Searching for Dark Matter Axions

by LESLIE J ROSENBERG & KARL A. VAN BIBBER

The search is on for one of the dark matter candidates so eagerly sought by astrophysicists—a conjectured relic particle from the time of the Big Bang called the axion.

HUBBLE'S DISCOVERY IN THE 1920S of the uniform outward expansion of the Universe raises the profound question of its ultimate fate. Averaged over the whole Universe,* a matter density equivalent to a mere thousand or so hydrogen atoms in the volume of your room would provide just enough gravitational attraction to eventually arrest its outward expansion, which we call the "critical density." When we tally up the mass of the Universe by what we can see—stars, galaxies, gas clouds—we find this visible matter accounts for less than one percent of critical density. Nevertheless, in the past few decades astronomers and astrophysicists have found compelling evidence for the existence of "dark matter" which seems to total to about critical density. More intriguing still is that the bulk of it is not likely to be ordinary stuff such as hydrogen or heavier atoms, but rather relic particles from the time of the Big Bang. The most etherial of the usual suspects is an extremely light particle called the "axion," whose interactions with anything are so vanishly small that—in spite of accounting for 90 percent of the mass of the Universe—it has evaded

**A comment concerning nomenclature. An under-dense universe would expand forever with a finite expansion rate; it is termed an "open universe." If the density of the universe were to be too high, it would eventually stop expanding and then begin contracting towards the "Big Crunch." This is called an "over closed universe." The twilight case of exactly the right density would lead to an "exactly closed universe" or just a "closed universe"; here the universe asymptotically approaches zero outward expansion, but never turns around. Refer to previous articles in this issue by Alan Guth and the Goldhabers for more detailed explanations.*

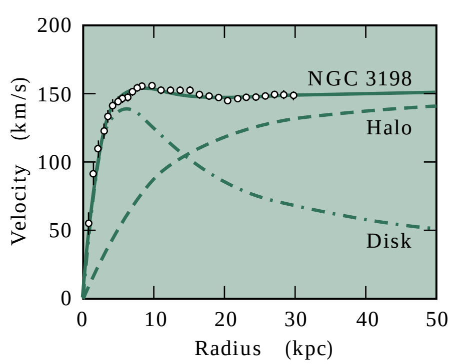
Roberto Peccei

being discovered or discarded since it was predicted to exist by particle physicists twenty years ago. But an experiment now underway at Lawrence Livermore National Laboratory (LLNL) may finally be able to tickle the axion into decaying inside our apparatus. Or then again, as so often before, it may have the last laugh.

FIRST, WHY DO WE BELIEVE in the dark matter? Much of the now overwhelming evidence in gravitationally bound astronomical systems is dynamical—for example the rotation curves of spiral galaxies, including our own Milky Way galaxy. Basically, just as the speed of rotation of the earth about the sun measures the mass of the sun, the tangential velocity of a star in the disk of a spiral galaxy determines the total mass interior to its orbit. In the case of the planets of our solar system, the further one goes out, the weaker is the force exerted by our sun, and therefore the orbital velocities of the planets go down roughly like the inverse square root of the mean orbit radius. (Pluto's year is roughly 250 of ours, not only because its radius and therefore circumference is 40 times larger than ours, but because it is traveling $40^{1/2}$ or approximately six times slower than we are.) Naively one would expect that for the stars or gas clouds further and further out from the center of a spiral galaxy to see the same behavior. But there's the rub—in every spiral galaxy we have seen, the rotation curve (velocity versus radius) is flat as far out as there is light or radio signals to look at (see the illustration on the right). The flatness of the rotation curve bespeaks a total galactic mass many times greater than the visible mass, and there are no indications that the dark matter "halo" may not extend much further beyond the visible spiral.

From this dynamical weighing of spiral galaxies, one would infer a density of the Universe now several percent of closure density. Estimates from rich clusters of galaxies move the number up 10 to 30 percent, and systematic residuals from the smooth outward Hubble flow on huge distance scales are consistent with numbers like 40 to 200 percent of closure density. Other ways of determining the total mass of the Universe are more or less consistent with this picture.

