densities. The team used a diagnostic called the Velocity Interferometer System For Any Reflector (VISAR) to record the velocity of reflected laser light by measuring the light's Doppler shift. Through VISAR's transparent lithium fluoride window, they also observed dramatic changes in the optical properties of deuterium. "During these 30-nanosecond-long dynamic compressions, we clearly see hydrogen transitioning from transparent to opaque and then becoming as reflective as a metal foil," says Millot. Further analysis and comparison with state-of-the-art simulations at Livermore will likely enhance understanding of the behavior of hydrogen and other matter at extreme density.

A research team led by Livermore physicist Ray Smith and including researchers from UC Berkeley and Princeton University has used ramp compression on diamond, the hardest known material and a form of carbon, the fourth most abundant element in the universe. Diamond may reside in the cores of Neptune and Neptune-sized giant planets, which are common in our galaxy. The experiments achieved pressures as high as 5 terapascals—15 times the pressure at Earth's core and comparable to pressures at the center of Jupiter and Saturn. This pressure was achieved by ramp-compressing diamond to almost four times its normal density and more than six times the pressure previously achieved in similar experiments by the same team at the Omega laser. Eggert notes that at pressures exceeding 1 terapascal, diamond is theorized to transition to a different solid phase called BC8, which may be harder than ordinary diamond. NIF experimenters are attempting to create that phase in the laboratory for the first time.

## Models Keep Improving

"We are now measuring material properties on NIF at pressures up to a billion Earth atmospheres," notes Swift. The improvement in HED understanding has not come without surprises, in part because materials can behave entirely differently under HED environments, whereas materials science theories have been based on experiments conducted at much lower pressures and temperatures. "We sometimes fail to predict complex material behavior," says Swift. "For example, we're discovering crystalline structures we didn't know existed but which have a bearing on material strength." In addition, some materials can be stronger than simulation codes predict because a shock can damage the crystal lattice, making the material stiffer.

Remington, Rudd, and Justin Wark of the University of Oxford reflected on the growing importance of HED experiments in a paper they published in 2015. "Regimes of science hitherto thought out of reach in terrestrial settings are now being accessed routinely," they wrote. "There are a multitude of new regimes of science that are now accessible in laboratory settings. Matter can now be studied experimentally with precision at very high pressures and over very short timescales."

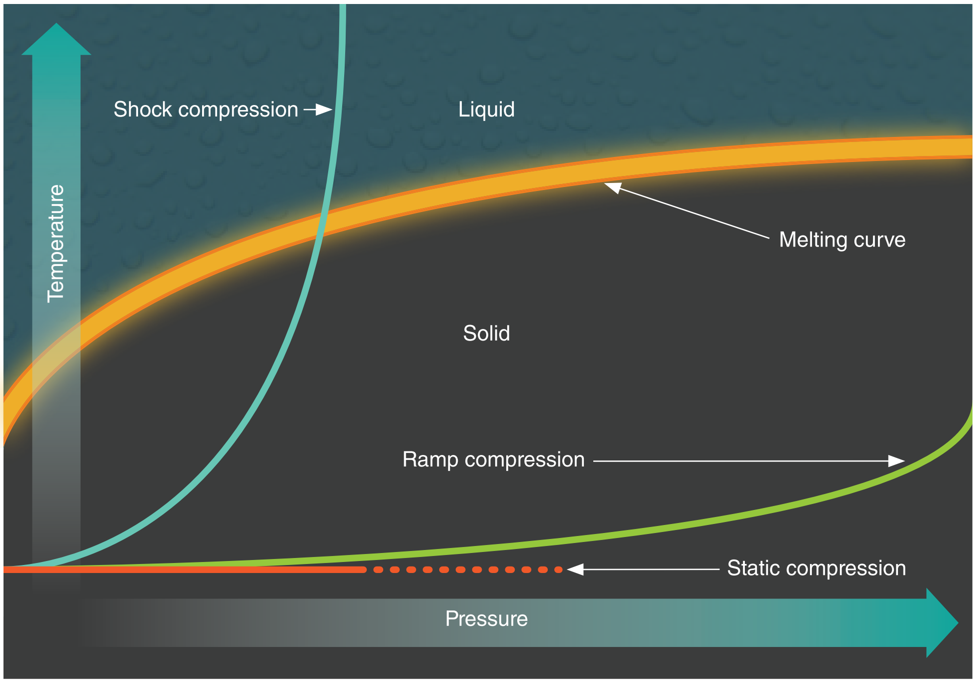
Physicist Alan Wan observes, "Thanks to these NIF experiments, we have obtained much greater understanding of HED physics." He adds, "In HED science, the United States is clearly out front in the world. Lawrence Livermore and the nation need to remain the center of excellence for HED science. We're doing things no one

