Science & Technology Review

January/
February 2004

National Nuclear
Security Administration's
Lawrence Livermore
National Laboratory

The Axion Hunt

Also in this issue:

- Mapping Phonons in Plutonium
- Plant and Wildlife Monitoring
- Buoys House Radiation Detectors

About the Cover

The overall makeup of the universe—including the amount of dark matter—is well agreed upon among physicists, astronomers, and astrophysicists. But what constitutes the dark matter? Researchers have determined that one answer to that question is a hypothetical elementary particle called the axion. A Livermore team and others are searching for this elusive particle, as described in the article beginning on p. 4. Shown on the cover are Livermore team members (from left) Leslie Rosenberg, Stephen Asztalos, and Darin Kinion with the axion experimental apparatus in the center. The experiment's microwave cavity, amplifiers, and superconductiong magnet reside directly beneath this apparatus in an underground pit. The Eagle Nebula is shown in the background. (Nebula photo is courtesy of the National Aeronautics and Space Administration.)

Cover design: Kitty Madison

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on assuring 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 10 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.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the World Wide Web at www.llnl.gov/str.

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Lawrence
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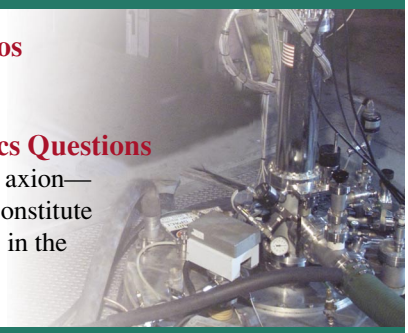

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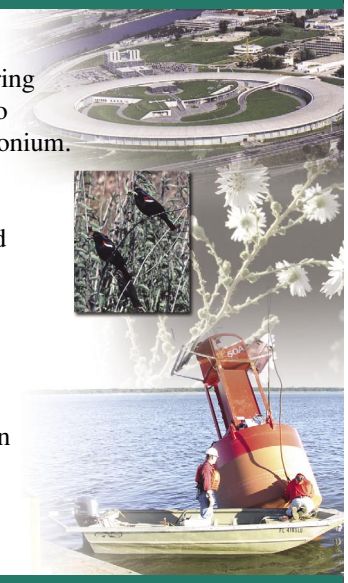

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S&TR Staff

Scientific Editor
Donn H. McMahon

Managing Editor
Ray Marazzi

Publication Editor
Pam MacGregor

Writers
Arnie Heller, Ann Parker, Gabriele Rennie, and Katie Walter

Art Director and Designer
Kitty Madison

Compositor
Louisa Cardoza

Proofreader
Carolin Middleton

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Diagnostic kit uses Lab technology

A Hawaii-based company is producing chemical diagnostic kits, based on a Laboratory technology, that permits the U.S. military to check the safety of munitions. Known as field-portable thin-layer-chromatography (TLC) units, the kits are produced by Ho'olana Technologies of Hilo, Hawaii. Technology for the TLC kits was developed by researchers in the Laboratory's Forensic Science Center and licensed in July 2001 by Alu Like Enterprises LLC to be manufactured by its subsidiary, Ho'olana Technologies LLC.

The new kits check whether munitions are safe for handling and storage. They analyze propellant mixtures found in munitions for the presence and quantity of stabilizers. Stabilizers normally comprise 2 to 5 percent of the propellant mixture found in munitions, and they protect against the propellant undergoing accidental rapid decomposition or burn. As the propellant ages, the stabilizer is slowly consumed until its ability to stabilize is severely reduced. The propellant is then past its useful life and must be destroyed. Propellant stabilizers are used in artillery shells, mortars, missile warheads, and bombs. Former Laboratory employee Jeff Haas led Livermore researchers at the Forensic Science Center in developing the TLC technology. The team included analytical chemists Jeanne Bazan, Greg Klunder, Pete Nunes, and Richard Whipple.

The test kits contain all the components necessary to perform TLC in the field, including miniaturized laboratory equipment such as battery-operated stir boxes and heating plates. The kits perform quantitative analysis by using digital imaging tools to determine quantities and ratios of stabilizers in the propellant. The field kits also require a much smaller sample size than traditional laboratory TLC processes to determine if targeted chemicals are present. Ho'olana Technologies has just completed its first contract, delivering 50 complete TLC kits to Lawrence Livermore for research and development for the U.S. Army.

Contact: Richard Whipple (925) 422-6314 (whipple2@llnl.gov).

Marine plankton's role in stabilizing modern climate

A trio of scientists, including a researcher from the Laboratory, has found that humans may owe the relatively mild climate in which their ancestors evolved to tiny marine organisms with shells and skeletons made out of calcium carbonate.

In an article titled "Carbonate Deposition, Climate Stability and Neoproterozoic Ice Ages," in the October 31, 2003, issue of *Science*, University of California at Riverside researchers Andy Ridgwell and Martin Kennedy, along with Livermore climate scientist Kenneth Caldeira, reported that the increased stability in modern climate may be due in part to the evolution of ocean plankton with shells and skeletal material made out of calcium carbonate. They conclude that these marine organisms helped prevent the ice ages of the past few hundred thousand years from turning into a severe global deep freeze. "The most recent ice ages were mild enough to allow and possibly even promote the evolution of modern humans," Caldeira said. "Without these tiny marine organisms, the ice sheets may have grown to cover the Earth like in the snowball glaciations of the ancient past, and our ancestors might not have survived."

The researchers used a computer model describing the ocean, atmosphere, and land surface to look at how atmospheric carbon dioxide would change as a result of glacier growth. They found that, in the distant past, as glaciers started to grow, the oceans would absorb carbon dioxide from the atmosphere, making the Earth colder and promoting an even deeper ice age. When marine plankton with carbonate shells and skeletons were added to the model, glacial growth was buffered because the ocean was chemically not able to absorb large amounts of carbon dioxide from the atmosphere.

In Precambrian times (which lasted until 544 million years ago), marine organisms in the open ocean did not produce carbonate skeletons. Around 200 million years ago, calcium carbonate organisms became critical to helping prevent Earth from freezing over. When the organisms die, their carbonate shells and skeletons settle to the ocean floor, where some dissolve and some are buried in sediments. These deposits help regulate the chemistry of the ocean and the amount of carbon dioxide in the atmosphere.

Contact: Kenneth Caldeira (925) 423-4191 (caldeira2@llnl.gov).

From Quarks to Livermore to the Cosmos

PHYSICISTS face a thorny set of basic questions that do not yet have definitive answers. These questions embrace physics from the smallest to largest scale. In the 2002 report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century,* the National Research Council boiled these questions down to eleven. Livermore Laboratory is involved in efforts to answer at least seven of them (see p. 11).

The article beginning on p. 4 describes an experiment, spearheaded by the Laboratory, that may ultimately provide the definitive answer to the question "What constitutes the dark matter of the universe?" This experiment searches for the axion—a particle more elusive than the neutrino. The axion may be the dominant component of cosmological dark matter, which we know cannot consist of already-discovered particles.

Livermore is also involved in developing the Large Synoptic Survey Telescope (LSST), which is designed to probe the nature of dark energy, another mysterious entity in the universe. Each night, the LSST will yield 10 or more terabytes of data. Sorting through these enormous databases requires high-performance image- and signal-processing capabilities, some of which Livermore's engineers and astronomers pioneered in the Massive Compact Halo Objects experiment. These efforts on behalf of LSST will also benefit Livermore programs that must handle large imagery databases in other contexts.

Through its support of the Main Injector Neutrino Oscillation Search (MINOS), the Laboratory is aiding the effort to measure neutrino masses. In this experiment, a beam of neutrinos generated at Fermi National Accelerator Laboratory, about 13 kilometers west of Chicago, is aimed at a detector deep in a former iron mine in Soudan, Minnesota, 735 kilometers away. Livermore engineers and physicists contributed the design of the MINOS detector planes, which allowed sections of the planes to be lowered into the mine and assembled underground. (See *S&TR,* April 2003, pp. 13–19.)

Creating new states of matter at extremely high densities and temperatures is the task of the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory, another major physics collaboration with a significant Livermore connection. Inside this accelerator, gold ions collide with enough force to recreate a quark–gluon plasma on Earth. Livermore engineers designed three powerful magnets for the Pioneering High-Energy Nuclear Interaction Experiment detector at the RHIC, and Livermore physicists are leading two major experiments using the detector. (See *S&TR,* January/February 2003, pp. 4–9.)

Determining how the elements from iron to uranium were created will require a new facility—the Rare Isotope Accelerator (RIA). Recently, Department of Energy (DOE) Secretary Spencer Abraham endorsed the RIA as a high priority in his outline of DOE's 20-year science facility plan. The RIA will be the world's most powerful research facility dedicated to producing and exploring forms of nuclear matter. These experiments will allow scientists to view the processes that occur in supernovas as well as provide a greater understanding of the radiochemistry of nuclear weapons. Livermore has been active in the preliminary engineering and in defining the science goals of this new facility.

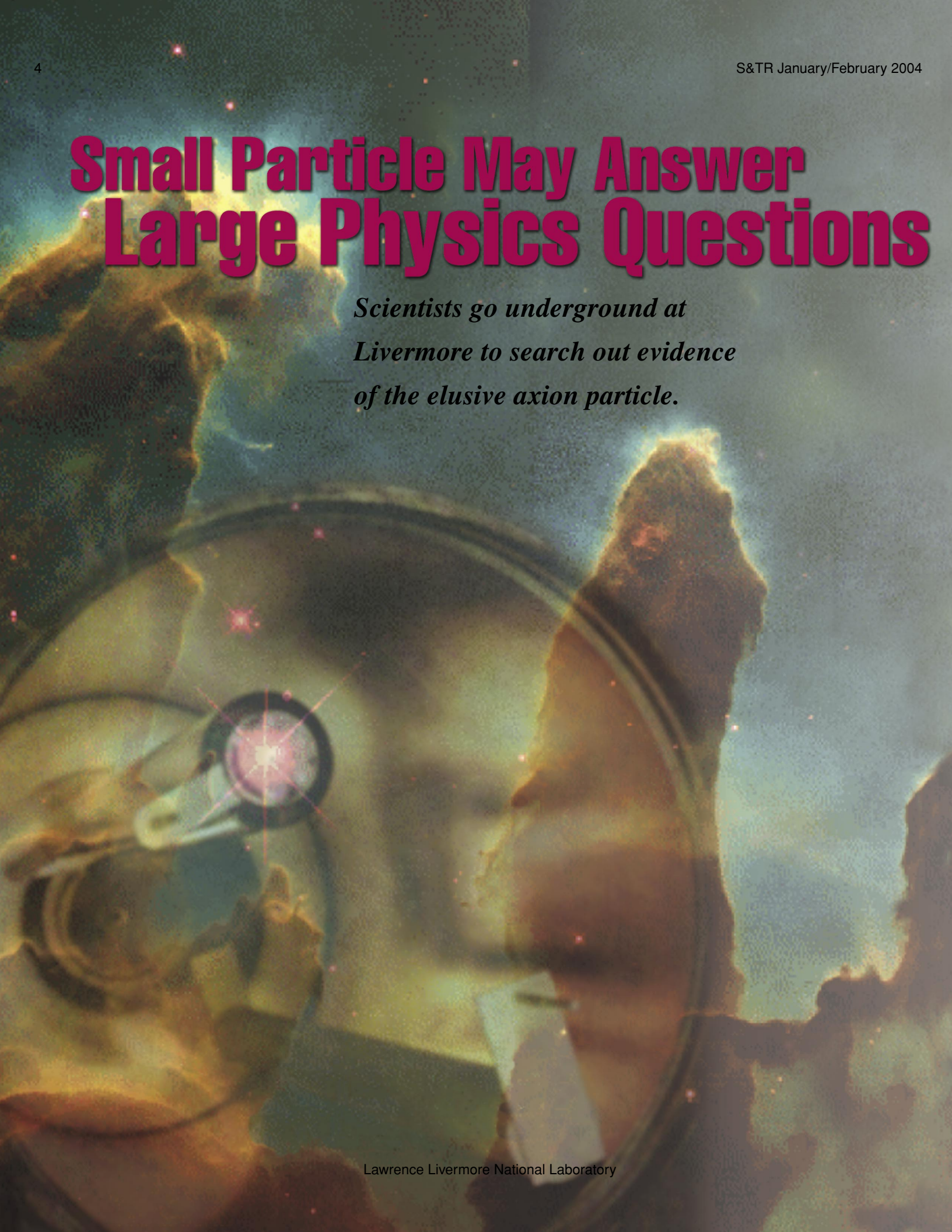
Livermore was one of four DOE national laboratories given the task of basic research and development (R&D) for the Next Linear Collider (NLC), which is the other major accelerator project endorsed by Secretary Abraham. The NLC is a 30-kilometer accelerator that will push the energy frontiers of physics to the teraelectronvolt (TeV) range, where physicists expect to find answers to some of the most fundamental questions of science, including the nature of mass and the mechanism of grand unification. In addition to accelerator R&D, the Laboratory has the lead in developing a photon–photon collider for the NLC. This machine will bounce high-power, high-repetition laser pulses off the particle beams with the goal of exploring physics beyond TeV energies, possibly approaching the Planck scale, where gravity is thought to unify with electromagnetism and the nuclear forces. (*S&TR*, April 2000, pp. 12–16.)