Rotation curve of the galaxy NGC 3198. Beyond 10 kiloparsec or so (approximately 30,000 light years), where the rotation curve should have begun to exhibit a $1/\sqrt{r}$ falloff, the rotation velocity hangs up at 150 km/sec.



Couldn't the missing mass simply be dark baryons—that is, ordinary nucleons and nuclei? Some, yes, but hardly all. A powerful limit on the total baryonic contribution to the mass of the Universe is provided by primordial nucleosynthesis—the formation of the light elements up through lithium, in the first few minutes after the Big Bang. The predicted abundances of deuterium, helium-4, and lithium-7 are each sensitive to the baryon-to-photon ratio in the early Universe. Consistency with our best observational abundances is only obtained within a narrow range of baryon-to-photon ratio corresponding to 2–8 percent of closure density. This constraint on the fraction of ordinary matter to less than 10 percent of closure density, in a universe that is at least 20 percent closed, is *prima facie* evidence for non-baryonic dark matter—relic particles from the Big Bang.*

Helen Quinn

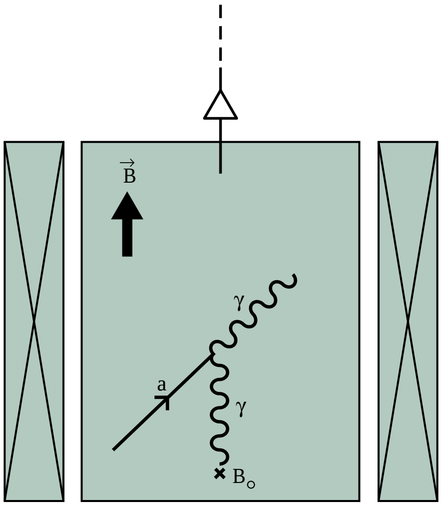
WHAT CONSTITUTES the dark matter of the Universe, and by implication the dark matter of our own halo is one of the premier questions in all of science today. As just mentioned, the baryonic contribution to the mass density is expected to be only a few percent, more than what is presently observed, mind you, but significantly less than the lower bound on the total mass density. Particle dark matter candidates fall into one or two camps. Namely they are categorized either as cold dark matter (CDM), that is, any particle relic which is slow-moving when it decouples from thermodynamic equilibrium in the early Universe, or massive neutrinos, which are relativistic at decoupling.

The distinction is more than just formal. Neutrinos must be considered a good candidate for at least some of the dark matter—after all we know they exist—and that they would have some small non-zero mass is certainly plausible. On the other hand, they are not likely to be dominant; too many swift neutrinos would have erased the structure formation we know grew into galaxies in the first few billion years. Also, the fermion spin statistics of the neutrino limits how many can be packed into confined volumes such as galactic gravitational potentials, and therefore neutrinos cannot constitute any significant fraction of our halo. The dominant term, rarely disputed any longer, must be cold dark matter (see the first article in this issue, "Inner Space & Outer Space" by Michael Turner). There are two leading candidates for CDM, one being a stable, weakly-interacting massive particle or WIMP, perhaps 10 or 100 billion electron volts in mass (10–100 GeV), arising from supersymmetric theories. The other is the axion.

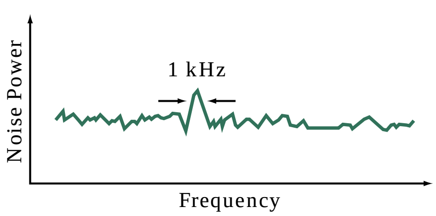
A last remaining blemish in the theory of the strong interactions is the unexpected conservation of a particular symmetry of Nature. This symmetry, called CP, designates how the world looks after the product operation of charge conjugation (changing particles into their antiparticles) and parity (spatial reflection). The evidence of the conservation of strong-CP is the absence of any measurable electric dipole moment of the neutron, whose best upper limit is now eleven orders of magnitude (one hundred billion times) smaller than the value one would expect from the Standard Model.

