

Underground detector yields tantalizing hint of dark matter

The dark matter that dominates the rotation and clustering of galaxies is thought to consist of heavy, weakly interacting particles not yet known but much sought after.

The cosmologists' widely accepted "concordance model" asserts that only about 15% of the mass of matter in the cosmos is baryonic—made of protons and neutrons. Most of the predominating nonbaryonic mass is presumed to consist of still unknown "dark-matter" particles without electromagnetic or strong nuclear interactions, but heavy enough to have been nonrelativistic in the early epochs of galaxy formation.

Just such weakly interacting massive particles (WIMPs) are predicted by most proposed extensions of particle theory's standard model. The leading WIMP candidate is the lightest of the many new species anticipated by the supersymmetry theories. Presumably created in the Big Bang, it could be stable and, with a mass something like 100 times that of the proton, abundant enough to account for the gravitational effects on the clustering and rotation of galaxies whose observation raised the dark-matter issue long ago.

In interactions with nucleons, WIMPs would have very small but non-vanishing elastic-scattering and production cross sections, comparable to those of the ordinary weak interactions. So particle-physics experimenters have been looking for the production of WIMP pairs in high-energy colliders. And on a more modest scale, they search for evidence of nuclei recoiling from collisions with WIMPs in detectors deep underground. As Earth sweeps through the dark-matter halo that is presumed to envelop and pervade the Milky Way, such detectors would record, at most, a few WIMP collisions a year per kilogram of active detector mass.

Given the limited masses and efficiencies of the detectors that have been operating for some time, one would not expect a statistically robust WIMP sighting until a new generation of up-scaled instruments has been operating for a few years. And indeed, the recently reported analysis by the Cryogenic Dark Matter Search collaboration of the final year's exposure of its

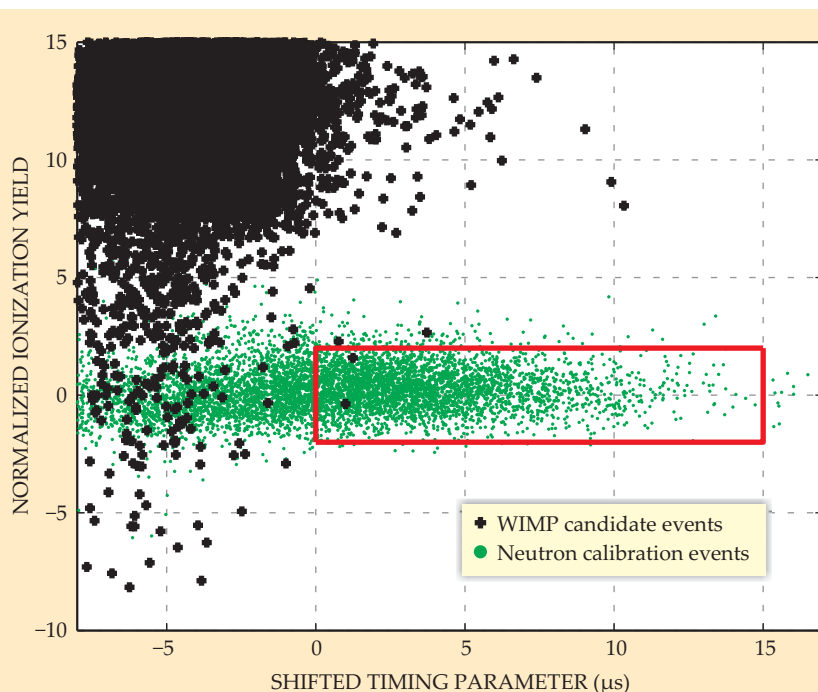


Figure 1. Ionization-yield and timing parameters for candidate WIMP-collision events that survived all prior event-selection cuts in the final year's exposure of the CDMS II dark-matter detector. The two parameters, described in the text, serve to weed out imposter events. Ionization yield is plotted in standard deviations from the mean for nuclear recoils, as measured with neutron collisions (green dots) in calibration exposures. The zero point of the timing parameter is shifted to its final cutoff value. In the signal region defined by the final cuts (red box), only two WIMP candidates survive. (Courtesy of CDMS.)

CDMS II detector yields a tantalizing but inconclusive result.¹

Two WIMP candidates

For two years CDMS II took data in the Soudan Laboratory inside an old Minnesota iron mine. The collaboration now reports that in its second year, the detector recorded two possible WIMP collisions. Neither event could be dismissed as an intruding or recoiling electron, or as a nucleus recoiling from a collision with a background neutron. But the group estimates a 23% chance that two imposters managed to squeeze past the event-selection cuts that reduced backgrounds a millionfold. Therefore the paper cautions that the results cannot be interpreted as signifi-

cant evidence of WIMP collisions. "But that doesn't mean the two events are not interesting candidates," says Blas Cabrera (Stanford University), one of the collaboration's leaders. In any case, the paper presents the most stringent upper limits to date on the WIMP-nucleon scattering cross section.

