EXCLUSION LIMITS ON THE WIMP-NUCLEON SCATTERING CROSS-SECTION FROM THE CRYOGENIC DARK MATTER SEARCH

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Abstract

The Cryogenic Dark Matter Search (CDMS) employs massive ionization- and phonon-mediated detectors to search for WIMPs via their elastic scattering interactions with nuclei while discriminating against interactions by other background particles. Limits on the WIMP-nucleon scattering cross-section, based on 3.1 kg d of exposure, exclude new parameter space in the 10 to 30 GeV WIMP mass region and also a portion of the region allowed by the DAMA annual modulation search (Ref. 1).

1 Introduction

There is extensive evidence that a large fraction of the matter in the universe is nonluminous. In recent years, there has been a growing consensus that the ratio of the matter density in the universe to the critical density, $\rho_m/\rho_{crit} = \Omega_m$, is greater than approximately 0.25. This is more than what can be accounted for by luminous matter, $\Omega_{lum} \sim 0.003h^{-1}$ (Ref. 2), or even by all baryons, $0.006h^{-2} < \Omega_b, < 0.016h^{-2}$ (95% CL) (Ref. 3), and hence there is a need for nonbaryonic dark matter. To achieve consistency between the amplitudes of CMB fluctuations and those of large-scale structure, it is necessary for much of the nonbaryonic dark matter to be "cold" - nonrelativistic at the time that gravitational collapse began.

Weakly Interacting Massive Particles, or WIMPs, are a candidate for nonbaryonic cold dark matter. They would interact only via the weak interaction (and gravity) and would have mass of order 100 GeV. Such a particle δ would have a relic abundance of $\Omega_\delta \sim 1$ (Ref. 4). Minimal supersymmetry provides a natural WIMP candidate in the form of the lightest superpartner (Ref. 5).

WIMPs are expected to have collapsed into a roughly isothermal spherical halo within which the visible portion of our galaxy resides. They scatter off nuclei via the weak interaction; the expected spectrum of recoil energies (energy given to the recoil nucleus by the interaction) is exponential with characteristic energy of a few to tens of keV. The expected event rates depend on the exact model for the WIMP and are 1 $\text{kg}^{-1}\,\text{d}^{-1}$ or lower. Thus, a WIMP search experiment requires a threshold of a few keV and an extremely low rate of background (non-WIMP) events.

2 CDMS Detectors

One technique for rejecting background events is nuclear-recoil discrimination. WIMPs produce nuclear recoils via elastic scattering. Conversely, nearly all irreducible background sources (primarily photons from radon daughters and from natural radioactivity of the surroundings and of construction materials) produce electron recoils. Neutrons are an important exception. In the case of CDMS, discrimination between these two is performed by measuring, for every event, recoil energy via phonons and ionization via electron-hole pairs. The ratio of ionization to recoil energy, or ionization yield, for nuclear recoils is lower than for electron recoils. In Ge, the reduction is a factor of 3, as is seen for a CDMS detector in Figure 1. Such a detector's ability to reject the irreducible photon background is excellent, greater than 99%.

The CDMS detectors have been described in great detail elsewhere (Refs. 6, 7, 8). We note only those aspects of particular interest here. For both the thermal and athermal detectors, the drift field for the ionization measurement is supplied by electrodes deposited on the top and bottom faces of the disk-shaped detectors. These

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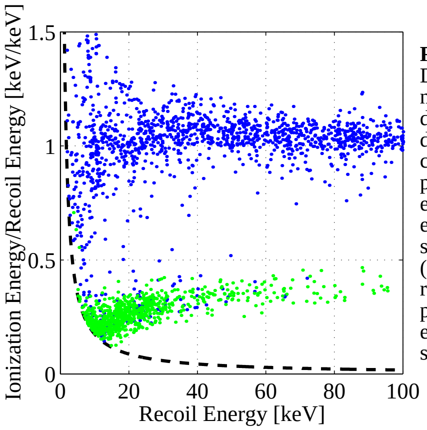


Figure 1: Demonstration of nuclear-recoil discrimination. Dark data points are veto-coincident data – primarily photons and electrons (producing electron recoils) and some neutrons (producing nuclear recoils). Light data points are taken during exposure to a neutron source.

electrodes are segmented radially to yield a central disk-shaped inner electrode and an annular outer guard ring.

