The CDMS-II Dark Matter Search and SuperCDMS

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The Cryogenic Dark Matter Search (CDMS) currently sets the most stringent limits on spin-independent WIMP-nucleon cross-section. The most recent data set, with six Si and six Ge detectors, combined with a six-detector run, sets a limit of 1.6×10^{-43} cm^2 (normalized to a single nucleon) for WIMP masses of 60 GeV and standard dark matter halo assumptions. Additional detectors have been installed, for a total mass of 4.75 kg Ge and 1.1 kg Si, to be run in 2006. The SuperCDMS proposal is a phased approach to scaling the CDMS direct detection technology up to larger target masses, with 8-kg, 27-kg, 150-kg, and one-ton stages, aiming for a final sensitivity below 10^{-46} cm^2. We present the status and immediate goals of CDMS, along with the continuing progress of SuperCDMS.

1. INTRODUCTION

The Cryogenic Dark Matter Search (CDMS) is an experiment for directly detecting dark matter in the form of weakly interacting massive particles using cryogenic detectors. WIMPs are expected to elastically scatter on nuclei with cross-sections on the weak scale, depositing a few to tens of keV of energy with a frequency lower than 1/kg d [1]. CDMS-II ZIP detectors have been designed with sensitivity to these rare events, achieving thresholds at or below 10 keV in recoil energy and good discrimination against dominant backgrounds. CDMS-II has taken data in the deep experimental site in the Soudan Underground Laboratory beginning in 2003, and is currently preparing a run with a substantially increased target mass of 4.75 kg Ge and 1.1 kg Si.

In order to extend this proven technique to the larger target masses needed to explore all cross-sections on the weak scale, the SuperCDMS project envisions a larger number of detectors, on larger one-inch-thick substrates, and with other improvements to the detector design. The development of thicker, advanced detectors for SuperCDMS is now in progress, and several detectors have successfully been fabricated on one-inch-thick substrates.

2. CDMS-II

2.1. Detection technique

The CDMS-II direct detection technique is based on Z-sensitive Ionization and Phonon (ZIP) detectors, which provide rich information about each event for event-by-event background rejection. Each detector is a cylinder of germanium (250 g) or silicon (100 g), 3.81 cm in diameter and 1 cm thick. Because of their larger mass and because of the enhanced coherent scattering of heavy WIMPs off of large nuclei, the Ge targets are expected to see a higher rate of WIMP scatters than the Si targets for all but very light WIMPs. The Si targets will become useful in the event of an irreducible neutron background, since they should have a comparable rate of neutron scatters but a much smaller WIMP rate than Ge.

In order to measure ionization, the bottom surface of each detector is covered by two electrodes. The inner one is a disk covering 85% of the surface, and the outer one is an annular ring covering 15%. These electrodes are biased at -3V for Ge detectors (-4V for Si), while the top surface serves as ground. Electrons and holes produced by a particle interaction in the crystal are separated in the applied electric field, and drift to the top and bottom faces of the detector respectively. The induced charge on the bottom electrodes is recorded with a FET readout.

The phonon measurement is accomplished with tungsten transition edge sensors (TESs). Every interaction in the crystal creates an initial cloud of high-energy phonons. These scatter often and down-convert to lower energy modes, which propagate more freely. The top surface of the crystal is patterned with superconducting aluminum fins, in which athermal phonons can break Cooper pairs to create quasiparticles. The quasiparticles migrate into the active tungsten strip of the TES, warming the electron system of the W. A small voltage bias across the TES keeps it at its superconducting-normal transition temperature (70-100 mK) by Joule heating, and negative electrothermal feedback (ETF) returns it to this biased state after any excursion. Because the tungsten is on its transition, the resistance increases very rapidly with temperature, so that the small heating caused by the quasiparticles entering from the aluminum fins is detectable as a change in the bias current, measured with a SQUID array readout. The top surface of each detector is divided into four quadrants, and each quadrant is covered by 1036 TESs biased and read out in parallel. The fourfold segmentation allows the determination of each event's location in the crystal.

