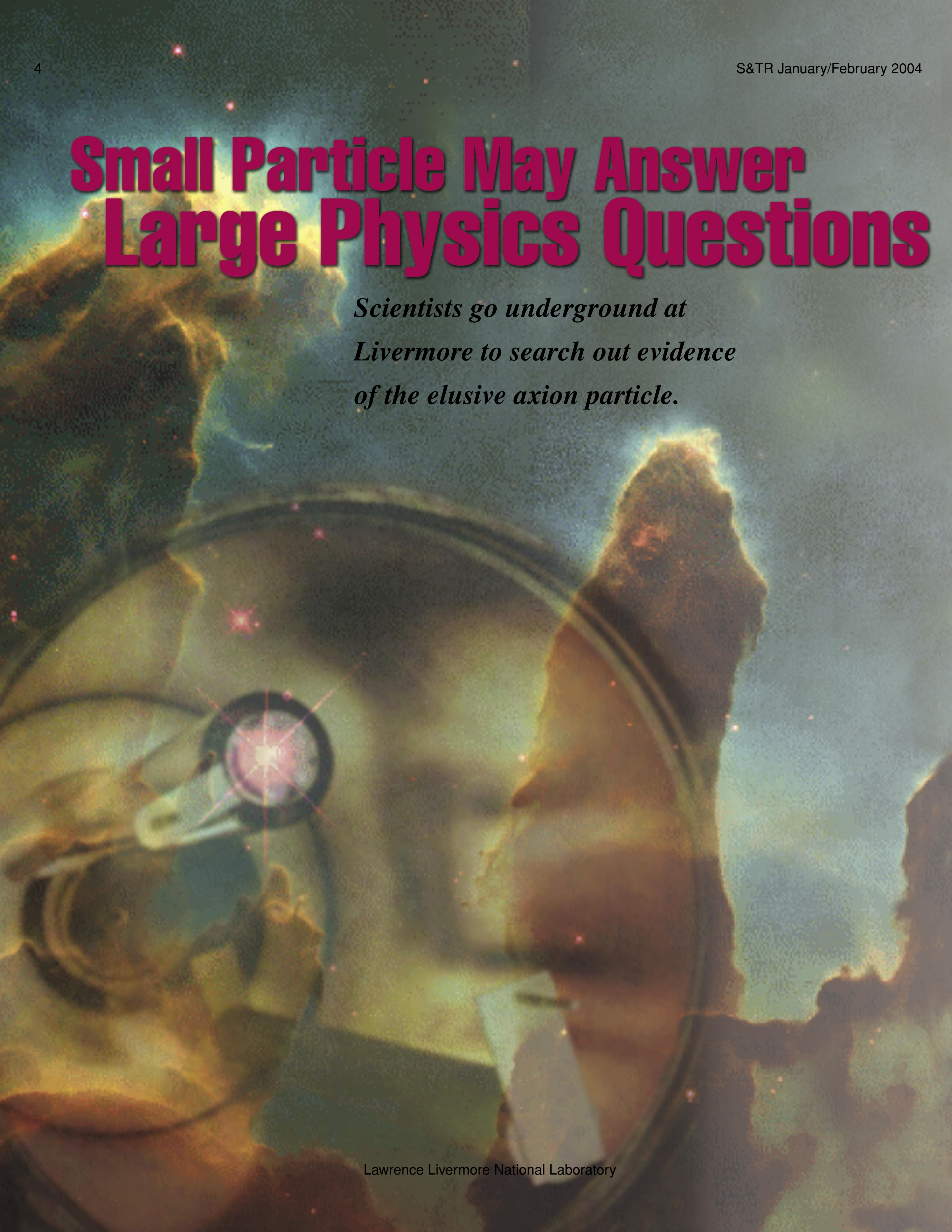
Small Particle May Answer Large Physics Questions

