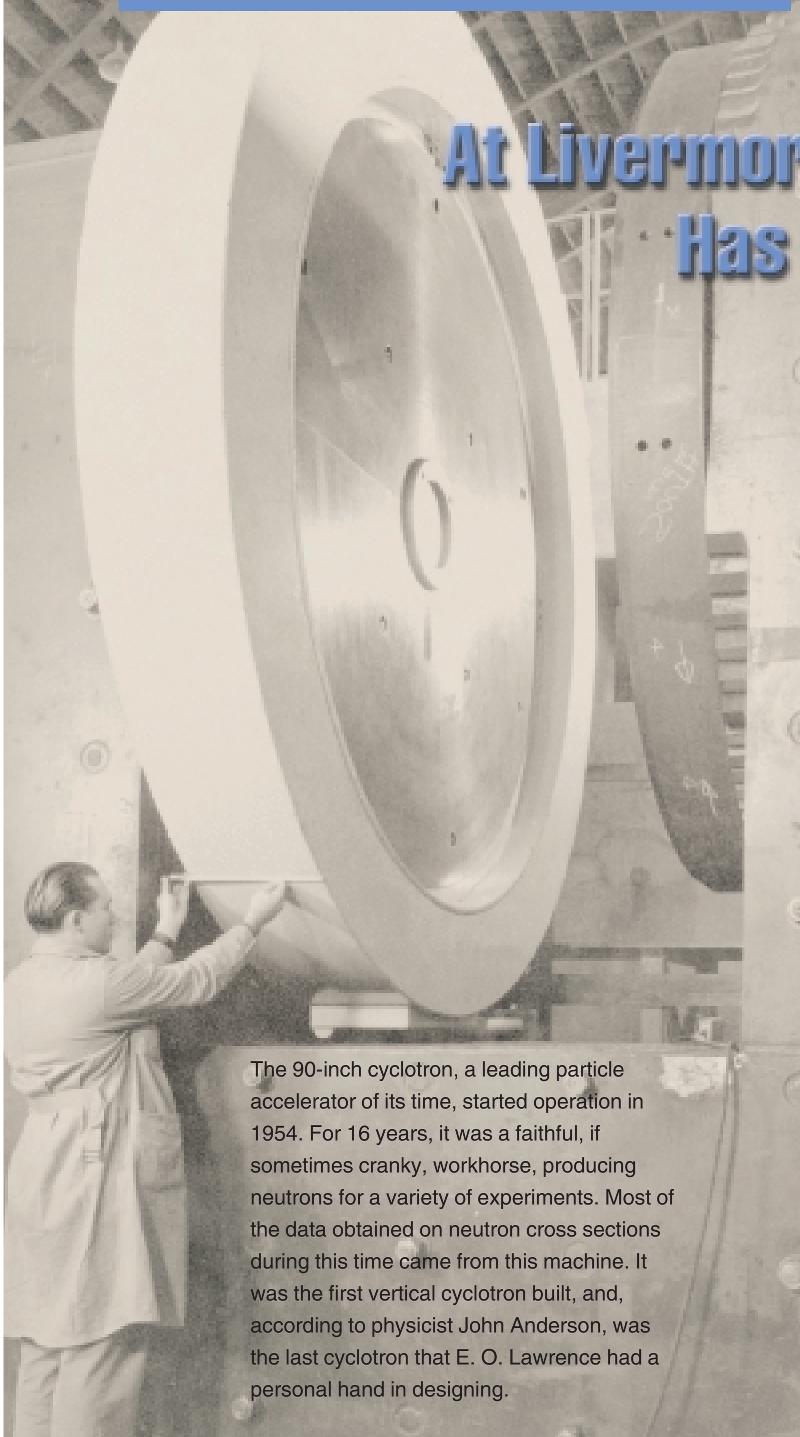
At Livermore, Audacious Physics Has Thrived for 50 Years



The 90-inch cyclotron, a leading particle accelerator of its time, started operation in 1954. For 16 years, it was a faithful, if sometimes cranky, workhorse, producing neutrons for a variety of experiments. Most of the data obtained on neutron cross sections during this time came from this machine. It was the first vertical cyclotron built, and, according to physicist John Anderson, was the last cyclotron that E. O. Lawrence had a personal hand in designing.