Why is Livermore involved in these basic science research projects? The answers are clear: Livermore has unique engineering expertise and capabilities, and as a result, major science projects seek our involvement. In addition, these projects push the frontiers in science and technology. Our participation is essential to maintaining a vigorous science and technology base at the Laboratory and is crucial in attracting the best and the brightest—those who in future years will lead the Laboratory in carrying out its challenging national security missions.

■ William H. Goldstein is associate director of Physics and Advanced Technologies.

Small Particle May Answer Large Physics Questions

Scientists go underground at Livermore to search out evidence of the elusive axion particle.



IN one of those interesting intersections of particle physics, astrophysics, and cosmology, scientists from Lawrence Livermore National Laboratory, the University of California at Berkeley (UCB), the University of Florida (UF), and the National Radio Astronomy Observatory (NRAO) have joined together to try to pin down an elusive particle. This particle, called the axion, if it is found to exist and is not just a hypothesis, would be a long-sought relic from the first fractional second of the birth of the universe and one of the most weakly interacting particles known. Experimental verification of the existence of the axion would not only help "balance the budget" for the missing mass of the universe but also clear up one of the thorniest issues in particle physics.

Betting on a Dark Horse

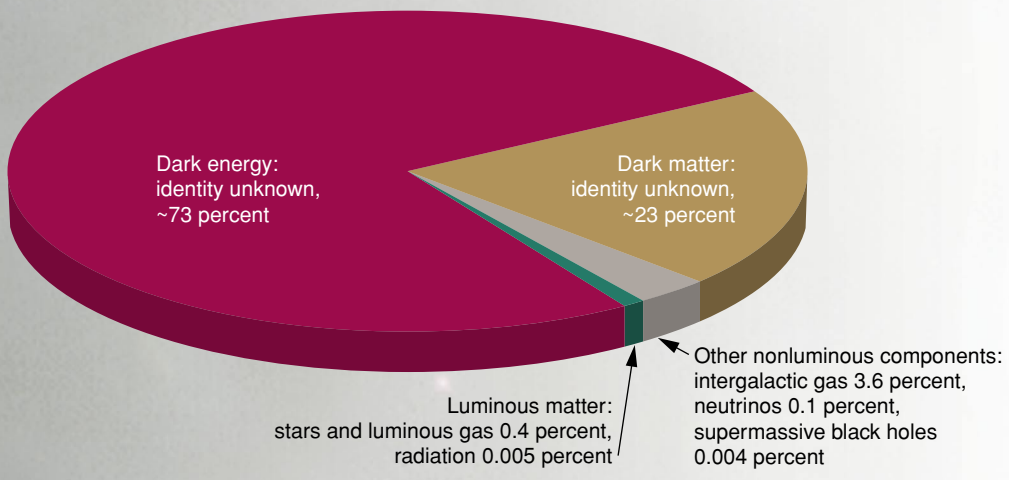
The overall makeup of the universe is well agreed upon among physicists, astronomers, and astrophysicists. Luminous matter—stars and galaxies—is a mere fraction of 1 percent. Other nonluminous matter, such as intergalactic gas, neutrinos, and so on, accounts for not quite 4 percent. The remaining mass and energy of the universe is divided between dark matter (about 23 percent) and dark energy (about 73 percent). What makes up these dark components is unknown. Most of the theories and some observations point to dark matter being predominantly a remnant—perhaps a new and unknown elementary particle—from the very beginnings of the universe, a time known as the big bang.

As to what these particles are, ideas tend to fall into one of two camps: cold dark matter or extremely massive neutrinos—neutrinos much more massive than the three ordinary ones we know. Cold dark matter would be some kind of particle that did not acquire much velocity when it was created in the early universe. Nearby cold dark matter particles are expected to move at about the speed of the stars in our galaxy—velocities that are slow compared with the speed of light.

Massive neutrinos, however, would have been moving extremely fast at their birth in the early universe, and they would probably still have velocities close to that of light. Enormous masses of neutrinos whizzing about seem unlikely, because the density needed to make up a significant portion of dark matter would have smoothed irregularities and prevented the formation of structures that evolved into galaxies in the first few billion years of the universe.

The predominant form of dark matter, most researchers agree, must be some kind of cold dark matter. But which kind, exactly? Two hypothetical elementary particles are the main candidates: a stable weakly interacting massive particle (WIMP) that is about 10 to 100 billion electronvolts in mass, and an axion—a very light particle with neither electric charge nor spin so it interacts hardly at all.

The axion's extreme lightness (trillions would occupy a sugar-cube volume of space yet weigh less than does half of a proton) and nearly nonexistent coupling to radiation conspire to make the particle incredibly long-lived, perhaps as long as 10^{50} seconds. The universe itself is estimated to be only 10^{18} seconds, or 100 billion years, old. The axion's longevity would make it a stable particle for all intents and purposes. If axions exist, they could make up the bulk of dark matter. With an estimated 10 trillion of them packed into every cubic centimeter of space in our galaxy, what they lack in mass



Scientists believe the cosmological inventory of the universe is now well delineated, although the exact compositions of dark matter and dark energy are yet to be determined. Scientists suspect that dark matter may be composed of particles that are a relic from the big bang—perhaps axions.

individually, they would make up for in sheer numbers.

In addition to answering the dark matter question, axions would also handily resolve a difficult issue in the Standard Model, which is the current theory that explains fundamental particles and how they interact. (See the box below.)

Whereas many experiments worldwide are dedicated to the WIMP search, only two are attempting to track down the axion: one in Japan (CARRACK2 at Kyoto University's Institute for Chemical Research), and the other at Lawrence Livermore under the leadership of physicists Leslie Rosenberg and Karl van Bibber. This team consists of researchers from Livermore, UF, UCB, and NRAO.

"All in all," says Rosenberg, "observing axions would help solve one of the eleven most important science questions of the new century, as set forth by the National Academy of Sciences two years ago. That question is: 'What is the dark matter?' At Livermore, we are seeking the answer and, if successful, we will be at the forefront of the most basic of basic science." (See the box on p. 11.)

Hunting the Elusive Axion

The Livermore experiment is the only one in progress that can challenge recent theoretical estimates of axion mass and coupling. Laboratory physicists Rosenberg, van Bibber, Darin Kinion, Christian Hagmann, Stephen Asztalos (project

Axions to the Rescue

The fact is, no one knows if the axion exists. But through observations and calculations, both astrophysical and quantum mechanical, researchers have determined that many pieces in the puzzle would support the existence of this most elusive particle; they have even narrowed the estimates for its mass.

The axion was first proposed as a way to explain a particularly thorny problem in particle physics, that is, the absence of charge-parity (CP) violation in strong nuclear interactions. In physics, if two systems are mirror images of each other but are otherwise identical, and if parity is conserved, all subsequent evolution of these two systems should remain identical except for the mirror difference. Nature, scientists have come to believe, generally prefers symmetry to nonsymmetry. That is, nature has no preference for right-handed versus left-handed behavior, at least as far as particle physics is concerned. In 1956, physicists Chen Ning Yang and Tsung Dao Lee realized that although many experiments had been conducted to show that mirror symmetry was true for the strong interaction (which holds the nucleus together) and for the electromagnetic interaction (which occurs between electrically charged bodies), no experiments had been conducted for the weak interaction (which is responsible for radioactive beta decay).

Experiments by physicist Chieng-Shiung Wu shortly thereafter showed that, contrary to what was expected, weak interactions did show a preference or "handedness" in cobalt-60. Wu observed the radioactive decay of cobalt-60 in a strong magnetic field. Her experiments proved that there was a preferred direction for emitting beta particles in a decay—in other words, the weak interaction violated the conservation of parity. The violation of parity conservation ran counter to all expectations.

In the 1970s, quantum chromo dynamics (QCD) was developed. QCD is the theory of the strong interactions that hold the nucleus together. This theory required that QCD have large amounts of CP violation, yet no such violations have ever been observed even in exquisitely sensitive experiments. However, a completely different source of CP violation, stemming from the weak interaction mentioned above, was discovered first in kaons and recently in mesons produced at the B Factory. (See *S&TR*, January 1999, pp. 12–14.) Whereas the relatively large effects from the weak interaction are measurable, the analogous CP-violating effects from QCD are somehow suppressed. In an effort to explain this phenomenon, Stanford University physicists Roberto Peccei and Helen Quinn proposed a new symmetry of nature that resulted in a particle dubbed the axion. Early estimates predicted an axion mass of 100 kiloelectronvolts. However, searches for this particle in high-energy and nuclear physics experiments ruled out axions heavier than about 50 kiloelectronvolts.

Astrophysical observations then led scientists to believe that axion mass must be no more than 10^{-3} electronvolts—nearly nine orders of magnitude less than originally predicted. Among those observations were the data gathered from a supernova explosion in 1987. By looking at the signals recorded from neutrinos detected on Earth from this particular explosion, astrophysicists concluded that if the axion mass was above 10^{-3} electronvolts, the supernova core would have been cooled not just by emitted neutrinos but by axions as well. If this was the case, the length of the neutrino burst associated with the supernova would have been far shorter than that observed.

Axions lighter than a microelectronvolt, however, would have been overproduced in the big bang, resulting in the universe being much more massive than it is. This would be at variance with current observations, where dark matter is at most a quarter of the closure, or critical density of the universe.

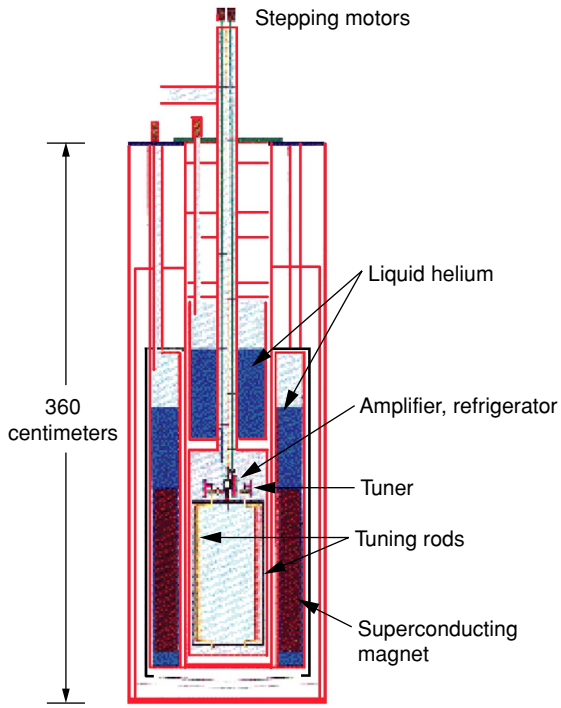
Refined calculations have led scientists to believe that the axion must lie in a mass window of approximately 10^{-6} to 10^{-3} electronvolts.

manager), graduate student Danny Yu, and others are preparing for the next phase of this experiment to track down and identify cosmically generated axions.