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

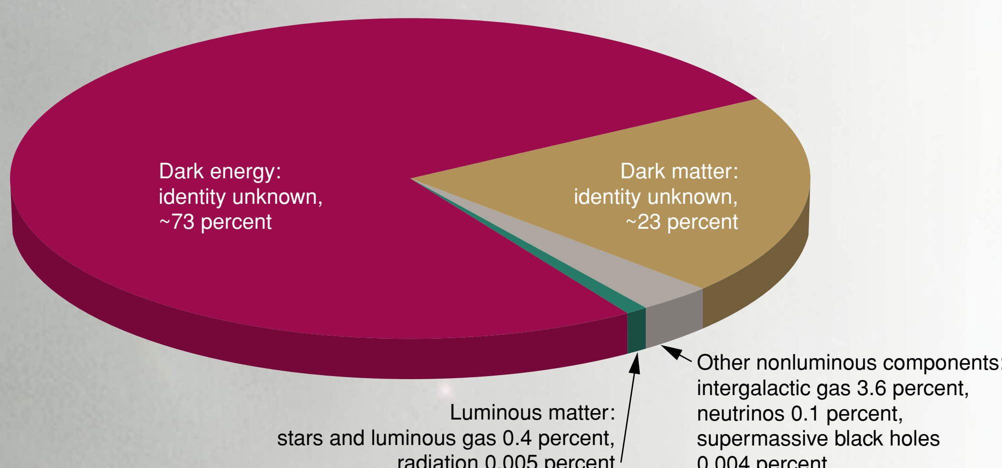
The overall makeup of the universe is well agreed upon among physicists, astronomers, and astrophysicists. Luminous matter—stars and galaxies—is a mere fraction of 1 percent. Other nonluminous matter, such as intergalactic gas, neutrinos, and so on, accounts for not quite 4 percent. The remaining mass 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.

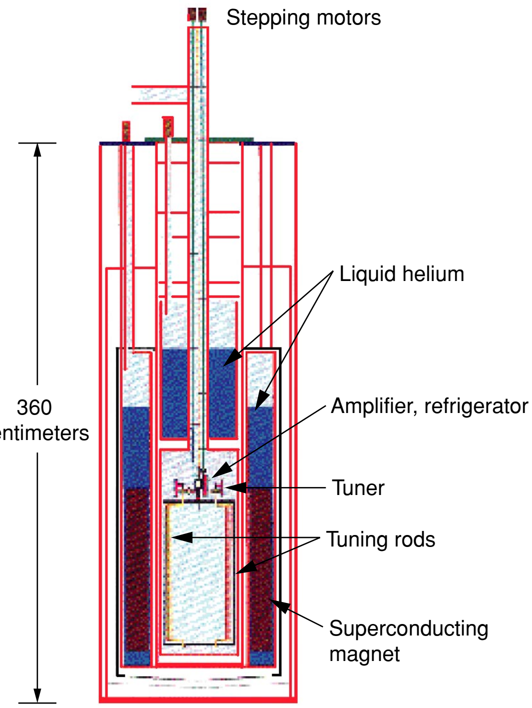
Refined calculations have led scientists to believe that the axion must lie in a mass window of approximately 10^{-6} to 10^{-3} electronvolts.