WHEN E. O. Lawrence selected Herbert York, a young physicist from Lawrence's Radiation Laboratory at Berkeley, to head the laboratory at Livermore, York had to come up with a starting point for possible programs, organization, and personnel at Livermore. The plan York developed called for four activities: thermonuclear weapons design, design and development of diagnostics for weapons experiments for both Los Alamos and Livermore, work on controlled thermonuclear reactions (in other words, fusion) for potential power sources, and basic physics research. All of these activities are, at heart, issues of physics. To understand the inner forces that govern a nuclear weapon, a fusion power source, or, indeed, the interior of a star requires knowing how the thermonuclear process works.

From the Laboratory's earliest days, physicists have explored some of the most difficult issues in the highly specialized fields of nuclear, condensed-matter, plasma, atomic, and molecular physics. As a result, the physics organization has always been a testing ground for new concepts and an integral contributor to major Laboratory programs, many of which it

> *"Every great advance in science has issued from a new audacity of imagination."*
>
> *John Dewey, philosopher*

The Laboratory has always been interested in astrophysics puzzles. In the 1960s, Laboratory physicists authored key papers on gravitational collapse and supernova explosions. In 1976, Livermore physicists John Browne (left), now director of Los Alamos National Laboratory, and Barry Berman used the Livermore's linear accelerator to gather key data to revise estimates of the age of the universe.

helped create. From their initial focus on the thermonuclear process, the Laboratory's physicists have advanced theoretical understanding and spearheaded breakthrough after breakthrough in applied physics—from the inner workings of the atom to the farthest reaches of the universe.

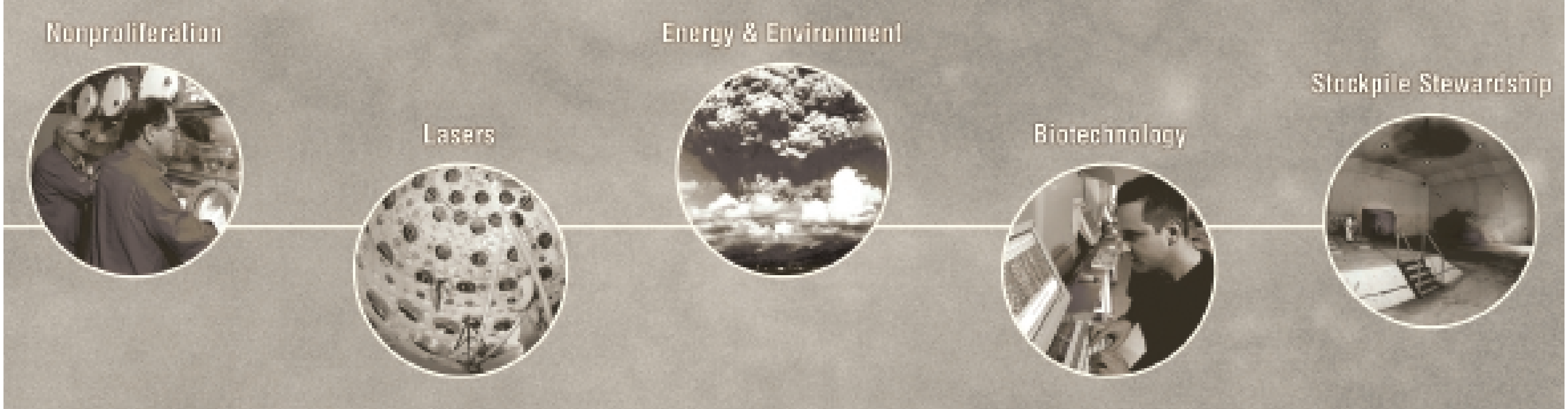
Exploring the Heart of a Weapon

Understanding a weapon's performance requires a thorough understanding of the properties of matter at extreme conditions—up to stellar temperatures and pressures—and of the interaction of matter with intense radiation. From the first days at Livermore, physicists made it their goal to better measure and validate material properties such as equations of state, opacities, and nuclear cross sections for these unique environments. Their tools included accelerators, gas guns, nuclear reactors, lasers, and nuclear tests on the one hand and advances in theory, powerful computers, and physics simulation codes on the other.

