

Shedding Light on Quantum Physics

Einstein's explanation of Planck's quantum hypothesis is the bedrock of Livermore laser research.

In a letter to fellow scientist Robert Hooke in 1676, Isaac Newton wrote: "If I have seen farther than others, it is because I was standing on the shoulders of giants." The giants to whom Newton was referring were Copernicus, Brahe, Galileo, and Kepler.

A host of Livermore scientists whose work delves into the nature of light and energy could very well claim to be standing on the shoulders of the 20th century's own physics giant: Albert Einstein.

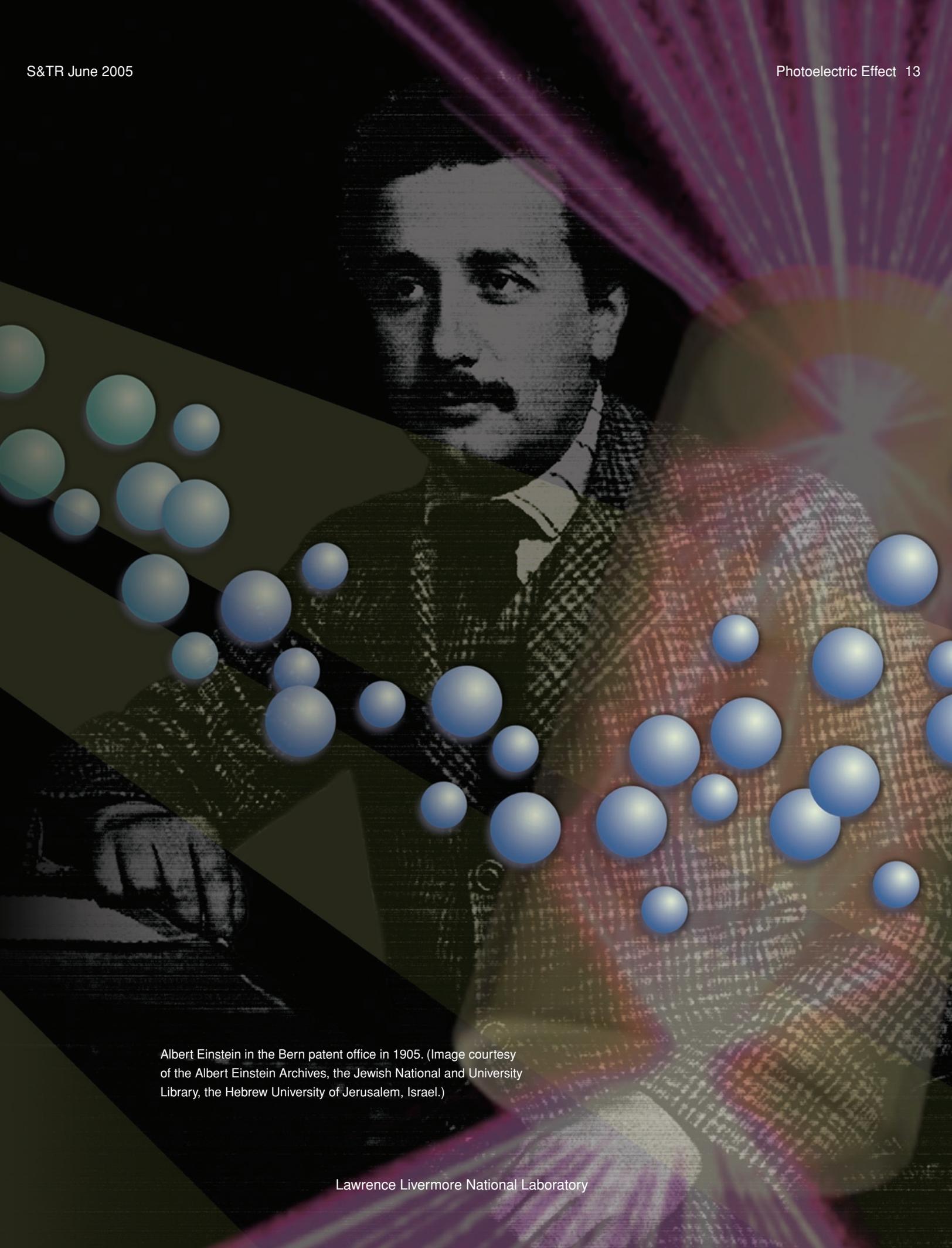
Livermore physicists using x-ray lasers and single-photon counting experiments to probe the mysteries of materials behavior and biological processes base their work on the tenets underlying two papers published by Einstein early in the last century. In one, Einstein put forth a theoretical explanation of light as a stream of particles. In the other, he explained how radiation is absorbed and emitted by atoms.

