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SuperCDMS SNOLAB - Status and Plans

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Abstract. The Super Cryogenic Dark Matter Search (SuperCDMS) and its predecessor CDMS have been at the forefront of the search for Weakly Interacting Massive dark matter Particles (WIMPs) for close to two decades. Significant improvements in detector technology have opened up the low-mass parameter space ($\lesssim 10$ GeV/c^2) where the experiment broke new ground with the CDMS low ionization threshold experiment (CDMSlite). Building on this success, SuperCDMS is preparing for the next phase of the experiment to be located at SNOLAB near Sudbury, Ontario. The new experimental setup will provide space for up to ~200 kg of target mass in a considerably lower background environment. The initial payload of about 30 kg will be a mix of germanium and silicon targets in the form of both background discriminating iZIP and low-threshold HV detectors, pushing the sensitivity towards WIMPs with even lower masses and improving the cross-section reach of SuperCDMS by more than an order of magnitude. The long-term goal is to reach the neutrino-floor below 10 GeV/c^2. We present the status of and plans for SuperCDMS at SNOLAB.

1. Introduction

The overwhelming evidence for the existence of dark matter [1] so far faces a striking absence of a convincing signal from any of the experiments trying to identify its nature. The long favored Weakly Interacting Massive Particle (WIMP) [2] with a mass typically somewhere between several tens and about a thousand GeV/c^2 as it emerges e.g. in the form of a neutralino from Supersymmetry [3] is starting to lose traction since no hint of such particles has been seen at the Large Hadron Collider at CERN [4] or in direct detection experiments which are now reaching a sensitivity where one could reasonably expect a discovery [5]. This lack of evidence makes it necessary to reconsider some of the assumptions that lead to the prediction of the standard WIMP. A large number of recent theoretical predictions favor dark matter particles with masses below about 10 GeV/c^2 (*low-mass WIMPs*) [6].

The Super Cryogenic Dark Matter Search experiment (SuperCDMS) focuses on this mass range, using cryogenic germanium and silicon detectors that are optimized for background rejection (iZIP detectors) and low threshold (HV detectors) respectively.

2. SuperCDMS Detector Technology

SuperCDMS detectors are made of cylindrical germanium or silicon crystals and are operated at a temperature of a few tens of mK. Interacting particles produce phonons that propagate through crystal and are eventually detected by superconducting transition edge sensors deposited at the flat surfaces. At the same time interactions produce electron-hole pairs that are drifted through the detector by an electrical field applied through electrodes at the detector surface. The average energy needed to produce an electron hole pair is 3.0 eV in germanium and 3.6 eV in silicon for interactions with electrons. This energy is larger by a factor of a few for interactions with atomic nuclei.

This difference in ionization efficiency is the basis of the background rejection capability of the SuperCDMS iZIP (interleaved Z-sensitive Ionization and Phonon) detectors: grounded phonon sensors are interleaved with biased charge collecting electrodes (opposite polarity on the two flat faces of the crystal). The ratio of the two measured signals is high for electron recoil (ER) events that are expected from most background radiation and low for nuclear recoil (NR) events. Due to the velocity distribution of the dark matter particles in our galaxy, the energy deposition through interactions with electrons would be in the eV range and thus very difficult to measure, while nuclear interactions would to lead to much larger signals for intermediate and high WIMP masses. Close to the electrodes, however, the charge collection efficiency is reduced, leading to ER events with a low charge-to-phonon signal ratio. This low ratio could be misinterpreted as indication for NR events. The iZIP sensor layout allows us to identify and discard such events close to the electrodes via the ratio of the measured charge signal on the two faces of the detector [7].

