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Preliminary Limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search (CDMS)

DS Akerib[1,2, *], PD Barnes Jr[3], DA Bauer[4], PL Brink[5], B Cabrera[5], DO Caldwell[4], RM Clarke[5], A Da Silva[2], AK Davies[5], BL Dougherty[5], KD Irwin[5], RJ Gaitskell[2], SR Golwala[2], EE Haller[6,7], J Jochum[2], WB Knowlton[6,7], V Kuzminov[8], SW Nam[5], V Novikov[8], MJ Penn[5], TA Perera[1,2], RR Ross[2,6,9], B Sadoulet[2,6,9], RW Schnee[1,2], T Shutt[2], A Smith[6], AH Sonnenschein[4], AL Spadafora[2], WK Stockwell[2,9], S Yellin[4], and BA Young[10]

[1]*Department of Physics, Case Western Reserve University, Cleveland OH 44106.* [2]*Center for Particle Astrophysics, University of California, Berkeley CA 94720.* [3]*Lawrence Livermore National Laboratory, Livermore CA 94550.* [4]*Department of Physics, University of California, Santa Barbara CA 93106.* [5]*Department of Physics, Stanford University, Stanford CA 94305.* [6]*Lawrence Berkeley National Laboratory, Berkeley CA 94720.* [7]*Department of Material Science and Mineral Engineering, University of California, Berkeley CA 94720.* [8]*Baksan Neutrino Observatory, Institute for Nuclear Research, Russian Academy of Science.* [9]*Department of Physics, University of California, Berkeley CA 94720.* [10]*Department of Physics, Santa Clara University, Santa Clara CA 95053.*

We are conducting an experiment to search for WIMPs, or weakly-interacting massive particles, in the galactic halo using terrestrial detectors. This generic class of hypothetical particles, whose properties are similar to those predicted by extensions of the standard model of particle physics, could comprise the cold component of non-baryonic dark matter. We describe our experiment, which is based on cooled germanium and silicon detectors in a shielded low-background cryostat. The detectors achieve a high degree of background rejection through the simultaneous measurement of the energy in phonons and ionization. Using exposures on the order of one kilogram-day from initial runs of our experiment, we have achieved (preliminary) upper limits on the WIMP-nucleon cross section that are comparable to much longer runs of other experiments.

1. Introduction

Observations of stars and galaxies over a large range of distance scales indicate the presence of a significant amount of dark matter that is unseen except for its gravitational effects [1, 2]. There is general consensus that most of the dark matter, on the order of the critical density, is comprised of a non-baryonic "cold" component. We are conducting an experiment to search for direct evidence of WIMPs, or weakly-interacting massive particles, a generic hypothetical candidate for cold dark matter.

The experimental challenge is defined in part by considerations of the early Universe and the properties of our Galaxy. Constraints from the thermal production of WIMPs in the early universe that yield a critical WIMP density today are satisfied by particles with masses in the 10–1000 GeV/c^2 range and cross sections on the scale of the weak interaction [3]. This range of particle properties suggests that supersymmetry (SUSY) or other extensions to the standard model may provide the dark matter [4]. If WIMPs exist they would now make up a major component of the dark matter in our own galactic halo [5]. For a standard halo comprised of WIMPs with a Maxwellian velocity distribution characterized by $v_{rms} = 270$ km/s and a mass density of 0.4 GeV/cm^3, the expected rate for WIMP-nuclear scattering is in the range 1–0.001 events per kilogram of detector per day and the expected recoil energy is as low as 1 keV [4, 6].

Despite considerable worldwide efforts, WIMPs have not yet been detected. Ultimately, experiments have been dominated by irreducible backgrounds, primarily photons and electrons from radioactive contamination or activation. Fur-

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ther progress can be made by discriminating background events from WIMP events. In the CDMS experiment rejection of 99% of the photon background is achieved using detectors that simultaneously measure the recoil energy in both phonon- and charge-mediated signals [7, 8]. The ratio of the two measurements distinguishes electron-recoil events due to background photons from nuclear-recoil events due to WIMPs since nuclear-recoils are less ionizing. Following a decade-long development effort, detectors have now successfully been run in a low-background environment. Our early data runs yield preliminary upper bounds on the WIMP-nucleon cross section that are comparable to much longer exposures of other experiments, illustrating the power of this technique.