Understanding Light as Packets

In March 1905, Einstein submitted a paper entitled "Concerning an Heuristic Point of View toward the Emission and Transmission of Light" to the German journal *Annalen der Physik*. The paper was the first of a series of papers Einstein

published that year that ushered in the era of modern physics. In this paper, Einstein resolved several mysterious properties of visible electromagnetic radiation, or light, by proposing that such radiation is quantized; that is, it is emitted from radiating objects in discrete packets. As might be expected, Einstein's novel explanation was so unanticipated that it took more than 10 years to be accepted by the physics community. It wasn't until 1921 that Einstein was awarded the Nobel Prize for his work in this area.

Einstein had been fascinated by the nature of light and electromagnetic radiation for years before the publication of his paper in 1905. Much of the work driving the development of physics in the late 19th and early 20th centuries concerned understanding the nature of light. In 1704, Newton published his book *Opticks*, in which he argued that light was composed of particles. However, by the end of the 19th century, James Maxwell's work on electromagnetic radiation had demonstrated that light and all other forms of such radiation were best explained as waves. At the beginning of the 20th century, a few properties of electromagnetic radiation had yet to



Albert Einstein in the Bern patent office in 1905. (Image courtesy of the Albert Einstein Archives, the Jewish National and University Library, the Hebrew University of Jerusalem, Israel.)

be explained, and these were the puzzles that Einstein set out to unravel.

Planck’s Mathematical Trick

One experimental puzzle of electromagnetic radiation that physicists encountered at the turn of the 20th century was so-called blackbody radiation. An ideal blackbody absorbs all radiation to which it is exposed and reflects none, so it appears black to the observer. The absorbed energy, however, is re-emitted to maintain thermal equilibrium. It is the

spectrum of this radiation that Einstein ultimately correctly explained.

The puzzling issue was determining the distribution of frequencies of the radiation from a blackbody. That is, predicting the intensity of radiation emitted by a blackbody at a specific wavelength. The classical approach, using Maxwell’s equations and conventional thermodynamics, leads to predictions that do not coincide with experimental data at the shorter wavelength end of the distribution.

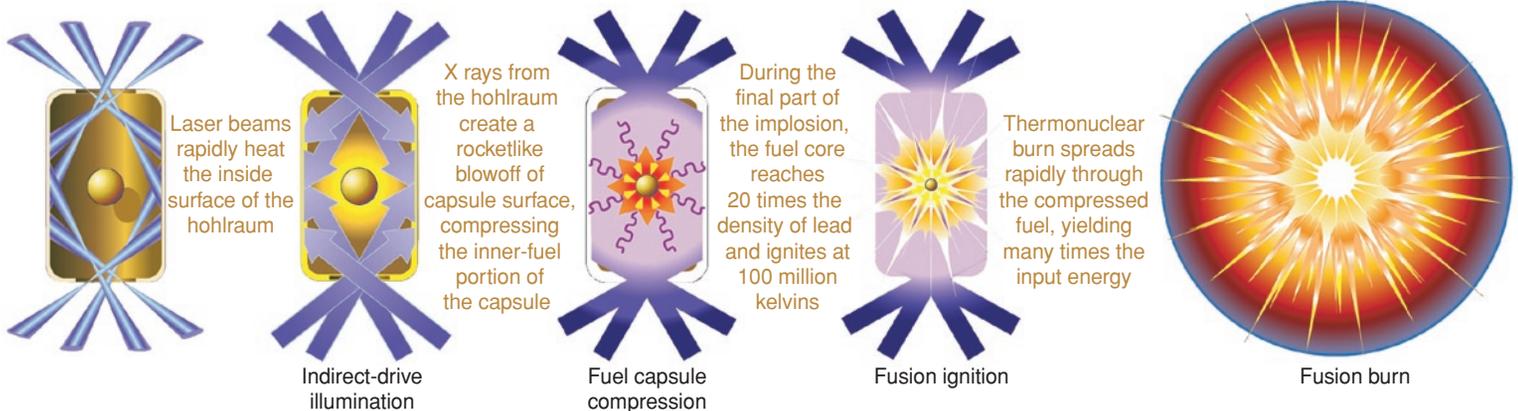
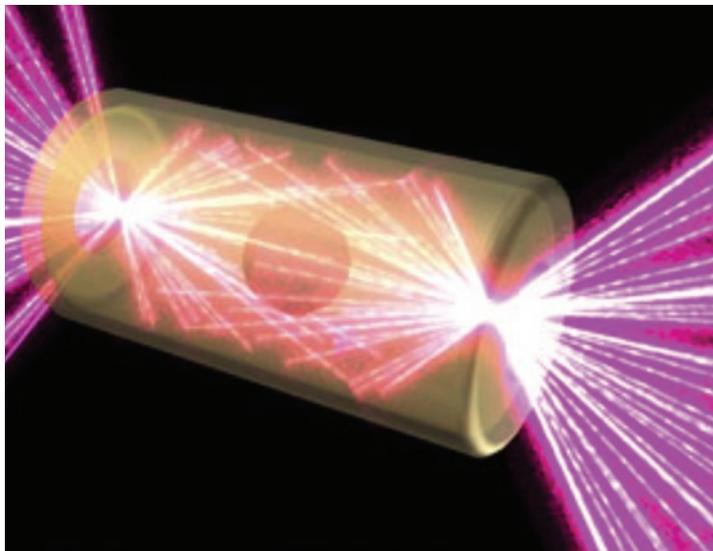
In 1900, German physicist Max Planck calculated the observed distribution of radiation energy in blackbodies based on the assumption that the oscillating atoms in the walls of the blackbody do not emit radiation at all energies—only at highly prescribed values. This assumption leads to a very different, and correct, expression for the distribution of radiation energy in a blackbody. Planck’s assumption was based on a theory about the properties of atomic oscillations—not about the true nature of light. In solving another puzzle about electromagnetic radiation (see p. 15), Einstein later realized that light itself was quantized.