The simultaneous measurement of ionization and

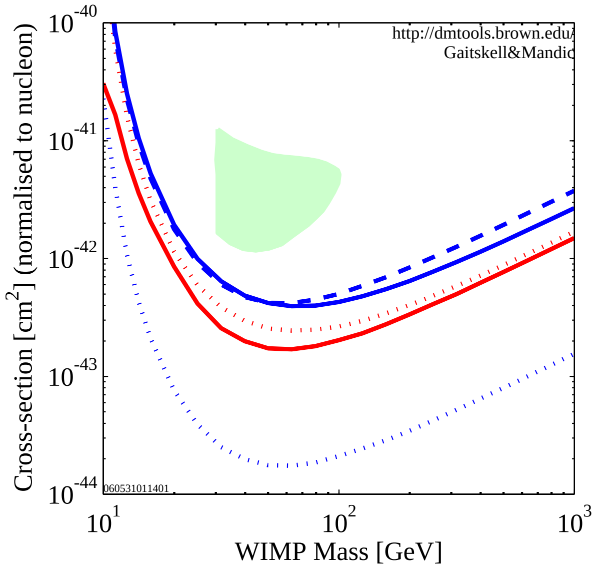

Figure 1: Current and projected WIMP exclusion limits from CDMS-II at Soudan. Parameter space above each curve is excluded at 90% confidence level. The dashed line is the limit from the Run 118 blind analysis, and the upper solid line is from the Run 118 "intended" analysis [3]. The upper dotted line is from Run 119 Ge with a 10-keV phonon threshold. The lower solid line is from Run 118 combined with Run 119 using a 7-keV phonon threshold. The lower dotted line is the projected 2007 sensitivity of CDMS-II at Soudan with five towers [4]. The solid region is the DAMA (1-4) 3σ allowed region [6] under the same standard model assumptions.

phonons gives two independent estimates of the energy deposited by a particle interaction. The phonon measurement is unquenched. The ionization of nuclear recoils is quenched by a factor of 3 relative to electron recoils with the same energy. This fact allows nuclear recoils, such as neutrons and WIMPs, to be distinguished event-by-event from electron recoils, such as gammas, X-rays, and beta-emitting contaminants, which form the dominant backgrounds. Cuts on the ratio of ionization to phonons (known as *ionization yield*) are able to reject $> 99.99\%$ of photon scatters in the energy range of interest in *in situ* calibrations with a ^{133}Ba source [3].

However, the ionization signal can be compromised near a detector's surfaces. Near the outer cylindrical edge there are field lines that end on the bare surface, so that some charges do not reach either electrode. These regions are excluded by accepting only events that are seen in the inner electrode, thus defining a fiducial volume. Near the top and bottom surfaces, some charges may diffuse to the "wrong" electrode before the drift field can effectively separate them, so that the ionization signal is suppressed. Electron recoils in this "dead region" can be misidentified as nuclear recoils and therefore WIMP candidates. In order to eliminate these problematic shallow events, the near-surface regions are excluded using phonon timing cuts.

When an event occurs near the metallized top or bottom surface of the detector, the initial high-energy phonons can down-convert more rapidly in the metal films. This allows them to be absorbed in the Al fins more readily, making the phonon pulses faster in both delay and rise time. Cuts on delay and rise time are used to reject near-surface events with efficiency $>$ 96% while retaining most bulk nuclear recoils ($>\sim$ 50%) [3].

Neutron scatters form a final background that cannot be individually distinguished from WIMP scatters. Given a number of candidate events, it is possible to statistically distinguish a neutron background from a WIMP signal in three ways. Neutrons will sometimes ($\sim$ 10% [2]) scatter in several detectors, while WIMPs will never scatter more than once. Neutrons should be seen in both Ge and Si, while all but the lightest WIMPs will be seen only in Ge. Finally, the spectrum of recoil energies produced by WIMPs and neutrons will be different for most of the possible range of WIMP masses.

