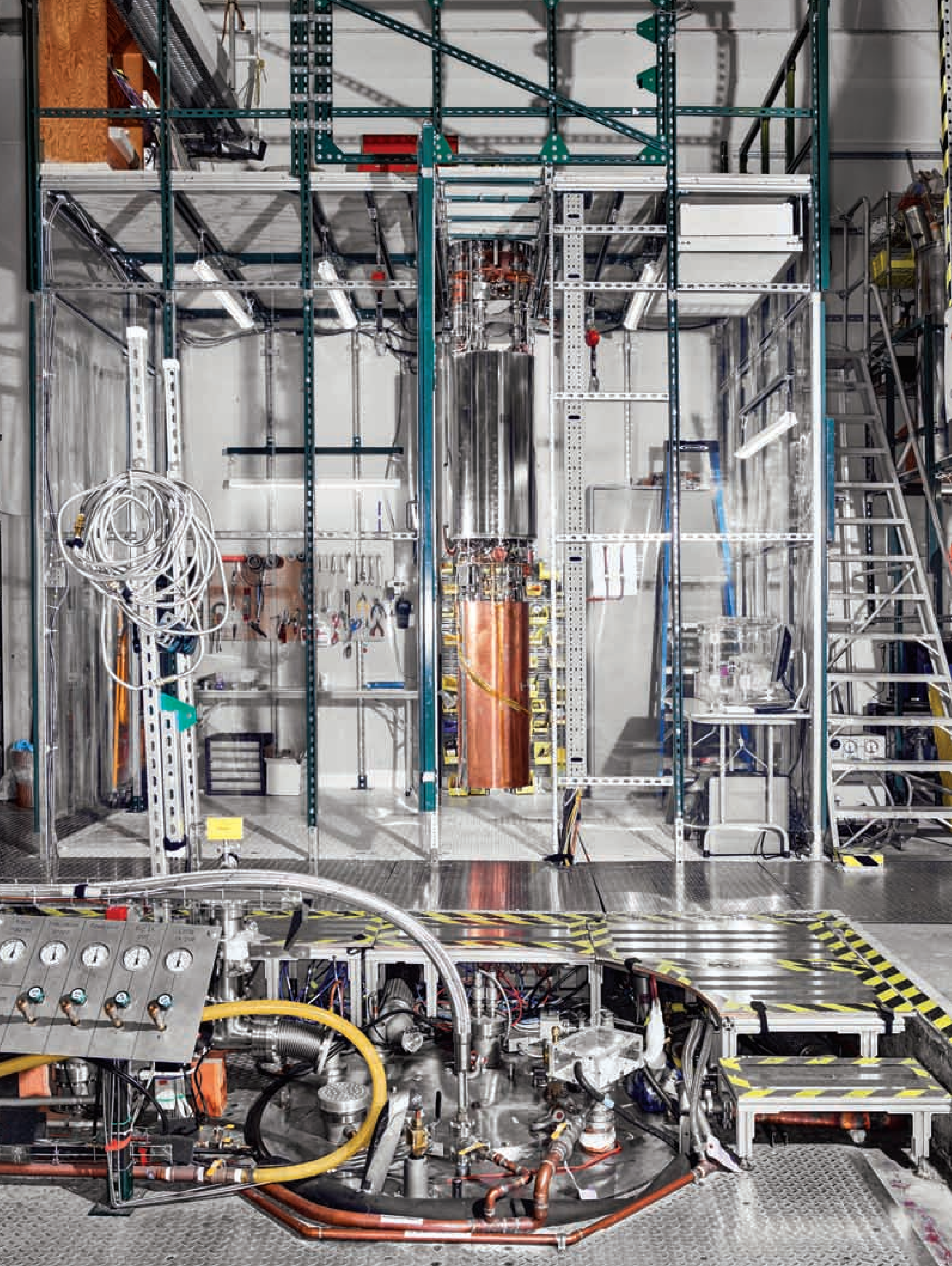


SEARCHING FOR THE DARK

ASTROPHYSICS

The Axion Dark Matter Experiment just entered the most sensitive phase yet in its search for invisible particles to explain the universe's hidden mass

By Leslie Rosenberg

IN THE BACKGROUND, the insert containing the heart of the ADMX experiment sits in a clean room. It will soon be lowered into a hole (*covered in this image*) in the foreground to begin a new run.

