WANTED: DARK MATTER

It's the most common material in the universe. There's probably some right here on Earth. So why is it so hard to find?

BY MARCIA BARTUSIAK

In Building 904 at Brookhaven National Laboratory on New York's Long Island, a hollow cylinder of copper, 16 inches tall, quietly sits in its liquid helium bath awaiting the passage of an elementary particle that may or may not exist.

Deep within the bowels of the Oroville Dam in northern California, a couple of two-pound chunks of germanium, each surrounded by an array of electronics and special shielding, are also in on the hunt.

Experimenters around the world are panning for celestial gold, hoping to snare the so-called dark matter that astrophysicists insist pervades the cosmos—although they've never seen it. Indeed, the prevailing wisdom states that there is far more of this mysterious stuff than there is ordinary matter. The stars and galaxies we're familiar with evidently tell us as little about the real structure of the universe as a pair of oncoming headlights tell us about the shape of a car.

At first the hunt for dark matter was conducted chiefly through telescopes; even if the dark matter is made up of subatomic particles, as seems likely, there has to be a lot more of it out there than here on Earth. No one really thought laboratory experiments could be sensitive enough to detect the amounts that pass through our planet. But thanks to some major advances in detector technology, more than a dozen groups around the globe are now looking.

Each research team has staked out a different theoretical territory, betting that its own custom-made detectors have the best chance of finding evidence of the invisible universe. "It's like the long shot in a horse race," says Floyd Stecker of the NASA Goddard Space Flight Center in Maryland. "The chances are small, but the payoff will be big, likely a Nobel Prize."

The first glimmer that something was amiss in our understanding of what makes up the universe came in the 1930s. Fritz Zwicky, an eccentric but brilliant Caltech astronomer, noticed that galaxies in clusters were moving around so fast that they should, by rights, not stay in the clusters at all. Since something was clearly keeping them there, he surmised that some extra, hidden mass must be present to supply the gravitational glue. The problem was brought closer to home in the 1970s, when stars at the outside edges of the Milky Way and other spiral galaxies were found to be orbiting faster than theory would predict; individual galaxies, it seemed, also harbored a reservoir of unseen matter whose gravity kept their stars from escaping.

While almost all astronomers agree that the dark matter is real, they can detect it only by its gravitational influence on visible matter. And since everything from protons to planets exerts gravity, dark matter can, in theory, be made of pretty much anything. A number of astronomers are perfectly happy with the idea that it consists of more or less ordinary stuff—a host of faint dwarf stars, perhaps, or dark, Jupiter-like planetoids. But others doubt it.

"For one thing, our theories of how the visible stars formed have a hard time making these other objects," says David Seckel, a particle-physicist-turned-cosmologist at the University of California at Santa Cruz. "Also, from what we know about galaxy formation, it is hard to create a universe filled with galaxies if dark matter is like ordinary matter." Finally, current

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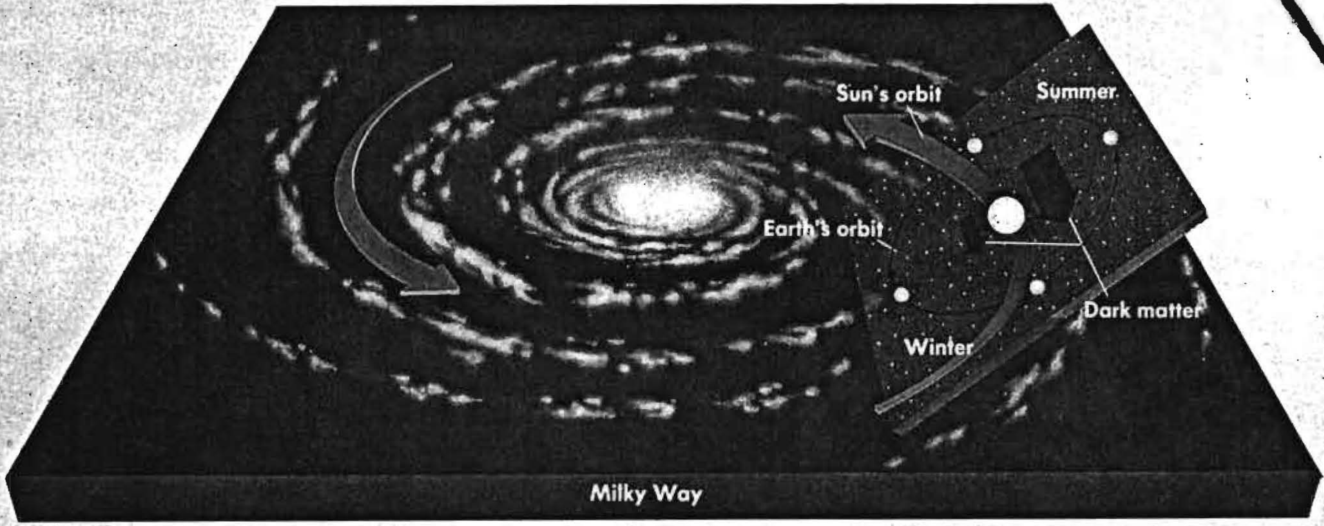


