THE CDMS II DARK MATTER SEARCH AT THE SOUDAN UNDERGROUND LAB

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The Cryogenic Dark Matter Search (CDMS) experiment employs low-temperature germanium and silicon detectors in its direct-detection search for Weakly Interacting Massive Particles (WIMPs). These detectors have been operated last year at a deep site (780 m) in Soudan, Minnesota. Two distinct data sets have been produced: the first run (Run 118) used the same four Ge and two Si detectors as previously used in a WIMP-search data run at the shallow site at Stanford University (SUF), while the second run (Run 119) included two additional Ge detectors and four new Si detectors. The Run 118, with 52.6 live days exposure before cuts, currently gives the world's lowest exclusion limit on the coherent WIMP-nucleon scalar cross-section for all WIMP masses above 15 GeV: 4×10^{-43} cm^2 for a WIMP mass of 60 GeV/c^2 (90% confidence level). Run 119, with 74.5 live days exposure before cuts and more Ge detectors, is expected to have a reach 2-3 times lower than the previous Run 118 limit. We briefly discuss the CDMS experiment, the analysis methods, and present the results of Run 118.

1 Introduction

The nature of dark matter is one of the most important questions of cosmology today. The problem dates back to the observations of anomalous high kinetic energies of galaxies in a distant cluster by Fritz Zwicky in 1933 [1]. His measurements indicated that there was significantly more mass present than could be accounted for by visible matter. Since then, many observational pieces of evidence, at different cosmological scales, have been found in support of the existence of dark matter. In particular, recent observations of the Cosmic Microwave Background (CMB) [2] together with studies of large-scale clustering, the Sloan Digital Sky Survey [3,4], and supernova redshift data [5,6], have allowed more accurate measurements of the various cosmological parameters. The present picture suggests that ~23% of the energy in the Universe is in the form of non-baryonic dark matter. An even more mysterious dark energy contributes another ~73%, while only ~4% is in the form of familiar baryonic matter.

The Cryogenic Dark Matter Search (CDMS) experiment seeks to directly detect dark matter in the form of Weakly Interacting Massive Particles (WIMPs) [7], a generic name for heavy particles interacting at the weak scale with baryonic matter. Supersymmetry provides a natural WIMP candidate in the form of the lightest supersymmetric particle (LSP), which must be stable if R-parity is conserved [8,9]. Recent models favor a LSP with mass of ~100 GeV/c^2.

A reasonable model for the distribution of dark matter in our own galaxy is that it forms a roughly isothermal spherical halo with a mean velocity of ~230 kms^{-1} [10]. If the galaxy's dark matter halo is indeed composed of WIMPs, they should interact occasionally with the target nuclei in dark matter detectors on Earth. Given the above WIMP masses and velocities, the

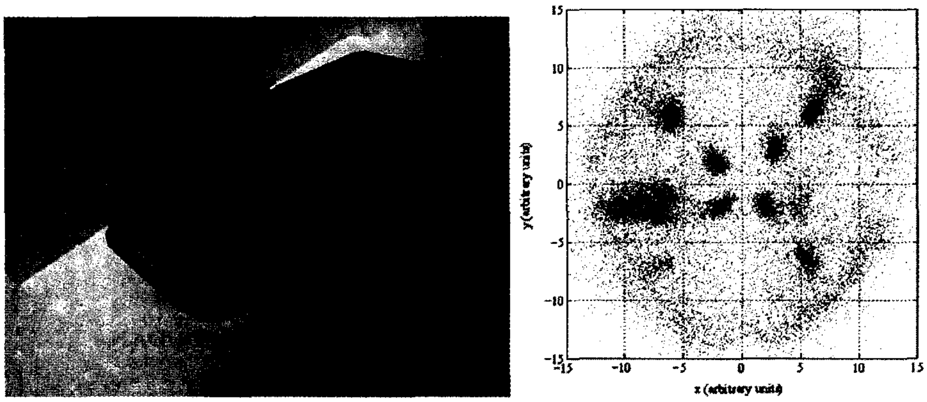

Figure 1: Left: A ZIP detector and its housing. Right: Map of the detector surface obtained by comparing the arrival times of the 4 phonon signals (each point represents one event). This has been demonstrated by exposing a Si ZIP detector to collimated sources (see text and Ref.12).

energy imparted to a nucleus in an elastic scattering would be on a scale of 10 keV, with an expected rate < 1/kg/day[11]. In order to be sensitive to such rare, low-energy elastic scatters, the CDMS-II detectors are designed to have a low energy threshold and low background event rate in the signal region. Most background particles interact with the electrons in the detector mass (e.g. by Compton scattering, K-capture, etc.), producing *electron recoils*, while WIMPs are expected to interact with the nuclei and give rise to *nuclear recoils*. The strategy of the CDMS experiment is to distinguish *event-by-event* the nuclear recoils from the electron recoils by measuring both the ionization and phonon energies of interactions within Ge and Si detectors. We also use timing information from the athermal phonon signals to further discriminate electron-recoil events near the surface of the detectors, which can be potentially mis-identified as nuclear recoils.