An international team of astronomers has found evidence of a potentially habitable planet orbiting the star closest to our solar system, Proxima Centauri. Seen in this artist's depiction, this exoplanet, named Proxima b, has a mass approximately 1.3 times that of Earth and orbits its parent star every 11.2 Earth days.

else can do. It's a way to leverage the nation's scientific prowess."

NIF can transform astronomy into an experimental science to better interpret observations and refine the latest models of the evolution and composition of stars, planets, and cosmic rays, as well as the dynamics of asteroid and meteor impacts, the response of space hardware to dust and debris impacts, and the effect of prolonged radiation exposure on nuclear reactor components. These are indeed exciting times for the astrophysicists, planetary physicists, and materials scientists who are pioneering new directions in HED science and regularly announcing exciting new discoveries. NIF's rising shot rate—increased from 194 in fiscal year 2014 to more than 400 in fiscal year 2016—is enabling more Discovery Science experiments, shorter down time between them, and greater opportunities to explore new ideas.

Remington credits Discovery Science campaigns with bringing new ideas, science, and diagnostic techniques to NIF through the many outside collaborations. "We inevitably have a better facility and better science coming out of NIF when we have new people coming in with new ideas, creative instincts, and challenges."




Ramp compression is used on NIF to obtain crucial data on the strength and equation of state of a material. This technique preserves the material's structural integrity as it is subjected to enormous pressures, while keeping temperature lower than is possible with conventional shock compression, as the figure shows. This advantage is essential to investigating the cores of planets, including those located outside the solar system.

Arsenlis adds that the experiments help recruit, retain, and train a new generation of HED researchers. By their very nature, the experiments attract talented physicists and challenge theories in ways that can be experimentally tested. HED experiments at NIF, he says, are often extremely complex and require researchers to exercise the full range of modern computational and experimental capabilities. "A lot of physics is happening in every experiment, and we have to make sure the conditions are right," he notes. "At the same time, a huge engineering effort is underway to build the required targets and diagnostics. All this creates a lot of opportunities for talented young researchers."

—*Arnie Heller*

**Key Words:** Astrophysical Collisionless Shock Experiments with Lasers (ACSEL), astrophysics, collisionless shock, cosmic ray, Discovery Science Program, exoplanet, high-energy-density (HED) science, hydrogen, Jupiter, National Ignition Facility (NIF), Omega Laser Facility, Neptune, planetary science, super-Earth, Target Diffraction In Situ, Velocity Interferometer System for Any Reflector (VISAR), Z Pulsed Power Facility.

