Searching for Tiny Signals from Dark Matter

FOR decades, physicists have struggled to unravel the mysteries of so-called dark matter, a postulated invisible form of matter that constitutes more than 20 percent of the universe and is key to understanding the formation—and fate—of the universe. Many scientists hypothesize that a subatomic particle, called an axion, constitutes dark matter. These scientists calculate that every cubic centimeter of space could contain about 100 trillion axions, all produced during the big bang some 12 billion years ago.

Axions have no electric charge or spin, extremely small mass (a trillion times less than that of an electron), and little interaction with ordinary matter. As a result, detecting these invisible particles requires extremely sensitive equipment. A Livermore experiment, known as the Axion Dark Matter Experiment (ADMX), is designed to find the elusive particle by measuring its decay into a microwave photon in the presence of a strong magnetic field. (See *S&TR*, January/February 2004, pp. 4–11.)

The microwave photon's faint signal must be amplified to an extreme degree to be detected. The capacity to distinguish weak photons during axion decay was significantly enhanced in 2008 when the ADMX team added sensitive amplifiers about the size of computer chips to the experimental apparatus. Together with a new cooling system awaiting installation, these amplifiers should allow the team to detect even the weakest axions.

The high-gain, ultralow-noise amplifiers are based on superconducting quantum interference devices (SQUIDs), which may also have applications in quantum computing. (See the box on p. 18.) Livermore physicist Darin Kinion fabricated the units in cooperation with a group of University of California (UC) at Berkeley researchers headed by John Clarke, a professor in the Physics Department.

The ADMX effort began in 1995 with support from the Department of Energy Office of Science and Livermore's Laboratory Directed Research and Development Program. Physicists Karl van Bibber at the Naval Postgraduate School in Monterey, California, and Leslie Rosenberg from the University of Washington lead the experiment. Other researchers include Kinion and postdoctoral researcher Gianpaolo Carosi, who work in the Laboratory's Physical and Life Sciences Directorate; postdoctoral researcher Gray Rybka and graduate student Michael Hotz, both from the University of Washington; and Pierre Sikivie and David Tanner from the University of Florida. The amplifier development effort received funding from the Laboratory Directed Research and Development Program and, for work at UC Berkeley, from the National Science Foundation.

Livermore physicist Darin Kinion guides the experimental apparatus containing the microwave cavity and superconducting quantum interference device (SQUID) amplifiers into the cavity of a superconducting electromagnet for the Axion Dark Matter Experiment (ADMX). The disks on top of the ADMX device are thermal shields.

Tuning a Microwave Cavity

ADMX features a "tunable" microwave cavity, a copper-plated, stainless-steel cylinder similar in size to an oil drum (1 meter tall and 0.5 meters in diameter). A 1-meter-long superconducting electromagnet weighing 6 tons is wound around the outside of the cavity and generates 8 tesla, making it about 200,000 times more powerful than Earth's magnetic field. Presumably, some axions passing through the ADMX detection cavity will interact with the magnetic field generated by the superconducting magnet and decay into microwave photons. The SQUIDs will then amplify these signals to detectable levels.

When Zeros and Ones Intermingle

The same superconducting quantum interference devices (SQUIDs) that boost weak signals in Livermore's Axion Dark Matter Experiment (ADMX) may one day become an essential component of a radically different type of computer. The machine is called a quantum computer because it is based on the strange properties of atoms and subatomic particles.

In traditional computing, the basic unit of information—a bit—has a value of either 0 or 1. In contrast, quantum computers use a "qubit," in which the 0 and 1 states mix together. That is, qubits can take on both values simultaneously, a property known as quantum superposition. "We are trying to perform new types of computing using the properties of quantum mechanics, which are counterintuitive to our common sense," says Livermore physicist Darin Kinion.

Qubits can be represented by the spins of individual electrons confined in semiconductor nanostructures (often called quantum dots), by nuclear spins associated with single-atom impurities in a semiconductor, or in the proposed Livermore design, by the quantized (discrete) energy levels of a Josephson junction. The Livermore SQUIDs will be used to detect fleeting changes in the quantum state of qubits comprising a prototype computer.