2.2. Experimental site and shielding

Because neutrons cannot be distinguished from WIMPs event-by-event, it is important to achieve a low neutron background. This is achieved by placing the experiment deep underground, in the Soudan Underground Laboratory at 2090 meters water equivalent. At this depth, cosmic ray muon rate is reduced by a factor of 5×10^4 relative to the surface. The experiment is surrounded by a 45-cm-thick layer of polyethylene neutron moderator, inside of which are a 9-cm layer of lead, 4.5 cm of ancient lead (with very low ^{210}Pb content) and another 10 cm of polyethylene as the innermost layer. The polyethylene further reduces the flux of high-energy neutrons. Because most of the remaining neutron flux is produced by cosmic ray muons, an active muon veto surrounds the experiment. From simulations, the rate of unvetoed neutron events in the Soudan site is approximately 0.6 events per kg per year in Ge and 1.5 in Si [3, 4].

2.3. Data sets

CDMS-II has taken two data sets in the Soudan site: one, known as Run 118 [3], lasted from October 2003 through February 2004, while the second, known as Run 119 [4, 5], lasted from March through August 2004. Run 118 used one tower of six detectors: four Ge (1 kg) and two Si (200 g), and accumulated a total Ge exposure of 52.6 kg-days before cuts, or 22 kg-days after data quality and background rejection cuts. Run

119 added a second tower of six detectors, for a total of six Ge (1.5 kg) and six Si (600 g), and accumulated a total Ge exposure of 110 kg-days before cuts, or 34 kg-days after cuts.

During each running period, *in situ* calibrations with a ^{133}Ba gamma source and a ^{252}Cf neutron source were also taken. The ^{133}Ba data were interleaved with the WIMP-search data, and during Run 119, several hours of Ba data were typically taken every day. In order to limit the activation of the detectors by neutrons, the ^{252}Cf calibration was limited to a few hours on a few occasions during each run.

2.4. Analysis

In order to avoid the possibility of bias, both Run 118 and Run 119 were analyzed in a blind manner: the cuts were defined using the calibration data only, and the cut efficiencies and expected leakages were calculated using calibration data and the part of the WIMP-search data well outside the signal region. These tasks were completed while the WIMP-scattering signal region was still hidden.

Several classes of cuts are applied to the raw data. Data quality cuts exclude about 5% of all data: periods of bad data (as defined without looking in the signal region), pileup events, noise bursts, and events below the phonon energy threshold (typically 10 keV) or ionization threshold (typically 1-3 keV). Multiply-scattering events and events coincident with hits in the muon veto are rejected, with a negligible loss in efficiency for WIMPs.

A fiducial volume cut rejects events in the outer electrode (15% of the volume, although the cut is more strict in practice). In Run 118, the fiducial volume cut of the blind analysis was defined using a slightly noisier ionization energy estimate than the intended one, resulting in a slightly lower acceptance. Subsequent work after unblinding replaced this with the less noisy energy estimator; this was known as the "intended" analysis.

The nuclear recoil cut accepts only events with ionization yield contained in the nuclear recoil band, as defined using ^{252}Cf calibration neutrons, and has high efficiency. Finally, phonon pulse timing cuts reject events near the surfaces. Run 118 used simple cuts on the delay and rise time of the largest phonon pulse in any of the four phonon channels of the detector, with a nuclear recoil acceptance of about 50%. Run 119 used a similar, well-understood cut for the primary Ge result, but four additional timing analyses were also developed. These are capable of improved nuclear recoil acceptance without increasing the surface event leakage.

2.5. Results

Under the primary, blinded analysis, the Run 118 WIMP-search data set yielded no candidate events. The subsequent "intended analysis," with slightly higher acceptance in the fiducial volume cut, found a single event at 64 keV in a Ge detector, consistent with estimates of the background from beta-emitting surface contaminants[3].