2 The Experiment

2.1 CDMS Detectors

The CDMS ZIP (Z-dependent Ionization- and Phonon-mediated) detectors consist of cylindrical high-purity Ge or Si crystals (see Fig. 1). Each crystal is 1 cm thick, 7.62 cm in diameter, and has a mass of 250 g (100 g) for Ge (Si). The detectors are installed in close (2 mm spaced) vertical stacks, or "towers". A single tower consists of six ZIP detectors. The close packing helps to shield the detectors from low-energy electron sources on surrounding surfaces and also increases the probability that a background event deposits energy in more than one detector, which a WIMP should not do.

An external particle interacting in the crystal deposits energy in the forms of lattice vibrations (phonons) and charge excitations (electron-hole pairs). The phonon signal is an accurate measurement of the recoil energy independent of whether the external particle interacts with an electron or with a nucleus: by the time the phonon signal is detected, the electron-hole pairs have recombined in the electrodes, releasing the energy initially dissipated in their creation. Thus, all the recoil energy has been converted to phonons and is detected. At a given energy, recoiling electrons are more ionizing than recoiling nuclei, resulting in a higher ratio of ionization to phonon signal. This ratio, normalized to 1 for bulk electron recoils, is known as "ionization yield" (see Fig. 2) and forms the primary discrimination parameter for CDMS.

Charge electrodes on the two faces of the crystal are the sensors for the ionization measurement. The electrode is divided into an inner disk, which defines the fiducial volume (85%), and an outer "guard ring" used to reject events occurring near the bare unpolished edges of the detector. The electrodes are maintained at different voltages to supply an electric field, so that electrons and holes drift through the crystal. In the case where all the electrons and holes drift across the crystal, the integrated current equals the total ionization. There are, however, two cases for which the ionization signal can be underestimated: first, charged impurities in the crystal can trap drifting electrons and holes. Routine flashing with LEDs with both electrodes grounded neutralizes these impurities, reducing the trapping by several order of magnitude. The second case corresponds to events occurring within a few μm of the detector's surface (primarily from low-energy electrons). In these *surface events*, a fraction of the electrons (or holes) can travel against the electric field and be collected on the "wrong" electrode. This effectively reduces the ionization signal, making discrimination based on ionization yield less effective. This region of incomplete charge collection is called the "dead layer".

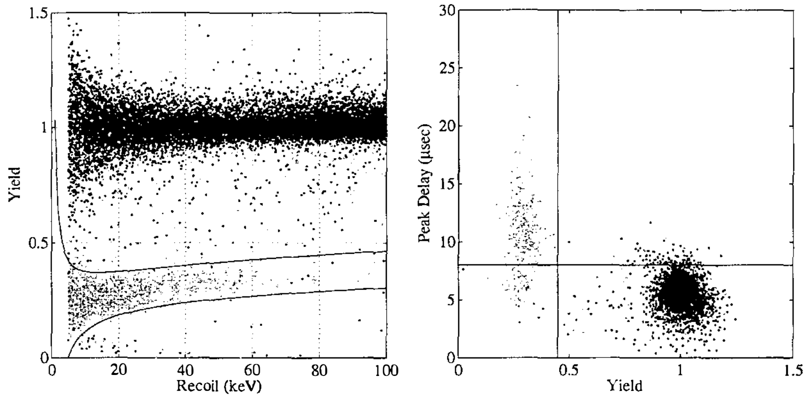

Figure 2: Ionization energy versus recoil energy (left) and ionization yield versus phonon start time (right) for a Tower 1 Ge detector. Black dots correspond to calibration events from a ^{133}Ba source (emits gammas only) and gray dots correspond to calibration events from a ^{252}Cf source (emits gammas and neutrons). The high-yield distribution of events are bulk electron recoils and the low-yield distribution of events are nuclear recoils. Surface electron recoils from the ^{133}Ba source appear as a low yield tail and have faster start time (see text).