Photographs by Ian Allen

Leslie Rosenberg is a professor of physics at the University of Washington. He has been hunting for axion dark matter for more than two decades.

THE COSMOS IS MOSTLY MADE OF SOMETHING WE CANNOT SEE.

That was the conclusion astronomers started to reach in the 1930s by looking at galaxy clusters, which should have blown apart unless some "dark matter" was binding them together. Scientists started taking the idea more seriously in the 1970s, when astronomers studying how fast galaxies rotated found the same thing. Soon researchers realized that dark matter was unlikely to be made up of normal matter and radiation. By now it seems nearly inescapable that more than 90 percent of the stuff in the universe that clumps together under gravity is some exotic material, perhaps a new particle left over from the big bang.

For a long time the most popular dark matter candidate was the theoretical weakly interacting massive particle (WIMP), which fits into the much loved but speculative theory of supersymmetry. Yet sensitive terrestrial WIMP detectors have found no signs of such particles despite decades of searching. It is certainly too early to write off WIMPs, but these null results have raised the profile of non-WIMP dark matter candidates.

A less well-known candidate is the axion, another theorized particle that would weigh much less than the WIMP but would have a similar tendency to ignore normal matter. If axions are dark matter, they would abound everywhere—tens or even hundreds of trillions of them could be floating around in every cubic centimeter around you. Their only effects on the rest of the universe would be felt through gravity—their accumulated mass would be substantial enough to tug on the orbits of stars in galaxies and of galaxies in clusters.

For more than 20 years I have been part of the Axion Dark Matter Experiment (ADMX) search for these particles. Although we have not found them yet, we have been steadily improving our technology. In 2016 ADMX began a new phase. It is now sensitive enough that it should be able to either detect axions or rule out the most plausible versions of them over the next five to 10 years. We stand at an important threshold, and exciting news is coming soon, either way.

THE ORIGIN OF AXIONS

I WAS A GRADUATE STUDENT in the 1980s shortly after the idea of axions first arose from a problem with a theory called quantum chromodynamics (QCD). QCD governs the strong force, which holds together atomic nuclei. It has been remarkably consistent with experiments, except when it comes to something called the strong CP problem. (CP stands for "charge parity.") QCD suggests that if you were to flip a particle's charge parity—that is, flip its electric charge and view it in a mirror—it would no longer follow the same rules of physics. Yet researchers have found no evidence that this is the case. This conflict between theory and experiment presents a serious conundrum—a crack in our best model of particle physics. The crack is the strong CP problem, and it suggests we are missing something big.

In 1977, when physicists Helen Quinn and Roberto Peccei were both at Stanford University, they realized that they could attack the strong CP problem in a simple, elegant way using the idea of broken symmetries. This concept, one of the recurring ideas in physics, goes like this: Sometimes nature is not sym-

IN BRIEF

Scientists are searching for unseen particles to explain the "dark matter" that seems to be exerting a gravitational pull on everything else in the universe.

An underdog candidate is the axion, a theoretical particle that could explain dark matter *and* solve a mystery about the "strong force," which binds atomic nuclei together.

The Axion Dark Matter Experiment recently became sensitive enough to either detect the most plausible versions of axions or rule them out.

metrical when it seems that it should be. For instance, if you stand a pencil on its end, there is a rotational symmetry whereby it is equally likely to fall in any direction. But what if it always falls in one direction? We would say that nature has made a choice and has "broken" the symmetry. When this happens in the context of particle physics, a new particle arises to maintain the underlying symmetry even though it appears, on the surface, to be broken. (The symmetry does not have to be obvious; it can be some abstract symmetry of the underlying mathematics.)