ALMOST TWENTY YEARS ago, Roberto Peccei and Helen Quinn at Stanford Linear Accelerator Center proposed a minimal and elegant extension of the Standard Model that did just the trick of suppressing strong CP violation in a natural way. Hot on the heels of their paper, Steven Weinberg and Frank Wilczek independently pointed out that if the Peccei-Quinn picture was in fact correct, there would be a smoking gun—a neutral spin-zero particle they termed the axion, that one could think of as a very light cousin of the neutral pion π^0. (A clear if somewhat fanciful discussion of exactly how the axion arises in particle physics is found in Pierre Sikivie's article "The Pool-Table Analogy to Axion Physics," *Physics Today*, December 1996.) The original model suggested a relatively heavy axion, a few hundred keV in mass, with couplings to matter strong enough to permit a host of searches in conventional nuclear and particle physics experiments. These searches found no such axion. Characteristically, the theorists quickly realized how to construct axion models with arbitrarily small mass and couplings, thus beating a hasty retreat from the encroaching experimentalists.

**The lower bound from primordial nucleosynthesis, 0.02, is well above the visible mass of the Universe, 0.005. Thus dark baryons must exist. The recently discovered MACHOs, observed through gravitational microlensing, are excellent candidates for such a baryonic component.*



The Feynman diagram above shows the conversion of a dark matter axion into a single real monochromatic photon in the presence of an external electromagnetic potential.



Hypothetical power spectrum showing what the axion signal would look like sitting on top of the black body plus electronic noise background.

But the most ironic feature implied by the theory of the axion was that the smaller the mass of the axion itself, the greater the fraction of the mass of the whole Universe the axion sea would comprise. As the couplings of the axion to anything (leptons, quarks, photons) are proportional to the axion mass, a daunting paradox arose. An axion of mass in the range of approximately 1 microelectron volt (1 μeV) would be an ideal dark matter candidate to close the Universe exactly, but possess couplings so vanishingly small as to be virtually undetectable.

In fact, had the Universe been overclosed by even a miniscule fraction in the earliest moments after the Big Bang, we would have already recollapsed and not been here to tell the story. That's why we believe that a value of approximately 1 μeV represents a fairly secure lower bound to the axion mass. An upper limit of 1 meV results from the fact that too much axion radiation from the core-collapse of supernova 1987a would have dramatically altered the neutrino burst that was observed by the Kamiokande and IMB experiments ten years ago. There are some dodges on both the high and low mass end of the presently allowed mass window for the axion, but the unaltered conclusion is that lighter values of the axion mass are likely to be more cosmologically significant, and that's where you want to begin looking.

If the axion is like the π^0, it can decay into two photons, $a \rightarrow 2\gamma$. So if it's the dark matter, why not just point a radio telescope towards the halo around a galaxy, and look for a monochromatic emission line not corresponding to a known source? In principle yes, but there's the gotcha. Both the extreme lightness and weakness of its coupling to radiation conspire to make the axion so irrelevantly long-lived as to be essentially a stable particle. (Overall the lifetime goes like the inverse-fifth power of the mass, so over the allowed range the lifetime goes from $10^{(38-53)}$ seconds.) The conundrum was beautifully solved by Pierre Sikivie in 1983, who realized that the axion could be stimulated to decay into a single real photon in the presence of a magnetic field, which represents a sea of virtual photons. To detect dark matter axions, he proposed an experiment consisting of three basic components (see top figure on the left): a high-Q tunable microwave cavity, permeated by a strong magnetic field, whose radio frequency power spectrum is measured by state-of-the-art ultra-low noise microwave amplifiers. The experiment is nothing more than a very sensitive radio receiver! The microwave cavity is slowly tuned, and the axion will show up as a narrow line in the spectrum when the frequency (times Planck's constant) equals the axion mass (times the speed of light squared). The line will be very slightly broadened by the average velocity of the axions in the halo; the fractional width of the sought-for-peak should not be more than about 10^{-6} (bottom figure). One should think of the local population of axions as a cold Bose gas of prodigious density (trillions in each sugar-cube volume) and with a very large quantum wavelength (10–100 meters).*