The CDMS II detector is a 5-kg array of 30 germanium and silicon crystals cooled to 40 mK. Each crystal is an 8-cm-diameter disk, 1 cm thick. Its flat surfaces are instrumented to detect a nucleus recoiling from a collision inside the disk. A colliding WIMP would produce a nuclear recoil energy of a few tens of keV. The recoil generates phonons and ionization in the crystal. Superconducting phonon sensors on

one surface measure the recoil's energy and position, and electrodes on the opposite surface measure the accompanying ionization.

The elastic collision of an MeV neutron off a nucleus in CDMS II is almost indistinguishable from a WIMP collision, except that the strongly interacting neutron will sometimes collide more than once as it traverses a stack of detector disks. Background neutrons can come from cosmic-ray muon interactions or from radioactive decays. But with the detector made of ultrapure materials and surrounded by active and passive shielding half a mile underground, the group estimates that there's less than a 10% chance that even one neutron created an imposter event during the detector's final year.

An enormously larger—but also more distinguishable—background of imposter events is created by gammas from nearby radioactive decays that penetrate the crystals and Compton scatter off electrons. The phonon energies created by the electron recoils are comparable to those from the nuclear recoils off neutrons (or WIMPs), but they leave more ionization in their wake. So the primary measurement used by CDMS to unmask and discard electron recoils was the so-called ionization yield: the ionization per unit phonon energy. Calibrating the detector with radioactive gamma and neutron sources, the group found that the ionization yield from Compton-scattering electron recoils was about four times the yield from nuclear recoils.

The group concluded that an event-selection cut exploiting the very clean ionization-yield distinction would reduce the electron-recoil background by a factor of several hundred. But that reduction alone would not suffice to achieve the demanding goal of having an expectation value of less than one surviving imposter from the tens of thousands of candidate events that passed all prior tests.

It was clear from the calibration runs that almost all of the electron-recoil events expected to sneak past the ionization-yield cut would be radioactive-decay betas that can penetrate just a few microns into the detector crystals, so that the electrodes register only a fraction of their ionization. To reduce that surviving surface-electron sample to one event at most, the group introduced a lower-limit cutoff on a timing parameter that combines the delay between the ionization and phonon signals and the phonon signal's rise time. Calibration data showed that rejecting all

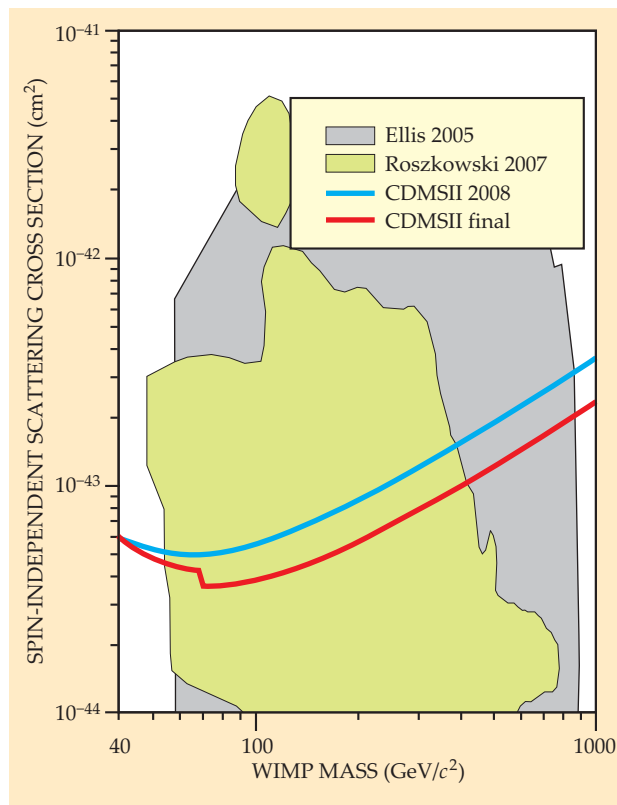


Figure 2. Upper limits on the cross section for the spin-independent elastic scattering of WIMPs off nucleons, determined from the total two-year exposure of the CDMS II detector (red), and from its first year (blue), in which no WIMP candidates were found. Green and gray areas indicate a range of predictions from supersymmetry theories.² WIMP masses below about 60 GeV appear to be excluded by searches at the high-energy colliders. (Adapted from ref. 1.)

events with the timing parameter less than some optimal cutoff near 15 μ s should do the trick.

The lockbox

In keeping with the “blind-analysis” philosophy that seeks to avoid unconscious biases in event selection, the CDMS team determined all of its precise cutoff values from calibration runs and, in the actual data runs, only from events well outside the “signal region” of events that remained viable WIMP candidates. As is now customary when particle physicists are looking for needles in haystacks, events in the signal region remained unseen in a lockbox until the data analysis was completed.

Figure 1 shows what the collaboration found when the lockbox was finally opened. It's a scatter plot of timing and ionization-yield parameters for the roughly 50 000 candidate events in CDMS II's final year that survived all prior hardware and software cuts. The red rectangle marking the signal region defined by the ionization-yield and timing cuts contains the two surviving candidate events.