2. Description of the Experiment

The CDMS detectors employ two distinct technologies for performing the phonon-mediated measurement of the energy ΔE deposited in a scattering event. One technology uses two neutron-transmutation-doped (NTD) germanium thermistors eutectically bonded to 1.3-cm-thick 6-cm-diameter 165-g cylindrical crystal of high-purity germanium. With the device in contact with a 20 mK bath, monitoring the thermistor resistances gives the temperature rise $\Delta T = C^{-1}\Delta E$, where C is the heat capacity. The resulting energy measurement has a FWHM resolution of 650 eV at 10 keV. The use of two NTDs permits the rejection of events that originate in one or the other NTDs.

The other technology uses quasiparticle-trap-assisted electrothermal-feedback transition-edge sensors (QETs). Tungsten meanders on a surface of a cooled 1-cm-thick cylindrical detector are held in the middle of its superconducting transition by electrothermal feedback using a voltage bias. Deposited energy drives the tungsten towards normal conduction which produces a current signal. The time integral of this signal is proportional to the deposited energy, which is measured to 650 eV (FWHM) in our 100-gram silicon targets; the technology is now being transferred to germanium targets. Since the phonon collection time is fast (a few microseconds), relative-timing information from the four sensors on a device allows a two-dimensional determination of the event position to a few millimeters.

The ionization measurement is made by applying a small bias voltage across the two sides of the semiconductor targets. Electron-hole pairs are collected efficiently throughout the bulk of the detectors, but trapping sites near the surface result in a 10–30μm-thick “dead layer” where charge collection is incomplete. An energy resolution of 640 eV has been achieved.

The remainder of the apparatus consists of specialized low-activity detector-housing modules mounted in a cryostat made from a set of shielded nested copper cans. The cans are cooled by conduction through a set of concentric horizontal tubes that are connected to a dilution refrigerator. The cryostat is shielded externally with lead for the reduction of the gamma rays and polyethylene for the reduction of neutrons [9]. Samples of all materials internal to the shield are carefully screened in a low-background HPGe counting facility for radio contaminants. Further shielding close to the detectors is achieved with ancient ultra-low activity lead which has a low concentration of ^{210}Pb, a beta-emitter. Due to the complexity of the detectors and cryostat the first phase of the experiment is being performed at a shallow site at Stanford University at a depth of 17 meters water-equivalent (mwe). Since cosmic ray muon flux is reduced by only a factor of 5 at this depth, further rejection of backgrounds is achieved with a hermetic plastic-scintillator muon veto.

2.1. Detector Performance

The capability of the detectors to distinguish photon backgrounds from WIMP-induced nuclear recoils is demonstrated using photon and neutron calibration sources; the neutrons serve as test particles to induce nuclear-recoil events. As discussed above, it is the ratio of the charge-mediated energy measurement to the phonon-mediated energy measurement that allows discrimination between electron and nuclear recoils. We define this ratio as the charge yield Y, which is the number of electron-hole pairs per eV of recoil energy.

In separate calibration runs the detectors were alternately exposed to photons from a ^{60}Co source and neutrons from a ^{252}Cf source. His-

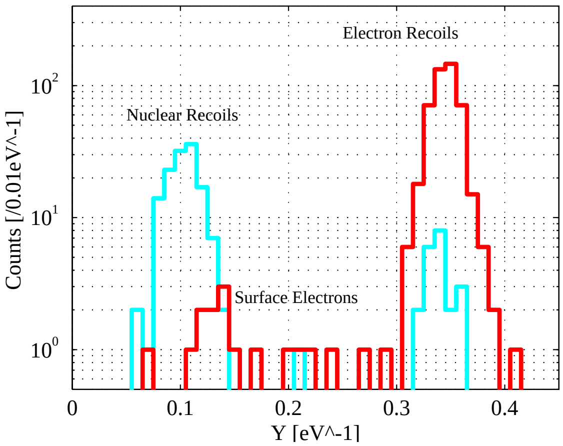

Figure 1. NTD-based germanium detector: charge yield in the recoil-energy range of 15–45 keV for ^{60}Co data (black) and ^{252}Cf data (grey). Gamma rejection of 99%is obtained for a nuclear-recoil acceptance of 98%.