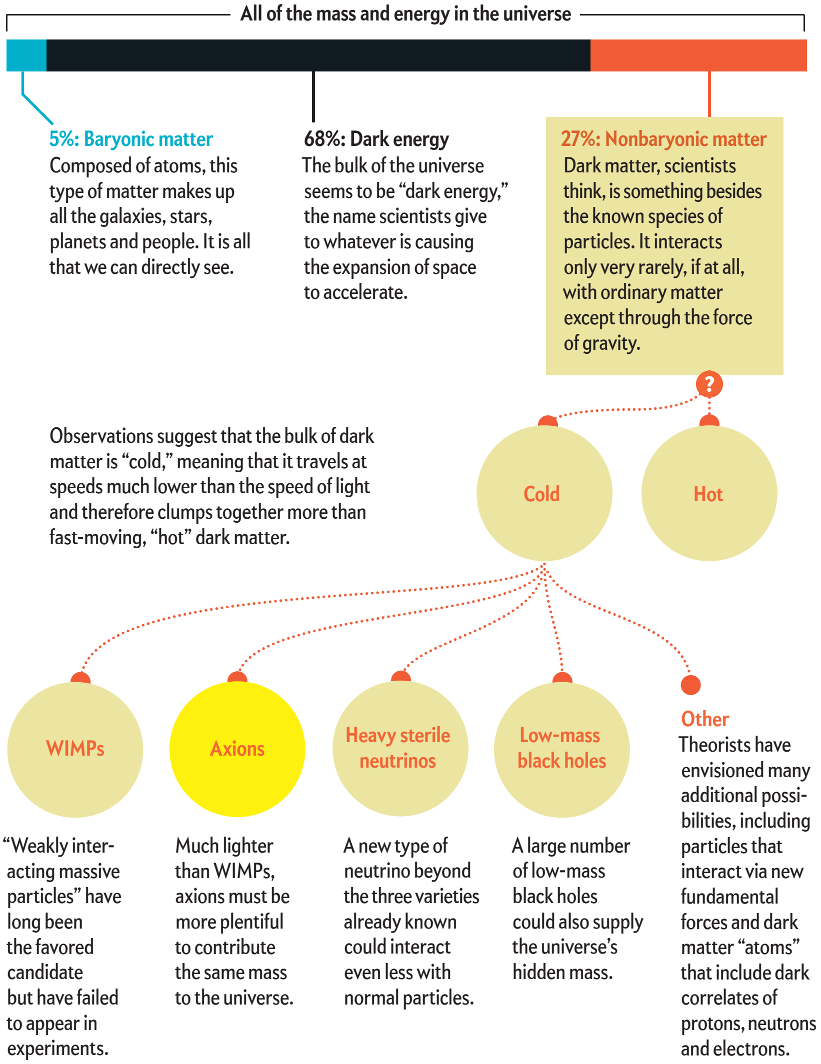
In what I thought was a brilliant insight, Quinn and Peccei applied this idea to the strong force. They speculated that a hidden type of symmetry related to this force has been broken. If this were the case, it would nullify the expected CP difference that theory predicted but that experiments failed to see. Problem solved. Shortly thereafter, in another brilliant insight, Steven Weinberg, now at the University of Texas at Austin, and Frank Wilczek, now at the Massachusetts Institute of Technology, realized this so-called Peccei-Quinn mechanism would result in a new particle: the axion. (Physics folklore says that the name was borrowed from that of a washing detergent because it "cleaned up" the strong CP problem.) By the mid-1980s theorists concluded that the big bang could have produced enough axions to account for dark matter.

The theory did not tell us how heavy axions would be or how likely they would be to interact with normal matter. We knew, though, that they had to be pretty inert because so far particle colliders and other experiments had not seen them. If they were extremely inert, they would also likely be very lightweight. And in 1987 a major cosmic event further limited the possibilities for the axion's mass. At that time a supernova exploded in the Large Magellanic Cloud, a nearby dwarf galaxy. Almost the entire gravitational binding energy of the star that collapsed escaped in the form of neutrinos, some of which made it to underground detectors here on Earth. If axions had a mass of even a few milli electron volts divided by the speed of light squared (meV/c^2) (somewhat more than one billionth the mass of the electron), they would have been produced in the explosion and distorted the escape time of the neutrinos on their way to Earth. Because experiments observed no such distortions, we knew the axions must have a smaller mass. Such light axions have extraordinarily feeble interactions with normal matter and radiation. For instance, a relatively mundane particle called the neutral pion decays into two photons roughly once every 10^{-16} second. A light axion would decay into two photons once every 10^{45} years—and that is many, many orders of magnitude longer than the age of the universe. The axion would be by far the least interactive particle known.