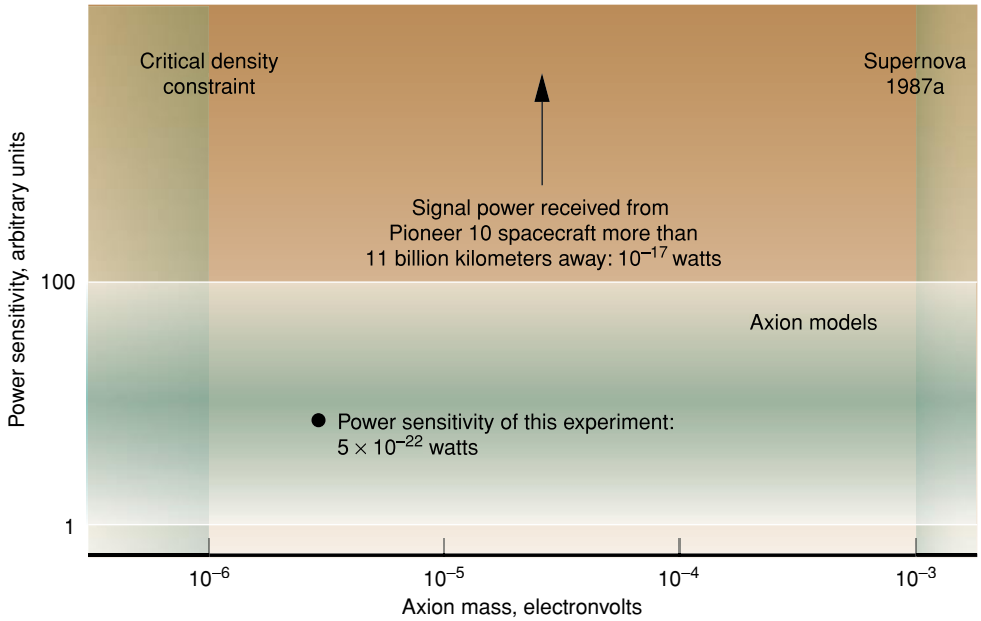
The experiment is based on the theory that an axion, when it does interact, decays into two photons with frequencies in the microwave range of the electromagnetic spectrum. UF professor Pierre Sikivie and others formed the idea that an axion could be stimulated to decay into a single photon in the presence of a large magnetic field threading a microwave cavity. The experimental setup, which contains a sensitive radio receiver, requires a tunable microwave cavity permeated by a strong magnetic field and ultralow-noise microwave amplifiers.

The microwave cavity is slowly tuned over a range of frequencies. When the proper frequency of the axion-emitted photon is reached, the axion signal should appear as a narrow line in the spectrum. This experiment sounds simple, but there are some hidden "gotchas." For instance, the expected signal, corresponding to only a few hundred axion decays per second, would be extremely faint. Rosenberg explains, "For an idea of how small of a signal we're looking for, consider the signals received on Earth from the Pioneer 10 spacecraft's transmitter. When Pioneer 10 was at the periphery of our solar system, its signal was 10^{-17} watts. The axion signal will be considerably weaker than that—optimistically, 10^{-22} watts. And with Pioneer 10, we knew what frequency to look for, a luxury we don't have with the axion search."

The Livermore axion experiment began in 1995 with funding from the Department of Energy's Office of Science, which supports basic science in the public interest. Livermore's Laboratory Directed Research and Development (LDRD) Program had supported the work that laid the groundwork for the experiment. The goal for the experiment was to extend LDRD efforts on one major front: increased power sensitivity. Livermore's



The axion experimental setup. An 8-tesla, 6-ton superconducting coil is wound around the outside of a copper-plated stainless-steel cylinder about the size of an oil drum. A set of tuning rods inserted into the cylinder's cavity is moved by stepper motors to tune the frequency of the cavity. Helium cools the cavity, reducing the background noise. Amplifiers boost the faint axion signal.



Using evidence from particle physics experiments and astrophysical observations, scientists have set bounds for the axion mass and for the likelihood of the axion coupling with a photon of given frequency in the Livermore experiment. The likelihood is so small that the signal expected will be many orders of magnitude less than the signal strength received from the Pioneer 10 spacecraft.

plan to do this was to increase the sensitivity of the amplifiers and increase the size and magnetic-field strength of the cavity volume.

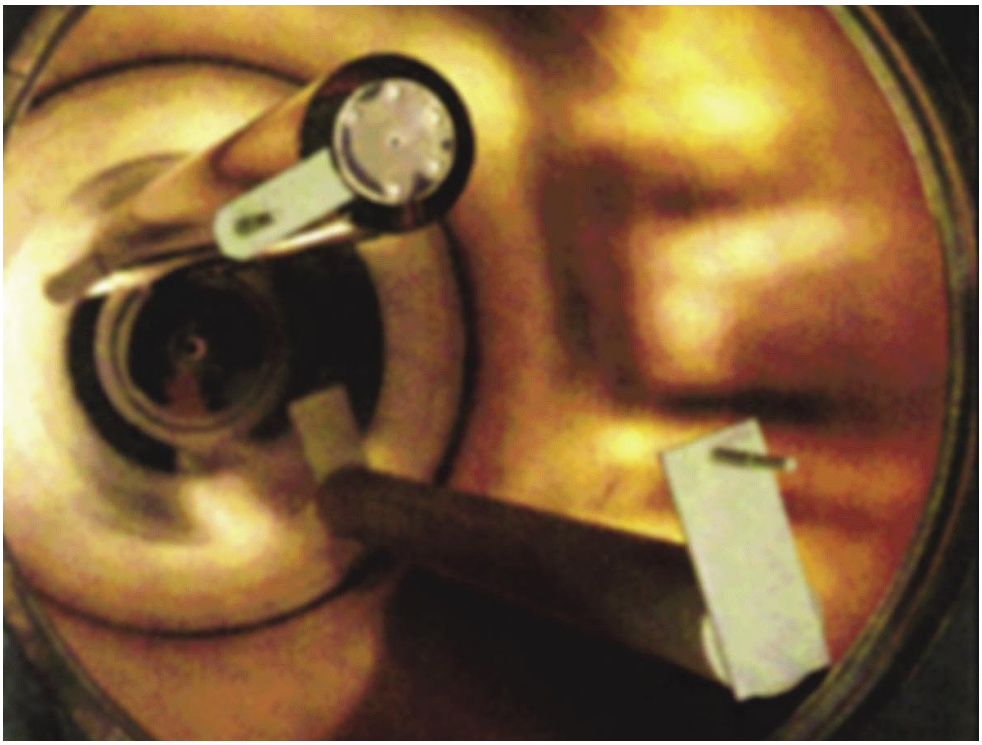
The initial proof-of-principle experiments, conducted in the late 1980s at Brookhaven National Laboratory and UF, validated the technology and strategy of the microwave cavity approach. However, they lacked the power sensitivity by two or three orders of magnitude to actually detect an axion. The experiment at Livermore has a much higher total magnetic-field energy, which increases the power conversion and allows the experimenters to edge into the sensitivities theoretically needed to detect cosmic axions from the galactic halo. Models have predicted a density of about 10 trillion axions per cubic centimeter in Earth's galactic neighborhood.

Whereas the first experiments had microwave cavities the size of a small coffee can, the Livermore cavity—a copper-plated stainless-steel cylinder—is closer in size to an oil drum (1 meter tall and 0.5 meter in diameter). A powerful 8-tesla superconducting electromagnet is wound around the outside of the cavity. The coil itself weighs 6 tons, and the remaining cryostat weighs another 6 tons. The magnet's static magnetic field, which is used to coax axions into decaying, is about 200,000 times more powerful than Earth's magnetic field. Because the precise frequency of the axion decay is not known, the team has to be able to tune the cavity resonance over the range of possible frequencies, from 0.3 to 3 gigahertz. To do this, a set of tuning rods—metal ones for increasing the frequency of the cavity and ceramic ones for decreasing it—are inserted into the cavity. The rods are moved by stepper motors in tiny, incremental steps of a few hundred nanometers every minute. The lowest frequency occurs when both rods are nearest the wall of the cylinder. The frequency increases (for metal) or decreases (for ceramic) as one or the other approaches the center of the cavity.

The Livermore experiment incorporates the latest available technology for "hearing" any axion signals and separating them from the noise. A very small excess of microwave photons above thermal and electronic noise levels would signal the decay of an axion. Because the expected signal from the decay of an axion is so faint, sensitive amplifiers are needed to boost the signal to detectable levels. The amplifiers used were built by the NRAO and are based on the heterostructure field-effect transistor (HFET)—an exotic semiconductor device developed for military communications and now widely used by radio astronomers to amplify weak radio signals.

The first amplifiers had a noise temperature (which is the figure-of-merit for microwave amplifiers) of about 4.3 kelvins

Livermore physicist Darin Kinion helps guide the experiment tower containing the microwave cavity and amplifiers into the magnet bore.



The view from above the axion experiment's resonant cavity shows the inside of a copper-lined cylindrical cavity (50 centimeters in diameter and 1 meter deep) and two tuning rods.

(4.3°C above absolute zero). More recent NRAO amplifiers reach down to 1.5 kelvins. By comparison, the microwave amplifier in a home satellite TV receiver has a noise temperature of approximately 100 kelvins. In the experimental cavity, the signal output is amplified by low-noise, room-temperature amplifiers and transmitted to a receiver. The receiver then cleans up the signal so that only the portion of bandwidth that might contain a signal is recorded. (This is the same process that happens inside a radio: the receiver selects, amplifies, and converts into audio the music at a particular station's frequency and eliminates everything else.) The lower the noise the better. Lower noise allows detection of weaker signals, or in this case, weaker-coupled axions.

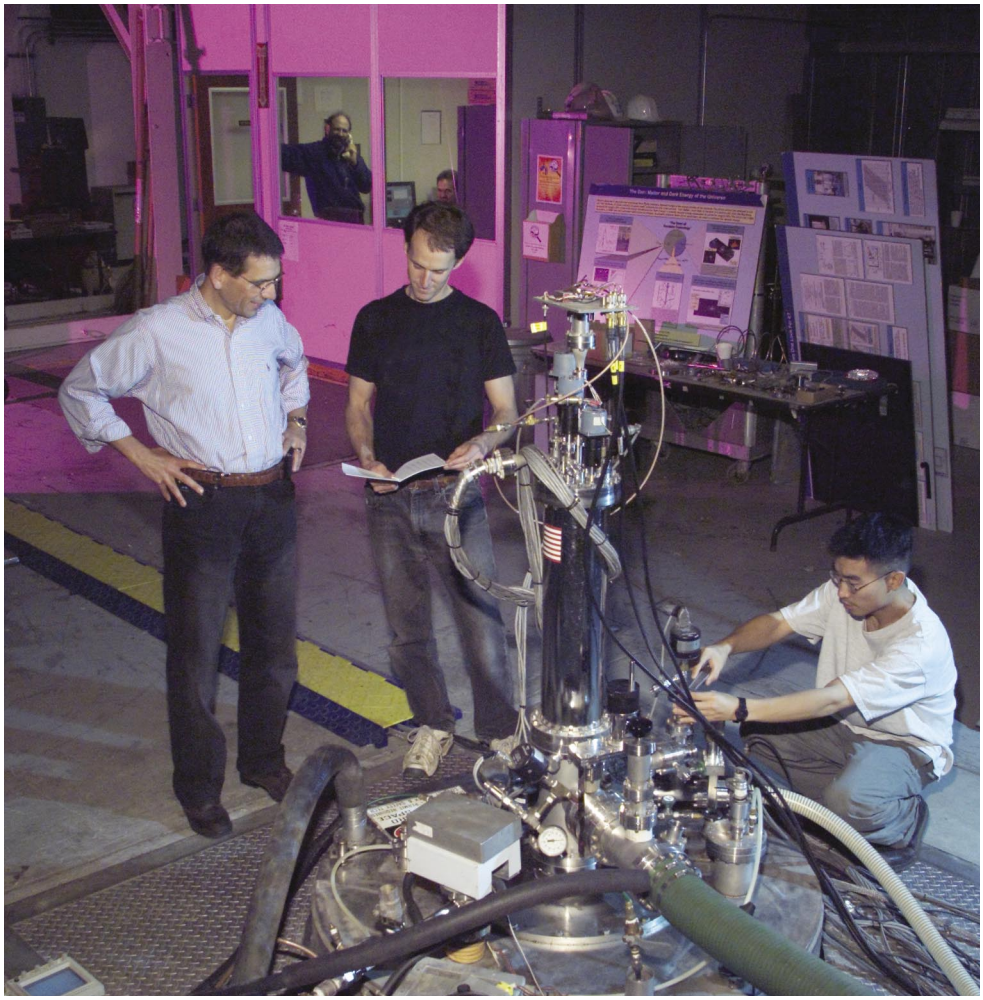
By early 1996, the Livermore axion experiment was running and producing data. The research team continues to explore the region from 0.3 to 3 gigahertz, which corresponds to an axion mass of 1.2 to 12.4 microelectronvolts. This experiment has increased power sensitivity by two orders of magnitude over the previous experiments and is the first such search to probe realistic axion models. Although no axion decays have yet been detected, these results better refine the upper-limit estimates of axion densities in Earth's galaxy.

