CDMS and SuperCDMS

Wolfgang Rau
for the CDMS and SuperCDMS collaborations
Department of Physics, Queen's University Kingston ON, K7L 3N6, Canada
E-mail: rau@owl.phy.queensu.ca

Abstract. The CDMS experiment has operated cryogenic Ge and Si detectors for several years in a well shielded underground environment searching for signals from Weakly Interacting Massive dark matter Particles (WIMPs). Due to the low background and excellent background discrimination power, CDMS has provided the best sensitivity for WIMP-nucleon interactions for most of the past decade. New detectors with larger mass and further improved background discrimination, developed for the successor experiment SuperCDMS, have recently been deployed; WIMP search measurements are foreseen to resume before the end of 2011. In this paper we discuss the results from CDMS - in particular the constraints on low mass WIMPs recently proposed to explain results from other dark matter experiments - and present the status of and plans for SuperCDMS.

1. Introduction

Weakly Interacting Massive Particles (WIMPs) [1] have been proposed as one of the most probable solutions to the long standing dark matter problem [2]. Simple kinematic considerations lead to the conclusion that – due to the galactic escape velocity of about 600 km/s – elastic scattering of galactic WIMPs with electrons would in most cases lead to negligible energy transfer, while nuclear recoils will yield energies in the range of tens of keV. The very low expected interaction rate [3] stands in stark contrast with the high rate of interactions from environmental radiation in an unshielded detector. In direct dark matter detection experiments, shielding against cosmic radiation is achieved by operating in deep underground laboratories [4] and using veto detectors for the remaining cosmic ray muons, while environmental radioactivity is suppressed by elaborate shielding configurations and careful selection of construction materials. Suppression of remaining background is often achieved by detector specific methods to discriminate between electron recoil background and candidate nuclear recoil events.

The Cryogenic Dark Matter Search (CDMS) experiment has achieved an unprecedented control and understanding of the background in its cryogenic ionization detectors. Over much of the past decade CDMS has provided the most sensitive test of potential WIMP-nucleon interactions [5, 6, 7, 8, 9, 10] and was only recently surpassed by the XENON experiment [11]. SuperCDMS, the successor of CDMS, is about to start measurements with new and improved detectors [12] and an increased target mass with the aim to enhance the sensitivity by a factor of about 5-8, being limited by the residual cosmogenic background at the current location. The next phase of SuperCDMS with a further increase in target mass by an order of magnitude is planned to be installed at SNOLAB near Sudbury, ON (Canada), the deepest large underground laboratory worldwide.
Section 2 describes the CDMS technology, followed by a discussion of our main data analysis (section 3) and a discussion of the recent joint analysis of CDMS and EDELWEISS data (section 4). Section 5 is dedicated to a specific analysis aimed at lowering the analysis threshold at the cost of an increasing background, in order to gain sensitivity for WIMPs with masses below 10 GeV. Finally we will discuss the status of the SuperCDMS experiment at the Soudan Underground laboratory (section 6) and our plans to move to SNOLAB (section 7) which includes a discussion of a detector test facility to be installed at SNOLAB in 2012.

2. CDMS Technology
CDMS detectors are based on cylindrical germanium or silicon single crystals, 7.6 cm in diameter and 1 cm high, which are equipped with a phonon sensor to measure the deposited energy and a charge collecting electrode to identify the type of interaction based on the ionization efficiency or yield, which is the ratio of the amount of collected charges to the total energy deposited in the primary interaction.

The phonon sensor is a superconducting tungsten film evaporated onto one of the flat crystal surfaces. The tungsten is held in the transition from the superconducting to the normal state (therefore called Transition Edge Sensor or TES) where a small change in temperature leads to a large change in the measured resistance. The phonon sensor is divided into four quadrants, each of which consists of about 1000 individual TES connected in parallel. The detectors are operated at roughly 40 mK.

The aluminum grid on the opposite face of the detector through which the bias voltage (typically 3 V) is applied, acts as charge collecting electrode. The grid is separated into two sensors, an inner disk and an outer ring, allowing us to discard events with incomplete charge collection caused by the distorted electric field at the edge of the detector. Figure 1 shows a sketch of the sensor layout of the CDMS detectors.

![Figure 1](image)

**Figure 1.** Sensor layout of CDMS detectors: one side is equipped with four phonon sensors (in quadrants), while the other side has two concentric charge electrodes. Events where the dominant charge signal occurs in the outer electrode are discarded. The phonon sensor layout allows event position reconstruction.