The Photoelectric Effect

By 1905, Einstein was at the University of Zürich finishing his doctoral thesis in which he used statistical mechanics (the study of the motion of objects using mathematical tools for dealing with large numbers of objects) to infer the size of molecules. With his mathematical skills and fascination with light, Einstein had a breakthrough insight: Planck’s explanation made perfect sense if the radiation in a blackbody was a collection of discrete light particles, which he called quanta.

In the paper he submitted to *Annalen der Physik*, Einstein explained that Planck’s

An artist’s rendering shows how laser beams deposit their energy on the inside surface of a metal cylinder or “hohlraum,” where the energy is converted to thermal x rays. The x rays heat and ablate the plastic or metal surface of the ignition capsule, causing a rocketlike pressure on the capsule, which forces it to implode.



The steps of an inertial confinement fusion reaction, in which more energy is produced than is used to initiate ignition. Under laboratory conditions, the sequence produces energy gain equivalent to the power of a miniature star, lasting for less than a billionth of a second.

mathematical result in fact provided the true characterization of light. He then used this insight to explain what was then considered an unrelated puzzle: the photoelectric effect.

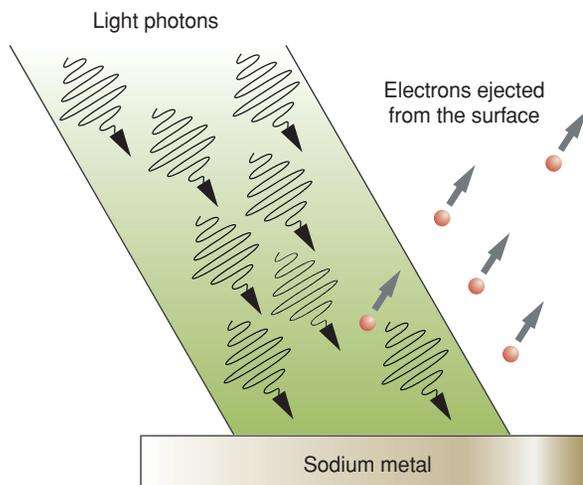
The photoelectric effect was first observed by Heinrich Hertz in 1887 and refers to the emission of electrons from the surface of a metal in response to incident light. When light is shone on certain metals, energy within that light is absorbed by electrons within the metals. This absorbed energy can cause the electrons to be photoionized, or ejected, from the surface of the metal.

The number of electrons ejected is proportional to the intensity of the light. This behavior is consistent with light being a quantum or a wave phenomenon. The energy of the ejected electron is proportional to the frequency of the light. However, if the frequency of the light drops below a certain threshold known as the work function (which is different for each metal), no electrons are ejected. For example, blue light causes sodium to release electrons, but red light does not. This property of the photoelectric effect could not be explained by characterizing light as a wave.

Einstein explained all aspects of the photoelectric effect with his light-quanta hypothesis in which light acts like small particles. He understood the work function as the amount of energy that the electron needs to be released from the atom. In the photoelectric effect, electrons in the metal absorb light quanta. If the energy of the quanta is greater than the work function, electrons are ejected. But if the energy is less than the work function, electrons cannot leave the metal, regardless of the number of quanta available.

Blackbodies and Fusion

Blackbodies are crucial for experiments performed at Livermore involving inertial confinement fusion, the process of compressing and heating hydrogen isotopes until they fuse together, releasing enormous amounts of energy. The National Ignition



A diagram of the photoelectric effect shows that light behaves like particles. The details of the photoelectric effect were in direct contradiction to well-developed classical physics. The explanation marked one of the major steps toward quantum theory.

Facility (NIF), scheduled for completion in 2008, will be used to achieve fusion ignition and burn. The facility and associated experimental efforts are the highest profile examples of fusion research at Livermore. (See *S&TR*, September 2003, pp. 4–14.)