Finding the Answer

The third-generation of axion experiments will require new technologies and techniques to further increase power sensitivity. These experiments will be able to detect axions even with the most pessimistic estimates of coupling and reach other parts of the frequency range not attainable with the current configuration. Rosenberg believes that these future experiments, once in place, will definitively answer whether axions exist.

For this search, HFETs would not be sensitive enough, so the team is turning to a new type of radio-frequency amplifier based on a superconducting quantum interference device (SQUID) developed by a research group under the direction of UCB physics professor John Clarke. Kinion is collaborating with Clarke's team to develop the new amplifier, which uses a direct-current SQUID made from superconducting niobium and can operate at frequencies well above 3 gigahertz—with record-low noise temperatures of 0.005 kelvin. Once this radio-frequency amplifier and its niobium SQUID are part of the experiment, the signal-to-noise ratio from axion decay will get a much-needed boost, which should make it possible to detect even the most elusive axion.

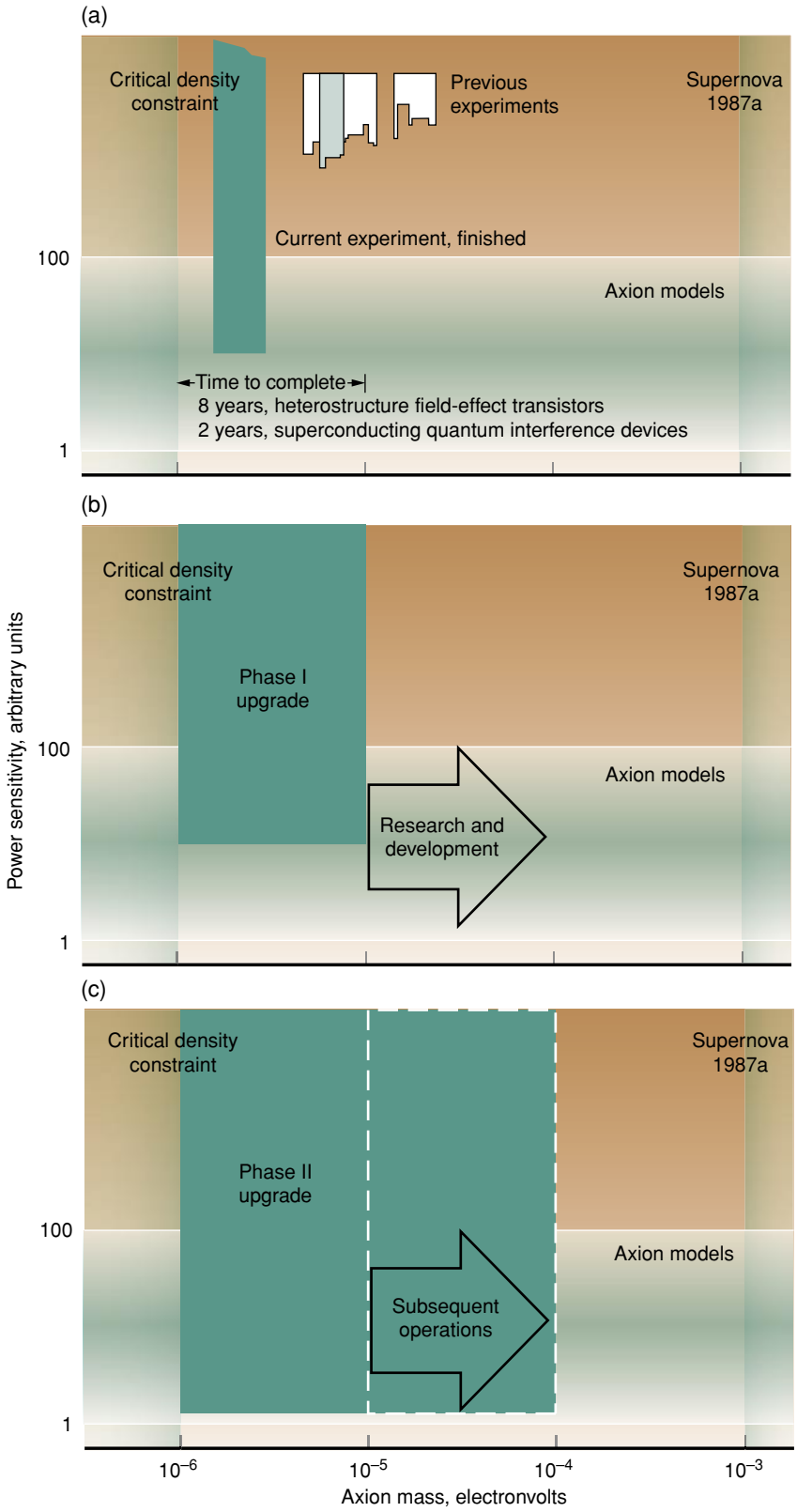
"What this means," says Rosenberg, "is that, for the first time, the experiment will be sensitive to weakly coupled axions, even if axions are a minority contribution to the local dark matter halo. These are the axions considered to be the most promising of the axion-based dark matter models. Once we have commissioned this upgrade, we will go back over the ground we have already covered and look for axions with greater power sensitivity. The new upgrade will be sensitive enough to detect even the weakest signals. In other words, this upgraded search will likely be the definitive search."



Livermore team members (from left) Karl van Bibber, Stephen Asztalos, and Danny Yu work on the axion experimental apparatus. Leslie Rosenberg and Darin Kinion man the control room where signal data are recorded.

The plan for the proposed upgrade has been favorably received by the scientific community and the funding agencies, notes Asztalos. But until the fate of funding for the upgrade is known, the team will continue with the present experimental setup. “We are taking data with the current cavity through the first of 2004,” says Asztalos. “By then, we’ll have searched all the frequencies the present configuration can reach. At that point, we’ll change out the tuning rods to access a different frequency range.”

In addition, graduate student Yu and the team will be injecting a pseudo-axion signal into the cavity. As Yu explains, “Our numerous simulations indicate we should be able to detect these very small signals under the present conditions. But to confirm these findings, we will inject a synthetic signal of the same strength and shape directly into the cavity and see whether we find it in our data analysis.” This plan requires that the noise be well characterized, and Yu notes that the team has done its homework in this regard. “The noise output from the amplifiers is the biggest current uncertainty,” Yu adds.



(a) The current experimental setup is just sensitive enough to detect the strongest of axion signals in a narrow band of possible mass for the axion. Using conventional amplifiers based on conventional heterojunction technology, the lowest decade of the axion mass range can be scanned in 8 years. (b) With the superconducting quantum interference device amplifiers in place for the Phase I upgrade, the team will be able to scan at the current sensitivity more than four times faster and can scan more of the mass range supported by theoretical axion models. (c) In the Phase II upgrade, a dilution refrigerator will lower the system noise temperature from 1.5 kelvins to about 0.002 kelvin, making the experiment sensitive enough to detect the weakest of signals. The Phase II experiment will be the definitive search for the axion.

Is It Here or There or Anywhere?

The team will be on a five-year timeline once the upgrade is funded. The first two years will be devoted to the commission and construction phase. The upgrade will not be an easy one, notes Rosenberg. Azstalos concurs. "It's somewhat like building a dark room and then crawling around to search out those pinholes that tiny amounts of light leak through," says Azstalos. "Those leaks then need to be patched. Because the axion signals are so weak and the SQUIDs are so sensitive, there can be no stray electromagnetic signals. So we must be sure there are no electromagnetic leaks."

This is a tall order when the entire experimental setup is experiencing a magnetic field of 8 tesla and the detectors are the most sensitive in the world to magnetic flux. Good shielding, says Asztalos, is key to the upgrade. "Although the SQUIDs will be some distance from the cavity, we nonetheless need to use a compensating magnet and layers of superconducting and iron shields, similar to those installed around computer screens. Once we have the SQUIDs functioning correctly, we'll be ready to start operation."

The ensuing series of experiments will then stand to answer these questions once and for all: Does the axion exist? Does it constitute the dark matter that we know is there but cannot see?

"Livermore is poised to answer these fundamental and important questions," says Rosenberg. "These questions unite the grandest scale (the universe) to the smallest scale (particle physics). And no matter what we discover, it will be illuminating. Either we will find the axion, proving that it exists and is part of the cosmological evolution of the universe, or we won't. If we don't find the axion, then something else—perhaps another particle, or symmetry, or path—makes up dark matter. Failure to find the axion would signify that an argument somewhere in the chain of theory is broken. But where? And how far back in the chain do scientists look for the faulty link? If there is no axion, there must be entirely new physics—some strange, new physics that we cannot as yet fathom. And that, too, would be very interesting indeed."

—Ann Parker

Quarks to Cosmos: Connecting the Smallest to the Largest

In 2002, the National Research Council released a report entitled *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*. The council's eleven key questions, listed below, focus on the intersection of the universe at its two extremes—the very large and the very small.

What is the dark matter?
What is the nature of the dark energy?
How did the universe begin?
Did Einstein have the last word on gravity?
What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
How do cosmic accelerators work, and what are they accelerating?
Are protons unstable?
Are there new states of matter at exceedingly high density and temperature?
Are there additional space–time dimensions?
How were the elements from iron to uranium made?
Is a new theory of matter and light needed at the highest energies?

Livermore's search for the axion particle would help scientists determine the makeup of dark matter. Other efforts at Livermore, ongoing or planned, would help answer five others, indicated in red.

Key Words: axion, charge-parity (CP) violation, dark matter, heterostructure field-effect transistor (HFET), microwave photons, particle physics, superconducting quantum interference device (SQUID).

For further information contact Leslie Rosenberg (925) 422-4681 (ljrosenberg@llnl.gov).

A First Look at Plutonium's Phonons

SINCE the discovery of plutonium in 1941, the element has both awed and perplexed scientists. The element's complexity and radioactivity have rendered it a challenge to study, but scientists persist because of the need to predict plutonium's behavior under various temperatures and pressure conditions and project how plutonium parts in weapons might change over time. Understanding the properties of plutonium is critical for the safe handling, use, and long-term storage of this material.

Livermore physical chemist Joe Wong is leading a team that has recently taken the first measurements of phonon dispersions in gallium-stabilized delta plutonium. This work sheds light on the movement of atoms in the crystal lattice of plutonium and provides a crucial piece in understanding the element's properties. The research is being conducted in collaboration with the European Synchrotron Radiation Facility in Grenoble, France, and the University of Illinois at Urbana–Champaign. The project is in its first year of funding from Livermore's Laboratory Directed Research and Development Program.