If dark-matter detectors are truly picking up WIMPs, the number detected should be a few percent higher in summer, when the motions of the Earth and sun through the galaxy's cloud of WIMPs are combined, and fewer in winter, when the Earth lags behind.

theories of how matter was formed in the Big Bang also tend to argue against the dark matter being stars or Jupiters. As a result of these and other arguments, many cosmologists have come to believe that dark matter is composed of something more inherently elusive.

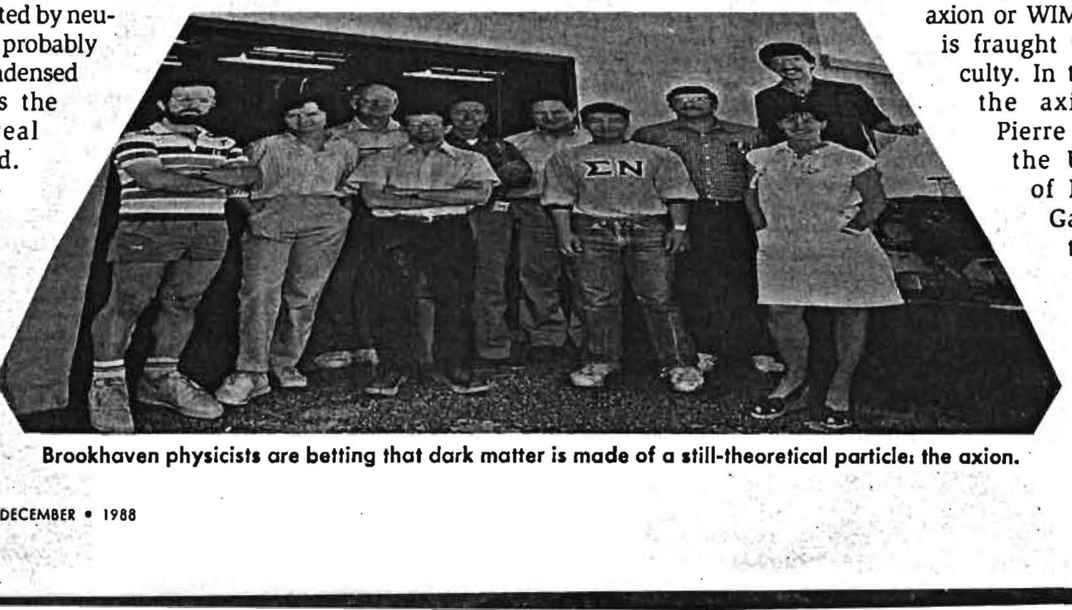
One of the first candidates was the neutrino, a particle that had a number of things going for it. Neutrinos were already known to exist (the Big Bang spewed out hordes of them), and they were unobtrusive: neutrinos could pass through people and planets alike as though they were ghosts. But no one was sure whether neutrinos had any mass at all. And even if they did, computer simulations showed that a universe dominated by neutrinos would probably not have condensed into galaxies the way the real universe did. That discovery quickly took neutrinos out of the running.

