Dark matter direct detection with SuperCDMS
Soudan

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Abstract. The Cryogenic Dark Matter Search Experiment (CDMS) and its successor, SuperCDMS, have had a long history of establishing world-leading upper limits on the interaction of Weakly Interacting Massive Particles (WIMPs) with standard model nucleons. SuperCDMS uses arrays of cryogenic germanium detectors to achieve excellent discrimination between the nuclear recoils expected for WIMP interactions and radioactively produced electron recoils through the collection of ionization and athermal phonons. Recent analyses of the data collected from the current installation of Interleaved Z-Sensitive Ionization and Phonon (iZIP) detectors have probed new regions of the WIMP parameter space, particularly in the region of low-mass WIMP interactions. This paper will discuss the current work of the SuperCDMS collaboration.

1. Motivation
There is strong evidence that approximately 27% of the mass-energy density of the universe is comprised of an invisible, non-interactive component commonly known as “dark” matter [1]. Astrophysical and cosmological constraints require that the dark matter be cold, neutral, stable, and massive, with weak scale interactions [2, 3], while compelling evidence from cluster merger 1E0657-558 (the “Bullet Cluster”) provides support for the argument that the majority of dark matter is also non-baryonic [4]. Extensions to the standard model of particle physics provide several promising candidates, including a class of supersymmetric candidates collectively known as “Weakly Interacting Massive Particles”, or WIMPs [3, 5].

2. CDMS, SuperCDMS and the iZIP detector
The Cryogenic Dark Matter Search Experiment (CDMS) [6, 7, 8, 9, 10] seeks to directly detect nuclear recoils from the elastic scattering of WIMP dark matter on the nuclei of semiconducting crystals cryogenically cooled to \( \sim 50 \text{ mK} \). CDMS uses Z-sensitive Ionization and Phonon (ZIP) detectors (Figure 1, left) to perform simultaneous measurements of ionization and athermal phonon signals, for event-by-event discrimination in the removal of backgrounds. For each event, the ionization yield (Figure 1, right) can be defined as the ratio of ionization to phonons,

\[
Y = \frac{Q}{P},
\]

where \( Q \) is the collected ionization energy and \( P \) is the phonon recoil energy. The suppression of ionization yield in nuclear interactions relative to electron interactions provides the ability to
discern between nuclear and electron recoils, in turn establishing a significant handle for removing backgrounds from the analysis. The expected scenario in the CDMS detection paradigm is the following. An entering WIMP scatters from an electron or nucleus within the detector, resulting in the release of ionization and phonons within the crystal. Application of a bias voltage across the crystal allows collection of the released charge carriers. Meanwhile, athermal (recoil and Luke-Neganov) phonons are collected by arrays of superconducting tungsten Transition Edge Sensors (TES) [11]. Detailed descriptions of the readout chain and data acquisition systems have been addressed in past publications (see, for example, [12]).

While ionization yield is an excellent discriminator, incomplete ionization collection can lead to the leakage of background events into the nuclear recoil region. In particular, past challenges include leakage from surface events on the top and bottom of the detector, where the charge collection faces attrition due to electronic carrier trapping [13]; and sidewall events, where trapping may occur on the outer walls of the detector and the charge is not fully collected on the ionization electrode. This challenge was especially prominent in the detectors of CDMS II, which collected ionization on one side and phonons on the opposite side (Figure 1, left) [6].

Beginning with the installation of SuperCDMS, the detector design was significantly modified to address the surface event backgrounds faced by CDMS and CDMS II. The Interleaved Z-sensitive Ionization and Phonon (iZIP) detector was developed in part to address the issue of incomplete ionization collection by allowing collection of both charge and phonons on both sides of the detector (Figure 2). Each face of the detector contains 4 phonon readout channels: 3 inner channels and an outer guard ring. Each side also contains an inner and outer electrode for charge fiducialization. Ionization and phonons are collected on both sides of the detector; biasing of the charge sensors determines the charge carrier collected on each side. Surface events are collected completely on one side of the detector. A uniform field is established in the bulk of the crystal, drifting charge carriers symmetrically to both sides (Figure 3). Surface event discrimination and identification of events collected in the outer electrode allow the definition of an optimal fiducial volume for analysis and enable an efficient separation of surface and bulk events. The interleaving of the phonon and ionization rails creates a complex electric field concentrated at the surfaces of the detector, such that events occurring near a surface are entirely collected on one side of the detector.
Figure 2. Top-side layout of the iZIP detector. Note the “mercedes” geometry of the interior channels and the interleaving of the ionization and phonon rails. The ionization lines and phonon sensors on each side are interleaved with a 1 mm pitch. The detectors are operated with a 4 volt bias across the crystal, with ionization lines on side 1 biased at +2V and side 2 biased at -2V, while the phonons sensors are 0 volts. The detectors are 76 mm in diameter and 25 mm thick. Figure from [14].

