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Status and prospects of the SuperCDMS Dark Matter experiment at SNOLAB

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Leading cosmological surveys and models provide strong indications for cold Dark Matter (DM) being one of the major constituents of our Universe. However, direct experimental observation of the hypothesized galactic flux of DM particles streaming through the Earth remains an open quest. Following up on the successful operations at Stanford and Soudan, the SuperCDMS collaboration is currently constructing a generation-2 direct DM search experiment at the SNOLAB underground facility in Sudbury, Canada. The experiment will employ two types of cryogenic Ge and Si detectors capable of detecting sub-keV energy depositions. The unique mix of target substrates and detector technologies allows for a simultaneous study of intrinsic and external backgrounds as well as exploring the DM mass range below 10 GeV/c^2 with world-leading sensitivity.

The two detector types are referred to as high voltage (HV) and interleaved Z-dependent ionization and phonon (iZIP) detectors. While the iZIP detectors are able to measure both phonon and ionization signals, which makes it possible to discriminate between nuclear and electronic recoils and to characterize backgrounds, the HV detectors solely measure the phonon signal. By applying a bias voltage on the order of 100 V, the primary ionization signal gets amplified in form of secondary phonons through the Neganov-Trofimov-Luke (NTL) effect yielding a lower energy threshold and excellent energy resolution for low-mass DM searches.

In order to extend the sensitivity to lower energy deposition thresholds, a precise understanding of the detector response down to the semiconductor bandgap energy of O(eV) is required. This effort is driven by a comprehensive detector testing program of SuperCDMS prototype devices at various test facilities and the development of a sophisticated Detector Monte-Carlo to guide the data analysis and model building. The current status and prospects towards science operation with SuperCDMS at SNOLAB will be reviewed in this article.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08 – 01.09.2023
University of Vienna

*Speaker

PoS(TAUP2023)076

1. SuperCDMS at SNOLAB

An overview of the SuperCDMS experiment at SNOLAB is shown in Fig. 1. An assembly of six individual Ge and Si cryogenic detectors surrounded by a hexagonal copper housing is referred to as a "tower". The initial payload for SuperCDMS SNOLAB will be four towers with in total 18 Ge and 6 Si detectors in different configurations. The towers are cooled down to 15 mK using a closed-loop dilution refrigerator that utilizes cryocoolers to establish 50 K and 4 K thermal stages. The cold region of the experiment is referred to as the SNOBOX and is enclosed by multiple shielding layers. While the SNOLAB rock overburden provides shielding against cosmic rays equivalent to about 6000 meters of water, additional layers shield the sensitive detectors from radiogenic contamination internal to the apparatus and from the rock cavern. The outer water tanks and outer polyethylene shield provide protection from neutrons originating from the cavern. A gamma shield made from lead layers graded in radiopurity protects from external gamma-rays and the inner polyethylene layers serve to absorb radiogenic neutrons emitted from the cryostat and gamma shield. The whole assembly rests on top of a seismic platform to provide isolation from major seismic events.

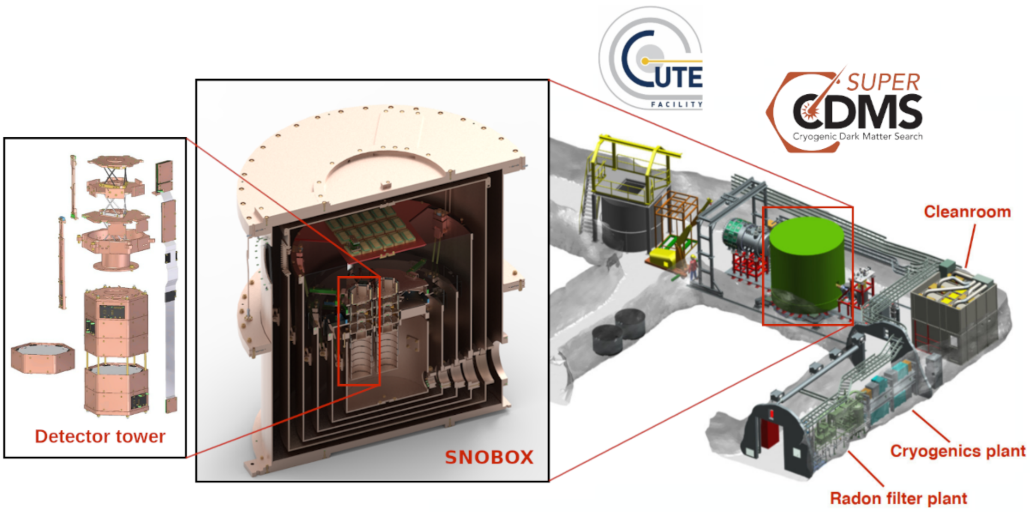

Figure 1: Overview of SuperCDMS SNOLAB. From left to right: Detector tower consisting of six cryogenic detectors in a copper housing; SNOBOX housing four towers; experimental infrastructure at SNOLAB including the CUTE detector testing facility, a low-radon cleanroom and the cryogenics system.