But neutrinos were just the first in a long line of suspects. Theoretical physicists are forever coming up with brand-new particles that should exist if their theories are to make any sense. And if these particles really do exist, they might be ideal for explaining dark matter. For instance, to explain the workings of the strong nuclear force (which keeps atomic nuclei from flying apart), physicists have predicted the existence of the axion, a particle whimsically named after a laundry detergent. Perhaps more than a trillion times lighter than an electron, the axion is so insubstantial that trillions could be stuffed into every cubic inch of space around us and we'd never notice.

There are also a number of particles that pop up in the equations of theorists trying to unify nature's various forces. In their schemes, every known or predicted particle in the universe should have a "supersymmetric" partner. The Z particle, for example, should have its zino, the W particle its wino, the photon its photino, and the quarks their squarks. Collectively these have come to be known as WIMPs, or weakly interacting massive particles. Each would be roughly as heavy as ten or more protons, yet still, like the featherweight axion, be terribly indifferent to ordinary matter.

WIMPs are popular with physicists because, says Seckel, they "kill the most birds." Not only does one variety explain dark matter very nicely and fill in the spaces in supersymmetry theories, but another also helps solar physicists explain why the sun is putting out fewer neutrinos than theory predicts. WIMPs falling into the sun's core would cool it, thereby damping neutrino production. Moreover, a universe dominated by WIMPs might generate just enough gravity to balance the force of its expansion, keeping the cosmos from either expanding forever or collapsing—a balance cosmologists believe should exist, for both scientific and aesthetic reasons.

Trying to corner an axion or WIMP, though, is fraught with difficulty. In the case of the axion, says Pierre Sikivie of the University of Florida at Gainesville, the notion that one



Brookhaven physicists are betting that dark matter is made of a still-theoretical particle: the axion.

ILLUSTRATION BY GEORGE RETSECK; PHOTOGRAPH COURTESY BROOKHAVEN NATIONAL LABORATORY

The sun should have captured a bellyful of WIMPs in the course of its 5 billion years.

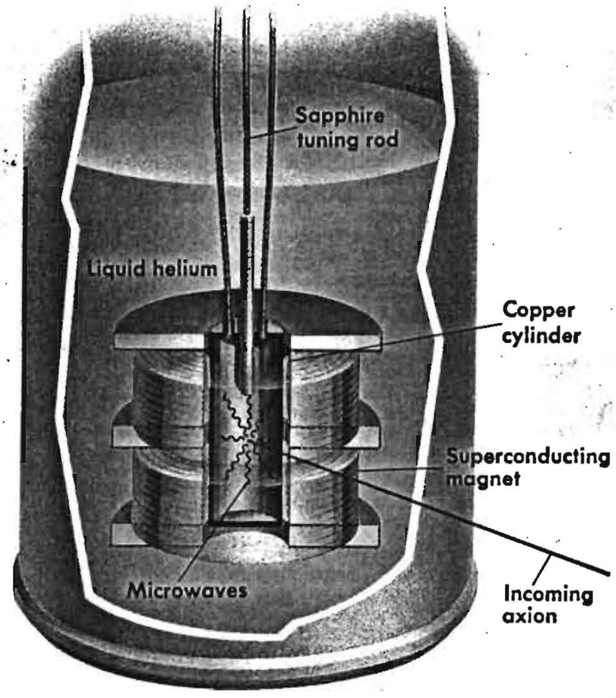
couldn't be snared was not unreasonable. The particle, if it exists, could whiz through a series of steel bank vaults lined up from here to Pluto and not bump into one atom. How could one possibly catch such a will-o'-the-wisp?