The phonon signal carries information about the event position, including the depth or z-position, giving rise to the name Z-sensitive Ionization and Phonon detector or ZIP. For more details about the detectors see e.g. [13].

The detectors are mounted in stacks of six, attached to a mechanical structure (the tower) with low heat conductivity, which brings the detector wiring up to 4 K and holds the first stage amplifier circuits (SQUID based for the low-impedance phonon sensors and FET based for the high-impedance charge readout). The towers are mounted in the innermost of a set of nested copper cans (icebox) which are attached to the different thermal stages of a dilution refrigerator by a horizontal set of concentric cold fingers. Thanks to this configuration the detectors can be fully surrounded by lead and polyethylene shielding against gamma and neutron radiation from the environment as well as radioactive trace contamination in the refrigerator. The outermost layer of the setup is a set of plastic scintillator detectors to identify residual cosmic ray muons (muon veto) which may interact inside the setup and generate WIMP like events [13]. The setup has been operated for WIMP search from 2003 until 2008 with up to five towers (30 detectors).
3. Main CDMS Analysis

The analysis is described in detail in [10]. Here we give a short summary of the main points.

Out of the 30 CDMS ZIP detectors 19 were from germanium and 11 from silicon; due to their better performance and much higher sensitivity for WIMP interactions, only germanium detectors were considered in the analysis discussed here. Several of the detectors suffered from insufficient performance during parts of the measurements. The data from these detectors were removed from the dark matter search for the respective periods; however they were included in the identification of multiple scattering which cannot happen for WIMP interactions. For all remaining detectors events in the outer part (identified by the outer charge electrode) were removed since the distorted electric field configuration at the edge of the detector can lead to reduced charge collection and thus to a potential misidentification of electron recoils as WIMP-candidate events.

A major part of the analysis is a careful analysis of the expected background. Two major types of background need to be considered: the first type are interactions from neutrons which produce nuclear recoil events and therefore are not distinguishable from WIMPs on an event-by-event basis; the second type are surface electron recoil events which suffer from reduced charge collection.

Neutrons from radioactive processes in the material surrounding the experiment (mostly the rock walls) are negligible due to the thick polyethylene shielding. Neutron background from construction material in the experiment is estimated based on contamination measurements of such materials. The event rate from this source is expected to be in the range of 0.03-0.06 for the latest data period comprising a total of 612 kg-days (raw exposure).

Neutrons can also be produced by muons interacting in material surrounding the detectors; those neutrons can have very high energies and thus penetrate the neutron shielding, leading to an expected background of $0.04^{+0.04}_{-0.03}$ events in the same data set. Muons interacting in the experimental setup can be identified thanks to the highly efficient (well above 99%) muon veto detectors (for details see e.g. [13]) and thus do not contribute to the background.

When produced close to the electrodes, the initially energetic charge carriers can move against the external electric field and enter the wrong electrode which reduces the amount of collected charges. This can lead to electron recoils with a reduced charge yield typical for nuclear recoils. Fortunately also the phonon signal of such events is changed: the fast thermalization due to the phonon-electron interaction in the metal layers at the nearby surface leads to a difference in pulse shape, identifying these surface events. This discrimination, however, is not perfect and comes at a significant cost of signal efficiency. In the latest data set the expected background from this source is $0.8^{+0.3}_{-0.2}$ events and thus dominates our background estimate.

The complete analysis was performed based on calibration data (gamma and neutron calibrations), multiple scatter events and events outside the signal region to avoid bias (blind analysis). The effective exposure of the latest data period, after all the discussed data selection criteria were applied, was 194 kg-days. After finalizing the analysis, the signal region was inspected for the first time and 2 candidate events were identified. This is perfectly compatible with the expected background of roughly one event total and a careful inspection concluded that the parameters of the events allow no further conclusion about the true nature of the events (residual surface event background or actual nuclear recoil events). Combined with earlier data taken with the same setup this leads to an upper limit on the WIMP-nucleon cross-section as shown by the light (red) solid line in figure 2. [10] The limit is calculated based on Yellin’s optimum interval method [14]. The two kinks in the limit curve (around 40 GeV and 70 GeV respectively) are a consequence of this method since different intervals are selected to determine the limit for different mass ranges.
4. Joint CDMS-EDELWEISS Analysis

The EDELWEISS experiment also uses cryogenic germanium detectors to search for potential WIMP-nucleon interactions [15]; the effective exposure of CDMS (energy dependent with a maximum of 379 kg-days) is slightly lower than that of EDELWEISS (384 kg-days), but the EDELWEISS threshold is higher (20 keV compared to \(\sim 10\) keV for CDMS) with a few background events just above threshold. Overall CDMS is slightly more sensitive especially at lower WIMP masses. The similarity in both technology and sensitivity prompted us to pursue a joint analysis [16]. Since the same target material is used it is straightforward to just add the effective exposure and combine the list of candidate events in order to obtain a combined upper limit on the WIMP-nucleon cross-section. The result of this analysis is shown in figure 2 together with the individual CDMS and EDELWEISS limits. The slightly reduced sensitivity of the combined analysis when compared with CDMS data alone results from the events just above threshold in the EDELWEISS data set. For comparison also the most recent limit from the XENON100 experiment is plotted which is so far the only experiment that surpassed the CDMS sensitivity.