Simple enough, but there is some fine print. The first problem is that the expected axion signal is exceedingly small. Even in the present large-

Design of the present experiment. The superconducting magnet has a clear-bore diameter of 60 centimeters, a length of 1 meter, and a maximum field of 8 tesla. The coil itself weighs 6 tons, and the entire experiment 12 tons.

scale experiment, the axion signal is optimistically 10^{-22} watts. Compare this with the signals received on earth from the 4-watt transmitter aboard the Voyager spacecraft at the periphery of our solar system—a whopping 10^{-17} watts. And secondly—unlike the axion—in the case of the Voyager, you obviously knew where to look in frequency!

Undaunted, two small pilot experiments ran in the late 1980s, one a Rochester-Brookhaven National Laboratory-Fermi National Accelerator Laboratory collaboration sited at Brookhaven, and one at the University of Florida. Both were proof-of-principle efforts to validate the technology and strategy of the microwave cavity experiment. Not surprisingly, no axion was found by either, as they lacked power sensitivity by two to three orders of magnitude than required even for the more optimistic axion-photon couplings. But plenty was learned, and in 1989 a collaboration drawing on the expertise and personnel from both experiments was formed to explore launching a full-scale experiment capable of realizing cosmological sensitivity. The collaboration presently consists of Lawrence Livermore National Laboratory, Massachusetts Institute of Technology, University of Florida, Lawrence Berkeley National Laboratory, Fermilab, and Institute of Nuclear Research, Moscow.

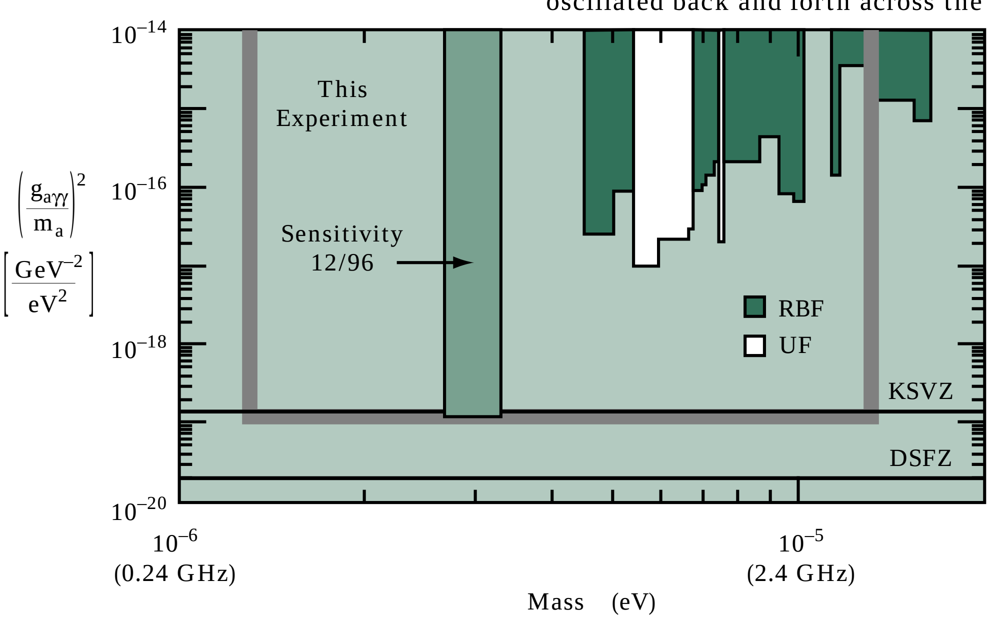
*This density may seem at variance with the much smaller value at the beginning of the article. It should be remembered that galaxies are very special places, representing deep gravitational potentials formed precisely by the accumulation of cold dark matter.