Five years ago Sikivie arrived at an imaginative solution. While teaching a course on electromagnetism, it occurred to him that if an axion passed through an intense magnetic field (roughly 200,000 times that of Earth), it should decay and emit microwaves at a specific frequency. Inspired by Sikivie's insight, a team of physicists at Brookhaven built an axion detector consisting of a copper cylinder surrounded by a superconducting magnet. The cylinder is just the right size so that it will resonate at microwave frequencies, as an organ pipe resonates at a given frequency when filled with air. If an axion passes through the cylinder, the magnet should make it decay; the resulting burst of microwaves would produce hardly more than a trillionth of a trillionth of a watt of power, but it should make the cylinder resonate enough to be detected.

After two years of searching, the Brookhaven researchers have yet to see a signal, but that's not too surprising. The resonant frequency depends on the axion's exact mass, which is not yet known. "It's as if we're looking for a specific station on a radio that has five million channels," says Bruce Moskowitz of the University of Rochester, a collaborator on the project. The work goes on: Moskowitz and his colleagues are scanning the frequencies from 1 to 6 gigahertz, using copper cylinders of different sizes and repositioning a sapphire rod in each to subtly adjust the frequency.

Dark-matter detection in the laboratory is tricky in more than just technical ways; funding is scarce, and researchers may spend years developing an instrument that could become obsolete with a change in theory. Thus, some dark-matter detectors have other roles as well. Two research groups, looking for a rare radioactive process known as double-beta decay, came to realize that their germanium detectors—set deep underground to avoid interference from cosmic rays—could also hunt for certain types of WIMP. One experiment was situated in a gold mine nearly a mile beneath the Black Hills of South Dakota; the other is still operating hundreds of feet below California's Oroville Dam.

The search hinges on the idea that if there are enough WIMPs passing through a detector, one should occasionally hit a germanium nucleus dead on. Because the WIMP would be moving at some 200 miles a second, the nucleus would recoil violently, generating a stream of detectable electrons. Such detectors aren't very sensitive, but they have already firmly ruled out certain "heavy" neutrinos as dark-matter candidates; if they were numerous enough to serve as dark matter, these particles should have been recorded hundreds of times a day. The investigators saw nothing.



A passing axion will decay into microwaves in an intense magnetic field, setting a copper cylinder vibrating perceptibly.

Bernard Sadoulet of the University of California at Berkeley, a participant in the Oroville experiment, sees these first attempts as a vital training exercise for the next generation of dark-matter detectors. One of the ideas Sadoulet and his colleagues are now considering involves a pure-crystalline detector made of germanium, boron, or silicon that would attempt to spot the heat a WIMP generates when it bangs into an atomic nucleus. After such a collision, a set of phonons, or sound waves, would ripple through the crystal and just slightly raise its temperature. The difficulty is in developing a sensor sensitive enough to measure a rise in temperature as small as a millionth of a degree.