![Exclusion limits on the spin-independent WIMP-nucleon cross-section under standard assumptions about the galactic dark matter halo (for details see the individual references). The light (red) solid line is the limit derived from the standard analysis of CDMS-II data [10]. Also shown are the more recent limits from EDELWEISS (dash-dotted) [15] and XENON100 (dotted) [11]. The black solid line is the result of the joint analysis of CDMS and EDELWEISS data [16].](image)

There are in fact different possibilities to combine the data of different experiments. For this first joint analysis it was decided beforehand that the above method, just adding exposures and event lists, should be used; however we considered a set of different possibilities [17] which take advantage of the a-priori knowledge of the differences in expected background between the two experiments. More details about the advantages and disadvantages of some of these methods can be found in [16].

5. Low Threshold Analyses

Several experiments in the field of direct detection of dark matter have claimed evidence for a positive signal, most notably the DAMA/LIBRA collaboration, observing an annual modulation in the low energy region of their recoil spectrum in a large NaI target, which is proposed to be caused by the variable speed of the earth relative to the galactic WIMP distribution due to the combination of the earth’s rotation about the sun and the sun’s movement within the Milky Way [18]. A more recent claim comes from the CoGeNT experiment which employs low-background and low-threshold germanium detectors operated at 77 K. An exponential rise in the low-energy part of the spectrum is interpreted as evidence for WIMP scattering in the detector [19]. Hooper et al. [20] proposed a consistent interpretation of the results from DAMA and CoGeNT in terms...
of low-mass WIMPs. More recently also CRESST published data showing an excess of events consistent with a low-mass WIMP interpretation [21].

The energy transfer to a given target nucleus drops strongly with the WIMP mass as shown in figure 3. Lowering the threshold thus can drastically increase the expected interaction rate for low mass WIMPs. The threshold in the standard CDMS analysis is set with the goal to have a near background-free experiment which leads to the maximum discovery potential; however, even at low energy the event rate is rather low. Thus a lower threshold in CDMS leads to a significant improvement in the sensitivity for low-mass WIMPs.

![Figure 3. Expected energy spectra from elastic scattering of WIMPs with a mass of 5 GeV/c² (dashed line) and 10 GeV/c² (solid line) respectively off germanium nuclei, calculated according to [22]. Lowering the experimental threshold drastically increases the sensitivity for low-mass WIMPs (approximate thresholds for standard and low threshold CDMS analyses are indicated).](image)

We have applied this philosophy in slightly different ways for two of our data sets. The first data set was taken at a shallow site at Stanford (Stanford Underground Facility, SUF) with only \( \sim 15 \) mwe of shielding against cosmic radiation leading to a significant background rate, but the good electronic noise environment allowed for a very low trigger threshold of \(< 1\) keV for some detectors [23]. The second data set is the same as discussed above for the CDMS standard analysis. The background here is lower, but the worse electronic noise led to a threshold of 2 keV [24].

Figure 4 shows the low-mass WIMP interpretation of CoGeNT and DAMA/LIBRA by Hooper et al. [20] as shaded regions. Also shown is the preferred region originally published by CoGeNT. This proposed evidence is contrasted with the limits obtained by our standard analysis as well as our two low-threshold analyses mentioned above. While the data set from Stanford still leaves a significant fraction of the overlap region found by Hooper et al. [19] untested, this interpretation is in strong tension with the low-threshold analysis of our data taken at Soudan.

It should be noted that part of the original favored region published by CoGeNT extends to below the CDMS limit, but more importantly: more recent discussions of the CoGeNT data [26] seem to indicate that the uncertainty on the background in CoGeNT is underestimated in the above publication. This allows the favored region to shift to considerably lower cross-sections removing the tension between CDMS and CoGeNT, but potentially also weakens the claim for a signal.