After opening the lockbox, the group carefully reexamined the electronic records to make sure the detector elements had been working normally on the two days, several months apart, when the two events were found. “We could find no reason to reject either

one,” says Jodi Cooley (Southern Methodist University), who led the data analysis effort.

The quoted 23% probability that both events were imposters comes largely from the group's estimate that the expectation value for the number of surface-electron events that snuck past the timing cut is 0.8 ± 0.2 . Choosing cuts is a tradeoff between eliminating imposters and saving real events. The group reckons that its hardware and software cuts would have rejected about 70% of all true WIMP collisions.

Limits and disputes

As a function of putative WIMP mass, figure 2 shows the upper limit on the cross section for spin-independent WIMP–nucleon elastic scattering based on the discovery of, at most, two WIMP collisions in the detector's two-year exposure. (Like all the other detectors that rely on the enormous sensitivity enhancement that comes from coherent scattering off all the nucleons in a heavy nucleus, CDMS II is almost blind to the expected spin-dependent term in the elastic-scattering amplitude. See *PHYSICS TODAY*, April 2008, page 22.)

The new limits, the most stringent yet reported, bite significantly into the range of supersymmetry predictions also shown in the figure.² WIMP masses below about 60 GeV were thought to be excluded not by theory but by the null

results of WIMP searches at the LEP and Tevatron colliders. In experiments like CDMS II, a few recoil energies can't specify the WIMP mass. But the fact that both CDMS II events had relatively low recoil energies, near 15 keV, suggests a mass somewhat lower than 60 GeV.

The only definite claim of WIMP-collision sightings to date was first announced in 2000 by the DAMA collaboration, whose sodium iodide detector sits in Italy's Gran Sasso underground laboratory.³ DAMA's disputed results have for some years conflicted with the elastic-scattering upper limits reported by CDMS and the XENON10 collaboration, whose 15-kg liquid-xenon detector also sat at Gran Sasso (see *PHYSICS TODAY*, August 2007, page 16). But theorists David Tucker-Smith, Neal Weiner, and coworkers have been suggesting since 2001 that the DAMA events might be inelastic collisions in which WIMPs are raised to a putative excited state perhaps 100 keV above their ground state.⁴

Such collisions would be rarer with germanium than with the heavier iodine or xenon nuclei. But now the CDMS collaboration, looking for evidence of such inelastic collisions in the CDMS II run, claims to have largely ruled out what little of the range of

WIMP mass splitting had not already been excluded by XENON10. "But I think," says Weiner, "we'll have to wait for the new xenon experiments to know whether WIMP excitation explains DAMA."

The CDMS II detector is now being upgraded at Soudan to SuperCDMS, a 15-kg array with larger germanium crystals. The collaboration's longer-term goal is a 100-kg detector more than a mile underground at SNOLab in Sudbury, Ontario. In the ongoing quest to elucidate dark matter, a key issue being addressed in the current round of underground detector experiments is: Which of the competing detector technologies is best suited for upscaling to detectors massive and sensitive enough to yield a convincing WIMP sighting—or the demolition of a promising theory?

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Neutral atoms are entangled in hyperfine states via Rydberg blockade

An interaction between highly excited atoms can be used to engineer a superposition of low-energy quantum states, as two research groups now demonstrate.

Ions and neutral atoms held in electromagnetic traps are two of many candidates that may one day become the qubits in a quantum computer: Their hyperfine states could serve as the computer's ones and zeroes. Ions interact via long-range Coulomb forces, which can facilitate creation of the entangled states that are the prerequisite for quantum computation. But that same Coulomb interaction gives rise to collective motions that can disrupt a qubit array. Atoms aren't susceptible to such disruptions. But they're also more difficult to entangle.

Last year two research groups independently demonstrated a long-range interaction, called Rydberg blockade, between trapped neutral atoms; they published their results in a pair of back-to-back papers. (See *PHYSICS TODAY*, February 2009, page 15.) One group, led

by Mark Saffman and Thad Walker at the University of Wisconsin–Madison, showed the blockade in its simplest form: When two atoms were separated by several microns, exciting one into a Rydberg state—an energetic state with a large, delocalized electronic wavefunction—prevented the other from being similarly excited.¹ The blockade works because the energy of two Rydberg atoms with respect to the ground state is less than twice the energy of one Rydberg atom, so the second Rydberg excitation is shifted out of resonance with the excitation laser. The other group, led by Philippe Grangier and Antoine Browaeys of the Université Paris–Sud, the Institute d'Optique, and CNRS, used Rydberg blockade to entangle two atoms, with one in the Rydberg state and the other in the ground state.²

Cryogenic Materials Characterization

ARS Manufactured
Closed Cycle
3 K — 800 K

Mixed Gas Cooler
Low Cost
80 K

4K

UHV 10^{-11} Torr
Ultra Low Vibration
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