CDMS has employed Berkeley Large Ionization- and Phonon-mediated (BLIP) detectors to collect the data presented here. For a BLIP detector, the phonon measurement consists of measuring the temperature change of the 165 g Ge crystal using neutron transmutation doped (NTD) germanium thermistors eutectically bonded to the crystal. These detectors operate at 20 mK. The BLIP baseline energy resolution is 500 eV FWHM ionization and 700 eV FWHM heat. The resolution has been measured *in situ* using 10.4 keV ^{68}Ga X-rays (arising from internal cosmogenic activation) to be 1.35 keV FWHM ionization (at 10.4 keV) and 1.50 keV FWHM heat (at 31.2 keV).

CDMS also uses athermal phonon-mediated detectors that employ a similar ionization measurement. Athermal phonons enable a measurement of event position in addition to recoil energy; event position can be used to reject surface events (see discussion in Section 4). Silicon versions of these detectors were run in the low-background facility during 1998 (Ref. 7). Germanium detectors are being tested now (Ref. 8) and will be operated in the low-background facility in late 1999.

3 Low-Background Environment and Cryostat

The low rate of WIMP interactions necessitates operation at a site with low background-particle flux. CDMS operates its detectors in a tunnel 16 meters water equivalent underground on the Stanford University campus. This overburden stops the hadronic component of cosmic ray air showers and reduces the muonic component by a factor of 5. This shallow site was chosen for the initial phase of CDMS due to its proximity to many of the participating institutions.

To establish a low-background cryogenic environment, CDMS has constructed a custom, radiopure, right-angle extension to a modified Oxford S-400 dilution refrigerator. The cryostat has been described in great detail in (Ref. 9).

Several layers of shielding surround the cryostat. Outermost is a highly efficient scintillator veto to tag muon-coincident photons, electrons, and neutrons. Inside the veto is a lead shield, which reduces the photon flux from muon-induced reactions and natural radioactive decays in the tunnel walls and dilution refrigerator. Additional photon shielding is provided by an ancient lead shield inside the cryostat. The photon flux measured by the detectors *in situ* is roughly 60 $\mathrm{kg}^{-1}\ \mathrm{keV}^{-1}\ \mathrm{d}^{-1}$ overall and 2 $\mathrm{kg}^{-1}\ \mathrm{keV}^{-1}\ \mathrm{d}^{-1}$ anticoincident with veto.

Neutrons with energies capable of producing keV nuclear recoils in the detectors are produced by muons inside and outside the veto. These neutrons are moderated by a 25 cm thickness of polyethylene between the external lead shield and cryostat. Provisions for additional moderator internal to the ancient lead shield have been made, though this moderator has not yet been installed.

4 Electron Background Reduction

As described in (Refs. 10, 11), CDMS's initial runs were hampered by a dead layer in the ionization measurement and an electron background. To address these problems, CDMS has pursued many avenues. As mentioned above and as discussed in (Refs. 7, 8), fast phonon pulse shape discrimination works very well in identifying dead-layer events because they occur near the surface and yield a different athermal phonon pulse shape; Ge athermal detectors are currently in testing. Improvement of the ionization electrodes has also been pursued and has yielded a new blocking electrode, described in (Ref. 12). These new electrodes raise dead-layer events out of the nuclear-recoil band.

Other changes have also been made. The detectors have been packed close together, 3 mm apart, with no intervening material, and the electrodes radially segmented. Therefore, the outer ionization electrodes shield the inner electrodes from low-energy particles emitted by contaminants on the surfaces of the housing. In addition, new care was put into the cleanliness of the detector fabrication and testing environments. Finally, a large fraction of the housing was covered with 2 mm of detector-grade germanium, etched to remove surface contaminants.