Athermal phonons are collected using 3552 Transition Edge Sensors (TESs), photolithographically patterned on one face of the crystal. These TESs, each consisting of a 1-μm-thick tungsten film, are divided into four independent channels. The energy of the phonons is transmitted into the tungsten via superconducting Al collector fins: the phonons break Cooper pairs in the Al to produce quasi-particles, which then diffuse into the tungsten. The energy released in the tungsten raises the temperature of the film, increasing its resistance and reducing the current supplied by a voltage bias. The detector substrates are kept below ~50 mK and the tungsten is maintained stably within its superconducting transition by electrothermal feedback based on Joule self-heating.

This approach allows the extraction of additional parameters used for discriminating against surface events: the phonons pulse shape and arrival time. Electron recoils near the surface of the crystal have faster rising edges than bulk electrons recoils because of phonon interactions with the metallized surfaces. Thus, the timing parameters give an estimate for the depth (z coordinate) of the event (see Fig. 2). There is, however, a complication: these parameters depend on the (x,y) location of the interaction. The primary reason why pulse shapes vary is that the physical arrival time of phonons at the TESs depends on position: reflections off of the cylindrical surface become more important close to the edge of the crystal. This dependence can be corrected because the CDMS detectors allow a reconstruction of the position of the event: since the ZIP detectors have 4 phonon quadrants, a simple comparison of the pulse height and arrival times of the 4 phonon signals gives substantial information about the position (x, y coordinates) of each event within the crystal. This position reconstruction has been demonstrated by exposing a Si ZIP detector to a 12-hole collimated ^{109}Cd source, covering one surface of the detector, and a single-hole collimator ^{241}Am source (see Fig. 1) [12].

2.2 Shielding and Muon Veto

There are several external background sources that can imitate nuclear-recoils and therefore limit the WIMP sensitivity of the experiment: high-energy neutrons produced by cosmic ray muons interacting with the surrounding rock or shield, gamma rays and neutrons from radioactivity in the surrounding rock, and photons and electrons from radioactive impurities on surfaces. To reduce these backgrounds, the CDMS II experiment employs several layers of passive shielding as well as an active muon veto.

CDMS II is installed at the Soudan Underground Laboratory in northern Minnesota. The Soudan site provides 780 m, or 2090 meter water equivalent (mwe), of rock overburden, reducing the cosmic ray muon flux by a factor of 5×10^4. The corresponding neutron flux from the surrounding rocks is suppressed by a factor of ~ 300 compared to the shallow site at Stanford (SUF), where the first six ZIP detectors were operated during the course of 2001-2002. The remaining muon flux is tagged by an active muon veto, which consists of 40 scintillator panels surrounding the passive shielding. Each panel, connected to one or two photomultiplier tubes, have been arranged so that adjacent panels overlap. The efficiency of the muon veto is > 99.9 for muons passing through the apparatus, and > 99.4 for muons stopping within the shield. One muon per minute is incident on the veto and the combined veto rate (including ambient gammas) is 600 Hz. Within the enclosure defined by the muon veto panels, there are (from outside in) 45 cm of polyethylene neutron moderator, 9 cm of lead, 4.5 cm of ancient lead (for low ^{210}Pb content), and another 10 cm of polyethylene. The cryostat (see next section) and cold hardware surrounding the detectors constitute an average thickness of about 3 cm of copper, serving as a final shield around the detectors.

Beginning in November of 2003, the shield has been purged with a constant flow of old air to remove radon from the air near the detector volume. This purge has reduced the radon decay rate in the air around the icebox from 500 Bq/m^3 to 35 Bq/m^3, and the background of electromagnetic recoil events with low ionization yield in the detectors by a factor of two.

The remaining neutron background can be statistically estimated because they often scatter in more than one detector, and because they scatter equally in Si and in Ge detectors, whereas coherent WIMP interactions with nuclei are 6–7 times more likely in Ge than Si.

2.3 Cryogenics

The CDMS-II detectors operate at a base temperature of 50 mK inside a custom volume cooled by an Oxford Kelvinox 400-S dilution refrigerator outside the shielding. The detector cold volume is the innermost of six nested, cylindrical copper cans that together make up the CDMS cryostat or "icebox". These cans are thermally coupled to the temperature stages of the dilution refrigerator through a horizontal stem of five nested copper tubes and one solid cold finger. It is desirable for the refrigerator to be outside the shield because the refrigerator itself does not have as low a level of radioactive contamination as the specially screened copper of the icebox. The icebox is immediately surrounded by a 2-mm-thick mu-metal shield for isolation from external magnetic fields.