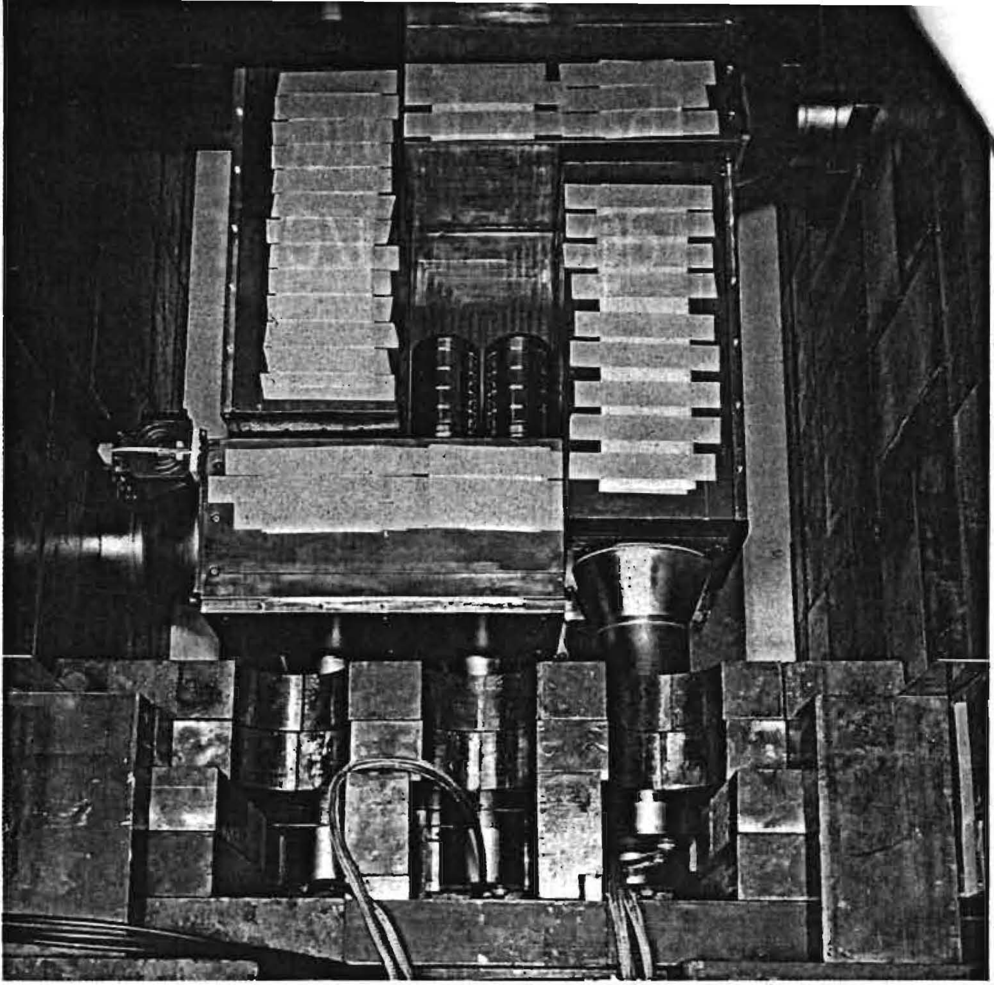
That is best accomplished by cooling the instrument to within twenty thousandths of a degree above absolute zero, a severe experimental challenge. The Berkeley group hopes to have a prototype, weighing a few grams, constructed within a year; a full-scale detector, weighing 1,000 grams, may take several years.

Other research teams are working on variations of this scheme, and each variation is advancing the current limits of technology in low-temperature physics. At Stanford, for instance, Blas Cabrera's group hopes to mount a series of thin superconducting films around a crystal in order to map the phonons as they strike the crystal's surfaces. The pattern of energy should, in theory, identify the characteristic signature of a WIMP more accurately than a simple temperature jump could.

Researchers in France, Germany, and the United States, including Andrzaj Drukier of the Applied Research Corporation in Maryland and several collaborators, have taken a com-

ILLUSTRATION BY GEORGE RETSECK

pletely different approach. They are designing boxes containing billions of microscopic grains of superconducting metal, each no bigger than a bacterium, suspended in a nonconducting material. "My philosophy," says Drukier, "is that small is beautiful." He proposes to sight a WIMP when it hits one of the grains; the resulting heat would flip the metal granule from a superconducting state to a normal state. The key to this task is the development of electronics that can distinguish the change of state in just one grain.



Top view of the Oroville Dam WIMP detector shows germanium at center, surrounded by shielding.

PHOTOGRAPH COURTESY LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA

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Having a variety of instruments is vital to this enterprise since different materials and techniques favor different types of WIMP; the greater the assortment, the better the chances that the true dark-matter particle, if it exists, will be detected. "One has to be clever to distinguish a WIMP signal from the background," notes Brown University physicist Robert Lanou. Cosmic rays could mimic a WIMP, but this can be avoided by going deep underground. More worrisome are electronic noises and the natural radioactivity of the detector and shielding materials themselves. The scientists involved in the South Dakota experiment went so far as to shield their ionization detector with 450-year-old lead from a sunken Spanish galleon. They reasoned that any residual radioactivity caused by cosmic rays would have disappeared after centuries in deep water, and that radioactive fallout from nuclear blasts could not have penetrated deep into the sea.