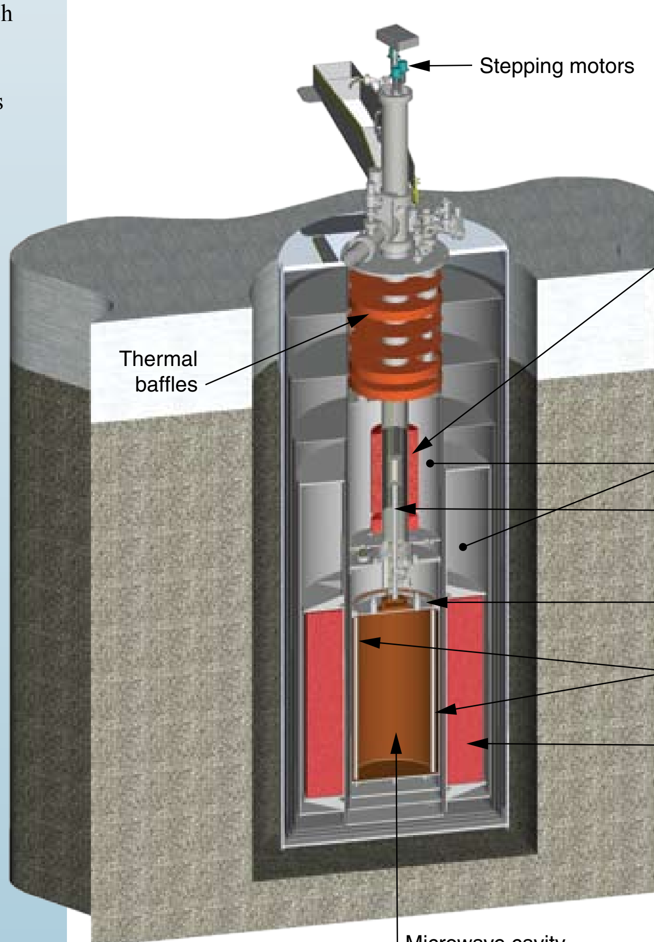
The SQUID development effort is part of a four-year-long Livermore project funded by the Intelligence Advanced Research Projects Activity. Part of the Office of the Director of National Intelligence, this organization invests in high-risk, high-payoff research with the goal of strengthening U.S. intelligence capabilities. The Livermore effort is aimed at building individual qubits, coupling a small number of them, and using a SQUID-based readout technique to record their states significantly faster than current methods.

Corporations such as IBM and Microsoft have been working on simple prototype quantum computers. However, constructing a full-scale quantum computer is a difficult task because quantum states are extremely fragile and difficult to detect and manipulate. "We have only a very short window of opportunity, less than one-tenth of a microsecond, to get information out," says Kinion. A longer readout process would collapse the fragile quantum state of the qubits. Because external disturbances would cause the machine to stop working, qubits must be shielded with layers of extremely cold superconducting fluids. "Even 1 kelvin is too hot," says Kinion.

Scientists believe quantum computers could easily solve problems that are too complex for even the most powerful supercomputers. For example, quantum computers could quickly find factors, prime numbers that are multiplied together to give the original number. Factoring a large number is so difficult for conventional computers that it is used by many cryptographic methods to protect data. Potential applications also include solving other difficult math problems, modeling quantum systems, and mining large databases for particular pieces of information.

To locate the axions, the team must slowly scan the range of possible cavity frequencies—from 300 megahertz to 30 gigahertz. For this operation, stepper motors move a set of tuning rods a few hundred nanometers per minute through the cavity.

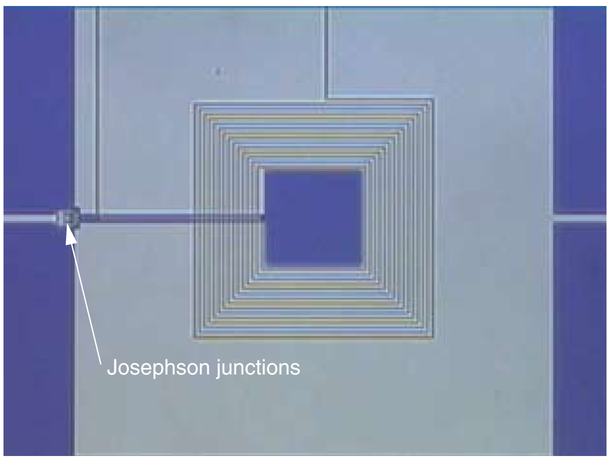
The original amplifiers, built by the National Radio Astronomy Observatory, were based on the heterostructure field-effect transistor, a semiconductor device developed for military communications and used by astronomers to boost weak radio signals. However, investigators decided the transistors were not sensitive enough for the weakest possible signals, so Kinion began a collaboration with Clarke's research group to develop amplifiers based on SQUID technology.