5 Results

Between mid-November, 1998, and mid-April, 1999, 35 raw live-days of data were collected using four new BLIP detectors incorporating the above changes. BLIPs 3 through 6 are stacked face-to-face vertically in a single detector housing. Restriction to events fully contained in the inner electrode yields an exposure reduction of 60% to 70%. BLIP3 is discarded because it displays a significant excess of anticoincident events, forming an electron band with a tail into the nuclear-recoil band. It suffered

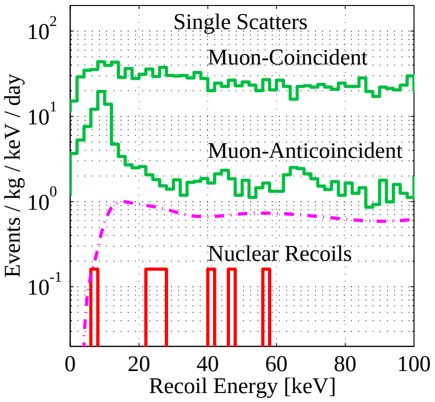
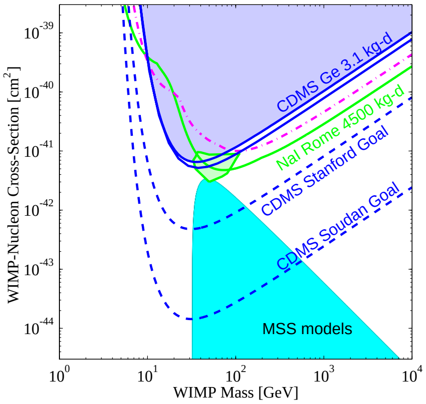


Figure 2 (left): Coadded recoil energy histograms for BLIPs 4, 5, and 6. Bottom: muon-anticoincident nuclear-recoil candidates. Upper lines: muon-coincident and anticoincident single-scatter photon spectra. Dash-dot: nuclear-recoil efficiency energy dependence.

Figure 3 (right): Spin-independent WIMP-nucleon scattering cross-section limits. Solid dark lines: 90% CL limits from these data: upper line: no background subtraction; lower line: with background subtraction. Shaded, heart-shaped region: DAMA 90% CL allowed region (Ref. 1). Dash-dot: combined Ge diode limit, dominated by Heidelberg-Moscow (Ref. 13).



additional processing steps that may have contaminated or damaged its electrodes. The final exposure is 3.1 kg d.

The spectrum of nuclear-recoil candidates in BLIPs 4, 5, and 6 is displayed in Figure 2. Only single-scatters are displayed; WIMPs will not multiply scatter. These events do not appear to be the tail of an electron distribution. There are a number of reasons to believe these candidates are recoils from neutrons scattering in the detectors. First, one multiple-scatter nuclear-recoil event appears in BLIPs 5 and 6. Based on simulations, this yields an expectation of 12 single-scatter neutron events (with large statistical uncertainty). Second, the rate of nuclear-recoil events is roughly the same as expected from unvetoable neutrons due to muon interactions outside the shield. Third, a Kolmogorov-Smirnov test yields a 72% probability of agreement of this spectrum with the expected shape of the spectrum of these unvetoable external neutrons. Finally, the summer, 1998, Si athermal phonon-mediated detector data yielded 2 to 4 nuclear-recoil candidates; extrapolation to these data yields an expectation of ~3 neutron events. In brief, within large statistical uncertainties, these data are consistent with a neutron background produced by muons outside the shield.

The derived 90% CL upper limits on the spin-independent WIMP-nucleon elastic scattering cross-section are displayed in Figure 3. The neutron background is statistically subtracted using the measurement by the Si single-scatter and Ge multiple-scatter nuclear-recoil candidates. New parameter space is excluded in the 10 to 30 GeV WIMP mass region, as is a portion of the region allowed at 90% CL by the DAMA annual modulation data (Ref. 1).

6 Conclusion and Outlook

CDMS has demonstrated significant progress in reducing the effect of its electron background and has begun to probe interesting WIMP parameter space. This improvement has been due to a new electrode technology that reduces the “dead layer” problem significantly and to detector mounting and production changes to reduce and shield contamination sources. CDMS is engaged in an extended run of the present set of detectors and expects 15 kg d of exposure. 3 Si and 3 Ge athermal detectors, combining surface event veto capability with improvements demonstrated in this run, will be deployed in fall 1999.

CDMS is constructing a second low-background facility at the Soudan mine at 2070 mwe. By eliminating the muon-induced neutron background, this deep site will enable CDMS to make an immediate large improvement in its sensitivity. Operation at the Soudan mine is expected to commence in summer 2000. Expected sensitivities for CDMS at Stanford and at Soudan are shown in Figure 3.

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