The nuclear cross section is particularly important for understanding how well a nuclear weapon performs; it has been of interest to the Laboratory from the start. The cross section is a measure of how likely it is that a particular reaction will occur between a nucleus of a particular material and an impinging particle. For nuclear weapons research, the particle of interest is usually a neutron, and the material is uranium, plutonium, steel—any of the materials that go into a nuclear device. Physicist John Anderson, who came to the Laboratory in 1956 and was associate director for Physics from 1978 to 1983, remembers, "In the 1950s, neutron physics was a hot topic. Many places were researching cross sections, but Los Alamos and Livermore were the only ones generating information applicable to weapons." Early Livermore physicists used two machines for gathering cross-section measurements: a Cockroft–Walton accelerator and the 90-inch cyclotron. These were replaced by the 100-megaelectronvolt linac, a linear accelerator still active today. The cross-section measurements obtained with these machines were used to continually improve weapons computer codes used to calculate a weapon's yield.

Cross-section measurements are also needed in the nation's present-day Stockpile Stewardship Program. Bill Goldstein, associate director for Physics and Advanced Technologies (PAT), explains, "One of the directorate's primary stockpile stewardship responsibilities is to support the Physical Data Research Program by providing validated data on material properties that are basic to weapons research." Just as in the past, physicists combine theory with computer simulations and laboratory measurements to provide the validated data needed for nuclear weapons simulations. With today's sophisticated tools, researchers can revisit some of the more difficult problems, reevaluating and refining measurements. One such example is a cross section in which a neutron smashes into a plutonium-239 atom, resulting in one plutonium-238 atom and two neutrons. Getting a good value for this cross section is particularly important because the production of plutonium-238 by neutrons is a major diagnostic for interpreting the results of past underground nuclear tests. For more than 40 years, large uncertainties in this cross section's value have limited the usefulness of plutonium-238 production as a nuclear test diagnostic.

In 2001, a five-year collaboration between Livermore and Los Alamos produced new measurements of this crucial reaction. The Livermore team, led by physicist John Becker, developed an innovative measurement approach using gamma-ray spectroscopy. Resolving the cross section from the experiments required a combined, intensive effort by experimentalists, nuclear theorists, and modelers. The new



measurements promise a better understanding of the data collected from past nuclear tests, aiding current stockpile stewardship efforts.

The Laboratory's tradition in developing and using state-of-the-art accelerators has continued unabated since the early days. Livermore partnered with the Stanford Linear Accelerator Center and Lawrence Berkeley National Laboratory in the 1990s to build the 2.2-kilometer-circumference B Factory, which is elucidating the origin of the matter–antimatter asymmetry in the universe. (See *S&TR*, January/February 1997, pp. 4–13.) The team is now helping design the 25-kilometer-long teraelecronvolt Next Linear Collider to better analyze physics beyond the Standard Model. (See *S&TR*, April 2000, pp.12–16.)