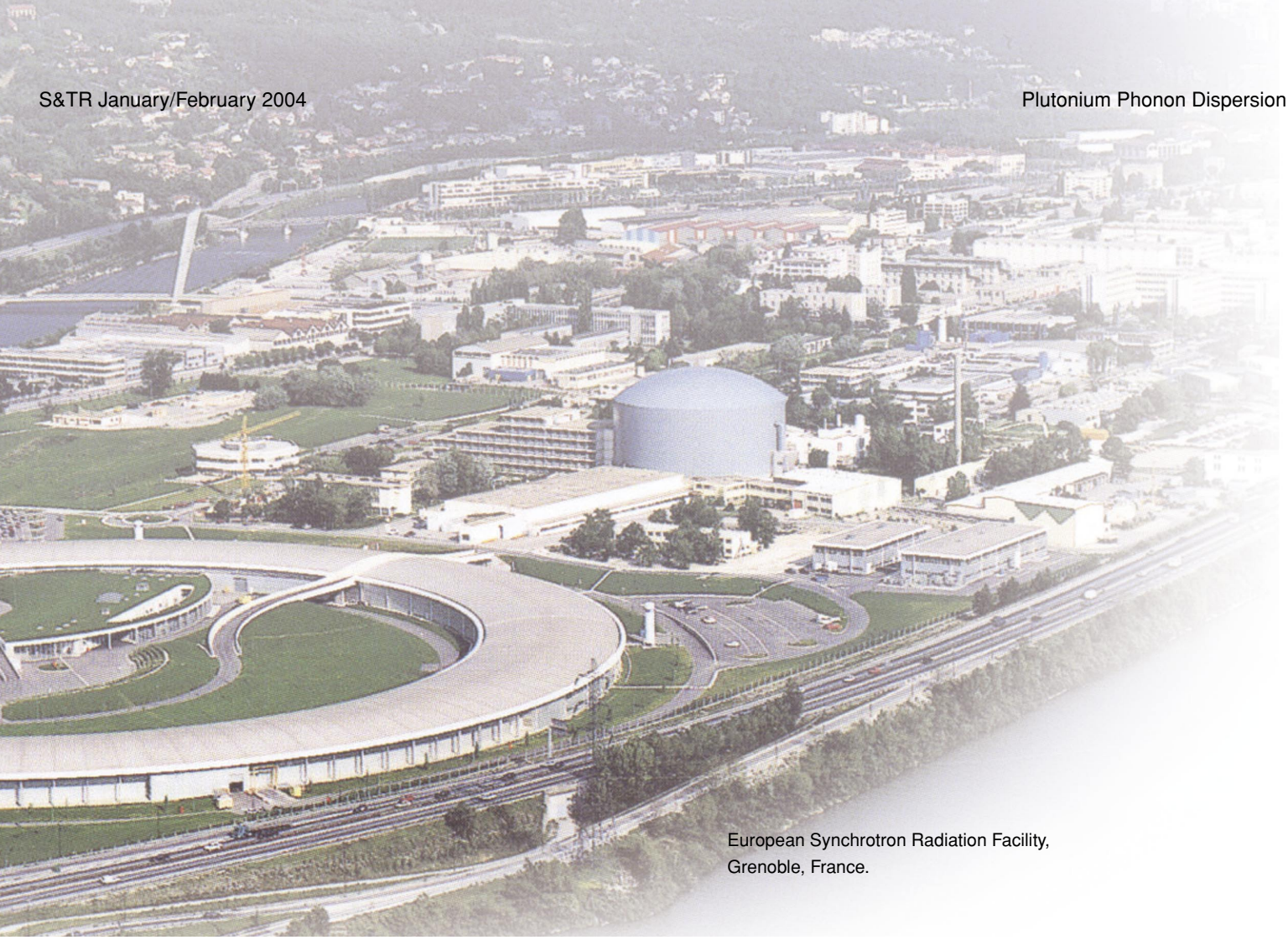
Phonons are lattice vibrations produced by the movement of atoms in a solid. Their variations along different crystallographic directions, called phonon dispersion curves (PDCs), describe how atoms move within a solid and are key to understanding many physical and structural properties, such as force constants, sound velocity, elasticity, heat capacity, and phase stability.

Plutonium and its alloys have defied phonon measurements for the past 40 years for several reasons. First, inelastic neutron scattering, the conventional method used to map phonon dispersions in most solids, requires large single crystals approximately a few millimeters in size, and it is not possible to grow plutonium crystals this large. Inelastic neutron scattering also would not work because of the high neutron absorption rate of plutonium—a quality that makes it ideal for nuclear weapons. Theoretical computations of plutonium's PDCs based on standard first-principles methods are difficult because of the complex correlating behavior of the element's electrons. Only recently has progress been made on the theoretical front to calculate the properties of plutonium. Thus, the PDCs for plutonium and its alloys have remained unknown experimentally and theoretically.

The element's complicated arrangement of 94 electrons contributes to its unpredictable behavior and difficulties in developing theories for plutonium's PDCs. As Wong explains, "If one is trying to make phonon predictions for systems with one or two electrons, it is quite easy. But when a system has 94 electrons, and many of them behave in any number of different ways, all bets are off." With most elements, electron behavior is relatively constant and predictable. However, in plutonium, the electrons are correlated. That is, what one electron does affects other electrons, and no adequate theories could predict those effects.

Plutonium's Peculiar Properties

On the periodic chart, plutonium sits halfway across the row of elements called actinides. The electrons on the outer shell of the elements in this row are progressively filled. The first few elements in the row are those whose electrons contribute to the bonding between atoms. Elements farther down the row, such as plutonium, have outer shells whose electrons may or may not participate in the bonding of atoms, and this variable leads to several unpredictable behaviors. Bonding or nonbonding behaviors are strongly reflected in the motions of the atoms in terms of the energy of the phonons

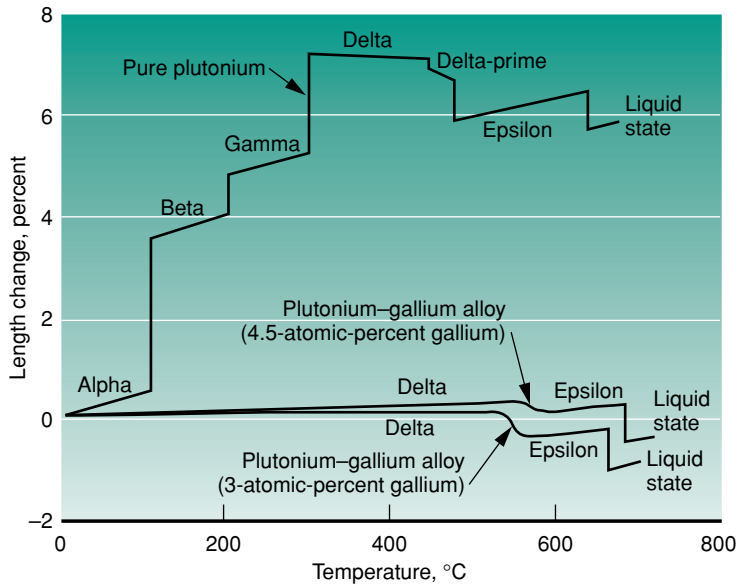


European Synchrotron Radiation Facility, Grenoble, France.

and their dispersion along various directions. Studying the phonon dispersions could answer some of the key questions scientists have about plutonium's behavior in its various phases and in different environments.

One of plutonium's unique physical properties is that the pure metal exhibits six solid-state phase transformations before reaching its liquid state, passing from alpha, beta, gamma, delta, delta-prime, to epsilon. Large volume expansions and contractions occur between the stable room-temperature alpha phase and the element's liquid state. Another unusual feature is that unalloyed plutonium melts at a relatively low temperature, approximately 640°C, to yield a liquid of higher density than the solid from which it melts. In addition, the elastic properties of the delta face-centered cubic (fcc) phase of plutonium are highly directional (anisotropic). That is, the elasticity of the metal varies widely along different crystallographic directions by as much as a factor of six to seven.

Wong's team focused on the delta fcc form of plutonium for phonon measurements because this form is stable at high temperatures and the highly symmetric fcc structure can be retained at room temperature by adding less than 2 atomic percent of an alloy metal such as gallium. For the initial feasibility study



Plutonium can be stabilized at room temperature by adding a small amount of a rare earth metal such as gallium.

and preliminary data analysis, Wong collaborated with physics professor T. C. Chiang at the University of Illinois.

To overcome the obstacles presented with the inelastic neutron scattering method, Wong worked with physicist Michael Krisch at the European Synchrotron Radiation Facility, which has a high-resolution inelastic x-ray scattering (HRIXS) beamline suitable for measuring phonons in plutonium. HRIXS's extremely bright x-ray sources and high-performance focusing optics enable researchers to conduct experiments on materials that are available only in small quantities. For many of the actinide elements such as plutonium, the sample volume is as small as one ten-thousandth of a cubic millimeter.

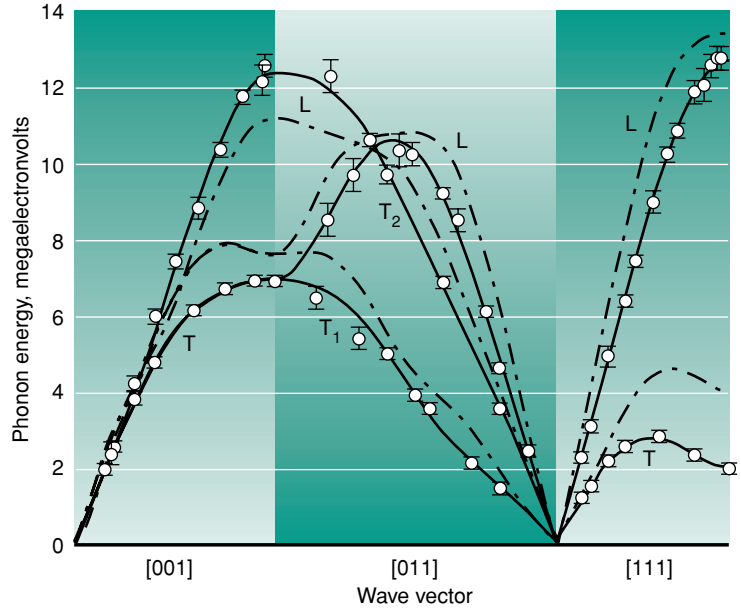
Mapping Phonon Dispersion Curves

Researchers directed a high-energy (21-kiloelectronvolt), high-brightness x-ray microbeam measuring 30 by 60 micrometers onto a single grain in large-grain polycrystalline specimens, each 10 micrometers thick. The specimens were prepared from a plutonium–gallium alloy containing approximately 2-atomic-percent gallium. Single-crystal domains of the fcc delta-plutonium were selected. The phonon energy was then measured and mapped along the three principal directions as a function of the scattering angle, which determined the wave vector of phonon propagation. When the motion of the atoms is along the same direction as the phonon wave propagation, a longitudinal (L) mode is produced. When the motion of the atoms is at a right angle to the phonon wave propagation, a transverse (T) mode is produced.

Scientists can interpret property characteristics from these phonon dispersions. For instance, they observed a profound elastic anisotropy in plutonium, more than in any other fcc metal known. Data also showed that the T [111] mode exhibits a pronounced bending along the transverse branch. Wong and his colleagues believe these features can be related to the phase transformations of plutonium and to the strong coupling between the vibrational structure and the electron instabilities on plutonium's outer electronic shell.

The resulting dispersion values generally agreed with the theoretical calculations based on recent dynamical mean field theory results. The theory incorporates correlation effects among plutonium's electrons and calculates phonon spectra at arbitrary wavelengths.

The experiments confirmed that recent theories explaining plutonium's phonon dispersions have been on the right track. However, a few quantitative differences warrant further study. Laboratory physicists Dan Farber and Florent Occelli and metallurgist Adam Schwartz are collaborating with Wong to gather more data. The team is interested in studying the effects of combining different amounts of gallium with plutonium and in determining how the phonon behavior affects the stability of the various chemical and structural phases of plutonium.