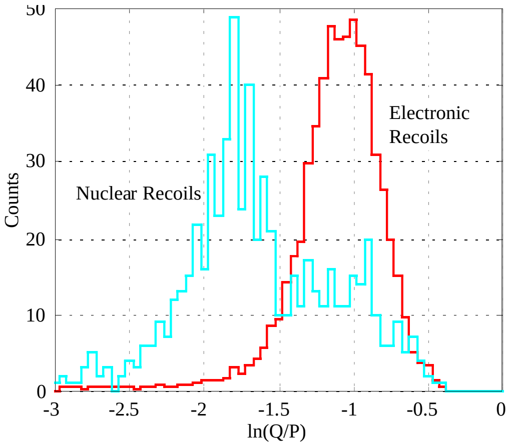

Figure 2. QET-based silicon detector: charge yield in the recoil-energy range of 30–100 keV for ^{60}Co data (black) and ^{252}Cf data (grey). Gamma rejection of 99% is obtained for a nuclear-recoil acceptance of 75%.

tograms of the charge yield are shown in Figures 1 and 2 for NTD and QET detectors, respectively. These data show that 99% of photon-induced recoils are rejected while high acceptance is maintained for nuclear recoils. The events between the main recoil peaks are due to electrons that deposit energy in the dead layer and thus have a low charge yield relative to electron recoils in the bulk.

3. Low Background Counting

3.1. Data Sets

Several data runs have been taken in the low-background facility over the past year. We have shown that the experiment can be successfully operated on month-long timescales with energy resolutions comparable to calibration data. We have also learned that the rate of photon and neutron backgrounds are consistent with or less than the expected level, providing important confirmation that we can reach our goals at the shallow site and that our screening procedures were effective in limiting these sources of background.

The rate versus energy from a 1.60 kg-d exposure of a 165-g NTD-based germanium detector shows a number of features (Figure 3). The uppermost curve is the full data set (following event quality cuts) and is dominated by photon events coincident with the muon veto; the peak at 9 keV is due to florescence of copper by muon-related photons. The middle curve, events in anti-coincidence with the muon veto, represents a factor of 20 reduction in rate. The line at 10 keV is consistent with internal ^{68}Ge which undergoes electron capture and leads to a ^{68}Ga x-ray. The broad distribution below 18 keV is due electrons from tritium decay on the surface of the detector. We have also observed a tritium distribution in events intrinsic to the NTD-Ge thermistors and have since demonstrated that tritium diffuses out of the NTDs at 550 C, similar to the temperature used during the eutectic bonding. It should therefore be possible to control this contamination in future detectors by baking the NTD prior to bonding.

A cut on charge yield to select nuclear recoils, which is based on a fit to neutron calibration data, results in the solid histogram in Figure 3. At low energy, the spectrum is dominated by the tritium events that have low charge yield and survive the cut. Above the tritium endpoint the remaining events are likely due to beta emitters in surface contaminants such as ^{40}K from human perspiration or ^{210}Pb from radon plating. Further steps are now being taken to control the contamination by a surface etch of the detectors late in the fabrication process and through more careful handling

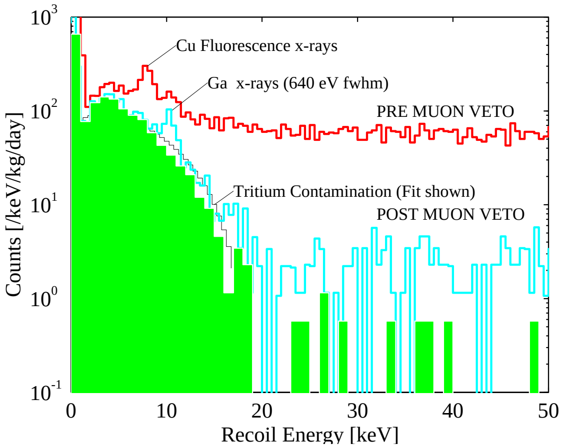

Figure 3. Event rate versus recoil energy for a 1.60 kg-d exposure of a 165-g NTD-based germanium detector. The shaded histogram are events that pass the nuclear recoil cut.