Interestingly, if the axion mass is too small, we have new problems. Because of the intricacies of the process by which we think axions were created near the beginning of the universe, the lower the axion mass, the greater the mass density of axions

Dark Matter Contenders

Something unseen appears to be exerting a gravitational pull on the normal matter in galaxies and clusters throughout the cosmos, but what is it? Scientists have theorized several potential explanations for the "dark matter" they think makes up about a quarter of the total mass and energy in the universe. These possibilities fall into various categories, as outlined.



5%: Baryonic matter
Composed of atoms, this type of matter makes up all the galaxies, stars, planets and people. It is all that we can directly see.

68%: Dark energy
The bulk of the universe seems to be "dark energy," the name scientists give to whatever is causing the expansion of space to accelerate.

27%: Nonbaryonic matter
Dark matter, scientists think, is something besides the known species of particles. It interacts only very rarely, if at all, with ordinary matter except through the force of gravity.

Observations suggest that the bulk of dark matter is "cold," meaning that it travels at speeds much lower than the speed of light and therefore clumps together more than fast-moving, "hot" dark matter.

"Weakly interacting massive particles" have long been the favored candidate but have failed to appear in experiments.

Much lighter than WIMPs, axions must be more plentiful to contribute the same mass to the universe.

A new type of neutrino beyond the three varieties already known could interact even less with normal particles.

A large number of low-mass black holes could also supply the universe's hidden mass.

Other
Theorists have envisioned many additional possibilities, including particles that interact via new fundamental forces and dark matter "atoms" that include dark correlates of protons, neutrons and electrons.

Graphic by Jen Christiansen

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SCIENTISTS attach sensors to the experiment insert (*1*). Above the insert's copper-plated cavity is a liquid-helium reservoir surrounding electronics (*2*).

that results. Should the axion mass be too small, the big bang would have produced way more axions than necessary to account for dark matter. There are substantial uncertainties about this mechanism, and theorists have come up with clever ways to evade the issue, but to me, it becomes increasingly implausible to have axions with masses much below one micro electron volt divided by c^2 (μeV/c^2).

To recap, axions cannot be too heavy, or else we would have seen them already, either through particle colliders or through their effects on the evolution of other stars. Moreover, axions cannot be too light, or else there would be too much dark matter. Determining exactly what these mass limits are is very challenging, but a reasonable range of allowed dark matter axion masses is in the neighborhood of around 1 μeV/c^2 to 1 meV/c^2. This range is the "sweet spot" for the axion mass, but such particles would be so unreactive to normal matter and radiation that they have been dubbed "invisible axions."

SIKIVIE'S GREAT IDEA

WHEN QUINN AND PECCEI first theorized the existence of axions, physicists at Stanford and elsewhere began searching for them in the explosions produced at particle colliders. Yet the very properties that make the axion an attractive dark matter candidate—its feeble interactions with ordinary matter and radiation—made these searches feel hopeless. It was frustrating to know that we may be bathed in a dense sea of particles—about 10 trillion axions or more per cubic centimeter—that are impossible to conjure up in the laboratory.

Then Pierre Sikivie of the University of Florida had a clever idea: rather than trying to create axions in accelerators, we could search for the cosmic axions that make up the vast, pervasive sea of dark matter around us. Sikivie imagined a magnetic field filling a cylindrical cavity that was devoid of everything except, presumably, the cosmic axions that flood all of space. When an axion interacted with the magnetic field, its total energy would be almost completely converted into a photon. This interaction would be much more likely to occur if the cavity was tuned to resonate with the same frequency as the photon produced by the axion. Because axions' mass is very small, and the cosmic ones near us are presumably moving at speeds similar to the rest of the Milky Way, their energy is tiny, so the resulting photon would be somewhere in the microwave frequency range. Exactly where, though, is a mystery until we know the precise axion mass. For this reason, experimenters would need