Phonon dispersions along the principal crystallographic directions [001, 011, 111] in a plutonium–gallium alloy. The longitudal and transverse wave vectors are denoted by L and T, respectively. The experimental data are shown as circles. The solid lines are the data's fits to the Born–von Karman model of lattice dynamics. The dashed lines are theoretically calculated dispersions for pure delta-plutonium based on the recent dynamical mean field theory.

Wong says, "These results not only add knowledge to our understanding of the properties of plutonium but also give us real data to test the existing theories and gain more confidence in those theories. We want to continue to gain scientific insight into plutonium's behavior in various environments, so we can contribute to the success of the Laboratory's science-based stockpile stewardship mission."

—Gabriele Rennie

Key Words: actinides, dynamical mean field theory, gallium, phonon dispersion curve (PDC), plutonium.

For further information contact Joe Wong (925) 423-6385 (wong10@llnl.gov).

A Walk on the Wild Side

The big tarplant (*Blepharizonia plumosa*) is widespread throughout Livermore's Site 300 but extremely rare elsewhere.

RARE and endangered plants and animals at Lawrence Livermore? Perhaps surprisingly, there are a few at the heavily developed main site, even as suburban Livermore edges ever closer. Twenty-four kilometers to the east, nestled in California's Coast Range, the Laboratory's Site 300 is home to many more. Here, at the Laboratory's testing range for high explosives, interesting flora and fauna abound on 28 square kilometers of rolling grasslands and steep ravines.

At the main Livermore site, California red-legged frogs (*Rana aurora draytonii*), a federally listed threatened species, live in a small creek and are regularly monitored. They are also breeding in a drainage retention basin on site for the first time now that Laboratory wildlife biologists have controlled the bullfrog (a nonnative predator) population. The California tiger salamander (*Ambystoma californiense*), which may soon be listed as threatened, has been seen near the Livermore site.

"White-tailed kites (*Elanus leucurus*), a California fully protected bird of prey, are successfully fledging their young most years at the main site," says Livermore wildlife biologist Mike van Hattem. "Typically, we see many of the same birds here that we see in a suburban environment." No rare native plants have been found at the Livermore site.

At Site 300, golden eagles are a common sight and feral pigs wreak havoc now and then on the environment. A variety of plants and animals thrive in the site's grasslands and vernal pools, including a species of poppy discovered in the last decade that was thought to be extinct. Seven other species of rare plants are also found at Site 300 alongside numerous rare species of bats, mice, amphibians, snakes, beetles, eagles, hawks, and smaller birds.

Biologist Thom Kato, group leader for Livermore's Environmental Evaluations Group in the Environmental Protection Department, has overall responsibility for wildlife monitoring and research at the Laboratory. The wildlife biologists in his group conduct monitoring programs required by existing permits and pursue efforts to track the distribution and abundance of rare and endangered species. The majority of their monitoring and research efforts are directed at Site 300, so that staff there can plan appropriately for explosives testing. "Our goal is to be in a

When a controlled fire burns through an area at Site 300, it removes most vegetation but leaves behind patches of unburned ground where big tarplants (*Blepharizonia plumosa*) can mature, flower, and provide seed for the following year.

position to meet constantly changing regulations and ensure overall regulatory compliance," says Kato. "That requires being fully familiar with all species at Site 300."

Stalking the Wild *Blepharizonia Plumosa*

Most of Site 300 is undeveloped, and the area has been closed to the public since the testing range was established in the mid-1950s. Biologists cite these factors and the frequency of controlled burns for the existing botanical diversity at Site 300. Of the eight rare plants there, restoration or monitoring activities are being conducted for three of them.

The large-flowered fiddleneck (*Amsinckia grandiflora*) exists in two populations; however, one of these may have been lost as a result of heavy rains in 1997. Just one other natural population is known to exist. An active program is under way to maintain these habitats and establish additional experimental populations because the overall numbers of the large-flowered fiddleneck are shrinking.

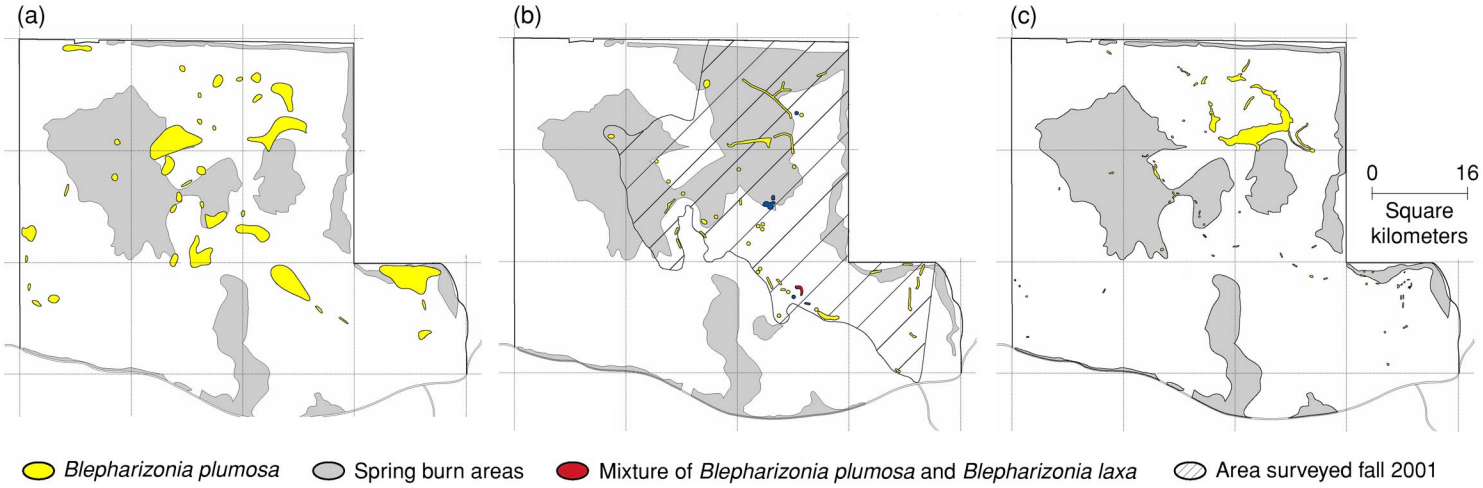
Better news exists about the diamond-petaled poppy (*Eschscholzia rhombipetala*). Experts thought this plant to be extinct, but it was rediscovered at the Carrizo Plain (California central coast) in 1992 and then at Site 300 in 1997. Laboratory biologists discovered a second population in 2002, and the number of plants in the original Site 300 population appears to be expanding.

The third rare plant actively monitored is the big tarplant (*Blepharizonia plumosa*), which is widespread throughout the site but extremely rare elsewhere. Monitoring has shown that populations of the big tarplant were somewhat larger in 2002 than those observed in 2001, particularly in areas burned in the past but not burned in the spring of 2002. Because controlled burns are such an integral part of safety management at Site 300, this apparent correlation with changing numbers of a rare plant warrants attention.

Detailed monitoring has shown that the big tarplants themselves don't survive direct contact with the late-spring and early-summer fires because the fall-blooming plants are still small at this time. But the burns are patchy, so some plants survive in the unburned patches and are able to mature, flower, and provide seed for the following year. The next year's plants have the advantage of reduced competition from other plants in the burned area and often come back in even greater numbers.

Some areas of Site 300 are burned every year for safety reasons, while other areas have burn requirements that vary from year to year. "If there is flexibility with regard to burning, we could explore the possibility of giving an area a rest when the big tarplant population is down so that populations can expand the following year," says Tina Carlsen, an ecologist. "Conversely, we could burn the population area and see if the tarplant comes back in greater numbers.

"Now, we're working to establish a statistical correlation between the controlled burns and populations of the big tarplant. A challenge is that we must consider many other contributing factors besides the fire itself, such as the time of the fire, weather conditions, other plants and animals in the area, and so on. Every year is slightly different. Ecology is a complicated science."



The data are not conclusive, but it appears that populations of the big tarplant (*Blepharizonia plumosa*) may come back in greater numbers two years after being burned, as shown in these Site 300 maps for years (a) 2000, (b) 2001, and (c) 2002. Controlled burns are conducted in late spring or early summer, and plants are surveyed in the fall.

For the Birds

In 2002, the Laboratory began to prepare a new Environmental Impact Statement (EIS) evaluating the environmental consequences of continuing operations. An important aspect of the EIS is providing up-to-date information on sensitive ecological resources at the Laboratory. As part of gathering this broad array of ecological data, a census was started of bird species at Livermore. Gathering this information helps to ensure that mission activities at Site 300 go on as planned and are not interrupted by regulatory requirements aimed at protecting declining populations of migratory and other bird species. Because too little was known about Site 300 bird populations to adequately prepare the EIS, van Hattem started a program to count resident and migratory birds. A team of biologists and volunteers has identified 103 species, of which 24 are state or federal species of special concern and two, the Swainson's hawk (*Buteo swainsoni*) and willow flycatcher (*Empidonax traillii*), are listed as California-threatened and endangered species.

The team elected to use an established and well-defined national protocol known as the Monitoring Avian Productivity and Survivorship (MAPS) Program. MAPS was created in 1989 by the Institute for Bird Populations (IBP) of Point Reyes Station, California, to assess and monitor the vital rates and population dynamics of more than 120 species of North American land birds in order to provide critical conservation and management information on their populations. Since its first season, MAPS has grown nationally from 16 to 570 monitoring stations and has received the support and endorsement of many federal agencies and conservation groups. Because MAPS is a widely accepted methodology, the Laboratory is able to defend the information that it collects and bases its decisions on, and can provide important information to a much broader national effort.

Birds are captured in mist nets, banded in accordance with a permit from the Bird Banding Laboratory (BBL) of the U.S. Geological Survey Biological Resources Division, and released unharmed. Information on the habitat, sex, and estimated age and health of banded birds goes to the BBL. Working with biologists all over the country, the BBL and the IBP have established an unprecedented storehouse of data on birds available to all citizens and agencies.

"Site 300 is on the Pacific Flyway—one of the four major North American migratory routes—so we get all kinds of visitors," says van Hattem. "We've banded a varied thrush (*Ixoreus naevius*) found usually in the redwoods and a black-throated sparrow (*Amphispiza bilineata*) that belongs near Mono Lake on the eastern side of the Sierra Nevada." Van Hattem has also directed a search of nesting sites for the tricolored blackbird (*Agelaius tricolor*), a

(a) A mist net is set up near the Elk Ravine Bird Banding Station at Site 300. (b) A female common yellow-throat (*Geothlypis trichas*) is trapped in the mist net, then later banded and released unharmed.

federal species of concern whose numbers are declining throughout its range.

While continuing to provide important data needed to fulfill environmental protection requirements, these and other avian monitoring programs will allow wildlife biologists to identify and describe patterns of bird populations across time and space, not only at Site 300 but also in broader geographic areas. Researchers can then begin to identify how these patterns are related to the ecological characteristics and population trends of various species, their habitat characteristics, and the ever-unpredictable weather. Working with Site 300 staff, wildlife biologists can also suggest ways to carry out programmatic activities while ensuring that site activities have minimal direct effect on migratory birds and do not result in violations of regulations protecting some species. Efforts to integrate management actions and conservation strategies with programmatic activities may even help to reverse the decline of bird populations and maintain stable or increasing populations.

A Safe Haven

"As time goes on, there will be more concern about the health of our ecosystem," Kato says. "We have the unusual and important task of helping to ensure that the Laboratory performs its primary mission while at the same time contributing to the conservation, and potentially to the eventual recovery, of endangered species at Livermore."

Two male tricolored blackbirds (*Agelaius tricolor*) in the wild. A search for the nesting sites of these birds is ongoing at Site 300.

By offering a safe haven for rare flora and fauna, Livermore is helping some of the rich diversity of our world to survive and thrive.