When the charges are drifted through the detector, they deposit additional energy into the phonon system equivalent to the Coulomb energy corresponding to their charge times the applied voltage bias (Neganov-Luke effect, [8]). In the HV detectors this effect is used to generate a large phonon signal for each electron hole pair. With the planed bias voltage of +50 V on one and –50 V on the other face of the detector, this signal is much larger than the primary phonon signal and the phonon sensors effectively measure the number of electron-hole pairs. An ER/NR discrimination as in the iZIP detectors is no longer possible. However, since charge collecting electrodes are no longer needed, the phonon sensor layout can be optimized leading to a noticeably improved energy threshold. [9]

3. SuperCDMS at SNOLAB

SuperCDMS and its predecessor CDMS have been operating successfully for many years in the Soudan Underground Laboratory (overburden of about 700 m of rock or ~2100 mwe (meter water equivalent)) in Soudan, MN, with a payload of up to ~9 kg, providing world-leading sensitivity in the direct search for WIMPs with every release of new data [10, 11]. Reaching limitations from cosmogenic radiation and intrinsic radioactivity of the setup, operations were stopped and the experiment decommissioned at the end of 2015. Presently, SuperCDMS is preparing for the next phase of the experiment to be deployed at SNOLAB near Sudbury, ON. With 2000 m of overburden or 6800 mwe of shielding, the residual cosmogenic radiation at SNOLAB is considerably lower than at Soudan; SNOLAB also provides excellent infrastructure and helps minimize contamination in the setup, as the whole laboratory is operated as a class 2000 cleanroom.

3.1. Experimental Setup

The new SuperCDMS detectors will be stacked in groups of six and attached to a mechanical structure (*tower*) that provides the thermal and mechanical connection to the cryostat and also carries the SQUID-based pre-amplifier for the phonon readout (at the 600 mK stage) and the HEMT-based pre-amplifier for the charge readout (at 4 K), as well as the wiring between the 4K-stage and the detectors which will be operated at ~30 mK. Figure 1 (left) shows the new detectors with their respective sensor layout and the first prototype tower. The initial payload will consist of four such detector towers, one with six Ge iZIP detectors, one with four Ge and two Si iZIP detectors and two with four Ge and two Si HV detectors each. The towers will be mounted in the centre of a set of nested copper cans providing thermal shielding and thermal connection to the different stages of the tower. It is designed to hold up to 31 towers or a total payload of ~200 kg to allow for cost-effective upgrades. This cryostat is connected to a cryogen-free dilution refrigerator through a set of concentric horizontal copper tubes with a solid rod in the centre for the lowest temperature stage acting as cold-fingers. The signals will be brought out through a second set of tubes on the opposite side of the cryostat, ending in a large vacuum tank with signal feedthroughs. Also located inside this tank is an auxiliary cooling system that intercepts the heat from the signal cables and provides the bulk of the cooling power to the warmer (50K- and 4K-) stages of the cryostat.

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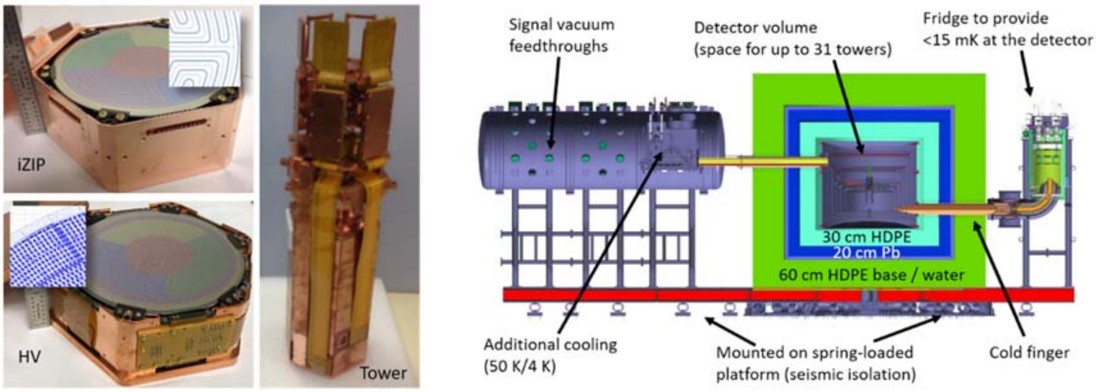

Figure 1. Left: SuperCDMS SNOLAB detectors (10 cm diameter, 3.3 cm high). The overlaid color pattern indicates the split between the different phonon sensors optimized separately for iZIP and HV detectors. The insets show the iZIP's interleaved pattern with thin charge collecting electrodes and the wider phonon sensors, and the much higher density of the phonon sensor of the HV detector, improving the phonon collection efficiency and thus resolution and threshold. The first prototype tower is also shown. Right: Experimental setup: the detector cryostat is connected to the dilution refrigerator and the vacuum tank through which the signals are brought out, and surrounded several layers of shielding. The whole setup sits on a spring-loaded platform to isolate it from seismic activity.