The Run 119 WIMP-search data contained a single candidate event after all cuts. This event, at 10.5 keV in a Ge detector, would also be consistent with the expected background. Subsequent investigation showed that this event occurred during a period of compromised detector performance after the detectors were exposed to a very strong calibration source. Therefore, this event is interpreted as an ordinary gamma scatter in a time period that should have been excluded. Because it was not excluded by the data quality cuts defined in the blind analysis, however, it is counted as one event in setting exclusion limits from Run 119 [4].

WIMP exclusion limits in the cross-section - mass plane are shown in Fig. 1. The Run 118 limits are shown for both the zero-event blinded analysis, and the "intended analysis" with one event. A standard isothermal, spherical WIMP halo is assumed, with a mean WIMP velocity of 230 km/s. All cross-sections are normalized to a single nucleon. Only the spin-independent case is shown here.

2.6. Current status

Since the end of Run 119, three additional towers have been installed in the Soudan facility, for a total of 30 detectors (19 Ge and 11 Si, or 4.75 kg Ge and 1.1 kg Si). Because of improvements in handling during detector fabrication and testing, the three new towers are expected to be cleaner than the two used in Run 119, and it is hoped that they will show a substantial decrease in beta-emitting surface contaminants. A cooldown for the beginning of the five-tower run is scheduled for June 2006, and the run will continue through December 2007.

The existing Run 118 and Run 119 data sets are being re-analyzed together in a unified analysis. This will further develop the advanced analyses, and apply them to the full data set.

CDMS-II has demonstrated its ability to achieve good background rejection and low thresholds, and remains limited by exposure. Scaling this proven technology up to larger masses is a clear avenue to a next-generation dark matter search experiment.

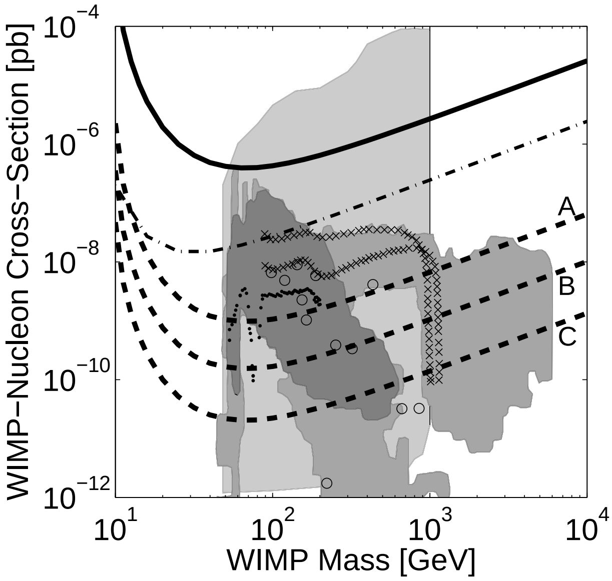

Figure 2: Projected WIMP sensitivity of SuperCDMS. The solid line shows the exclusion limit from Run 118, and the dot-dashed line indicates the expected final sensitivity of the five-tower run. The three dashed curves show the proposed reach of SuperCDMS phases A, B, and C. The lightest gray region is the theoretical region of interest from a scan of MSSM parameter space [10]. SuperCDMS will probe nearly all recently-proposed split-supersymmetry models (Xs [11] and dots [12]) and much of the mSUGRA region [13] (medium gray), including most post-LEP benchmark points [14] (circles) and nearly all the subset (dark gray) consistent with a supersymmetric interpretation of muon g - 2 measurement.

3. SuperCDMS

The SuperCDMS proposal takes a phased approach towards a ton-scale dark matter search. SuperCDMS Phase A envisions a 27-kg experiment, Phase B is 150 kg, and Phase C is 1000 kg. Bridging the gap between CDMS-II and SuperCDMS, a development project has been proposed to run 5 kg of SuperCDMS detectors in the existing CDMS-II facility in Soudan in 2008. The phased approach ties increases in mass to continuing improvements in detector fabrication and data analysis, and background reductions, so that each stage can remain background-free [7–9] in exploring new WIMP parameter space (see Fig. 2).