3 The WIMP Search Data Sets

The first Soudan WIMP-search run (Run 118) started on October 11, 2003 and lasted until January 11, 2004. Excluding time for calibration, cryogen transfers (3 hours/day), periods of elevated base temperature and high noise, we obtained 52.6 live days with the four Ge and two Si detectors of "Tower 1" [14]. The same Tower, with identical detector configuration, had been previously used in a WIMP-search data run at the shallow site at Stanford University (SUF) [13]. The hardware trigger threshold was set below 2 keV in most detectors, with a background trigger rate of 0.1 Hz.

The second WIMP-search run (Run 119) lasted from March 25, 2004 through August 8, 2004. In this run, we operated the same six detectors plus an additional two Ge and four Si (for a total of 1.5 kg Ge and 600 g Si). We obtained 74.5 live days after subtraction of bad datasets and dead times.

During both runs, the WIMP search was interrupted for calibrations, in which an external radioactive source was placed near the detectors. A ^{133}Ba gamma source with distinctive, penetrating lines at 276 keV, 303 keV, 356 keV and 384 keV, was used for energy calibration and studies of the detector response to electron-recoils. These lines are sufficiently energetic that the photons can punch through the copper cans of the cryostat and reach the detectors. As the phonon channels typically start saturating (and become non-linear) above 200 keV, we used these energy lines to calibrate the charge channels and then calibrate the phonon channels against the charge for electron-recoils. The excellent agreement between data and Monte-Carlo simulations and the observation of the 10.4 GeV Ga line from neutron activation of Ge indicated that the energy calibration was accurate and stable to within a few percent.

For Run 118, most of the barium calibration data were taken in the first half of December 2003, with occasional earlier and later calibration runs for checks of performance and stability. The Run 119 barium data sets, totaling 8 million events (roughly twice as many Ba events per detector as in Run 118), were taken more uniformly throughout the run, giving a calibration sample that has both high statistics and a similar distribution in time to the WIMP-search data. A ^{252}Cf neutron-emitting source was used to characterize the detector response for nuclear-recoils. Because exposure to the californium source activates the Ge substrate of ZIP detectors, the neutron calibration sample was kept small (215,000 events) and was not interspersed uniformly with WIMP-search data. The excellent agreement of the observed californium neutron spectrum with Monte Carlo predictions demonstrates that the recoil energy calibration using electron-recoils remains valid for nuclear recoil events.

4 Analysis

The analysis of both Run 118 and Run 119 were performed *blindly* in order to ensure an unbiased treatment. In particular, we adopted the policy that the nuclear-recoil region of the WIMP-search data was not inspected until all cuts and analysis thresholds were defined using *in situ* gamma and neutron calibrations. A preliminary, wide WIMP-search cut was defined, and all events passing this cut were hidden from users until unblinding. The very large barium calibration data set of Run 119 has been divided into two halves: one half was used for developing cuts, especially the timing cuts for rejecting surface events, while the other was masked during cut definition and later used for calculating cut efficiencies and leakage of electromagnetic backgrounds into the signal region. This procedure was not used in Run 118, due to its smaller sample of barium calibration data.

A number of data quality cuts have been applied to the WIMP-search data. We removed all non-optimal data sets (or parts of data sets), in particular periods of known poor detector performance, elevated base temperature, and higher pre-trigger noise. We also cut the events with abnormally-shaped charge pulses (pile-ups for example) and events below the analysis threshold in recoil energy (ordinarily below 10 keV). These data quality cuts removed $\sim$5% of the events. As described in section 2.1, the amplitude of the pulse in the outer ionization electrode, or "guard ring", can be used to reject events in the annular region near the outer edge of the crystal (15% of the detector volume), where the ionization signal may be incomplete.

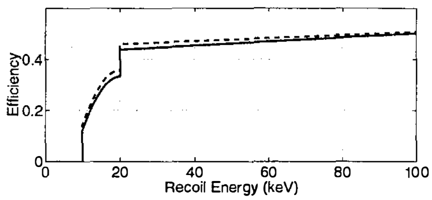

Figure 3: Run 118 efficiency of the combined cuts as a function of recoil energy, both for the blind analysis (solid) and for the second, non-blind analysis (dashed).