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In his search for purity, Lanou has envisioned a detector that makes use of liquid helium. "Helium is clean, quiet, simple, and inexpensive, about five dollars per liter," he says. And at temperatures near absolute zero every possible contaminant freezes out while helium, which has no natural radioactive isotopes that could cause a disruption, remains liquid. Twenty liters of helium could conceivably register up to 100 events a day—that is, if the WIMPs are cooperative and other, spurious signals can be suppressed.

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If a signal is indeed found, physicists have a clever way of checking whether it is real. Imagine the dark-matter WIMPs hovering around and through the Milky Way like a tenuous fog. The solar system would be moving through this dark-matter mist as the sun orbits around the center of our galaxy. In summertime Earth's motion in its orbit parallels the sun's motion through the Milky Way; thus, it would pass through the sea of WIMPs a bit faster. "Like a car speeding through the rain and picking up more raindrops on its windshield, Earth would pick up a few more WIMPs," explains Andy Gould of the Stanford Linear Accelerator Center in California. In winter, on the other hand, there would be fewer WIMPS than average. A genuine WIMP signal should therefore rise and fall by several percent over a year's time. It's a tiny effect, admits Gould, but a potentially observable one.

Others are not so sure. UCLA physicist David Cline believes observation of dark matter in the laboratory is likely to fail; the signal is just too faint. But there are a number of other ways that WIMPs might give themselves away. If our entire galaxy is truly submerged in a halo of WIMPs, the sun should have captured a bellyful over the course of its 5 billion years. Earth, too, could be pooling WIMPs in its core. If so, some of these WIMPs could annihilate, emitting neutrinos much more energetic than those emitted by normal stellar processes.

Several underground experiments originally designed to learn whether protons decay are already on the lookout for this WIMP-related signal. A better view will come with the next generation of neutrino detectors now being proposed, such as a vast array of phototubes strung for hundreds of feet under a deep lake, with the high-energy neutrinos being spotted by the special light they emit as they speed through the water.

WIMPs should also be annihilating in the Milky Way's dark-matter halo,

> **"It's as if we're looking for a station on a radio that has five million channels."**

sending out gamma rays and antiprotons, and both should be detectable. But finding them could prove even more difficult than finding WIMPs in the lab. Space-based detectors could help, but they won't be launched for years, if ever.

Some physicists don't like the idea of passive detectors at all. They'd rather create WIMPs in powerful particle accelerators. "The results could blast this whole business out of the water," says Cline. For supersymmetric particles, says Kim Griest of the University of Chicago, the smoking gun would be a sort of hole in the accelerator debris, an indication that some unknown particle is taking energy away in the collision. Intensive searches are already under way at CERN in Europe and Fermilab in Illinois.

"Finding just one supersymmetric particle," explains Griest, "would probably mean that they all are there," and the lightest and most stable of these particles, something like a photino or Higgsino, would be an excellent candidate for dark matter. But if the accelerators don't reveal the presence of a squark or slepton soon, it may call into question whether a WIMP of any kind can be the dark matter. Meanwhile, at Brookhaven, researchers are about to try their own dark-matter creation scheme, making axions by sending a laser beam through a powerful magnetic field.

"Of course, the dark matter could be something no one has thought of," says Griest. A variety of odd candidates abound, such as "boson stars," "quark nuggets," and "shadow matter." One perpetual contender is the magnetic monopole, a still-theoretical particle that carries just a north or a south magnetic charge, but not both. "Monopoles are now out of fashion," notes Indiana University astronomer Stuart Mufson, "but detecting just one could change all that." A large collaboration of Italian and American scientists will soon take a look with the new Monopole, Astrophysics, and Cosmic-Ray Observatory located under the Gran Sasso mountain in Italy.

No matter which of the dark-matter detectors proves successful, "people would be overjoyed by just one event," says Gould. The occasion would be as momentous as the discovery in 1965 of the universe's microwave background, the fossil echo of the Big Bang itself. "We're talking of a new Copernican revolution," says Drukier. And if such a discovery were to happen tomorrow? "I'd retire," says David Seckel with a laugh. "I'd retire." ☐

Marcia Bartusiak wrote about the Milky Way in September.