A hohlraum serving as a blackbody is the target at which the NIF lasers are pointed. In this case, the hohlraum is a small, gold cylinder approximately 1 centimeter long and half a centimeter in diameter in whose center resides a spherical fusion-fuel capsule. When the hohlraum is hit with 300 trillion watts of laser beam energy, its metal is heated to a high temperature, creating a 3-million-degree x-ray oven. The energy radiating from the hohlraum implodes the capsule and ultimately ignites the fusion fuel (deuterium and tritium), which begins the ignition reaction.

Livermore physicists Mordecai Rosen and Larry Suter, both leading experts on laser hohlraum physics, have been instrumental in the development of the fusion project. “NIF hohlraums can serve as a physics factory in which we study high-energy-density physics, including fusion” says Rosen.

Answering Questions of Radiation

The second Einstein paper, which set the stage for future discovery of the laser,

was published in 1917 by *Zeitschrift für Physik* and entitled “On the Quantum Theory of Radiation.” In this paper, Einstein continued his inquiry into the properties of light and matter with an explanation of how radiation is absorbed and emitted by atoms.

In particular, he described three main processes for how radiation interacts with matter: spontaneous emission, absorption, and stimulated emission. In absorption, an atom absorbs a quantum of radiation and reaches a higher energy state known as an excited state. In stimulated emission, an atom in an excited state decays to a lower energy state by emitting a quantum of radiation; emission is caused by an incident quantum with the same energy as the emitted quantum. In spontaneous emission, an atom in an excited state decays to a lower energy state without an external “catalyst.” These processes are key to understanding how lasers work.

Isolating Single Photons

Livermore scientists Thomas Huser and Chris Hollars of the Chemistry and Materials Science (CMS) Directorate have an everyday appreciation of the implications of both the photoelectric effect and radiation emission. With Laboratory Directed Research and Development (LDRD) Program funding, Huser, a physicist, and Hollars, an

analytical chemist, are applying single-molecule spectroscopy to biophysical measurements. The researchers first attach fluorescent labels to single biomolecules. Then they image the fluorescent biomolecules either on surfaces or diffused in solutions to characterize them and determine their interactions with other molecules of interest.

Imaging requires a laser to excite single photoluminescent molecules located at the focus of a confocal optical microscope. The confocal microscope eliminates much of the background noise that normally comes with a detection technology

sensitive enough to identify a single-photon event.

Each photon fluoresced by the molecule is detected by an avalanche photodiode, which is commonly used in this type of research. In the photodiode detector, an incoming photon hits the photodiode lattice material—a mix of indium, gallium, and arsenic—and creates a photoelectron. “This phenomenon is precisely what Einstein was describing,” says Huser. That photoelectron, in turn, hits another electron and collides with the atomic lattice, releasing additional electrons via secondary ionization. These resulting electrons also are accelerated,

which induces an avalanche of electrons. As a result of this amplification, one photon creates a strong electrical pulse, which constitutes the detection of the photon.

Each molecule can emit only one photon every few nanoseconds, which means that Huser and Hollars are looking at sequences of millions of emitted photons over a period of minutes. A close examination of the precise time that each photon arrives at the detectors can be used to describe the state or behavior of the labeled biomolecule. “After the statistical analysis, we were able to show that we are, indeed, detecting single-fluorescence-

A Long History of Laser Research

The National Ignition Facility (NIF) is the latest project in a long history of laser research at Livermore. “The Laboratory has been building lasers for over 30 years, and the focus of these efforts has evolved to include both defense and scientific applications,” says physicist Joe Nilsen.

Physicist Chris Barty cannot put too fine a point on it. “Lasers and Livermore have a big overlap,” says Barty. “Livermore is the world leader in at least two aspects of lasers.” Barty cites those two aspects as high-energy lasers, such as NIF and Nova, and high-average-power lasers, such as those used in the uranium atomic vapor laser isotope separation (U-AVLIS) process.

Livermore has also led laser research in the areas of high-peak-power lasers and x-ray lasers.

High-Energy Lasers

High-energy lasers are used at Livermore to provide the energy densities required for inertial confinement fusion and to study high-energy-density physics. Typically, these lasers work in short bursts for tens of nanoseconds.

Livermore’s successful high-energy Nova laser became operational in December 1984 and at the time was the world’s most powerful laser. After 14 years and more than 14,000 experiments, Nova fired its last shot. Nova and a demonstration project, the Beamlet laser, served as the proving ground for Livermore’s next-generation high-energy laser project, NIF, the 192-beam facility designed to ultimately achieve thermonuclear ignition.

High-Average-Power Lasers

High-average-power lasers typically provide laser energy with trains of pulses or continuous pulses. In the early 1970s, Livermore’s U-AVLIS Program began. This system used copper-vapor and dye lasers and was

designed to enrich uranium for nuclear power applications. The system technology also has applications in precision machining, pumping ultrashort-pulse lasers, creating laser displays, and treating skin conditions.