A combination of ionization-yield and phonon-timing cuts rejects virtually all calibration electron recoils while accepting most of the nuclear recoils. The ionization yield cuts are calculated for each detector from the californium calibration neutrons. This is the primary gamma background rejection cut of the ZIP detectors. As described in section 2.1, recoils within a few μm of a detector's surface (primarily from low-energy electrons) can have an incomplete charge collection, making the discrimination based on ionization yield less effective. However, these events can be effectively rejected by phonon timing cuts because they have, on the average, faster phonon signals than those from bulk electron recoils. The phonon timing cuts are based on both the rise time of the phonon pulses and the phonon start time relative to the ionization signal. In Run 118, we achieved 80% nuclear recoil acceptance for 20% electron-recoil acceptance by using these two timing parameters independently. Further analyses under study in Run 119 combine the existing parameters in more sophisticated ways, in particular taking into account their correlations, and define new pulse-timing parameters with richer information. The rich timing and position information provided by the ZIP detectors are expected to substantially improve the efficiency of the rejection of the electron-recoil surface events.

A conservative estimate of the combined efficiency of all cuts on a WIMP signal for Run 118 is shown in Fig. 3. The efficiency is forced to zero below 10 keV for all detectors, and below 20 keV for one Ge detector, to reflect the analysis thresholds. We estimated the number of electron-recoil events misidentified as nuclear recoils in the entire Run 118 WIMP-search data to be 0.7 ± 0.3 events for all Ge detectors [14]. Monte Carlo simulation predicted 0.05 ± 0.02 neutrons (mostly unvetoed) produced from muon interactions outside the shielding over the course of Run 118 [14].

5 Results

The blind analysis of Run 118 ("Tower 1") revealed no nuclear-recoil events in 52.6 kg-days raw exposure in the Ge detectors (between 10-100 keV) [14]. A subsequent non-blind analysis, with a more optimal pulse-fitting algorithm, contained one nuclear-recoil candidate event at 64 keV which marginally passed the fiducial volume cut. This event is consistent with the expected surface-event misidentification quoted in Section 4. Under the assumptions of a standard galactic halo, these data yield to the lowest limit on the spin-independent WIMP-nucleon elastic scattering cross-section for WIMP masses larger than 15 GeV/c^2. This limit is a factor of four below the best previous limit set by EDELWEISS [15] and a factor of eight better than our limit with the same Tower 1 at Stanford [13]. The usual interpretation of the DAMA annual modulation signal [16] under these assumptions is clearly incompatible with our Run 118 limit.

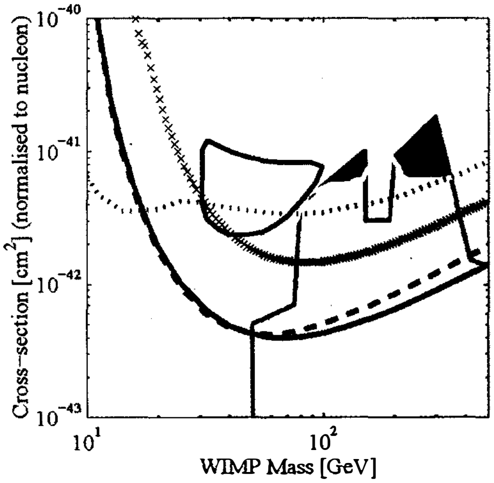

Figure 4: Current WIMP exclusion limits from CDMS-II at Soudan. The regions above each of the curves are excluded at 90% CL. The solid line is the limit from the Run 118 blind analysis, and the dashed line is from the Run 118 non-blind analysis. The thick dotted curve is the result from CDMS at Stanford. The X's are the EDELWEISS 2002 (and 2003) results. The solid region is the DAMA (1-4) 3σ allowed region under the same standard model assumptions. Further details concerning this plot can be found in Ref.14.

The Run 119, with 96.8 kg-days of Ge exposure before cuts and improved analysis methods, is expected to have a reach 2-3 times lower than the previous Run 118 limit.

Although its primary analysis focuses on WIMPs with spin-independent couplings, for which coherent scattering from the entire nucleus enhances its sensitivity, CDMS also sets competitive limits on WIMPs with spin-dependent couplings [17].

6 Future CDMS runs at Soudan

After the end of Run 119 in August 2004, we warmed up the cryogenic apparatus to install an additional eighteen detectors in the Soudan icebox. This gives a total of 30 detectors stacked in 5 Towers (4.75 kg Ge and 1.1 kg of Si target mass). Preparations are underway to start the next run with these detectors, which will complete the CDMS II project. Subsequent to CDMS II, more improved detectors may be added as part of the SuperCDMS development project (see Ref. 18 for more details).

Acknowledgments

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