Figure 3. Electric field lines produced by interleaved ionization and phonon lines in the iZIP detector. Figure from [14].

3. SuperCDMS Soudan Installation
SuperCDMS is an upgrade to the CDMS and CDMS II experiments, and is currently running as a five-tower installation of germanium iZIP detectors in the Soudan Underground Laboratory (SUL) in Soudan, MN, located in an iron mine 2341 feet underground. SuperCDMS employs both passive and active shielding (Figure 4) to reduce external photon and neutron backgrounds from radioactive and cosmogenic sources, and is surrounded by successive layers of copper (∼0.5 cm), lead (22.5 cm), and polyethylene (50 cm) [6]. The shielding is surrounded by a 5-cm-thick muon scintillator veto, which identifies any influx of charged particles (in addition to some neutral particles). Furthermore, the mine in which SUL is housed provides a 780 meter rock overburden, which is 2090 meters water equivalent (mwe). The latter reduces the surface muon flux by a factor of $5 \times 10^4$ [6]. Nuclear recoils due to external neutrons are well suppressed by the
4. Current work, recent studies, and analysis results

In continuation of the search for WIMPs, there have been a number of ongoing and recently published studies by the SuperCDMS collaboration involving the CDMS II germanium ZIP detectors and the currently installed iZIP detectors of SuperCDMS Soudan.

4.1. Continuing studies

CDMS II reanalysis  
SuperCDMS has undertaken a reanalysis of the data from CDMS II. This reanalysis was prompted by the discovery of an issue in the algorithm for the reconstruction of ionization pulses which required an upgrade in the software [23]. The publication for this
analysis is currently in preparation.

**Search for annual modulation** SuperCDMS is searching for an annual modulation in the data from CDMS II. Analysis of the data above a threshold of 5 $keV_{nr}$ (i.e. keV, nuclear recoil equivalent energy; threshold set by the trigger efficiency) [16] yielded no significant modulation in the CDMS II low-energy data. Studies are underway to study the systematic uncertainties of an analysis extending to lower energies. This publication is also in preparation.

**Nuclear recoil energy scale** The nuclear recoil energy scale in Ge is important for understanding the energy scale of nuclear recoils in germanium. This analysis compares Monte Carlo to neutron calibration data. This publication is in preparation.

### 4.2. Low energy germanium likelihood analysis

In 2014, the SuperCDMS collaboration released a maximum-likelihood analysis of the low-energy germanium data in CDMS II [17] using a combination of GEANT4 Monte Carlo and calibration data to model the detector backgrounds. In contrast to an earlier, external analysis of the low-energy germanium data, which claimed a significant excess in the nuclear recoil event rate, CDMS found no statistically significant WIMP component.

### 4.3. Demonstration of rejection for iZIP detectors

The surface rejection of the iZIP detectors (Figure 5) operated at SUL was demonstrated in a study of the effect of surface and housing contamination from Pb-210, a product of the radon decay chain [14] (Figure 6). Two Pb-210 sources were installed on side one and two of the top and bottom detectors, respectively, of iZIP Tower 3, yielding approximately 70 events per hour per source. Using detector T3Z1 with the lead source facing side 1, the rejection power of the iZIP was studied on approximately 2500 live-hours of Ba-133 calibration data (Figure 7), and established an upper limit on the leakage fraction of less than $1.26 \times 10^{-5}$ at the 90% confidence level between 8-115 $keV_{nr}$. One low-yield outlier was observed in the ionization yield plane which was easily removed with the application of a phonon symmetry cut. This study demonstrated the rejection requirement for the use of iZIP detectors at SNOLAB. See the article on “SuperCDMS SNOLAB Dark Matter Search” by P. Brink, this proceedings.