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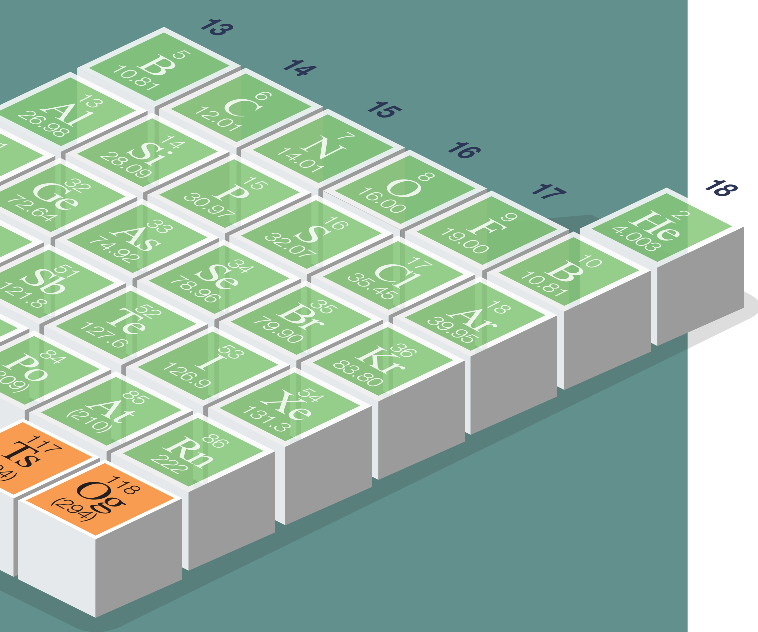
# GETTING TO THE **END** OF THE **MATTER**

THE number 118 is higher than 117, but the search for superheavy element 117 may have tested the ingenuity and resolve of the scientific community more than did element 118. Finding these and other superheavy elements of the periodic table—those with an atomic number (Z) greater than 104—is a matter of close international scientific cooperation, experimental creativity, and pioneering and exacting data analysis. Synthesizing and investigating these elements expands scientists' knowledge of the chemical and physical behavior of matter.

Six Russian and American research institutions, including Lawrence Livermore National Laboratory and Russia's Joint Institute for Nuclear Research (JINR), located in the city of Dubna, collaborated on the discovery of element 117. The paper announcing 117's detection was published in April 2010, whereas evidence for the heavier element 118 had come out four

The current periodic table of the elements shows the newly named elements (numbers 113–118) in the lower right. With the naming of elements 113, 115, 117, and 118, discovered by the Livermore–Dubna collaboration, the seventh row of the table is complete. If heavier elements were to be discovered, element 119 would begin a new row.




years earlier, the result of work done by Livermore and Dubna, in part because the target isotope used to generate 118 is longer-lived and easier to obtain.

Superheavy elements have very brief half-lives—the time required for a quantity of the element to decay by one-half, often measured in seconds to milliseconds. Synthesizing these elements requires accelerating beams of neutron-rich ions at a target coated with a high-Z element. Among the collisions that follow, a few—less than a dozen out of 10 billion billion ($10^{19}$)—will form atoms that promptly decay by emitting alpha particles—helium ions containing two neutrons along with the two protons. For instance, an atom of element 117 decays into 115 by emitting an alpha particle, thereby losing two protons, then 115 decays to 113, and so on, until the nucleus fissions into two fragments. Each alpha particle's position, energy, and formation time can be measured. The whole cascade produces a set of decay products unique to the element created during the initial collision. From the decay products researchers can thus determine the original element.

To generate just a few atoms of 117, the team needed to bombard a target coated with berkelium-249 with a neutron-rich beam of calcium-48 ions. Oak Ridge National Laboratory's High-Flux Isotope Reactor (HFIR) generated the berkelium-249, a rare isotope with a half-life of 320 days, producing just milligrams. HFIR shipped the isotope to the Research Institute of Atomic Reactors, which made berkelium-coated targets and sent them to Dubna, where the experiments were performed. The clock was ticking—everything had to be completed before too much of the short-lived berkelium decayed.

## Finding One Event in a Billion Billion

Now the ion beam bombards the target for months, during which the collected data are analyzed in real time. Proving a decay chain observed during an experimental run represents atoms of a new element is as much a matter of mathematical analysis and ruling out other possibilities as of observation. "In general, it takes about one billion random events before you see something that looks like the first true event," says nuclear chemist Nancy Stoyer, a member of the team focusing on superheavy elements since 1995. "Our concern was the event's random probability—was it real or random error? We wondered if we could use the data itself. Could it tell us the chance that the event was a random one?" Stoyer and her husband, nuclear chemist Mark Stoyer, along with other members of the Livermore team, pioneered the development of probability-based analysis methods for the superheavy element search.