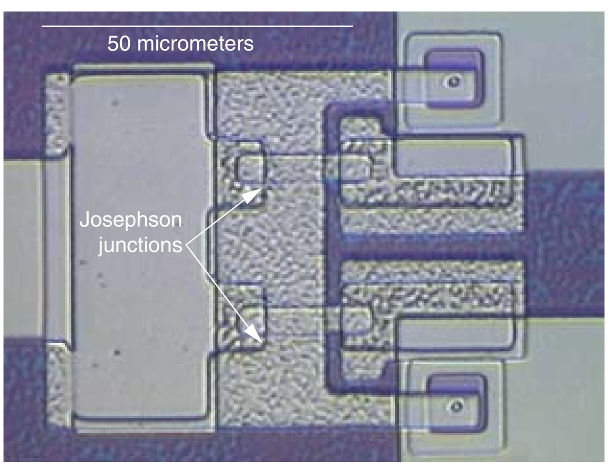
A cross section of the ADMX device shows an 8-tesla, 6-ton superconducting magnet coil wound around the outside of a cylinder the size of an oil drum. Stepper motors move a set of tuning rods in the cylinder's cavity to adjust the cavity's frequency. Helium cools the cavity, reducing the background noise so the ultrasensitive SQUID amplifiers can boost the faint axion signal.

A SQUID is composed of a superconducting loop containing two parallel Josephson junctions, which are made of a thin layer of insulating material sandwiched between two layers of superconducting metals. Josephson junctions are named for British physicist and Nobel Prize recipient Brian Josephson, who in 1962 predicted that pairs of superconducting electrons could "tunnel" through nonsuperconducting material from one superconductor to another.

SQUIDs are sensitive to the magnetic field penetrating the superconducting loop area. That is, the voltage measured across the device is a function of the total magnetic field inside the loop. The device is often configured as a magnetometer to detect extremely small magnetic fields, such as those generated by living organisms. For example, SQUIDs are commonly used as detectors in medical magnetoencephalography imaging. Other applications include oil and mineral exploration, geothermal energy surveys, and gravitational wave detection.



Each 1-millimeter-square, 200-nanometer-thick SQUID is composed of a superconducting loop containing two parallel Josephson junctions, which consist of a thin layer of insulating material sandwiched between two layers of superconducting metals.



This photomicrograph shows the two Josephson junctions used in SQUID amplifiers.

World's Most Sensitive Detector

Kinion produced the 1-millimeter-square, 200-nanometer-thick SQUIDs using UC Berkeley's photolithography facilities and techniques similar to those found in the semiconductor industry. The devices, made in part from superconducting niobium, are the most sensitive magnetic-field detector in the world, capable of picking up signals well below 1 yoctowatt (or 10^{-24} watts). ADMX will require 20 SQUIDs, each assigned to a different set of frequencies, to scan the entire frequency range.

"The biggest challenge we faced was designing a SQUID that could pick up trace differences in magnetic signals in close proximity to the 8-tesla superconducting magnet," says Kinion. He notes that during experiments at UC Berkeley, an unshielded SQUID routinely detected the magnetic field generated by a passing subterranean Bay Area Rapid Transit train about 1 kilometer away. To isolate SQUIDs from outside magnetic fields, the ADMX team enclosed them in a lead-plated box surrounded by concentric layers of materials.

Despite the extreme sensitivity of the SQUIDs and the shielding surrounding them, signals from axion decays could be overwhelmed by thermal and electronic noise emitted from electronic instruments. Therefore, the entire experiment is cooled with liquid helium to below 4.2 kelvins to provide a quiet sensing environment. When a more powerful cooling system is installed later this year, the amplifier will operate at less than 0.1 kelvins. It will then be able to detect even the most elusive axion as well as scan the microwave cavity four times faster than the current system.

The research team is confident that if axions exist, ADMX will detect them. Discovery of an axion would help scientists better understand the mysterious dark matter that permeates the universe, the force that binds atomic nuclei, and the nature of quantum physics.

—Arnie Heller

Key Words: Axion Dark Matter Experiment (ADMX), Josephson junction, quantum computing, qubit, superconducting quantum interference device (SQUID).

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