Hunting for WIMP

by ANTHONY L. SPADAFORA

SINCE THE DAWN of the Copernican revolution some four hundred and fifty years ago, modern science has progressively shown that our Earth does not occupy a privileged location at the center of the Universe. We orbit a rather ordinary star that, along with hundreds of billions of other stars, is a member of a spiral galaxy, of which there are likewise billions of others. Current work in cosmology proposes yet a further step in this revolution: we, and the known world around us, are not even made of the form of matter that comprises the bulk of the Universe! This bold hypothesis – that there is a vast amount of dark matter in the form of a flux of a new type of elementary particle—is now being put to the test in a number of deep underground laboratories.

For over 70 years, it has been realized that astronomical observations indicate that perhaps as much as 90 percent of the mass of the Universe is dark (does not emit or absorb light or other forms of electromagnetic radiation), but makes its presence known only by its gravitational effects. A number of different approaches to understanding the nature and the amount of dark matter are currently being pursued, and this has become a very active area of research. While much progress has been made in the past few years, we are clearly facing a challenging problem as we know neither the kind nor the amount of the matter we are looking for. Yet, clever experimental techniques have been devised and with their improved sensitivities and progressively longer running periods are starting to elucidate the problem.

DETERMINING THE AVERAGE DENSITY of matter in the Universe is a main effort in contemporary observational cosmology. Knowing how much matter exists is essential if we are to understand how galaxies and their marvelous large scale pattern of clusters formed. The mass density is also a key parameter in

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understanding how the Universe as a whole evolved and what its ultimate fate will be—continued expansion or a collapse in a "Big Crunch."

Since the 1930s, astronomers have been faced with the dark matter conundrum: the matter we see—stars, gas, dust—can only account for a tiny percent of what we believe to be the total mass of the Universe. The average density of matter is now thought to be dominated by some other, invisible component. One approach to this problem is to search for astrophysical objects that fail to radiate light (see the article by Kim Griest on page 8). However, through the modern particle physics-cosmology connection, they do not appear to explain the bulk of dark matter, and some other form of matter is needed.

Theorists believe they understand very well how the hydrogen and helium that comprise over 99 percent of the atoms of the stars we see were formed in the Big Bang. They can predict with considerable accuracy how much deuterium (a rare isotope of hydrogen) should also have been formed. Combining theory with recent precise measurements of this cosmic deuterium abundance, cosmologists can put tight constraints on how much of the dark matter can be made of ordinary matter (that is, made of quarks and leptons). These constraints lead us to the startling conclusion that most dark matter must be made of some yet undiscovered type of elementary particle.

Theorists, ever imaginative, have proposed many possible candidates for this new form of dark matter, the so-called "non-baryonic" component. One of the leading ideas is that it is in the form of WIMPs, or Weakly Interacting Massive Particles. These are neutral particles, roughly about a hundred times more massive than a proton, that interact only very weakly with ordinary matter. They were produced in the Big Bang, and as the Universe expanded their density decreased to a low level. They are left as a relic flux throughout

space and are thought to have accreted to form the dark "halos" of galaxies such as our own Milky Way.

When particle theorists were asked what kind of elementary particle a WIMP could be, they were quick to realize that the hypothetical "neutralino" fits the bill. These are neutral superpartners of Standard Model particles predicted by supersymmetry, the leading extension to the Standard Model (see the article by Michael Dine in the Winter 1999 issue of the *Beam Line*, Vol. 29, No. 3). The lightest supersymmetric particle is thought to be stable. A neutralino with a mass just above the range excluded by current accelerator searches (mass > 32 GeV/c^2, depending on the theoretical model) could account for the non-baryonic component of the dark matter. However, it should be noted that no supersymmetric particle of any type has yet been observed, despite careful searches at accelerator laboratories. This somewhat tarnishes the luster of the neutralino as a dark matter candidate but doesn't deter the experimenters. It may be that current accelerators simply are too low energy, and a discovery awaits a future machine, such as CERN's Large Hadron Collider.