6. SuperCDMS at Soudan
To overcome the limitation from surface events discussed in section 3, we have developed a new type of detector with a different sensor layout. The most important changes are a larger mass per detector module achieved by an increased thickness of the crystals (one inch instead of 1 cm),
phonon sensors on both sides of the detector and a new geometry of the charge sensors which now are interleaved with the phonon sensors. These new detectors are called iZIP where the “i” stands for interleaved. Figure 5 shows a sketch of the new geometry of the phonon sensors (three equal inner sensors and an outer circle rather than four equal quadrants, for a better radial position determination).

Figure 6 demonstrates the effect of the interleaved electrodes: for events in the bulk the electrons and holes drift to the electrodes on opposite sides of the detector, while for events near the surface the charge carriers distribute between the electrode and the phonon sensors (acting as ground reference) on the same side of the detector. Thus, the ratio of the measured charge on both sides of the detector can be used to identify surface events with high efficiency. The surface event discrimination performance of these new detectors is considerably better than that of the CDMS ZIP detectors, while keeping a larger fraction of the actual nuclear recoil events. For more details on the iZIP detectors and their performance see [12] and [27].

In early fall 2011 SuperCDMS has implemented a full complement of 15 germanium iZIP detectors into the existing experimental setup at the Soudan Underground Laboratory - half as many as before since iZIP detectors have twice as many sensors as the CDMS ZIP detectors, but with an increased total mass of sim10 kg. After a commissioning period which is expected to last until end of 2011, dark matter search will restart and is expected to last for two to three years with a final sensitivity for the WIMP-nucleon cross-section of ~ 5 × 10⁻⁹ pb.
7. SuperCDMS at SNOLAB

The goal sensitivity for SuperCDMS at Soudan is given by the expected residual cosmogenic background at the depth of the Soudan Underground Laboratory (2100 mwe). This is the main motivation for the plans of SuperCDMS to build the next generation experiment with a total target mass in the 100 kg range at SNOLAB, the new underground laboratory near Sudbury, Ontario (Canada), which provides not only a several order of magnitude better shielding against cosmogenic radiation due to its larger depth of 6000 mwe, but is also operated as a whole as class 2000 cleanroom [4].

Work has started to develop detectors with larger diameters (100 mm) and further increased mass. The iZIP technology is expected to provide enough discrimination power between nuclear recoils and surface events to keep the background from this source negligible even for the total exposure aimed for with SuperCDMS at SNOLAB (order of hundred kg-years). However, in our existing test facilities the discrimination power cannot be tested, since it is impossible to recognize surface events that are misidentified as nuclear recoils due to the presence of actual nuclear recoil events from neutrons produced by cosmogenic radiation. Therefore we have started to construct a well shielded detector test facility underground at SNOLAB. The heart of this facility is the cryostat formerly used for the first CDMS measurements at Stanford. The cryostat has been refurbished so that the larger detectors can be mounted directly in the cold volume inside the cryostat. The cryostat will be installed in a dry-well surrounded by a cylindrical (passive) water shield of \( \sim 3.7 \) m in diameter and height. Figure 7 shows a sketch of the setup.

The external background rate per detector is expected to meet the specifications of <1 neutron/day and <1 gamma/second [28]. This will allow us to test the discrimination against surface events to better than 1 in \( 10^6 \). In order to minimize the operational costs the cryostat will be automated and equipped with re-liquefiers for the cryogenic liquids. Installation at SNOLAB is expected in 2012.

8. Conclusion

The sophisticated detector technology employed by CDMS has led to a decade of leading results in direct dark matter search with unprecedented background control. Continued improvements in detector design and eventually the move to SNOLAB for a further reduction in cosmogenic background will guarantee that the successor experiment SuperCDMS continues to play a leading role in WIMP search for the coming years.

A first step towards SNOLAB will be the installation of a well shielded cryogenic detector test facility at SNOLAB. This facility will be commissioned in 2012 and will be used to qualify the detectors for SuperCDMS at SNOLAB.

With the experimental sensitivity starting to cut deep into the parameter range favored by theoretical considerations and cosmological observations we can expect an exciting time in dark matter search over the next few years.
Figure 7. Sketch of the shielded test facility for SuperCDMS at SNOLAB. The detectors will be mounted in the enlarged sample volume inside the cryostat. The cryostat sits in a dry well inside the water shield. The cylindrical water tank has a diameter and height of about 3.7 m; the thickness of the water layer is ~1.5 m (slightly less at the bottom). The gashandling and temperature and pressure control and monitoring systems are connected to the top of the cryostat; to change the detectors or calibration source configuration, the water will have to be drained to gain access to the bottom of the cryostat.

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