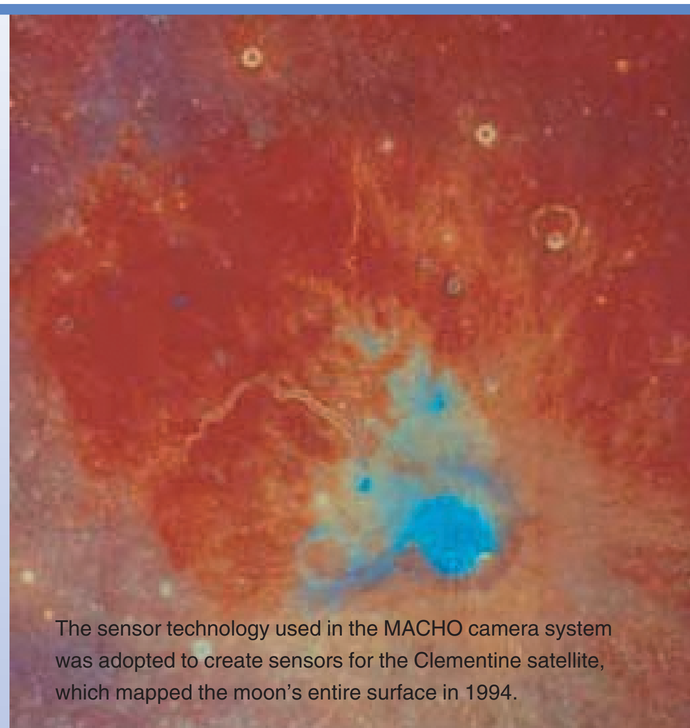
Divining the Heart of a Star

The same thermonuclear processes that drive a nuclear weapon drive the heart of a star. So, it's no surprise that astrophysics research at Livermore draws on the Laboratory's expertise in high-energy-density physics and complements the Laboratory's important stockpile stewardship responsibilities. In *Memoirs*, Edward Teller, who founded Livermore Laboratory along with E.O. Lawrence, notes, "From the beginning, and throughout the years to this date, Livermore has emphasized astrophysics and other branches of pure science in the recognition that great progress in applications cannot be made if science itself is neglected." In particular, Teller noted a paper by Stirling Colgate and Montgomery Johnson in 1960 that correctly described the mechanism and effects of an exploding star—a supernova. "The novelty in Montgomery and Stirling's work," explains Teller, "was their recognition that a shock wave, taking its origin in the center of the star and accelerating as it spread into the less dense regions of the star, was the first step in producing cosmic rays. That work is still cited as one of the more important papers in our current understanding of the universe." Research into astrophysics and general relativity continues, both at the Livermore branch of the University of California's Institute of Geophysics and Planetary Physics (see the box below) and within the PAT Directorate.

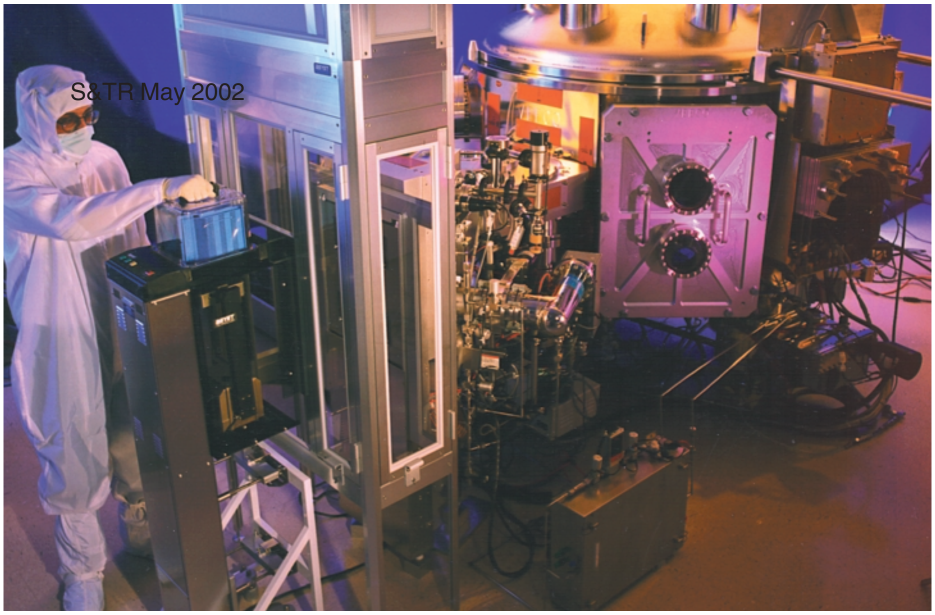
One example of current research applicable to astrophysics and stockpile stewardship is work on radiative opacity—that is, the study of how opaque a material is to the transport of photons. (See *S&TR*, April 1999, pp. 10–17.) Stellar opacity is concerned primarily with lighter elements, while opacity of nuclear weapon plasmas focuses on heavier elements; yet, the physics is similar for both. Researchers generally use detailed computer models to calculate opacities because it is extremely