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

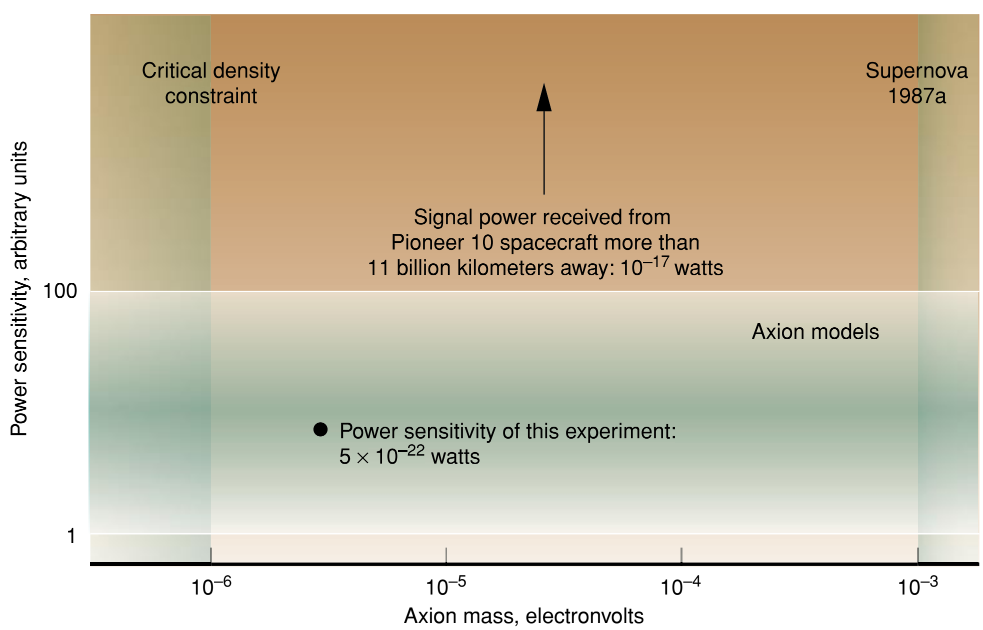
The experiment is based on the theory that an axion, when it does interact, decays into two photons with frequencies in the microwave range of the electromagnetic spectrum. UF professor Pierre Sikivie and others formed the idea that an axion could be stimulated to decay into a single photon in the presence 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.

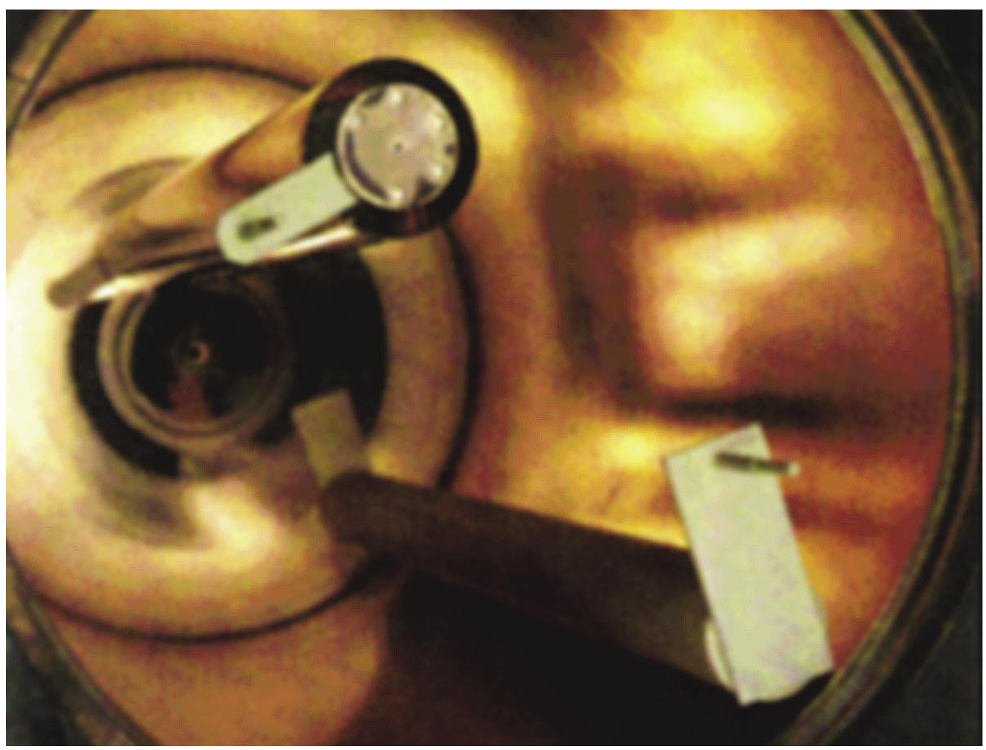
The initial proof-of-principle experiments, conducted in the late 1980s at Brookhaven National Laboratory and UF, validated the technology and strategy of the microwave cavity approach. However, they lacked the power sensitivity by two or three orders of magnitude to actually detect an axion. The experiment 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.