THOUGH WELL motivated, the above argument is basically theoretical conjecture. Modern cosmology has become an empirical science, and the next step is to seek observational or experimental evidence for such claims. A neutralino-type dark matter would be difficult, but not impossible, to detect. One approach is to search for it indirectly by looking for evidence of WIMP self-annihilation products, such as high-energy gamma's, antiprotons, or neutrinos. Various experiments are currently underway but have reported only negative results to date.

Another approach, taken by a number of groups, is to attempt the direct detection of these particles via their elastic scattering off an atomic nucleus in a crystal. These experiments are quite difficult: neutralino dark matter interacts in a detector extremely rarely—a few events per year per kilogram of detector mass. (Note that this implies that there is a WIMP collision with a nucleus in our bodies at very roughly a rate of one per day, but we certainly don't notice it!). Also, the very small energy deposition (only a few keV) is close to typical detection thresholds, so a very sensitive low-noise detector is required.

Distinguishing a positive signal from environmental backgrounds is another challenge for the direct detection of dark matter. In order to avoid being swamped by the usual low level radioactivity present in most materials, one needs to use the techniques of ultra-low-background experiments: the detectors and construction materials must be made of radio-pure materials, the experiment must be located deep underground to suppress cosmic-ray induced interactions, and the detectors must be carefully shielded.

At present, there are about 20 WIMP direct detection experiments operating, employing a number of techniques. Scintillators (for example, sodium iodide) have been a favorite because a large mass is easily obtained, but these experiments

are hampered by the difficulty of performing active signal/background discrimination. Instead of performing an absolute rate measurement, these experiments look for a seasonal variation (annual modulation) in the WIMP rate. This is a predicted variation of a few percent as the velocity of the Earth around the Sun either adds to or subtracts from the Sun's velocity as we make our way through the galactic WIMP wind. Indeed, the Dark Matter (DAMA) experiment operating in the Gran Sasso underground laboratory in Italy has observed such a modulation over a four-year running period. If this were confirmed to be due to WIMPs, it would be the first evidence for the direct detection of dark matter.

A N ALTERNATIVE approach, pursued by our group, the Cryogenic Dark Matter Search Experiment (CDMS), has been the use of cryogenic detectors, a new kind of detector developed to conduct this experiment. CDMS, a collaboration of 10 university and national laboratory groups, has developed detectors which are able to measure the vibrations (phonons) of the crystal when struck by a single passing WIMP. By using germanium or silicon semiconductor crystals, we can combine this phonon measurement with detection of the ionization liberated by the recoiling nucleus. The advantage of this hybrid approach is that it provides a means of discriminating between a WIMP-generated nuclear recoil and a background-generated electron recoil. As shown in the illustration (upper right), nuclear recoils generate only about a third the ionization that an electron interaction of the same energy does. Hence, with this technique we can reject 99 percent of background events and our 250 g crystals are as sensitive as much more massive scintillator detectors. However, this technique does not let us reject events from background neutron interactions—these also produce nuclear recoils and so can mimic a WIMP signal. As described below, we have developed strategies to reduce and identify this neutron background, although this is what ultimately sets a limit on the sensitivity of this type of experiment.

In order to measure the recoil energy of the struck nucleus, it is necessary to cool the crystal to a temperature of 0.02–0.05 K to reduce thermal vibrations. We have developed two types of recoil energy sensors. Our first approach with detectors (developed in Bernard Sadoulet's group at the University of California, Berkeley) uses very sensitive thermistors bonded onto 165 g germanium crystals (photograph on right). These thermistors have a measurable change in resistance for the very small temperature rise in the crystal when it is struck by a passing WIMP.