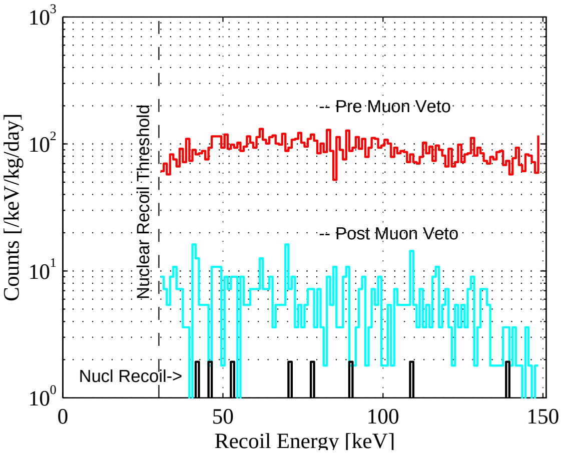

Figure 4. Event rate versus recoil energy for a 0.52 kg-d exposure of a 100-g QET-based silicon detector.

following the final etch (e.g., storage in dry nitrogen or vacuum). We also expect to reduce our susceptibility to beta sources external to the detectors by self-shielding them in a close-packed geometry. Finally, work is continuing on eliminating or reducing the dead layer, itself.

The energy resolution of the QET-based detector quoted above is due to recent 10-fold increase in phonon collection. Prior to this improvement, an exposure of 0.52 kg-d was obtained with a previous 100-g silicon detector. Rate versus energy for these data are shown in Figure 4. As with the germanium data, the muon veto leads to a factor of 20 reduction in rate. The events in the nuclear-recoil region above the threshold of 30 keV are consistent with the expected number of misidentified gammas.

3.2. Preliminary Dark Matter Limits

We use event rates consistent with nuclear recoils from the two data sets described above to place an upper limit on the WIMP-nucleon cross section for spin-independent couplings following reference [6]. Figure 5 shows these limits versus WIMP mass along with other experimental bounds [10, 11]. Also shown is the region expected for minimal supersymmetric models (MSSM) that give a relic density greater than 10% of the critical density for a Hubble parameter of 50 km/s/Mpc [4]. Although our exposure is far less than those of the previous experiments, the sensitivity is comparable, thus clearly demonstrating the advantage of background discrimination.

4. Conclusion and Plans

Following decade-long development efforts of cryogenic detectors and a cold shielded low-background environment in which to operate them, we have begun taking data to search for WIMPs. Data has been taken with two distinct detector technologies, both of which are on the verge of making major gains in sensitivity to dark matter. We have identified the primary background source that presently limits our sensitivity—low-energy electrons that suffer reduced charge collection. A number of strategies are in place to minimize this and regain the full effectiveness of our event discrimination technique. Once this has been accomplished, we expect to be limited by the ambient photon and neutron backgrounds at the Stanford site with an exposure of about 100-kg-d. To obtain this exposure we will instrument two silicon and four germanium devices with QET readout and six germanium devices with NTD readout, for a total of 200 g of silicon and 2 kg of germanium. Comparison of backgrounds in the Ge and Si will provide information on the backgrounds, especially neutrons. Multiple scattering of neutron back-

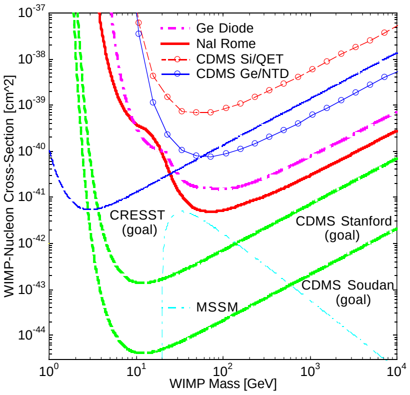

Figure 5. The WIMP-nucleon cross section for spin-independent couplings versus WIMP mass. Upper limits on the cross section are shown for recent runs of CDMS (preliminary), published results using NaI scintillators and Ge diodes, and the goals for CDMS and the CRESST experiment. The dashed region in the lower part of the graph bounds the region where supersymmetric particles could be the dark matter.

grounds in the detector arrays will also provide a handle for background subtraction.

In order to take full advantage of these advanced detectors, we plan to continue the experiment at the Soudan Mine. The 2000 mwe overburden at Soudan will attenuate cosmic ray muons by some 5 orders of magnitude, which will greatly reduce cosmogenic activity in the apparatus and greatly reduce the neutron background. Figure 5 shows the expected sensitivity for a 100-kg-d exposure at the Stanford site and a 5000-kg-d exposure at the Soudan site. For reference, the projected sensitivity of the CRESST experiment is also included [12]. As seen in the figure, the CDMS experiments will explore a significant new region of WIMP parameter space, and in particular, a region where supersymmetric models could provide the dark matter.

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