Searching the Universe

One ongoing project of the Livermore branch of the University of California's Institute of Geophysics and Planetary Physics (IGPP) involves an attempt to identify the dark, invisible matter thought to comprise most of the universe's mass. (See *S&TR*, April 1996, pp. 6–11.) In the late 1980s, Livermore astrophysicist Charles Alcock, applying an innovative imaging technology invented for the Strategic Defense Initiative, searched for occasional amplifications of starlight from outside the galaxy caused by the gravitational effects of large objects known as MACHOs (massive compact halo objects). In 2000, Alcock, now a professor at the University of Pennsylvania, won the American Astronomical Society's Beatrice Tinsley Prize for his research. The data, which were collected by early 2000, are now being analyzed. They are also being used in another IGPP project to study the Milky Way's structure and composition. The IGPP is also home to the Djehuty project to develop a next-generation, fully three-dimensional, stellar structure and evolution code that will run on massively parallel computers. (See article beginning on p. 4.)



The sensor technology used in the MACHO camera system was adopted to create sensors for the Clementine satellite, which mapped the moon's entire surface in 1994.



Livermore's early work on x-ray lasers and optics established technologies that led to its collaboration with industry and other national laboratories to develop extreme ultraviolet lithography for manufacturing the next generation of computer chips. Resulting microprocessors will be 100 times more powerful, and memory chips will be able to store 1,000 times more information than they do today. Livermore is the lead laboratory for optical design and fabrication, metrology, multilayer coating development, and mask fabrication for this project.

difficult to directly measure the opacity of materials hot enough to be in plasma form. In the early 1990s, physicists Forrest Rogers, Carlos Iglesias, and Brian Wilson built OPAL, a new model of stellar opacity that avoids many of the approximations and simplifying assumptions of earlier codes. In particular, OPAL accurately treats the myriad energy transitions in iron, which were previously overlooked in blocking radiation. OPAL calculations showed that iron, the most abundant heavy element in a star, can significantly impede radiation flow and therefore plays a major role in stellar properties. Throughout the 1990s, OPAL was refined through experiments on Livermore's Nova laser and on the Saturn pulsed-power machine at Sandia National Laboratories in Albuquerque. Data from these experiments and the codes they validate are being used to deepen astrophysicists' understanding of stars, strengthen fundamental knowledge of atomic processes in extreme environments, and provide greater confidence in the computational tools needed to maintain America's nuclear forces.

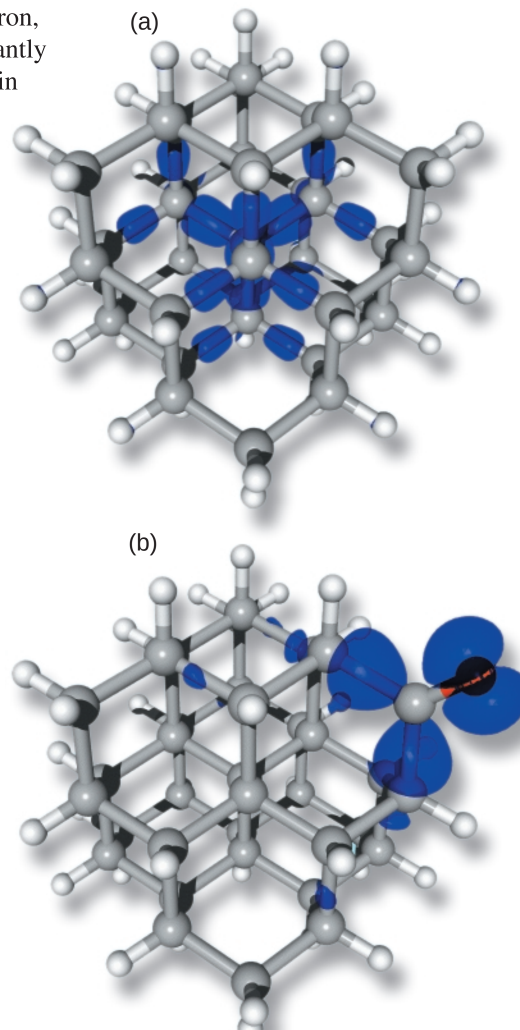
Creating Fusion in the Laboratory

It's little wonder that Herb York's original plan for the Laboratory included a group to research controlled thermonuclear reactions (CTR), or fusion energy. Not only are the physics processes of fusion similar to those of a nuclear weapon, but also interest in using fusion for power production was gaining ground in the early 1950s. The prospect was for a virtually inexhaustible, low-cost, safe, and environmentally attractive energy source.