Some of the technologies developed for the U-AVLIS system were also used in 1996 at the University of California’s Lick Observatory near San Jose, California, to demonstrate the laser guide star concept in which a laser beam is focused into the upper atmosphere, producing an artificial star to help improve telescope performance. The Livermore team, along with colleagues from the University of California and the California Institute of Technology, later installed adaptive optics and a guide star system on the 10-meter telescope at Keck Observatory in Hawaii. Since the installation, astronomers have been probing the deepest regions of the universe, obtaining astral images with resolution greater than that of other land-based telescopes or even the orbiting Hubble Space Telescope.

High-Peak-Power Lasers

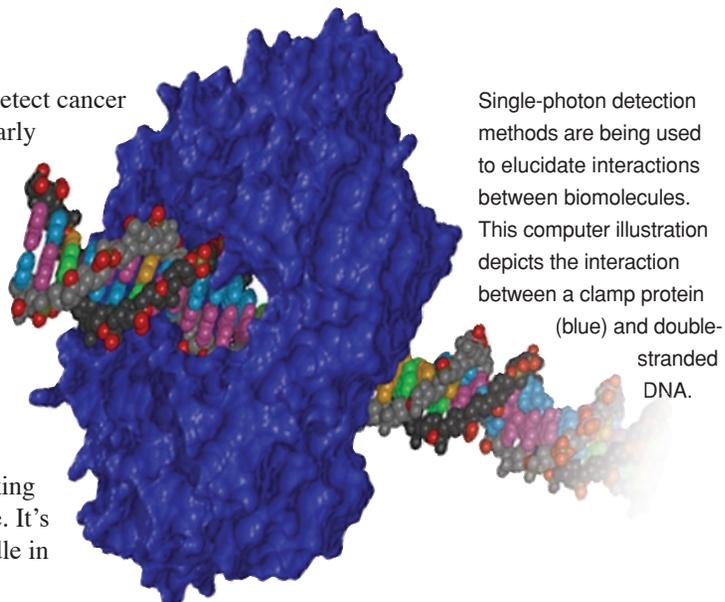
High-peak-power lasers are devices in which the laser power is packed into a very short pulse—less than a trillionth of a second in duration. These ultrashort pulses allow extremely high energy densities to be achieved in targets. Livermore’s high-peak-power Petawatt laser operated for 3 years, until 1999. At full energy of about 680 joules, the shots delivered more than a quadrillion watts (or petawatt, which equals 10^{15} watts) of power, exceeding the entire electrical generating capacity of the U.S. by more than 1,200 times. The Petawatt laser was developed originally to test fast ignition for inertial confinement fusion in the ongoing attempt to ignite a pellet of hydrogen fuel and harness the energy that powers the Sun. The power of the Petawatt also opened up entirely new physical regimes to study. Now, scientists can use lasers, not just particle accelerators, to study high-energy-density physics and the fundamental properties of matter. They may also be

photon events from a single molecule,” says Hollars.

Researchers involved in this highly multidisciplinary work combining chemistry, physics, and biology look toward studying single-biomolecule interactions between DNA, proteins, and other gene products. “Many processes have to occur on the molecular level to keep us healthy,” says Huser. Hollars and Huser plan to use their experimental capabilities to gain a better understanding of some of these fundamental processes. They envision mostly biomedical applications for single-molecule detection. “In cancer

research, we want to detect cancer in a person at a very early stage,” says Huser. “The hope is for researchers to develop single-molecule disease markers.”

Achieving those goals is certainly a challenge, and Huser points out that the work can be arduous. “Currently, we’re looking one molecule at a time. It’s like looking for a needle in



Single-photon detection methods are being used to elucidate interactions between biomolecules. This computer illustration depicts the interaction between a clamp protein (blue) and double-stranded DNA.

able to re-create in the laboratory the energized plasmas around black holes and neutron stars for astrophysical research.

