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RESULTS OF THE CRYOGENIC DARK MATTER SEARCH (CDMS) OBTAINED WITH THERMISTOR-INSTRUMENTED GERMANIUM CALORIMETERS

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WIMP scattering in a semiconductor target would produce less ionization per unit deposited energy than gamma rays do. Therefore, discrimination against background gamma rays can be achieved by simultaneously measuring the ionization and heat produced by scattering events. The Cryogenic Dark Matter Search (CDMS) experiment uses germanium and silicon detectors cooled to ~20 mK to attempt to detect weakly interacting dark matter. We discuss recent results obtained with NTD thermistor-instrumented germanium detectors. Currently, the background rejection capability of these devices is compromised by poor charge collection at the detector surfaces. Nevertheless, the limits on WIMP interaction rates derived from our measurements are close to the best achieved by other methods, with exciting prospects for improvement in the near future.

1 Introduction.

The challenge for WIMP detection is to achieve background counting rates less than 0.01 event/kg-day at low energies. One approach to solving this problem is to build detectors that can discriminate between WIMP scattering events and background events. Nuclear scattering produces less ionization in semiconductor targets per unit energy deposited than scattering on electrons. Since gamma rays, which are the dominant background source for dark matter searches, interact with electrons via compton and photoelectric scattering, while WIMPs make ionization only through the recoil of a target nucleus, a measurement of the ratio of ionization to deposited energy permits discrimination between the two types of interaction. At low temperatures, it is possible to measure both the heat deposited by an ionizing event and the amount of ionization, making this type of discrimination technologically feasible.

The Cryogenic Dark Matter Search (CDMS) collaboration has built germanium and silicon detectors which operate at a temperature of about 20 mK. Energy deposition is measured with two different technologies, (1) Neutron-transmutation-doped germanium thermistors capable of measuring temperature changes of less than 1 μK in an attached target crystal, and (2) Tungston superconducting transition-edge sensors, which respond to the initial high-energy phonon burst associated with a particle interaction. This paper describes detectors based on the first technology, while another paper in this volume (Clarke et al.) describes the second type of detector.

2 Thermal Measurement.

Calorimetric particle detectors typically consist of a target mass with low heat capacity weakly coupled to a low temperature thermal bath of much higher heat capacity. Energy deposited in the target material by a scattering event causes a temporary increase in its temperature, with the time scale of the thermal pulse determined by the strength of the connection to the low temperature bath. Sensitive thermometry allows a measurement of the deposited energy. There have been many implementations of this general scheme [1].

For germanium crystals, the heat capacity is $\sim$2 keV/(mole $\cdot$ μK) at a temperature of 20 mK. We measure the temperature increase of the target crystal with a small neutron transmutation doped (NTD) germanium thermistor, which is attached to the larger crystal with an Au-Ge eutectic bond. Detectors of this type, called Berkeley Large Ionization and Phonon devices (BLIPs), have been in development for several years [2]. Optimization of these detectors requires quantitative modeling of the thermal impedances, heat capacities and noise sources in the detector and its readout electronics in order to obtain the best possible energy resolution and threshold for a given detector mass. The sensitivity is limited by a decoupling of the electron system and phonon system in the NTD material, which constitutes an additional thermal impedance between the target crystal and the thermometer. This impedance limits the use of the detectors to very low counting rate applications, since the thermal relaxation time of the detector can not be faster than the time needed to achieve equilibrium between the electron and phonon systems, on the order of 5 ms for our detectors.

3 Ionization Measurement.

Charge produced in the crystal is drifted onto surface electrodes under the influence of 1-2 V/cm electric fields. Many different types of charge collection electrodes are possible in principle. Our usual electrodes are made by implanting boron atoms in the germanium surface to a density of 10^{19} cm^{-3}. These contacts suffer from a "dead layer" of poor charge collection near the surface which is well modeled by the equation $q_m(x) = (1 - f e^{-x/\lambda})$, where $q_m(x)$ is the fraction of collected charge at depth x in the implant. We fit data from exposure to an X-ray source with multiple low energy lines of varying penetrating power to find the constants $f = 0.3$ and λ =13 microns in an electric field of 2 V/cm [3].

The dead layer is a serious defect in these detectors because electrons incident on the detector surface from nearby beta-emitting contamination produce signals that are similar to those made by nuclear recoils. This is illustrated in figure 1c, which shows the response of a test device that was exposed to electrons from a source. We are currently studying alternative contact technologies that give improved charge collection.

4 Backgrounds and Shielding.

The setup and operation of the CDMS experiment has been described before in eg. Ref. [5]. The detectors are shielded from gamma rays by 16 cm of lead, with the inner layers made of low ^{210}Pb content material. The cryostat, which is designed to be filled with 42 detectors, or about 20 kg of total detector mass, is made almost entirely of low activity copper. All materials used were pre-screened for radioactive content.

The site of the CDMS I experiment is a shallow tunnel at the Stanford University with a 17 meters water-equivalent (m.w.e.) overburden. This is enough to effectively eliminate the hadronic cosmic ray component and reduce the muon flux to 45 $\mathrm{m}^{-2}\mathrm{s}^{-1}$. This muon flux leads to a large neutron flux from muon capture reactions on the high Z materials of the shield and cryostat. These neutrons would have interactions with our detectors indistinguishable from WIMP recoils on an event-by-event basis, so we eliminate them through a combination of active and passive shielding. Neutrons made in the lead shield are moderated down to low energies by a 25 cm thick layer of polyethylene between the lead and the cryostat. Neutrons made inside the cryostat itself can't be shielded against in this way, since there isn't enough room inside the cryostat for sufficient neutron moderator [5]. Instead, the entire shield is surrounded with a plastic scintillator anticoincidence counter, which detects the muons that make the neutrons. We have measured the efficiency of this counter for muons passing through the cryogenic detectors to be greater than 99.993% .