The Laboratory initially concentrated on the magnetic confinement concept for producing fusion power, in which a magnetic force field traps a plasma long enough to achieve fusion. Livermore's approach was to use reflecting magnetic fields—or magnetic mirrors—to confine the fusion fuel. The first CTR group leader, physicist Dick Post, remembers, "In 1952, hardly anyone understood even the simplest aspects of the confinement of plasma by mirrors. There just wasn't any prior work to go on." Livermore physicists started with the basics, studying fundamental plasma processes; developing

(a)

(b)



Recent Livermore quantum molecular simulations examined the effects of contaminants such as oxygen on silicon quantum dots. A single oxygen atom can make a big difference on a quantum dot because of the dot's large ratio of surface area to volume. (a) In a simulation of a nanometer-size (71-atom) silicon quantum dot, the white hydrogen atoms bond to the surface, making the dot less reactive. The purple region, or "cloud," shows where light-absorbing electrons are most likely to be located inside the dot. (b) When two hydrogen atoms are replaced by an even more reactive oxygen atom, the electron charge cloud is drawn toward the oxygen atom, dramatically changing the optical properties of the silicon dot.

Sensors for Personal Health and the Health of the Nation

Innovative sensor and detector development for medical, national security, and defense-related applications is another focus of Livermore's physicists. In the Medical Technology Program, physicists, bioresearchers, and others are developing tools to provide cost-effective treatment for acute stroke, cancer detection and therapy, diabetes treatment and diagnostics, and therapy for other prevalent diseases of national importance.

For example, a microbead immunoassay dipstick system under development could be used by personnel such as firefighters and paramedics to run sophisticated diagnostics at the emergency site using a simple, one-step measurement. It could also be used as a portable clinical laboratory for military operations and for detection of biowarfare agents. Another tool, the Smart Probe, promises to provide early and accurate detection of breast cancer. The probe's sensors measure optical, electrical, and chemical properties that differ between healthy and cancerous tissues. Sensors play an important role in a program to develop an advanced interceptor for missile defense programs. The Advanced Technology Kill Vehicle uses lightweight integrated sensing systems to guide and control it while intercepting a missile. Cryogenic detectors, such as the one developed by physicist Simon Labov and his team, can distinguish between background radiation and nuclear materials and show promise in helping guard against the proliferation of nuclear weapons. (See *S&TR*, April 1998, pp. 16–18.)

methods to measure the temperature, density, and diffusion rates in a hot plasma; and exploring ways to contain the plasma.

Weapons and fission energy research also benefited fusion energy efforts, particularly in the search for reactor materials. John Anderson explains, "Fusion reactions produce large quantities of neutrons that can 'activate' the materials they hit, making the materials radioactive. You need to know how much radioactivity is generated, and you need accurate neutron transport models, topics of interest to weapons researchers as well." Beginning with the Table Top Reactor in 1954, Livermore created a series of machines to study the concept of plasma confinement using magnetic fields. More recently, Livermore fusion energy scientists are revisiting the spheromak concept of magnetic fusion. (See *S&TR*, December 1999, pp. 18–20.)

The tantalizing possibility of fusion energy took another turn with the invention of the laser in 1960. Some Livermore researchers, including physicist John Nuckolls (who later became a Laboratory director), wondered whether laser light might be able to trigger fusion reactions. Nuckolls and fellow physicists Ray Kidder and Stirling Colgate used Livermore-developed codes to study the possibility of compressing and igniting a small amount of deuterium–tritium fuel with powerful, short-duration laser pulses. These calculations revealed that to achieve energy gain—that is, to get more energy out than is put in—the laser would have to compress the fuel to about 1,000 times its liquid density.