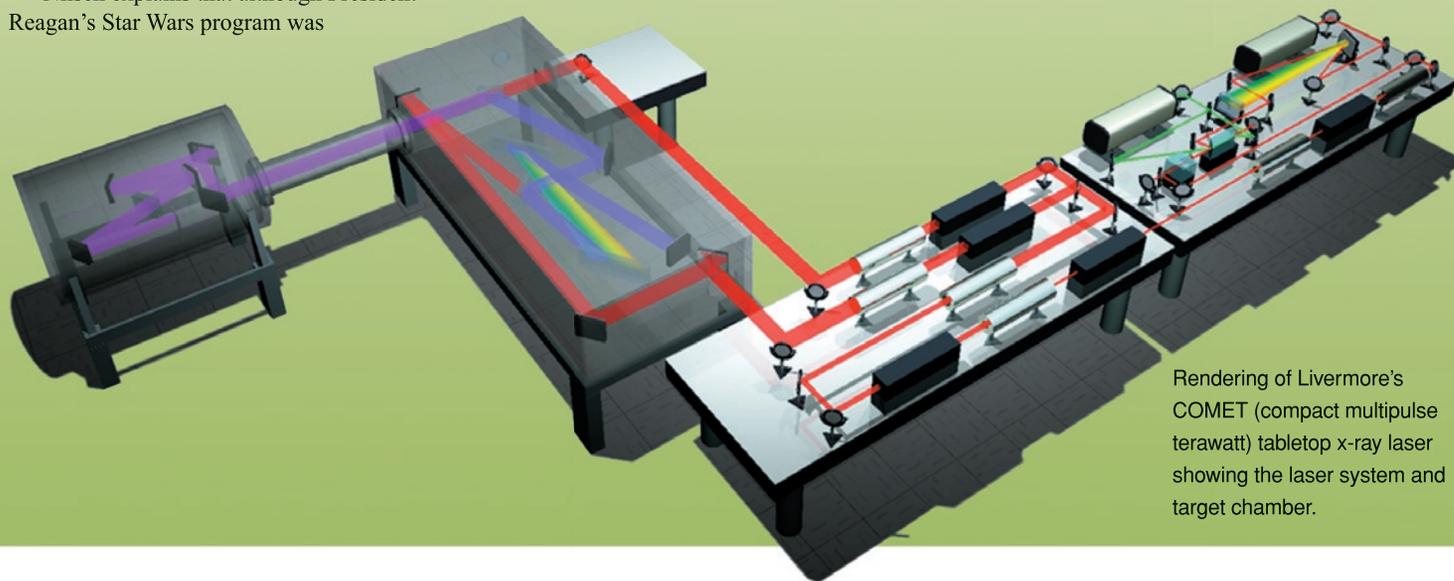
X-Ray Lasers

X-ray lasers produce coherent x-ray light and can be pumped from either nuclear explosions or from intense optical lasers. The x-ray laser program began in the early 1980s as part of President Reagan’s challenge to the scientific community to develop a defense against nuclear-armed ballistic missiles. This challenge led to the launch of the so-called Star Wars program, the Strategic Defense Initiative. In 1984, Novette, the forerunner of the Nova laser, was used for the first laboratory demonstration of an x-ray laser. With this laser, Livermore researchers assumed the role of leading the world in gaining new understanding of the physics of x-ray lasers.

Nilsen explains that although President Reagan’s Star Wars program was

eventually scaled back and transformed into the National Missile Defense Program, the knowledge gained from the earlier efforts have easily channeled to other research areas such as biotechnology, materials science, and materials analysis.

“The laboratory x-ray laser has become a high-repetition-rate tabletop facility used to develop plasma diagnostics such as interferometers,” says Nilsen. “We’re measuring the electron density of plasmas, and it is helping us validate our codes for calculating inertial confinement fusion experiments.” Nilsen also notes the tremendous technical advances made in x-ray technology over the years. “With a tabletop system, we now do x-ray interferometry without destroying the target or the interferometer. The development of novel x-ray optics has extended many of the sophisticated measurement techniques for optical lasers into the x-ray region.”



Rendering of Livermore’s COMET (compact multipulse terawatt) tabletop x-ray laser showing the laser system and target chamber.

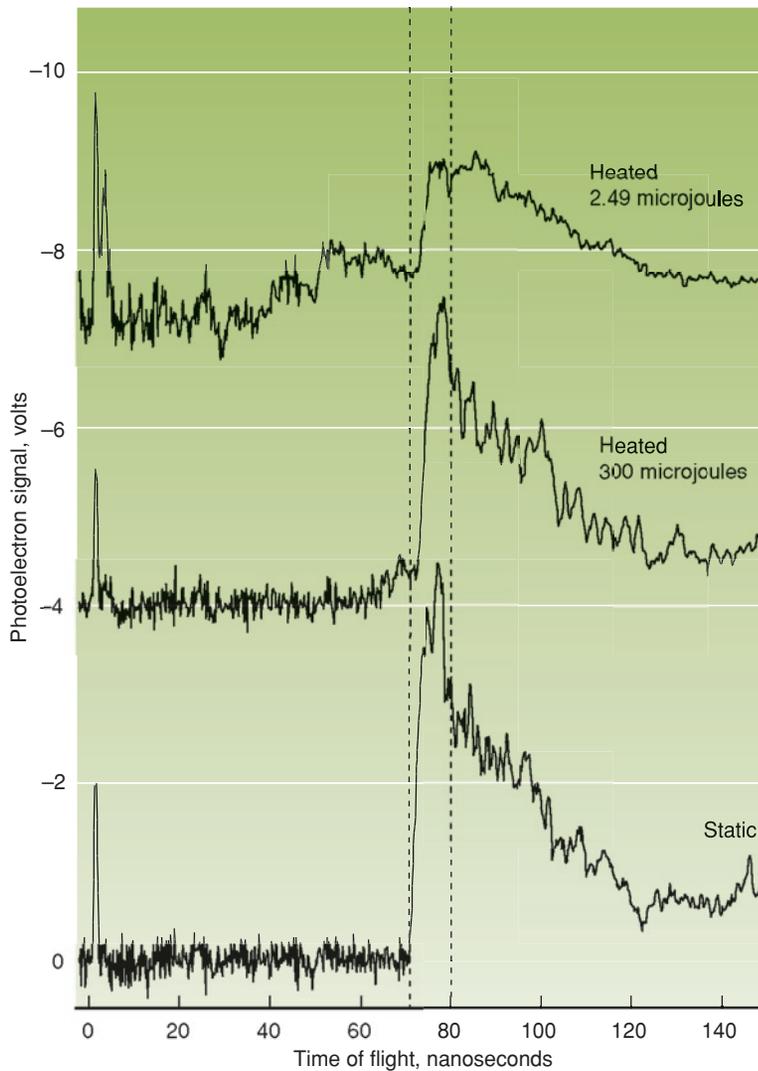
a haystack, but it would be impossible to achieve without Einstein's contributions," says Huser.