—Katie Walter

Key Words: birds, *Blepharizonia plumosa* (big tarplant), endangered species, plants, threatened species, wildlife.

For further information contact Thom Kato (925) 423-9642 (kato3@llnl.gov).

A captured male Luzuli Bunting (*Passerina amoena*) about to be released.

Smart Buoys Help Protect Submarine Base

HOMELAND security experts are evaluating a wide range of possible threats from terrorists. One of the more troubling scenarios is a small and crude nuclear device transported in and detonated from a boat located near a naval military base or a civilian shipping terminal. Thanks to a Livermore design, buoys outfitted with commercially available radiation detectors could soon play an important role by warning of the presence of nuclear materials in marine environments.

Two such buoys guard the marine entrance to the U.S. Navy's submarine base at Kings Bay, Georgia. Housing radiation detectors, telemetry systems, and solar- and wind-powered generators, the buoys are proving themselves in a demonstration project sponsored by the Defense Threat Reduction Agency (DTRA).

New Security Uses for Existing Technology

DTRA, a federal agency charged with safeguarding the nation from weapons of mass destruction, has formed a partnership with the National Nuclear Security Administration (NNSA) to evaluate commercially available technologies that could be deployed quickly to defend against threats posed by weapons of mass destruction. One of the agencies' top priorities is preventing nuclear weapons, including crude devices and so-called dirty bombs, from being delivered by unconventional means, such as by car or boat.

Livermore nuclear engineer John Valentine says that the goal is to improve the Department of Defense's ability to detect, identify, respond to, and prevent unconventional nuclear attacks. "We want to determine how we can protect military bases by using commercial technology to detect nuclear materials that might be delivered by truck or boat." He says that if the new detection devices are successful, they could also be installed in civilian areas such as busy ports.

Valentine, who led the engineering tasks for the buoy demonstration project, notes that Livermore experts have also taken part in nuclear detection system demonstrations at Kirtland Air Force Base in New Mexico, Camp Lejeune Marine Base in North Carolina, and Fort Leonard Wood Army Base in Missouri.

At Kings Bay, Georgia, two buoys containing radiation detectors guard the marine entrance as part of a demonstration project sponsored by the Defense Threat Reduction Agency.

All three projects involved demonstrating radiological "sentries" for monitoring large areas of land. The sentries, including stationary radiological sensors placed along roads and units mounted inside vehicles, were designed to identify and track any vehicle that posed a threat.

Located about 48 kilometers north of Jacksonville, Florida, Kings Bay is surrounded by islands, and the area has heavy recreational traffic. For the demonstration, the national laboratories were asked to use equipment capable of operating in marine environments and detecting nuclear materials that might be used by terrorists, demonstrate their reliability and performance, and incorporate them with a base's existing security system. The Livermore buoys are one of three water-based detector platforms under evaluation at Kings Bay. Two other designs, by Sandia and Los Alamos national laboratories, are floating platforms.

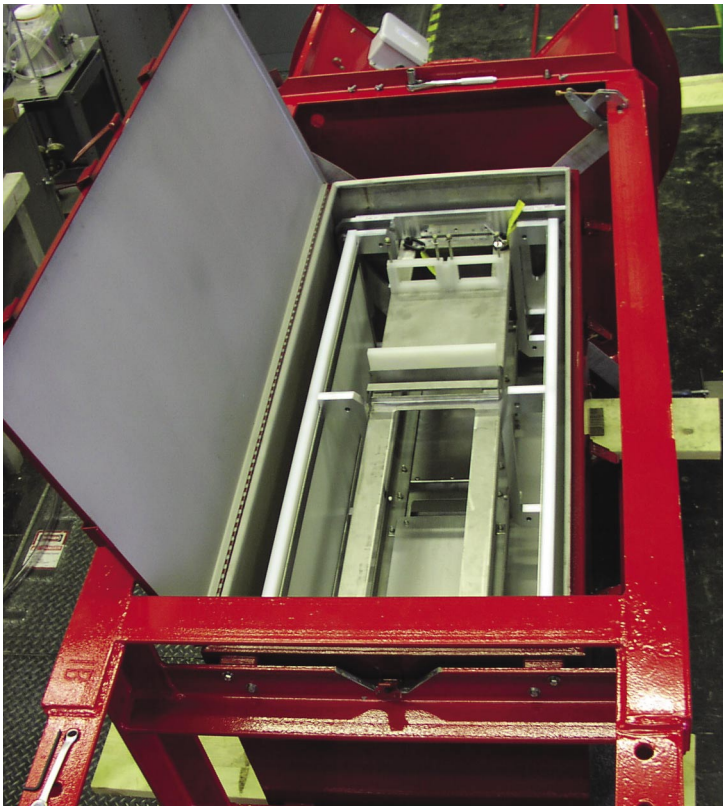
Valentine says that buoys offer several advantages for marine environments. They are built to withstand the rigors of salt water and high winds, they are unremarkable, and they can be situated in any body of water that is at least 10 meters deep. However, buoys also offer challenges such as furnishing adequate power to the detectors and other instruments, transmitting data to the base, and calibrating their detectors when the background radiation levels are not well known.

Buoy Design and Fabrication

The Kings Bay project involved Livermore people from the Engineering; Nonproliferation, Arms Control and International Security (NAI); Chemistry and Materials Science; and Computation directorates. The biggest challenge for the team, led by NAI's Jim Morgan, was to get from design to deployment in just four months. Designs for the two buoys (consisting of a base and tower) were finalized in October 2002. Two commercial stainless-steel buoys, one painted red and the other green, were manufactured in Houston and delivered by truck to Lawrence Livermore on Thanksgiving weekend for modifications. The buoys weigh 6,800 kilograms each and measure 2.4 meters in diameter by about 8 meters tall. About half of the base floats under water.

The team designed and then had constructed a pair of leakproof, stainless-steel enclosures for insertion inside each buoy tower. Within each enclosure is a shock-mounted internal frame on which several kinds of neutron and gamma-ray detectors are mounted so that the team can compare their effectiveness. "Although we are using some recently developed detectors, some of the detector technology in the buoys is about 50 years old," says Valentine. "Thus, in many respects, this project is best described as a novel implementation of existing technology. No one, to our knowledge, had ever put radiation detectors on buoys before."

Two commercial stainless-steel buoys, one painted red and the other green, were manufactured in Houston and delivered to Lawrence Livermore on Thanksgiving weekend 2002 for modifications. The buoy towers, which were attached in Kings Bay, are visible just behind the cab.



The team installed a stainless-steel enclosure inside each buoy tower for holding several kinds of radiation detectors and other sensors.

Sensors monitor the pitch, yaw, and roll of the buoy. Monitoring the buoy's orientation in three dimensions is important to recognizing a threat from the right craft. Other instruments record internal frame temperature (detectors are affected by heat), salinity of the water, and the status of an array of 12-volt photovoltaic batteries. The 16 batteries are powered by four, 55-watt solar panels and a small wind turbine.

Each buoy has a radio for transmitting data back to a receiver on base, where the data are carried by optical fiber to security headquarters. In addition, two video cameras are trained on the buoys from a pier about a kilometer away.

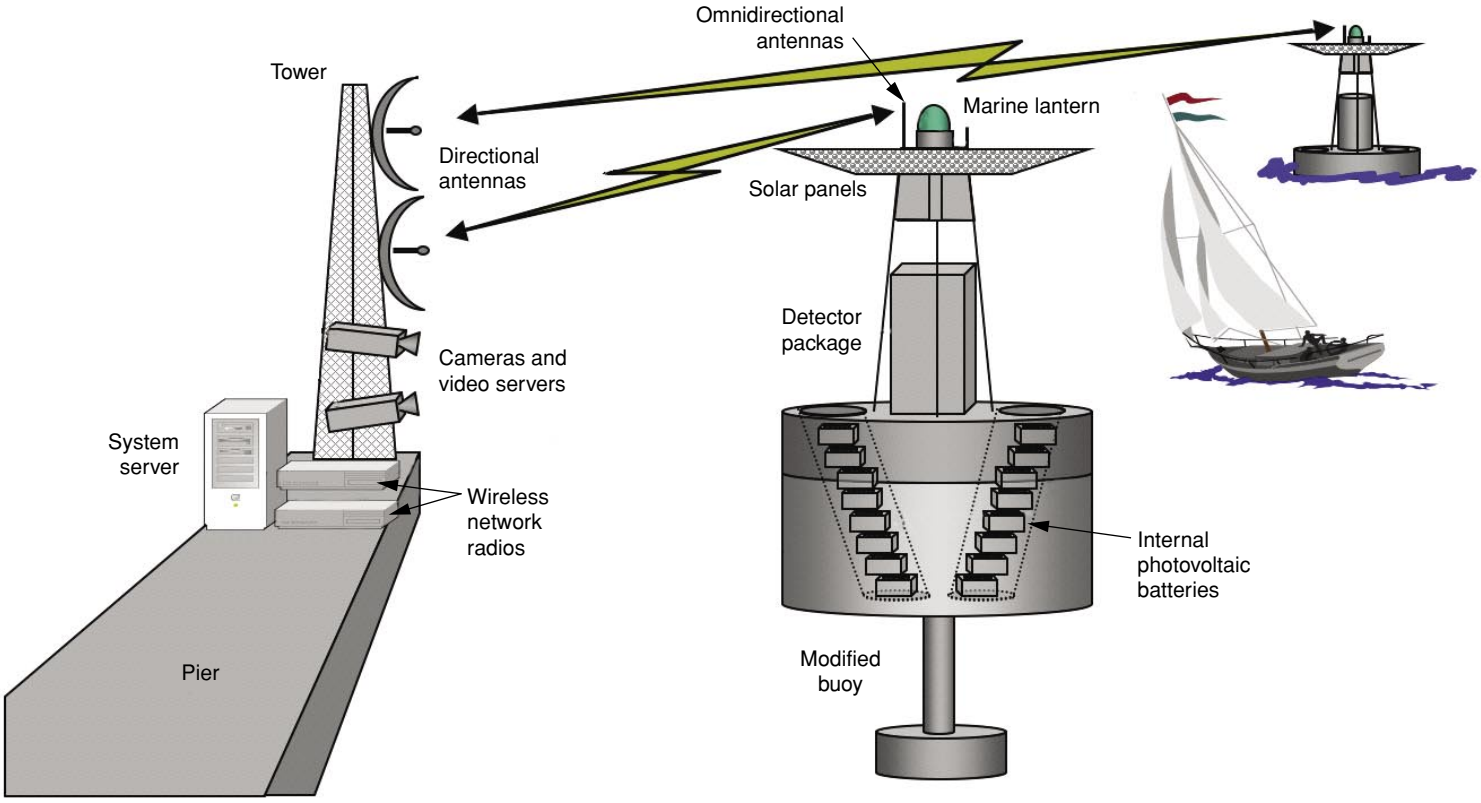
The buoys and their associated equipment arrived at Kings Bay on December 27, 2002. The two enclosures with all the equipment were mounted inside the towers early in January, and then the towers were mounted on the buoy bases. Following final assembly and testing, the buoys were attached to their anchors (5,600-kilogram chunks of concrete) and deployed on January 7, 2003, from a barge-mounted crane. The green buoy is in 15-meter-deep water, and the red buoy is in 10 meters of water. They are separated by 274 meters.

Putting the Buoys to the Test

The buoys are located about 2,200 meters outside a gate that opens and closes to let submarines in and out of the Kings Bay base. The Livermore team was required to obtain approvals from the Navy and Coast Guard for the exact location to place the buoys, which were officially numbered and entered on nautical charts.

"The buoys are serving as a test bed that allows us to evaluate the capabilities of the different detectors," says Valentine. The team is also tracking the performance of the onboard computer, telemetry, power systems, and sensors.