A second approach (developed in Blas Cabrera's group at Stanford University) uses transition-edge sensors to measure directly the phonons generated in the crystal by the nuclear recoil. These sensors use a tungsten superconducting thin film deposited on a 250 g germanium (or 100 g silicon) crystal. The tungsten is maintained just below its superconducting transition temperature, and the energy liberated by the phonons causes enough of a temperature rise to produce a measurable increase in resistance.
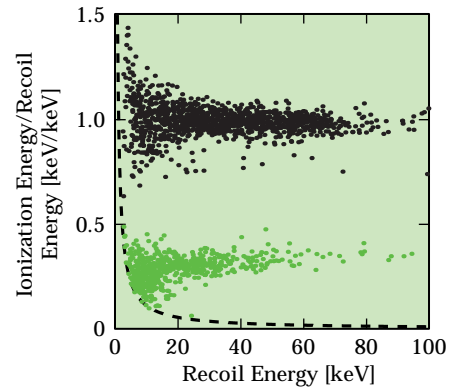
As seen in these calibration data taken with test sources, cryogenic detectors can distinguish between background gamma rays (black points) which scatter off electrons in the crystal and neutrons (or WIMPs) which scatter off nuclei (green points).

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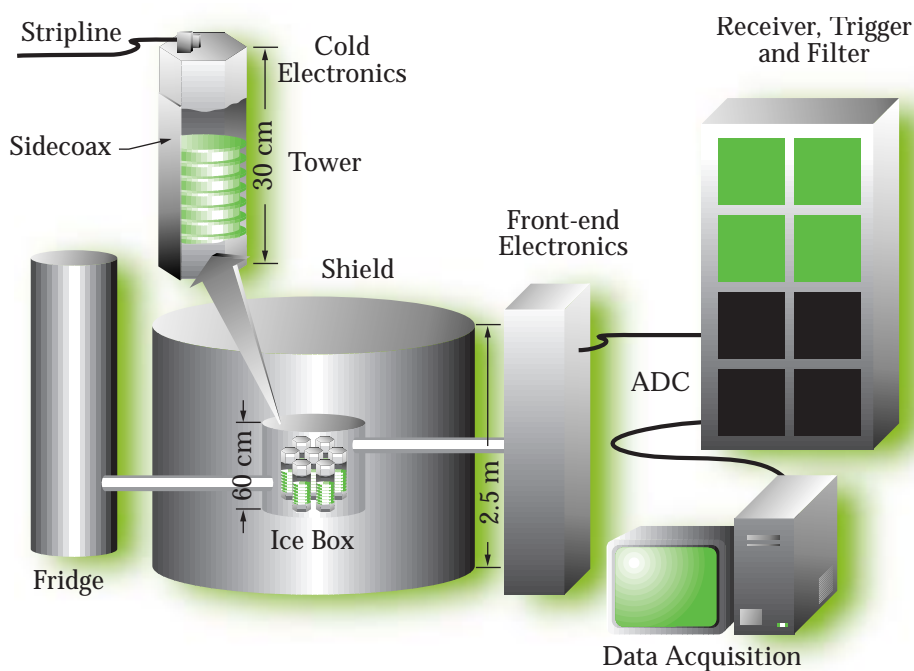CDMS germanium detectors used in the 1999 run.

A simplified schematic of the experiment is shown below. In order to operate at such low cryogenic temperatures a ^{3}He–^{4}He dilution refrigerator is necessary. (This is not common equipment for a particle physics experiment, but it is the workhorse of low temperature physics laboratories.) In order to minimize any background radioactivity from the refrigerator construction materials, we have designed a unique cryostat ("ice box"), made of seven layers of nested copper cans, that provides a cold volume of about 1 cu ft separated from the refrigerator by about 10 feet. The cryostat is shielded by layers of lead and polyethylene. As is common in such low-background experiments, we use "archeological" lead for the innermost layer of the shield. In this lead, which can be obtained from ancient shipwrecks, the radioactive isotopes common in freshly smelted lead have decayed to low levels. Polyethylene is used to "thermalize" the neutrons. That is, by elastically scattering on the hydrogen nuclei in the polyethylene, the neutrons lose much of their energy and fall below our detection threshold. Finally, we cover the entire outside area with plastic scintillator to veto cosmic rays—or, more importantly, any backgrounds they generate such as neutrons.

To get started with the experiment, we have set up CDMS I, the first generation of the apparatus, in the former High Energy Physics Laboratory endstation on the Stanford University campus. This has been a very convenient location for our development phase, but as a low background facility, it is a relatively "shallow" site, having only 11 meters of rock overhead. Nevertheless, we have been able to use this facility to obtain physics results. A recently completed run, employing a set of three detectors for about a year, has made it currently among the most sensitive experiments searching for dark matter.