Pulling Electrons from Metals

Art Nelson of the CMS Directorate has been using the photoelectric effect to study the properties of solids as they rapidly evolve. Using a technique called x-ray

photoelectron spectroscopy (XPS), a metal is exposed to a spectrum of x rays, and the energy distribution of the ejected electrons is measured. Every metal has a unique electronic-structure energy distribution. Studying these distributions—and how they change, for example, when the material is heated—offers scientists insights into the nature of the metal.

Photoelectrons from static and laser-heated ultrathin polycrystalline copper foil are induced using an x-ray laser. The resulting spectra are unique to each element and help scientists better understand the properties and behavior of materials under extreme conditions.



A pulsed monoenergetic x-ray source is required.

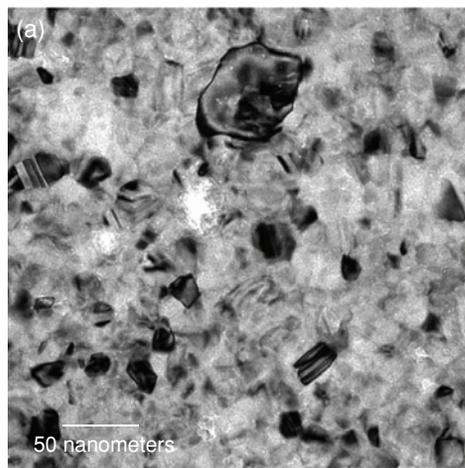
In 2001, Nelson, along with Jim Dunn of the Physics and Advanced Technologies (PAT) Directorate, began to use picosecond x-ray lasers as probes to study materials undergoing rapid changes. (With LDRD funding, PAT had developed a compact x-ray laser source and established an x-ray laser beamline to explore new science applications.) The team uses an optical laser pump and x-ray laser probe to understand the dynamics of a material from picosecond to picosecond.

In this technique, the optical-laser pump quickly heats the material producing an excited state or causing a phase transition (for example, melting). The x-ray laser measures the resultant perturbations by probing the state of the material's electrons at various times. "Because the pulse of an x-ray laser is so short," says Nelson, "one can get a snapshot in the picosecond range by analyzing the electrons ejected from the surface of the metal." Such analysis requires directly measuring the kinetic-energy distribution curve of the ejected electrons.

The team's goal is to understand the evolution and processes that occur in a heated material by interpreting the changes in its measured electronic structure.

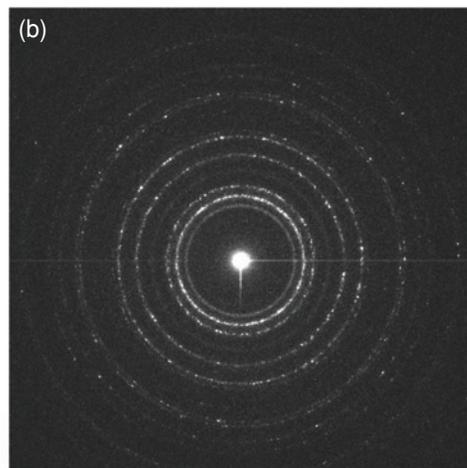
Dunn and Nelson form one of only a few teams in the U.S. currently working on x-ray laser source development and applications. According to Dunn, the advantage of x-ray lasers over optical lasers is significant in this type of work. The short wavelength and pulse of an x-ray laser make it optimal for looking at materials dynamics. Additionally, x-ray lasers have a high brightness and are directional, which means the beam can be directed to an exact location. Currently,

Nelson and Dunn are using x-ray lasers to study ultrafast laser-heated copper—a material being used for targets in NIF.