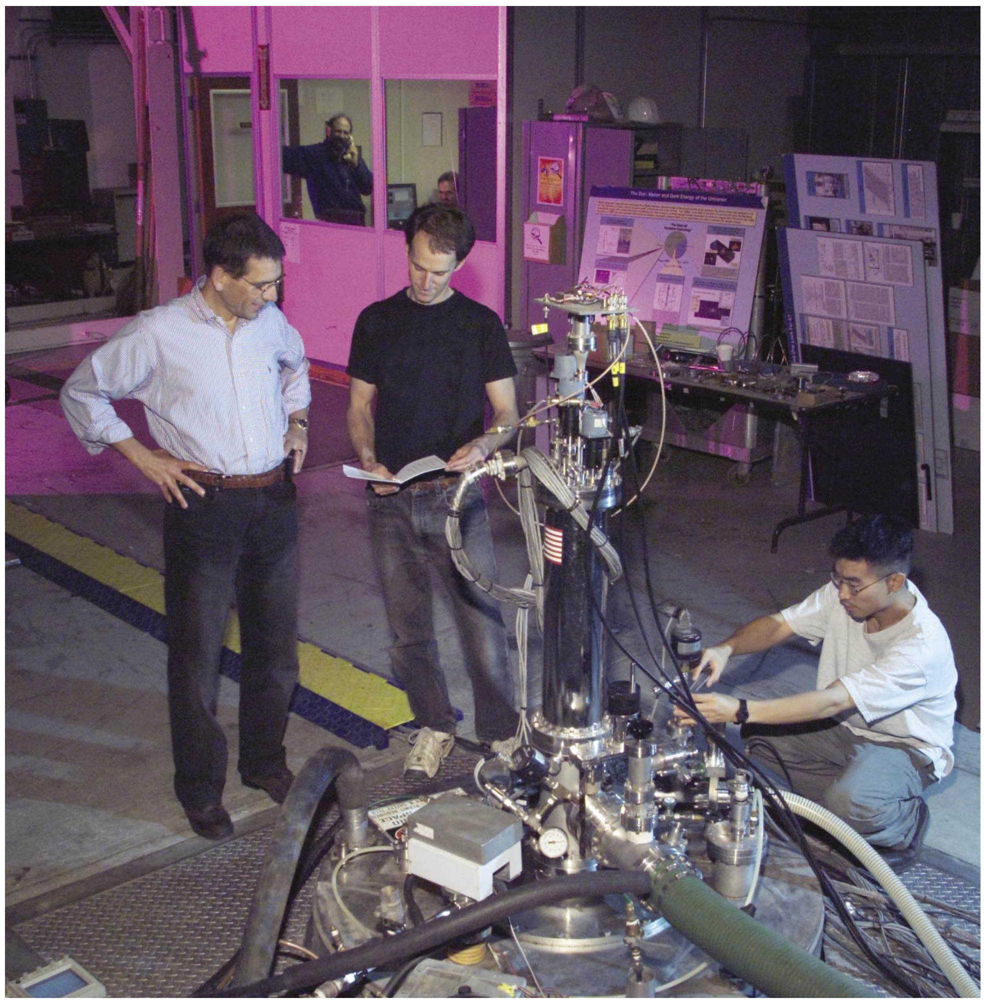
By early 1996, the Livermore axion experiment was running and producing data. The research team continues to explore the region from 0.3 to 3 gigahertz, which corresponds to an axion mass of 1.2 to 12.4 microelectronvolts. This experiment has increased power sensitivity by two orders of magnitude over 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.