3.1. Surface contaminants

The dominant background in CDMS-II is that of beta-emitting surface contaminants. Work is in progress to identify the source of these contaminants and minimize exposure to them in fabrication, handling, and testing. Surface analysis points most strongly to contamination by daughter products of radon that can plate out on detector surfaces. One of these, ^{210}Pb, undergoes beta decay with an energy of 63.5 keV and a 22-year half life. The exposure of the final three towers of CDMS-II to radon has been minimized, so the upcoming five-tower run will indicate the degree of further improvement needed to achieve the factor of five reduction in beta backgrounds relative to Run 119 targeted for SuperCDMS Phase A [7].

SuperCDMS Phase A projects that improvements in analysis techniques will yield an improvement of a factor of four in surface event rejection relative to Run 118. The advanced analyses developed during Run 119 are already approaching this goal. A combined analysis of the existing Run 118 and Run 119 data sets will further develop these techniques.

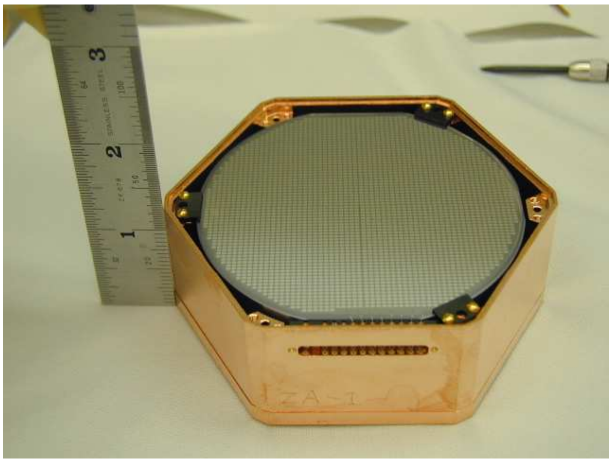

Figure 3: The first one-inch ZIP detector prototype for SuperCDMS, fabricated at Stanford and ready for cryogenic testing.

3.2. Experimental site

Although the neutron flux at Soudan is satisfactory for CDMS-II, it would become a significant background for SuperCDMS phase A and limiting for phases B and C. Therefore, a deeper site is needed. SuperCDMS has submitted a letter of intent to the SNOLab underground facility in Sudbury, Ontario, and received a strong endorsement from SNOLab as the site for Phase A. This site, at 6060 meters water equivalent, has a neutron rate of one per ton per year, low enough to be potentially suitable for all phases of SuperCDMS.

3.3. Detectors

Several detector improvements are envisioned as part of SuperCDMS, focused on increasing the target mass and improving the rejection of surface contaminant backgrounds. The target for SuperCDMS Phase A is a factor of five improvement in beta rejection. The basic detector for SuperCDMS is similar to the

CDMS-II ZIP detector, but fabricated on a 2.54-cm substrate instead of a 1-cm substrate. This gives a target mass of 635 kg per Ge detector, without increasing the area of the problematic top and bottom surfaces. In addition to the increase in thickness, the geometry of the TESs and Al fins has been optimized for faster phonon collection and better timing resolution.

The first one-inch Ge and Si models have successfully been fabricated, and are currently being tested (Fig. 3). These will be the detectors for the SuperCDMS development project and Phase A.

A variation on the ZIP detector design, known as the interleaved ZIP or iZIP, symmetrizes the phonon and ionization sensors without increasing the number of channels to be read out. Each face of the detector has one ionization electrode and two phonon sensors. This design has the potential to greatly improve surface event rejection through the partition of charge collection and through phonon timing. Several 1-cm iZIPs have recently been manufactured and tested [15].

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