"Element 117 has a long decay sequence," says Mark Stoyer. "It decays rapidly, so its random probability is very low. One of Livermore's most important contributions to the collaboration was the use of independent data analysis to verify the claim of discovery—a group at Dubna and one at Livermore checking each other's results. We also introduced random probability analysis." For 117, Livermore was joined by colleagues at Oak Ridge, Vanderbilt University, and the University of Nevada at Las Vegas. The team developed methods of simulating billions of nuclear events by generating them randomly using Monte Carlo calculations. Thanks to the careful analysis, the Livermore and Dubna groups were able to demonstrate that the decay chains observed in Dubna were real events, not random error of the detection method. Livermore's Roger Henderson conducted the data analysis that identified element 117.

## Introducing Oganesson, Tennessine, and Moscovium

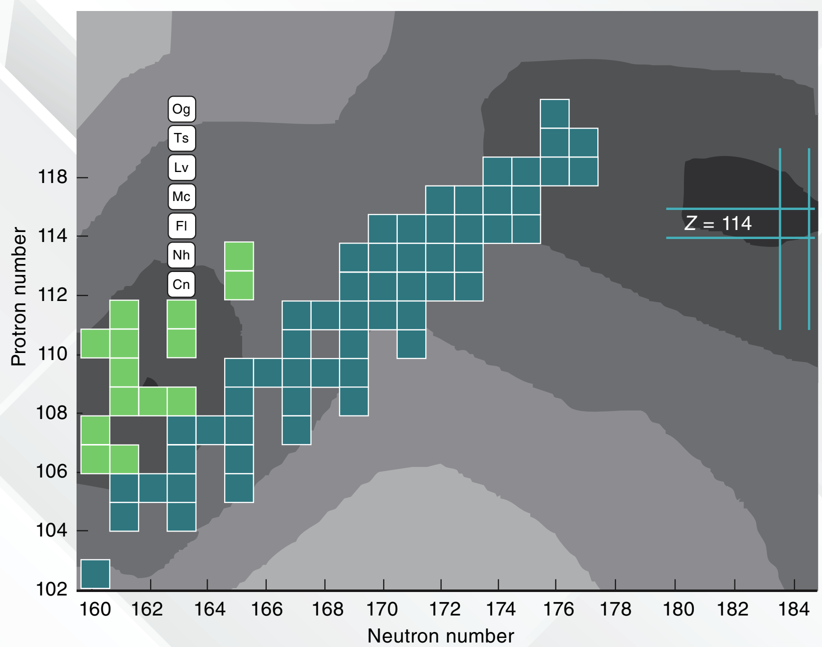
Following a multiyear, multilaboratory process of verifying results, the International Union of Pure and Applied Chemistry (IUPAC) agreed that the evidence added up to the detection of new elements. After an IUPAC release last June listing proposed names for public comment, the elements' new names have now become official. Oganesson, 118, is named for Yuri Oganessian, the leader of the Dubna team credited for discovering six elements altogether. Tennessine, 117, honors Tennessee, the home state of Oak Ridge, which has provided nuclear materials in superheavy element discovery for many years. Element 115 is now moscovium, also observed during the Dubna–Livermore collaboration. For element 113 the IUPAC approved the name nihonium, giving credit to a Japanese laboratory for a different isotope than that observed in the Livermore–Dubna experiments.

These four elements now join livermorium (116), named for the city where Lawrence Livermore is located, and flerovium (114), named for Georgy Flerov (the Russian founder of the Dubna laboratory), as the newest additions to the periodic table. The six elements, all discovered or observed by the Russian–American collaboration, fill out and complete the seventh row of the table.

The predominance of American and Russian names in the newest elements reflects the strength of collaboration between Livermore and JINR that began in 1989. Ken Hulet founded the group at Livermore, and over the years leadership passed to Ron Lougheed, Ken Moody, and then Dawn Shaughnessy, currently leader of Livermore's Nuclear and Radiochemistry Group. The Laboratory Directed Research and Development (LDRD) Program funded much of the research, while the Department of Energy's Office of Science funded some Livermore work, as well as Oak Ridge efforts to produce the isotopes needed for the 117 experiment. (See *S&TR*, October/November 2010, pp. 16–19.)