On January 16, 2003, a demonstration of all the prototype marine detector platforms was held before about 80 guests, including representatives from Congress, the Department of Defense, NNSA, DTRA, the Department of Homeland Security, and the Department of Justice. A pontoon boat carrying a variety of radionuclides passed by the detector platforms. In response, both buoys sent messages to base security that the background radiation limit had been exceeded. Valentine says that a guard in the base security building could see two icons (representing the two buoys) on a computer



Inside each buoy is a set of 16 photovoltaic batteries charged by four solar panels and a wind turbine. On shore, two directional antennas receive data from the buoys, and two video cameras are trained on them.

console turning from green to flashing red. Catherine Montie, DTRA program manager, gave the demonstration an "A+," and Valentine anticipates that the buoys will remain deployed while funding continues.

"The demonstration was an important first step," says Valentine. He is leading a follow-on effort that involves upgrading the computer software and hardware, establishing a temporary remote (from Livermore) monitoring capability, characterizing the marine background radiation around Kings Bay, and determining better the capabilities of the different detectors.

"We know a lot about terrestrial background radiation but much less about radiation levels on the water. We know that radiation levels can vary considerably during the day and night on land. That may also be true at sea. At Kings Bay, the water is brackish. During high tide, it is mostly salt water, and during low tide, it is mostly fresh water. The differences in salinity may cause changes in background radiation."

Valentine says the buoys could be integrated into the base security system in the near future. Then when a threat appears, a security guard will be able to click on a red flashing computer icon, see a real-time video image of the area around the buoy, and learn of the probable radioisotopes carried by the suspicious vessel.

Valentine also says that similar buoys could be put to good use in busy harbors. Proposals have already been submitted to deploy buoys with radiation detectors in the harbor at Oakland, California. Buoys, a common marine sight, may prove to be the next level of protection in the war on terrorism.

—Arnie Heller

Key Words: Defense Threat Reduction Agency (DTRA); homeland security; radiation detector; U.S. Navy submarine base at Kings Bay, Georgia.

For further information contact John Valentine (925) 424-3261 (valentine12@llnl.gov).

Following final assembly and testing, the buoys were deployed January 7, 2003, from a barge-mounted crane.

Patents and Awards

Each month in this space we report on the patents issued to and/or the 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.

Patents

Method for Fabricating Reticles for Extreme-Ultraviolet Lithography without the Use of a Patterned Absorber

Daniel G. Stearns, Donald W. Sweeney, Paul B. Mirkarimi
U.S. Patent 6,635,391 B2
October 21, 2003

Absorber material used in conventional extreme ultraviolet lithography (EUVL) reticles is eliminated by introducing a direct modulation in the complex-valued reflectance of a multilayer. A spatially localized energy source, such as a focused electron or ion beam, directly writes a reticle pattern onto the reflective multilayer coating. Interdiffusion is activated within the film by an energy source that causes the multilayer period to contract in the exposed regions. The contraction is accurately determined by the energy dose. A controllable variation in the phase and amplitude of the reflected field in the reticle plane is produced by the spatial modulation of the multilayer period. This method for patterning an EUVL reticle has the advantages of avoiding the process steps associated with depositing and patterning an absorber layer and providing control of the phase and amplitude of the reflected field with high spatial resolution.

Liposuction Cannula Device and Method

Paul J. Weber, Steven R. Visuri, Matthew J. Everett, Luiz B. Da Silva, Alwin H. Kolster
U.S. Patent 6,638,238 B1
October 28, 2003

A liposuction apparatus and method having an optional sonic or ultrasonic source with an axial lumen passage in which the shaft can be made to reciprocate (oscillate) in a nonrectilinear fashion. The apparatus may also contain the concomitant use of rectilinear reciprocation motion in addition to ultrasonic motion or energy along the shaft of the apparatus. The advantages of the liposuction apparatus are as follows: nonrectilinear single shaft reciprocating cannula; sonic or ultrasonic energy delivered to the distal tip; rectilinear reciprocating cannula with ultrasonic energy along a shaft from the handle; and any of the above reciprocating components powered by excess unused vacuum capacity in the liposuction aspirator (suction engine) apparatus. Three primary sources of energy are applied to the cannula shaft: the oscillating surgeon's arm motion of approximately 1 to 2 hertz; the reciprocating motion of about 100 hertz; and the optional concomitant motion delivered by the ultrasonic energy of, for example, 25 kilohertz.

MEMS-Based Thin-Film Fuel Cells

Alan F. Jankowski, Jeffrey D. Morse
U.S. Patent 6,638,654 B2
October 28, 2003

A microelectromechanical systems– (MEMS-) based thin-film fuel cell for electrical power applications. The MEMS-based fuel cell may be of a solid-oxide type, a solid-polymer type, or a proton-exchange-membrane type. Each fuel cell basically consists of an anode and a cathode separated by an electrolyte layer. In addition, catalyst layers can separate the electrodes (cathode and anode) from the electrolyte. Gas manifolds are used to transport the fuel and oxidant into each cell and to provide a path for exhaust gases. The electrical current generated from each cell is drawn away by an interconnect and support structure integrated with the gas manifold. The fuel cells use integrated resistive heaters for efficient heating of the materials. By combining MEMS technology with thin-film deposition technology, thin-film fuel cells with microflow channels and fully integrated circuitry can be produced. These fuel cells will lower operating temperatures of the electrical power application and will yield an order-of-magnitude greater power density than currently known fuel cells.

Optic for an Endoscope and Borescope Having High Resolution and Narrow Field of View

Gary F. Stone, James E. Trebes
U.S. Patent 6,639,739 B1
October 28, 2003

An optic with optimized high spatial resolution, minimal nonlinear magnification distortion, and limited chromatic focal shift or aberrations. The optic located at the distal end of an endoscopic inspection tool allows for a high-resolution, narrow-field-of-view image for medical diagnostic applications as compared to conventional optics for endoscopic instruments that provide a low-resolution, wide-field-of-view image. The image coverage is over a narrow (less than 20 degrees) field of view with low optical distortion (less than 5 percent pin cushion or barrel distortion). The optic is also optimized for best color correction as well as to aid medical diagnostics.

Compact Cladding-Pumped Planar Waveguide Amplifier and Fabrication Method

Andy J. Bayramian, Raymond J. Beach, Eric Honea, James E. Murray, Stephen A. Payne
U.S. Patent 6,640,040 B2
October 28, 2003

A low-cost, high-performance, cladding-pumped planar waveguide amplifier and fabrication method for deployment in metro and access networks. The waveguide amplifier has a compact monolithic slab architecture preferably formed by first sandwich-bonding an erbium-doped core glass slab between two cladding glass slabs to form a multilayer planar construction, and then slicing the construction into multiple unit constructions. Using lithographic techniques, a silver stripe is deposited and formed at a top or bottom surface of each unit construction and over a cross section of the bonds. Heating the unit construction in an oven and applying an electrical field ion-diffuses the silver stripe to increase the refractive indices of the core and cladding regions, with the diffusion region of the core forming a single-mode waveguide and the silver diffusion cladding region forming a second, larger waveguide amenable to cladding pumping with broad-area diodes.

Awards

Seymour Sack in Livermore's Defense and Nuclear Technologies (DNT) Directorate was one of three winners of the **2003 Enrico Fermi Award**. At an awards banquet in October 2003, Sack received a gold medal and a citation signed by President George W. Bush and Secretary of Energy Spencer Abraham. He was recognized for "his contributions to the national security of the United States in his work assuring the reliability of nuclear weapons and thus deterring war between the superpowers."

Sack, 74, received a B.S., M.S., and Ph.D. in physics from Yale University. He retired from the Laboratory in 1990 and continues as a Laboratory associate. During his 35 years at Livermore, he emerged as one of the foremost U.S. nuclear weapons designers. His weapon designs introduced insensitive high explosives, fire-resistant plutonium pits, and other important nuclear safety elements. Sack's design concepts are found in all U.S. stockpile weapons.

The Fermi Award recognizes scientists of international stature for lifetimes of exceptional achievement in the development, use, or production of energy—broadly defined to include nuclear, atomic, molecular, and particle interactions and effects. One of the nation's oldest and most prestigious science and technology awards, it dates back to 1956 and honors physicist Enrico Fermi, who in December 1942 led scientists at the University of Chicago in achieving the first self-sustained, controlled nuclear reaction. Information about the Fermi Award, prior winners, and their contributions is available online at www.sc.doe.gov/sc-5/fermi.

The **American Physical Society** (APS) has named **Steve Hatchett** of the Defense and Nuclear Technologies Directorate as an **APS Fellow** for his contributions to inertial confinement fusion (ICF). Hatchett is well known throughout the international ICF community for innovative implosion designs for fast ignition. These "cone focus" designs solve a critical issue—getting the fast ignition beam to the compressed fuel. Throughout his 20-year career at Livermore, Hatchett has been highly sought after as a collaborator, particularly by experimentalists. He is now working to identify opportunities and requirements for implosion diagnostics on the National Ignition Facility.

In October 2003, the **American Ceramics Society** (ACS) honored Livermore researcher **Jack Campbell** with the **George W. Morey Award**. The award cites Campbell's "work and leadership in the development, characterization, and manufacturability of phosphate laser glass for high-peak-power lasers." Campbell, now the group leader for Advanced Optical Materials for the National Ignition Facility (NIF), has been at Livermore since 1975. His early work involved the development of glass and polymer targets for the Laboratory's Nova laser. For most of the past 20 years, his goal has been to develop ever-higher-quality optics needed to transport and amplify beams for Livermore's various lasers.

The George W. Morey Award is named for a pioneer in the scientific study of glass. Morey, of the Carnegie Institution of Washington, systematically studied the composition and properties of a wide range of glasses, much of which is summarized in his classic 1938 textbook *Properties of Glass*.

T. G. Nieh of the Chemistry and Materials Science Directorate was recently named **Fellow of the Minerals, Metals and Materials Society** (TMS) for his expertise in superplasticity research. Superplasticity is the high-temperature deformation of metal and ceramics. Under normal room-temperature conditions, metal can be stretched so that it extends about 50 percent without fracturing. But when the metal is heated and its microstructure is modified, it can be stretched to 8,000 percent of its original length. Nieh discovered how to streamline the procedure and make it cost-effective so that it could be used on industrial assembly lines. Nieh's solution turned out to involve adding nanometer-size second-phase particles to an alloy to refine its microstructure during the thermomechanical process.

In naming Nieh a fellow, TMS cited his "contributions to the understanding of superplasticity behavior of metals and ceramics, including high-strain-rate superplasticity and superplastic ceramics." Although nearly 10,000 members from more than 70 countries belong to TMS, the society has no more than 100 living fellows at any time.

Abstracts

Small Particle May Answer Large Physics Questions

Scientists from Lawrence Livermore are searching for evidence of the axion—an elusive particle that may help "balance the budget" for the missing mass of the universe. If it were found to exist, the axion would be one of the most weakly interacting particles in existence. Experimental verification of the axion would also help explain the puzzle of charge-parity (CP) violation in particle physics. The experiment, funded by the Department of Energy's Office of Science, is based on the theory that an axion could be stimulated to decay into a single photon in the presence of a large magnetic field threading a microwave cavity. The experimental setup includes a tunable microwave cavity permeated by a strong magnetic field and ultralow-noise microwave amplifiers. The microwave cavity is slowly tuned over a range of frequencies. When the proper frequency of the axion-emitted photon is reached, the axion signal should appear as a narrow line in the spectrum. A proposed upgrade using amplifiers based on superconducting quantum interference devices (SQUIDs) would make it possible to detect even the weakest axion signal.

Contact:
Leslie Rosenberg (925) 422-4681 (ljrosenberg@llnl.gov).

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Atoms for Peace

Taking to heart President Eisenhower's "Atoms for Peace" message in 1953, Livermore scientists have applied their nuclear expertise to advance human health and national security.

Also in March

- *The height of the tropopause—the boundary between the troposphere and the stratosphere—provides another "fingerprint" of human effects on climate change.*
- *Livermore and Los Alamos have developed a common framework for evaluating the safety and reliability of nuclear weapons.*
- *A new experimental method developed at Livermore allows scientists to monitor the folding processes of proteins, one molecule at a time.*

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