In our data we found 13 nuclear recoil events. Regrettably, they are probably not the WIMPs we've been hunting, but rather are best explained as simply neutron-induced background events. One strong piece of evidence that we are seeing neutrons is that we have four events with interactions in more than one crystal—this is predicted by our Monte Carlo for neutrons, but is extremely improbable for WIMPs. Another indication is from a run the previous year, using a silicon detector. Silicon is about as sensitive to neutrons as germanium, but is much less sensitive

The layout of the CDMS II experiment being installed in the Soudan mine.

- Stripline
- Cold Electronics
- Sidecoax
- 30 cm
- Tower
- Shield
- Receiver, Trigger and Filter
- Front-end Electronics
- ADC
- 60 cm
- Ice Box
- 2.5 m
- Fridge
- Data Acquisition

to WIMPs. We saw four events in the silicon run, consistent with the conclusion that we are seeing the background neutron flux of the laboratory. And, it is important to note that there is reasonable agreement between the Monte Carlo simulation of the neutron background and the observed rates. For these reasons, our data provide a null result. We exclude a region in the mass versus WIMP-nucleon cross-section parameter space (see the illustration on the right).

It should be noted that this null result is at odds with the WIMP interpretation of the DAMA annual modulation observation. The rate observed by CDMS would be consistent with DAMA if the 13 events were in fact WIMPs, but the weight of the evidence strongly favors the neutron interpretation. Both groups are planning to take more data. The DAMA group intends to double its detector mass, and we are planning a major upgrade of CDMS.

CDMS I has shown that cryogenic detectors can be used to perform a sensitive search for WIMP dark matter. But to make inroads on the question of whether neutralinos are the ubiquitous dark matter, we need a much deeper site in order to be shielded from cosmic rays. The collaboration has recently been funded by the Department of Energy and the National Science Foundation to build CDMS II, a new version of the experiment to be operated in the Soudan mine in northern Minnesota. (Note that this location, near the Canadian border, has the dubious distinction of often recording the coldest winter

temperatures in the continental United States!) This former iron mine, now run as a state park, has been the home of the long-running Soudan II proton decay/neutrino detector. A new cavern is being excavated for the MINOS long baseline neutrino oscillation experiment from Fermilab (see the article by Maury Goodman in the Spring 1998 issue of the *Beam Line*, Vol. 28, No. 1). The laboratory area we will use for CDMS II is 700 meters underground, and at this depth the cosmic-ray muon rate is reduced by a factor of 10,000.

We are now embarking on the construction of CDMS II. For this experiment we will fabricate 42 new detectors, using transition-edge sensors. We will use both germanium and silicon crystals because, as we have found in CDMS I, their different relative responses to WIMPs and neutrons are a powerful technique for distinguishing a WIMP signal from the neutron background. We are building a new cryostat and shield and are installing a cleanroom in the underground laboratory. This construction will take about three years to complete. Even then, after it is fully assembled, we will need patience to operate the detectors for about three more years in order to obtain an exposure that will allow us to search for sypersymmetric dark matter with 100 times the current sensitivity. To rephrase an old adage, one might say the future is bright for doing cosmology deep underground. ◯
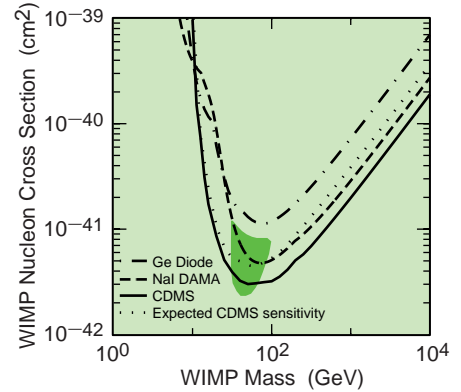
The result from the CDMS 1999 run shown as an exclusion plot. The values of the WIMP-nucleon scattering cross section above the solid line are excluded (at 90 percent confidence level) by the data. The darker green heart-shaped region shows the allowed values from the DAMA experiment.