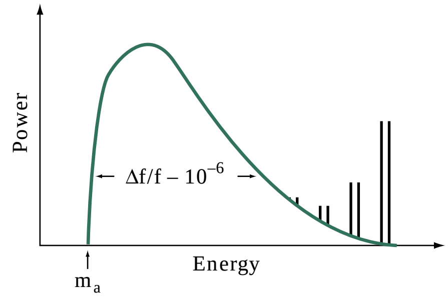
THE PHILOSOPHY of the present full-scale experiment was to close the gap on two fronts. The first was an increase in scale, as the power conversion goes like the total magnetic field energy, or B^2V. Whereas the first-generation experiments had the sensitive volume of a small coffee can, the present experiment has microwave cavities the size of an oil drum (see the drawing on the right). The second prong of the attack was to stay on top of the steady improvements in very low-noise HEMT microwave amplifiers. (HEMTs—High Electron Mobility Transistors—are exotic semiconductor structures originally developed heavily for military communications; they have become workhorses of radioastronomers.) The latest HEMT microwave amplifiers have noise temperatures below 2 kelvin.

The magnet cryostat being installed at Lawrence Livermore National Laboratory in spring 1995.

Top: The cryogenic tower and microwave cavity being assembled by Livermore physicist Chris Hagmann.

Bottom: The mass-coupling constant plane. Indicated are regions excluded by the first-generation experiments and the region already covered by the present experiment but still being analyzed. KSVZ and DFSZ indicate two very different axion models, but whose axion-photon coupling imply signal power differing by less than an order of magnitude.





Possible ultra-fine phase-space structure of the axion spectrum.

There is one additional feature of the new experiment worth commenting on, namely a parallel data stream which searches for extremely narrow structures, motivated by recent theoretical work on the phase space structure of cold dark matter. Sikivie and co-workers recently have proposed that as cold dark matter is dissipationless, that is, cannot transfer energy with its environment except by long-range gravitational interactions, axions falling into the gravitational potential of our galaxy will not quickly get "stirred up" into a thermal distribution. Their simulations of galactic evolution suggest rather that the spectrum of axions seen at the earth would consist of a series of sharp lines, the highest energy of which represents the last-infall component, and the lower-lying lines resulting from earlier-infall axions which have already oscillated back and forth across the galaxy one or more times, as the potential deepened (see figure on the left). Numerically, the last-infall lines could be several percent of the total axion signal. That much signal in such a narrow peak would represent a large gain in the signal-to-noise capability of the experiment, and needless to say, its discovery would contain a wealth of information about our galactic history!

The experiment was commissioned in November 1995, and data-production running began in early February 1996. The experiment has operated remarkably smoothly, the duty factor being nearly 100 percent. The experimental power sensitivity is demonstrably below the KSVZ limit (see illustration below). Note that KSVZ is not a radio station but one of two prototypical axion models named after its proponents. The other model, indicated as DFSZ (also named for its proponents), is somewhat more generic and is regarded as the goal for a definitive axion search. (Of course, the collaboration's point of view is that the definitive search is one that actually finds the axion!) The aim of the present effort is to cover the lowest decade in the next three years at or below the KSVZ limit. A future upgrade of the experiment may utilize Superconducting Quantum Interference Devices, or SQUIDs, with noise temperatures around 300 mK. This reduction in noise temperature would give us the required sensitivity to reach the DFSZ limit.

The particle astrophysics approach complements accelerator-based research on the most fundamental problems in physics and cosmology. It is not unrealistic to expect that between new initiatives in astronomy and particle dark matter searches such as this one, we will have within a decade an accurate understanding of the mass budget of the Universe. And if axions prove to be the right "dark horse" to have bet on, a half-century long puzzle in the Standard Model will have also have finally been put to rest.