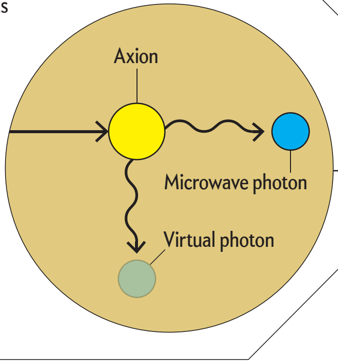
The Hardware

If axions are all around us, the Axion Dark Matter Experiment could find them on the rare occasions that they decay into microwave photons. To make this decay more likely, the experiment has a large magnetic field and a radio-frequency cavity that, if tuned to the same frequency as the photons produced by the axions, should encourage the transformation. In 2016 the project entered a new phase and began its most sensitive search yet.

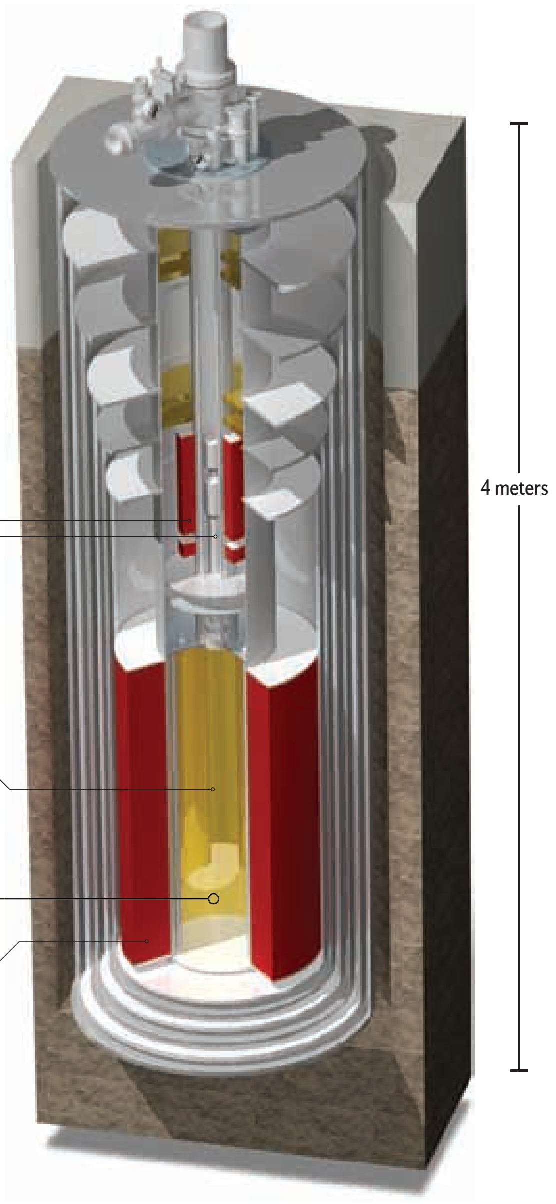
Bucking Magnet
This smaller magnet cancels out, or "bucks," the magnetic field of the main magnet in the vicinity of the SQUID amplifier, which relies on a tiny magnetic field created by the photons to detect a signal.

SQUID Amplifier
This device uses quantum-mechanical effects to detect and amplify the minute signal created when an axion decays into a photon.

Microwave Cavity
The heart of the experiment, this empty cavity is where scientists expect ambient axions, which should be present throughout space if they constitute dark matter, to transform into microwave photons under the right conditions.



8-Tesla Magnet
The main magnet in the experiment fills the cavity with a magnetic field that encourages the axions to decay into photons.



to continually adjust the resonant frequency of the experiment's cavity to "scan" the possible range in hopes of hitting on the right match for the axion.

The resulting signal would be very small, perhaps 10^{-21} watt or less, with accompanying noise of around the same amount. But very sensitive microwave detectors, collecting a signal for a sufficiently long time, should be up to the job. Two of my great loves are radio electronics and particle physics, so in my mind, Sikivie's ideas fit together powerfully.