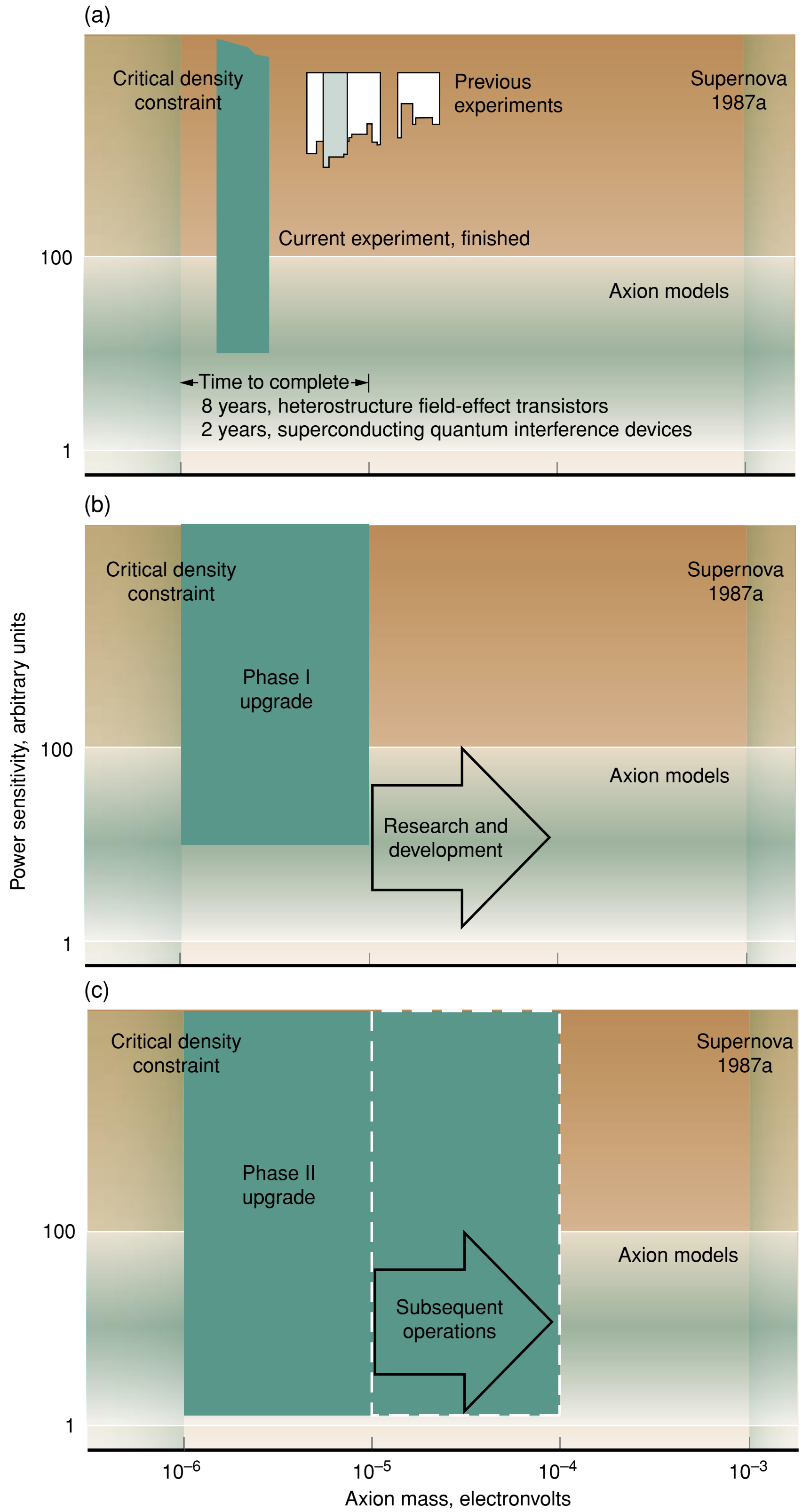
"What this means," says Rosenberg, "is that, for the first time, the experiment will be sensitive to weakly coupled axions, even if axions are a minority contribution to the local dark matter halo. These are the axions considered to be the most promising of the axion-based dark matter models. Once we 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).

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