A Silent Appreciation

Livermore physicists and other scientists around the world acknowledge

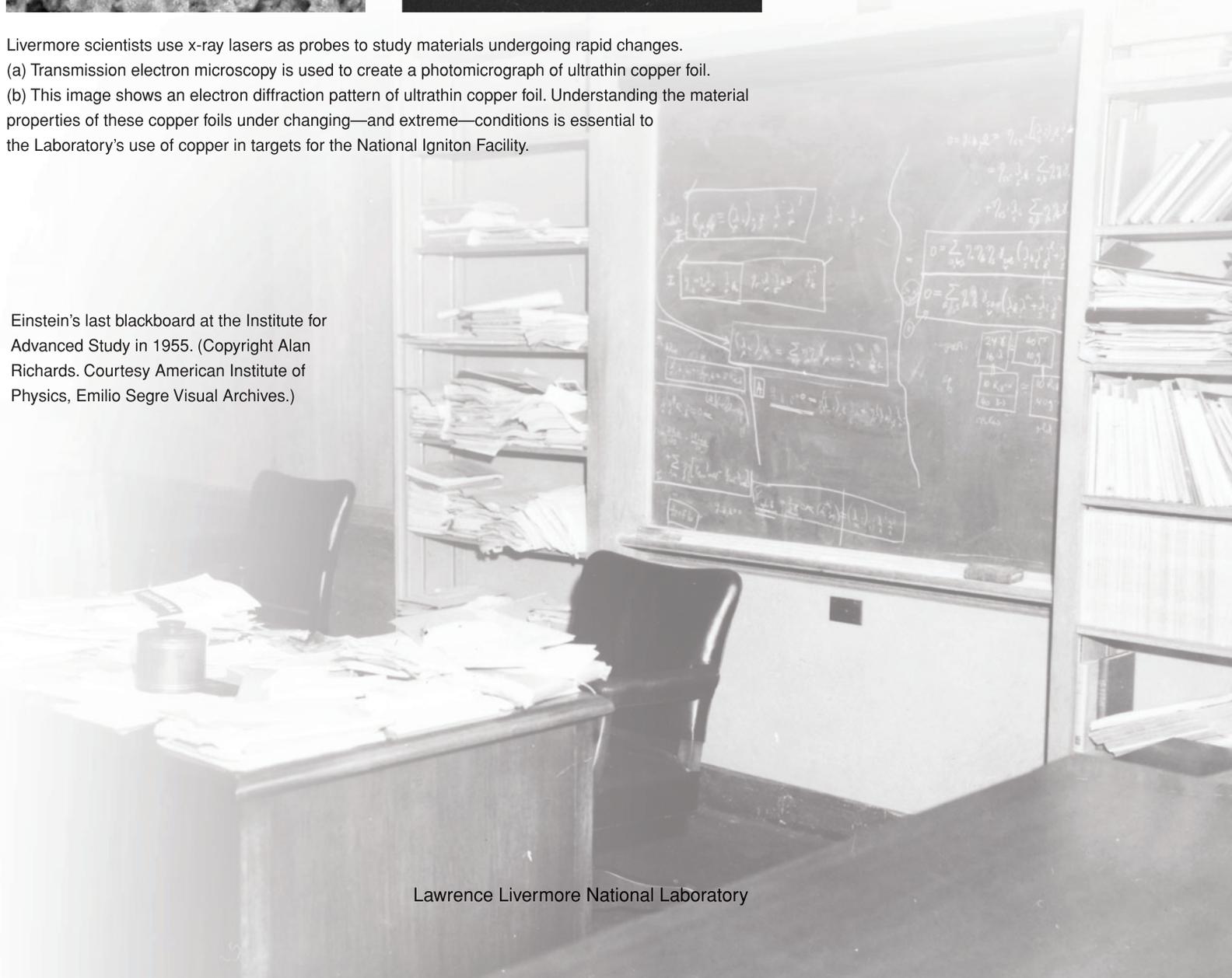


Livermore scientists use x-ray lasers as probes to study materials undergoing rapid changes.

(a) Transmission electron microscopy is used to create a photomicrograph of ultrathin copper foil.

(b) This image shows an electron diffraction pattern of ultrathin copper foil. Understanding the material properties of these copper foils under changing—and extreme—conditions is essential to the Laboratory's use of copper in targets for the National Ignition Facility.

Einstein's last blackboard at the Institute for Advanced Study in 1955. (Copyright Alan Richards. Courtesy American Institute of Physics, Emilio Segre Visual Archives.)



and revere the profound legacy that Einstein's 1905 papers have left us. And when future generations stand on the shoulders of today's physicists, they will see farther because of that legacy.

—Maurina S. Sherman

Key Words: Albert Einstein, blackbody radiation, hohlraum, inertial confinement fusion, light quanta, photoelectric effect, photons, quantum mechanics, single-photon detection, x-ray lasers, x-ray photoelectron spectroscopy.

For further information on the Laboratory's celebration of the World Year of Physics, see www.llnl.gov/pao/WYOP.