ADMX IS BORN

I RECEIVED MY PH.D. WHILE AT STANFORD in the 1980s, when the influence of Quinn and Peccei was still there, and axions made a big impression on me. They appeared to solve two huge mysteries in physics—the strong CP problem and the dark matter issue. And after Sikivie's paper, it seemed that there might be a way to detect them.

From Stanford, I moved to the University of Chicago, where I was privileged to work under the late James W. Cronin as an Enrico Fermi Fellow. There I became aware of the first attempts to put Sikivie's idea into practice, including the Rochester-Brookhaven-Fermilab experiment and a project at the University of Florida. Both lacked the sensitivity to detect axions in the plausible mass range, but they developed the basic hardware used by all subsequent experiments.

While in Chicago, I got to talking with Karl van Bibber, then at Lawrence Livermore National Laboratory, and David Tanner of the University of Florida, and we realized that we could improve on these efforts. We could begin by deploying a large cavity volume with a strong magnetic field—that would bring us

Illustration by Don Foley

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EQUIPMENT RACKS house ADMX's room-temperature microwave electronics (*1*). Engineers study sensor data from the experiment (*2*).

partway to the sensitivity we wanted. To go the rest of the way, we knew we would need better microwave amplifiers. They were the key to being able to pick up and boost the extremely weak microwave signal we expected axions to produce—yet the transistor microwave amplifiers available at the time were too noisy by far. We wanted an amplifier that was limited only by the unavoidable noise produced by quantum-mechanical uncertainty, but they did not yet exist in our frequency range.

Thus was the ADMX program conceived: We would start with a large magnet, the best available microwave amplifiers and liquid helium to cool the experiment to 4.2 kelvins to reduce noise. In the intermediate term, we would focus on developing quantum-limited microwave amplifiers. In the long term, we would add a "dilution refrigerator"—a system that would cool the cavity and amplifiers to temperatures around 100 millikelvins, thus reducing noise. It was an ambitious program—each phase would take about a decade. Fortunately, we had the backing of the Department of Energy's High Energy Physics division and a vision to carry us through.

THE EARLY YEARS

IN 1993 I MOVED TO M.I.T. to be an assistant professor, and once I was there, we formed a collaboration to begin the experiment. Lawrence Livermore supplied a large superconducting magnet and the experiment site. The gifted Lawrence Livermore physicist Wolfgang Stoeffl made the initial cryogenic design, and we are still using much of his ingenious system today. Tanner largely conceived and developed the innards of the experiment based on the early University of Florida project, and our group at M.I.T. built an ultralow-noise microwave receiver to pick up the signal. In 1998 we published the initial results from this early ADMX "phase 0"—the first experiment sensitive to plausible dark matter axions. We had not found the elusive particles, but we were off to a good start.

Meanwhile we pushed forward on the quest for an amplifier that would be sensitive to the faint microwave signals we expect axions to produce. Around then, I heard a talk by John Clarke, a brilliant quantum-device physicist at the University of California, Berkeley, on quantum amplification. He had been working on so-called superconducting quantum-interference devices (SQUIDs), which take advantage of the phenomenon of quantum tunneling—the ability of a particle to pass through walls or traverse barriers that a macroscopic object cannot. If a photon arose in the experiment, it would induce a small magnetic field in the SQUID that would disrupt this tunneling in a measurable way. The devices were exquisitely sensitive, but they did not yet exist for use on microwave-frequency signals. For that application, Clarke developed what is called a microstrip DC SQUID amplifier. This gadget has a clever geometry that allows the SQUID to operate at higher frequencies.

The plan was promising, but there were still some issues. The tiny signal magnetic fields of the SQUID would be swamped by the larger field inside the ADMX cavity. The DOE reviewed our plan and flagged the SQUID issue as "high risk." At this point, in early 2002, I moved to Lawrence Livermore, and my collaborators and I decided to divide ADMX into two sequential phases: "phase 1a" would demonstrate that SQUIDs can work in the experiment's large magnetic field. A later "phase 1b" would then add the dilution refrigerator we needed to get the experiment down to the low temperatures we required.