### 4.4. SuperCDMS Soudan low threshold analysis

The SuperCDMS low threshold analysis [18] was conducted using 7 low-threshold detectors selected from the current 5-tower iZIP installation in SUL. A blind analysis was performed on
Figure 7. Left: Charge symmetry selection of bulk events in iZIP detector. Blue points pass the symmetry cut (approximately equal energy deposition on both sides of the detector); red points fail the charge symmetry selection. Middle: Ionization yield versus recoil energy of Ba-133 calibration data. The red points (surface events) failed the charge symmetry selection shown on the left. Blue points pass the charge symmetry selection. One low yield outlier is easily removed via application of a phonon symmetry cut. The green band shows the \( \pm 2 \sigma \) nuclear recoil signal region, based on calibration data from Cf-252. Right: Charge partition of Ba-133 events. Electron recoils and surface events are well separated from the signal manifold. Figures from [24].

Figure 8. Left: Candidate events from the SuperCDMS low threshold analysis (2014) [18]. Right: 90 % Upper-limit on SI WIMP interactions, 95 % C.L (black). Figure from [18].

a 577 kg-day exposure, using a boosted decision tree (BDT) approach to search for light-mass WIMPs. At the time of publication (Figure 8), this analysis was the most sensitive search for light-mass WIMPs between approximately 3.5-6 keV\(_{nr}\), establishing a new upper-limit of \( 1.2 \times 10^{-42} \text{ cm}^2 \) at 8 GeV/c\(^2\).

4.5. CDMSlite

In CDMSlite, a single iZIP detector (~0.6 kg) is operated in a special one-sided configuration at high voltage, allowing for the Luke-Neganov amplification of ionization energy deposited during detector interactions [19]. This configuration attained a low energy threshold of 170 keV\(_{ee}\) and allows previously unprecedented sensitivity to low-mass WIMP interactions, establishing a new upper-limit of \( \sim 4.5 \times 10^{-42} \text{ cm}^2 \) at 6 GeV/c\(^2\) (Figure 9).
4.6. SuperCDMS high mass WIMP search

Currently, SuperCDMS is engaged in the analysis of the first high-threshold results from the 5-tower iZIP installation at SUL. SuperCDMS has operated a complement of 15 detectors for \( \sim 2 \) years of low-background running, interspersed with periods of Ba-133 and Cf-252 calibration data. The analysis is currently underway. Related studies include the work of J. Morales, “Understanding sources of noise in the Ge detectors of the CDMS experiment”, in this proceedings. Furthermore, significant progress is being made in the modeling of backgrounds and detector response using GEANT4 and the detector Monte Carlo. Additional details on this work will be discussed in future publications. Finally, with the allowed regions of minimal extensions to supersymmetry (SUSY) becoming increasingly constrained by experimental limits, a number of published works have begun to address the experimental implications of additional WIMP operators beyond the standard SD/SI interactions (see, for example, [20]). Several members of the collaboration have begun to explore a broader range of WIMP nucleus interactions describable by effective field theory (EFT) in the context of SuperCDMS [26].

4.7. Charge Transport

As detector sensitivity requirements become more demanding, a thorough understanding of detector behavior, including the characteristics of charge transport in germanium, becomes increasingly important. Studies on charge transport in high purity, low temperature germanium are discussed in the work of A. Phipps (“Charge carrier transport and capture in low temperature, high purity germanium”) and R. Moffatt (“Two-dimensional spatial imaging of charge transport in germanium at low temperature”), this proceedings.

4.8. R&D: Towards SuperCDMS SNOLAB

Research and development towards the next generation of cryogenic dark matter detectors has been conducted in parallel with current SuperCDMS operations. In the summer of 2014, SuperCDMS SNOLAB was selected as one of three primary generation-2 dark matter search experiments. A full discussion can be found in this proceedings in the work of P. Brink (“SuperCDMS SNOLAB Dark Matter Search”). In addition, performance measurements of the next generation 100-mm iZIP detectors conducted at the SuperCDMS test facility at the University of Minnesota is presented in the work of A. Kennedy (“Initial phonon and ionization
measurements of 100-mm-diameter germanium dark matter detectors for use in SuperCDMS SNOLAB”), also in this proceedings.

5. Conclusion

The SuperCDMS collaboration is currently engaged in a full program of of analysis, operations, and research and development for the next generation of dark matter direct detection through the use of high purity, low temperature germanium detectors. Analysis of the approximately two years of data collected with the currently installed iZIP payload is underway, while the detectors remain cold and running at Soudan Underground Lab. Continuing analyses of data collected with CDMS detectors have made significant progress, with several publications in preparation, along with concerted efforts to enhance understanding of the backgrounds and detector characteristics. We are optimistic that the cryogenic germanium detectors of the SuperCDMS experiment will continue to play a major role in the future of dark matter direct detection.

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