In 1962, a small laser fusion project started in the Physics Department to explore this possibility. In the early 1970s, new computer calculations showed that interesting laser fusion experiments could be done with lasers as small as 10 kilojoules and that energy gains could be achieved with a megajoule-size laser. By this time, interest in laser fusion was widespread, and in 1972, the Inertial Confinement Fusion (ICF) Program was formed at the Laboratory. From this program sprung a series of increasingly powerful lasers, beginning in 1975 with Janus, a two-beam system with under 50 kilograms of laser glass, and leading to the National Ignition Facility, which will have 192 beams and over 180,000 kilograms of optics and is now under construction.

The x-ray laser also owes its existence to Livermore's early research into the physics of lasers. In the 1970s, physicists realized that laser beams could be generated by ions with high-lying energy states. In the 1980s, Livermore generated the first-ever x-ray laser beams in an underground test and demonstrated the first x-ray laser in a laboratory setting. In the 1990s, a Livermore team developed a small tabletop x-ray laser ideal for probing and imaging high-density plasmas. (See *S&TR*, September 1998, pp. 21–23.) These small x-ray lasers are used to fine-tune equations of state for a variety of materials, including those of interest to stockpile stewardship. Development of the x-ray laser also established the technical skills that helped lead to short-wavelength projection lithography for mass production of integrated circuits—a technology of significant importance to the nation's semiconductor industry. (See *S&TR*, November 1999, pp. 4–9.)

Understanding the World, Atom by Atom

"The preeminent goal of physics in the 20th century was to understand the workings of the world at the most fundamental level," says Goldstein. In the earlier part of the century, as physicists began studying atoms and their constituents, they learned that Newton's laws of motion did not apply on the small scale. The powerful mathematical tools of quantum mechanics were developed, and when computers arrived mid-century, with their geometric growth in computing power, physicists were in a better position to address the complexities of many particles interacting to produce the bulk properties of material systems.

At Livermore today, physicists such as Giulia Galli use the supercomputers of the Advanced Simulation and Computing (ASCI) program to simulate matter at a more fundamental level than was previously feasible. (See *S&TR*, April 2002, pp. 4–10.) Computer codes have been developed that allow researchers to simulate the interactions of 10 to 1,000 atoms and see in detail the dynamic activity of nanoparticles of individual atoms and molecules. For the silicon nanoparticles known as quantum dots, quantum simulations reveal unique optical properties that vary with size and surface characteristics. Lasers made of silicon are now possible, as are silicon dots that could be used as fluorescent markers in biological research and as biological sensors.

Growing Leaders and Programs

Throughout Livermore Laboratory's history, the physics organization has been the birthplace of new scientific concepts. It has grown programs that then split off to become their own considerable forces, provided inspiration and support for a recent Nobel Prize winner whose work was carried out at the Laboratory, and developed many of the Laboratory's top leaders. All but one of the Laboratory's directors were physicists, and many—including Edward Teller, John Nuckolls, and Bruce Tarter—at one time or another headed the physics organization. "From early on, Physics has provided top leaders to the Laboratory, and we've also played a role in providing new programmatic directions for the Lab," says Goldstein. "I see both roles continuing into the future in our work to keep the Laboratory at the scientific cutting edge."

—Ann Parker

Key Words: astrophysics, dark matter, fusion energy, nuclear cross section, opacity, quantum mechanics, sensors, stockpile stewardship, tabletop laser, thermonuclear processes, weapons research, x-ray laser.

For further information about the Physics and Advanced Technologies Directorate, see:

www-pat.llnl.gov/

For further information about the Laboratory's 50th anniversary celebrations, see:

www.llnl.gov/50th_anniv/

In December 1998, Robert B. Laughlin, a longtime Livermore employee and a professor of physics at Stanford University, received the 1998 Nobel Prize for physics for work he did in the Laboratory's condensed-matter division in 1983. The prize—shared with Horst Stormer of Columbia University and Daniel Tsui of Princeton University—was awarded for the discovery that electrons acting together in strong magnetic fields can form new types of particles with charges that are fractions of electron charges. (See *S&TR*, January/February 1999, pp. 15–18.)

Photo: AP/Jonas Ekstromer