## The Future of Superheavy Element Research

The discovery of these new elements is part of a larger puzzle. Many fundamental questions remain about the limitations of matter and its chemical behavior at the far end of the periodic table. Shaughnessy and her colleagues are focusing on the




The island of stability is where nuclear chemists from Livermore and Dubna hope to find superheavy elements with half-lives longer than the millisecond timescale—perhaps long enough to be chemically useful. A portion of the table of isotopes focusing on the heavier isotopes is shown. Each colored box represents a synthesized isotope, with darker green representing the over 50 isotopes observed by the Livermore–Dubna collaboration, which was involved in the discovery of new elements nihonium (Nh), flevorium (Fl), moscovium (Mc), livermorium (Lv), tennessine (Ts), and oganesson (Og). [Copernicium (Cn) was discovered by Germany's GSI Helmholtz Centre.] A darker gray background indicates a longer half-life. Heavier, more stable isotopes are theoretically possible near a proton number ($Z$) of 114.

chemistry of the new elements. Shaughnessy says, "Element 114 [flerovium] is the Holy Grail, because of the many predictions about its chemistry—some say a metal, some say a noble gas—and because one of its isotopes has a half-life of about two seconds, long enough to enable study. Performing the experiments would not be trivial, but ways exist to do the chemistry." In 2017, an LDRD-funded project led by Livermore postdoc John Despotopulos will study the aqueous chemistry of flerovium to establish the techniques for studying the chemistry of isotopes that are manufactured in a particle accelerator and subsequently transported into a liquid-containing reaction chamber.

"As we get to this region of the periodic table, a nucleus has so many protons that relativity affects the behavior of the electrons," explains Shaughnessy. "The electrons move at speeds approaching a fraction of the speed of light, which increases their mass and causes them to bond differently from other elements in the group. If these predictions of relativistic quantum chemistry are correct, and 114 is not reactive, then science may need to rearrange the periodic table itself to reflect the nature of that bond."

However, the physics also beckons. Scientists would like to know where the table ends. At what atomic number is it no longer possible to make a new element? Physicist Richard Feynman suggested the periodic table could go to element 137, whereas Finnish chemist Pekka Pyykkö calculates that the elements could range as high as 172. The elements beyond oganesson will fill out the eighth row of the periodic table, where the outermost electrons will begin to populate the eighth shell and its subshells, known as orbitals. Oganesson's electrons populate the eighth shell's outermost orbital, 7f, and some elements in the eighth row would have electrons in the g orbital, which has never been observed and which would introduce new and unknown chemical behaviors.

The Livermore team is working with its Russian colleagues to find more isotopes of 118, with the Russians building an additional dedicated accelerator at Dubna. "This will increase the production rate of the superheavy elements by more than an order of magnitude—from 30 to 50 atoms per year to thousands," says Mark Stoyer. Their hope is to eventually find elements in the island of stability—a zone of the periodic table where elements with much longer half-lives may exist. However, getting there will require collisions between beams of heavier neutron-rich ions and targets coated with actinides, producing new isotopes with far more protons and neutrons, or collisions transferring multiple neutrons or protons between projectile and target—a new technique for super heavy element production. Dubna's new accelerator will allow the collaboration to try these techniques and open up novel experiments in chemistry, atomic physics, and mass measurement—and perhaps also leading to yet more names on the periodic table.

*—Allan Chen*

Livermore nuclear chemist Nancy Stoyer stands in front of the U-400 Cyclotron during a maintenance period at the Joint Institute for Nuclear Research in Dubna, Russia, where many superheavy elements were first synthesized and observed.

**Key Words:** berkelium-249, calcium-48, decay chain, flerovium, half-life, livermorium, moscovium, nihonium, oganesson, periodic table, superheavy element, tennessine, trans-actinides, transuranics.

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