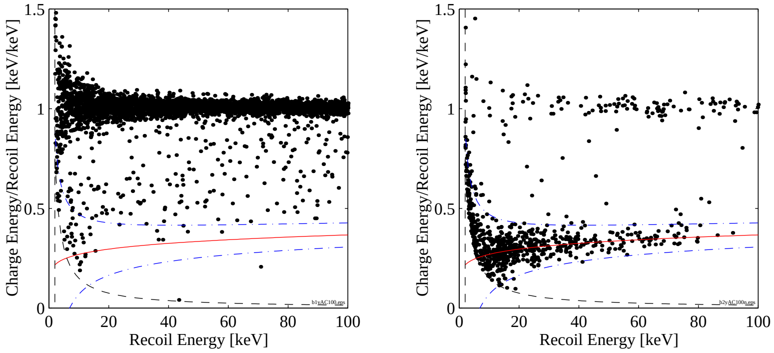
A new cryostat and shield are being prepared for an extension of our experiment called CDMS II, which will be located at the Soudan iron mine (2200 m.w.e.) in Tower, MN, USA. Detectors will be transferred to the new site when the irreducible neutron background at the shallow site from neutrons that leak through the shielding becomes the limiting factor in sensitivity.

5 Recent Results.

Figure 1 shows the results of exposing BLIP detectors to various calibration sources as well as the data from a 6.3 kg-day exposure of 2 165 g detectors with no source present. The background counting rate (Fig. 1d) appears to be dominated by electrons from nearby beta sources, which populate a band in the charge yield vs. recoil energy plane qualitatively similar to that seen in the electron calibration measurement (Fig. 1c), which was made with a small test device. At low energy, we have many events due to ^{3}H, which has a 18.6 keV beta decay endpoint energy. The level of ^{3}H contamination differs by a factor of 3 between the two detectors. At higher energies (20-100 keV), we find a smaller number of electrons of unknown origin.

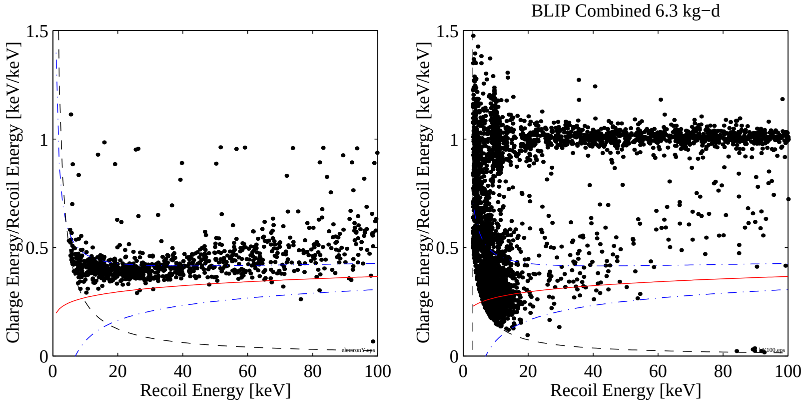
Figure 2 shows our 90% CL limits on the masses and cross sections of WIMPs that might populate our galactic halo, assuming a halo density of 0.3 GeV/c^{2}cm^3 and a velocity dispersion of 220 Km/s. In the future, we expect to improve these limits by reducing the background counting rates through reduction in contamination, improvements to the charge contacts, and further implementation of our transition-edge-sensor technology. As this paper goes to press, a new array of 4 BLIPs with better charge contacts has just begun collecting data.

Figure1. Exposure of BLIP detectors to various radiation sources. The ratio of electron-equivalent energy to recoil energy is plotted as a function of recoil energy. Dashed lines show the charge and thermal noise thresholds and the position of the nuclear recoil band, which is determined by fitting the neutron calibration data shown in (b).



(a) A 165 g BLIP exposed to gamma rays from ^{60}Co.

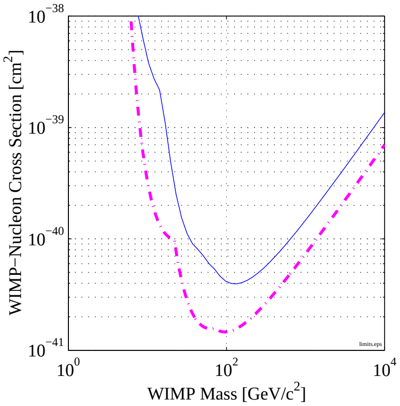
(b) A 165 g BLIP exposed to neutrons from ^{252}Cf. This source also produces some gamma rays.



(c) A small test device exposed to beta rays from ^{14}C.

(d) Combined background data from two 165 g BLIPs.

Figure2. Limits (90% CL) on masses and cross sections for coherent scattering of halo WIMPs. The solid line shows our result, which is completely enclosed at present by the envelope of limits obtained by others with conventional Ge detectors (dashed line)[6].



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