We began phase 1a by developing a system to protect the SQUID's sensitive magnetic field from the huge field of the experiment. We did this with a series of nested shields and magnets surrounding a large magnet called a bucking coil that would cancel out, or "buck," the main magnetic field. By the mid-2000s we had demonstrated that this system works, and we began work on the dilution refrigerator—the major element needed for ADMX's phase 1b.

THE EXPERIMENT GROWS UP

AROUND THIS TIME, I MOVED to the University of Washington, and the ADMX experiment came with me to a new and substantially upgraded site. Meanwhile the DOE and the National Science Foundation were conceptualizing "Generation 2" dark matter detectors meant to be huge improvements on the sensitivity of existing searches. Most of the experiments they had in mind sought WIMPs, but they were also interested in axions. Our ADMX phase 1b plans slotted closely into the Generation 2 program, and ADMX Gen 2 was born. Scheduled to begin operations in 2016 and to run into 2021, ADMX Gen 2 finally adds the dilution refrigerator into our experiment. It also more than doubles our effective data-taking rate. We have added substantial features to improve the experiment's sensitivity, and it can now conduct what we call a "definitive search"—a sweep over a broad range of axion masses, from around 1 to 40 µeV/c^2, that includes the sweet spot for predicted dark matter axions.

ADMX is now sensitive enough that it should be able to either detect axions or rule out the most plausible versions of them over the next five to 10 years.

ADMX has many complicated parts that must all work in concert, but most of its systems are now highly refined and reliable. The collaboration has grown to include Lawrence Livermore, U.C. Berkeley, the University of Florida, the University of Washington, Washington University in St. Louis, Pacific Northwest National Laboratory, Los Alamos National Laboratory, Fermi National Accelerator Laboratory, the National Radio Astronomy Observatory and the University of Sheffield in England. A new ADMX leadership team has emerged, with co-spokespersons Gray Rybka of the University of Washington and Gianpaolo Carosi of Lawrence Livermore.

Although we are now surveying the most likely mass range for dark matter axions, there is always a chance nature could surprise us. Searching in a slightly lower mass range is not hugely difficult, but outfitting our experiment to look for even higher masses is a challenge. As the axion mass increases, the cavity's resonant frequency needs to increase as well, and thus the diameter of the cavity must decrease, thereby reducing the available volume to search for axions. We could pack a large number of cavities inside a single big magnet to maintain a large volume, but doing so becomes a "Swiss watch problem": the complexity of such a system is daunting. We may also be able to live with a small cavity as long as we can increase the strength of the magnetic field to compensate. Such an increase is expensive, but research into this possibility is under way. Perhaps within five to 10 years increased magnetic field strength—to 32 or even 40 tesla—could expand the mass range of our search. At much higher axion masses—those approaching 1 meV/c^2—we may even be able to see a signal from space. If axions exist in this range and form dark matter halos around galaxies, radio telescopes could spot very weak emission lines.

Eventually ADMX and other projects will be able to fully explore the theoretical window of possible dark matter axion masses. The fact that the full plausible mass range is totally accessible to experiments makes axions an attractive candidate for dark matter, compared with some alternatives that we may never be able to test completely.

As our experimental work marches on, theorists are also making progress on trying to understand the nature of dark matter. Sophisticated cosmological models running on supercomputers are working on more reliable predictions of the axion mass. It is also possible, for instance, that axions would clump together throughout the universe in a different pattern than WIMPs would, in ways both subtle and dramatic. Future astrophysical experiments, such as the Large Synoptic Survey Telescope due to begin observations in 2019, may be able to map out the large-scale structure in the universe accurately enough to allow scientists to discriminate among the dark matter candidates.

Another possibility is that the axions predicted by quantum chromodynamics are just a reflection of some greater theory of physics existing on a higher energy scale. One such theory contender, string theory, predicts axions with much smaller masses than those probed by ADMX. String theory, however, is highly speculative, as are its predictions.

Twenty years ago the comfortable consensus was that dark matter is made up of WIMPs. Since then, the appeal of axions has increased. In the not too distant future, we should know whether or not they are the solution to the mystery of the invisible side of the cosmos. SA

MORE TO EXPLORE

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