We have developed integrated detector control and readout cards (DCRCs), which include a detector control system (biasing, setup of the pre-amplifiers etc.) as well as the complete readout electronics (analogue signal processing, digitization, trigger logic) and plug directly into the vacuum feedthroughs. iZIP detectors are controlled by a single DCRC, while HV detectors are controlled by two DCRCs each. Communication with the DCRCs is via Ethernet.

The cryostat is surrounded by a massive passive shielding. From outside to inside we have a layer of ~60 cm thick water tanks on the sides and the top of the setup and polyethylene underneath to stop radiogenic neutrons from the environment, followed by 20 cm of lead as the main gamma ray absorber. Inside the lead we have another 30 cm of high-density polyethylene primarily to absorb neutrons that are produced inside the setup; it also blocks originally high-energetic neutrons that punch through the outer neutron shield and are down-converted by the lead.

The whole setup is mounted on top of a spring-loaded platform to decouple the experiment from seismic activity that is common in an active mining environment like the Vale Creighton mine that hosts SNOLAB. Figure 1 (right) shows a sketch of the overall layout of the experimental setup.

3.2. *Infrastructure*

The experiment will be located in the *Ladder Lab* area of SNOLAB. A gantry crane that moves on rails along the main SuperCDMS drift will be used together with a movable single-arm crane to assemble the experiment. Even though SNOLAB is operated as a cleanroom, residual particulates, and in particular the high radon concentration in the laboratory pose a risk for the innermost part of the setup that includes the detectors. Therefore, a class 100 cleanroom will be installed at the end of the SuperCDMS drift where the detector towers will be installed in the inner cans of the cryostat; this whole assembly will then be lifted into the main experimental setup using the gantry crane. The air for the cleanroom will be supplied by a radon filter system that reduces the radon concentration in the air from about 130 to less than 1 Bq/m^3. The radon filter is located in a side drift which also includes the compressors and pumps for the cryogenic system. This drift will be separated from the rest of the laboratory by sound-proof walls to reduce noise in the experimental area, both to improve working conditions and to minimize the danger of acoustic noise coupling into the detectors, limiting the detector performance. Figure 2 shows the layout of the experimental infrastructure within the lab.

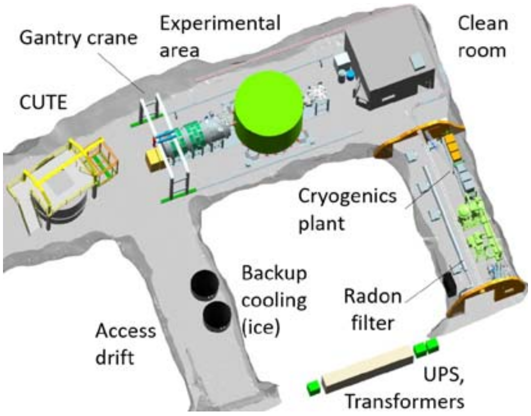

Figure 2: Ladder lab area of SNOLAB hosting SuperCDMS. The experiment itself is located in the main drift (top middle). Also shown is the gantry crane used for the assembly of the setup. Next to it is cleanroom for the assembly of the inner parts of the experiment. The drift on the right side includes the radon filter system for the cleanroom air as well as the cryogenics plant (compressors, pumps, water cooling). Next to SuperCDMS is the Cryogenic Underground TEst facility (CUTE) [12] which will be used to test SuperCDMS detectors prior to their installation in the main setup.

4. Status and Plans

SuperCDMS has been selected in 2014 by DOE and NSF as one of the next generation (G2) direct dark matter search experiments. Since then, SuperCDMS has completed the detailed technical design as well as all outstanding research and development required for this project. Prototype detectors (both iZIP and HV) have been produced and tested successfully. First tests including the full readout chain are imminent. The dilution refrigerator has been ordered and is under construction by the manufacturer. After approval of the detailed technical design and determination of construction readiness, expected in February 2018, the main construction phase of the experiment will start. Construction is expected to be completed and commissioning will start in 2020.

The sensitivity of the HV detectors in the initial payload is expected to be background limited where the main background contributions are ^{32}Si (in silicon) and cosmogenically produced ^{3}H (in germanium) as well as radon daughter products. With the expected levels of contamination we will reach a sensitivity of order of 10^{-43} cm^2 for the spin-independent WIMP-nucleon cross section in the mass range from 1-6 GeV/c^2 (about two orders of magnitude weaker at 0.5 GeV/c^2) [9]; this is about a factor of ten away from the final limiting background of the coherent solar neutrinos scattering signal. Figure 3 shows the expected sensitivity for the initial payload with conservative assumptions about background and detector performance and an analysis without background subtraction.

The very low expected thresholds make it also possible to search for electron interacting dark matter or dark photons, a field that has so far been largely unexplored due to technical limitations.

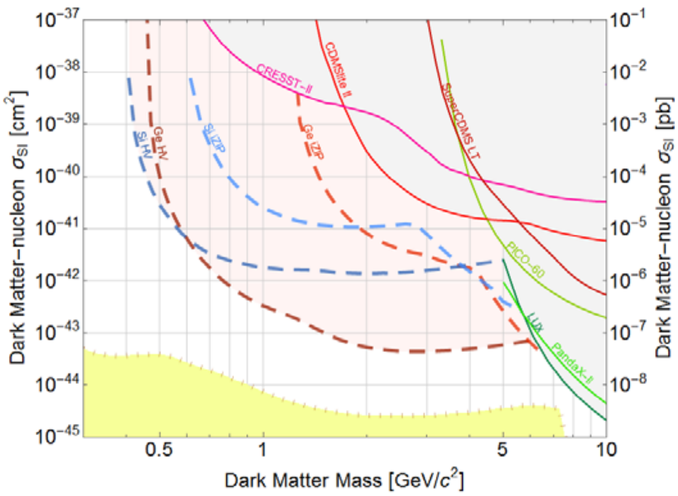

Figure 3. Published limits (solid lines [11, 13-16]) and expected sensitivity of SupeCDMS SNOLAB (dashed lines [9]). The sensitivity of the HV detectors will be background limited (^{32}Si in Si and ^{3}H in Ge, as well as ^{210}Pb). Conservative assumptions are made about background levels and detector performance. Future upgrades of the experiment with improved detectors (reduced background and at least partial re-gain of background discrimination at the lowest energies) and an increased payload will push the sensitivity to the ultimate limit set by coherent scattering of solar neutrinos (yellow area).

The nominal operations phase of SuperCDMS SNOLAB is five years; however, it is expected that progress in detector development will make it possible to replace some of the detectors at an earlier time leading to a continuous improvement of the detector performance, background and sensitivity of the experiment. The long-term goal is to reach the neutrino background over the whole mass range down to below 1 GeV/c^2. The SuperCDMS cryostat is large enough for the increased payload that will be required to achieve this goal. It will also be necessary to re-gain at least partial background discrimination at the lowest energies. Conceptual ideas how this can be achieved with improved detector resolution exist, and initial tests suggest that this is a promising route.

5. Conclusion

SuperCDMS is well on track for the construction and completion of the new experimental setup at SNOLAB by 2020. With an initial payload of ~30 kg of germanium and silicon detectors, SuperCDMS will make a significant leap forward in the sensitivity for WIMPs with masses below about 10 GeV/c^2. The sensitivity will reach to within about an order of magnitude of the ultimately limiting solar neutrino background. The large capacity of the cryostat (~200 kg) and the careful cryogenic design (operational temperature as low as 15 mK) and background management open the door for significant upgrades which have the potential to close this remaining gap and reach the neutrino floor.

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