The experiment is currently under construction with the shield base consisting of the seismic platform as well as the lower lead and polyethylene layers being completed in summer 2023. In parallel, a standalone dilution refrigerator test was performed reaching the targeted base temperature of 15 mK. The first two towers each consisting of six SuperCDMS HV (high voltage) detectors arrived at the SuperCDMS underground cleanroom (class 100, low-radon air supply) in May 2023. The remaining two towers are of a different detector type and are scheduled to arrive at SNOLAB in November 2023. After being utilized for testing of individual SuperCDMS prototype detectors over the last couple of years, the Cryogenic Underground TEst (CUTE) facility [1] at SNOLAB is now ramping up for the first production tower operation in a low-background environment for an extended testing period until spring 2024. The commissioning of the full experiment is scheduled for mid of 2025 with first science data-taking aimed for the end of 2025.

2. SuperCDMS detector technology

SuperCDMS SNOLAB will include two types of cryogenic Si and Ge detectors. These detectors consist of cylindrical crystals with common physical dimensions of 100 mm diameter and 33.3 mm thickness. Each Ge (Si) crystal has a mass of 1.39 (0.61) kg. The two designs are referred to as interleaved Z-dependent ionization and phonon (iZIP) detector [2] and high voltage (HV) detector [3]. They are differentiated by details of the superconducting sensors (patterned lithographically on the top and bottom surfaces), the operating bias voltages, and whether ionization is sensed directly or via the secondary NTL phonon signal caused by the charge carriers' drift in an electric potential. A picture of both designs and their channel layout is shown in Fig. 2.

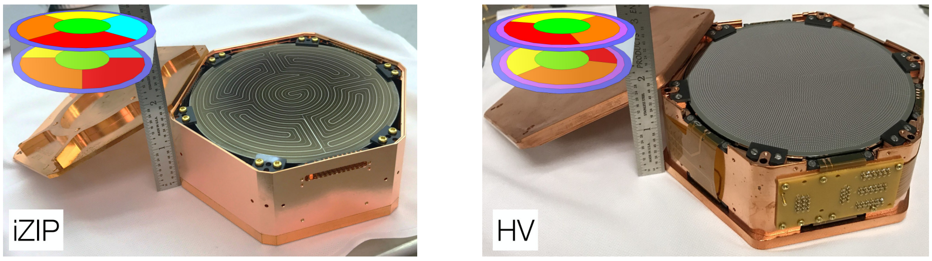

Figure 2: SuperCDMS SNOLAB detectors [6]. Left: iZIP. Right: HV. The iZIP detector has six phonon channels (inner core, four wedge-shaped, outer ring) and two ionization channels (inner + outer ring) on each side. The HV detector has six phonon channels (inner core, three wedge-shaped, two outer rings) on each side. The wedge channels of an iZIP (HV) detector are rotated by 45° (60°) with respect to the other side.

The iZIP detectors discriminate between nuclear recoils (NRs) caused by nucleon-coupled DM, neutrons and neutrino interactions, and electron recoils (ERs) caused by other backgrounds on the basis of the ionization yield $Y(E_r)$, which is typically lower for NRs. While the HV detectors only sense the phonon signal, which comes at the cost of a reduced ionization-yield-based NR/ER discrimination, they achieve a lower recoil threshold which drives the sensitivity reach towards lower DM masses. By directly sensing the number of created charge carriers N_{eh} or assuming a specific ionization model, the total phonon energy E_t can be decomposed into the original recoil energy E_r and the NTL phonon gain which depends on the applied bias voltage V_b and N_{eh}.

$$E_t = E_r + (N_{eh} \cdot e \cdot V_b) \approx E_r \cdot (1 + e \cdot V_b / \varepsilon_{\text{pair}} \cdot Y(E_r)) \tag{1}$$

The number of charge carrier pairs can be estimated by $N_{eh} \approx E_r / \varepsilon_{\text{pair}}$ using the average energy required to create an $e^- h^+$ pair in the crystal. A measurement of the ionization yield in Si down to $E_r \approx 100\,\text{eV}$ with a ~1 g SuperCDMS prototype HVeV (high-voltage with eV-scale resolution) detector has been published in [4]. The HVeV R&D program also plays an important role in developing and tuning the SuperCDMS Detector Monte-Carlo tools which are based on Geant4 and the G4CMP condensed matter physics expansion package. Recently, some results of the sophisticated DMC modeling efforts were published in [8].

3. Updated sensitivity projections

The collaboration recently released updated projections for the science reach of SuperCDMS at SNOLAB. Fig. 3 compares the nucleon-coupled DM exclusion results presented in [5] using the

Optimum Interval (OI) method to a profile-likelihood ratio (PLR) approach with updated detector performance characteristics and background estimates such as crystal bulk contaminants and cosmogenic activation products [6]. Further projections for an upgraded SuperCDMS experiment at SNOLAB as well as bounds presenting the ultimate limit of the technology can be found in [6].

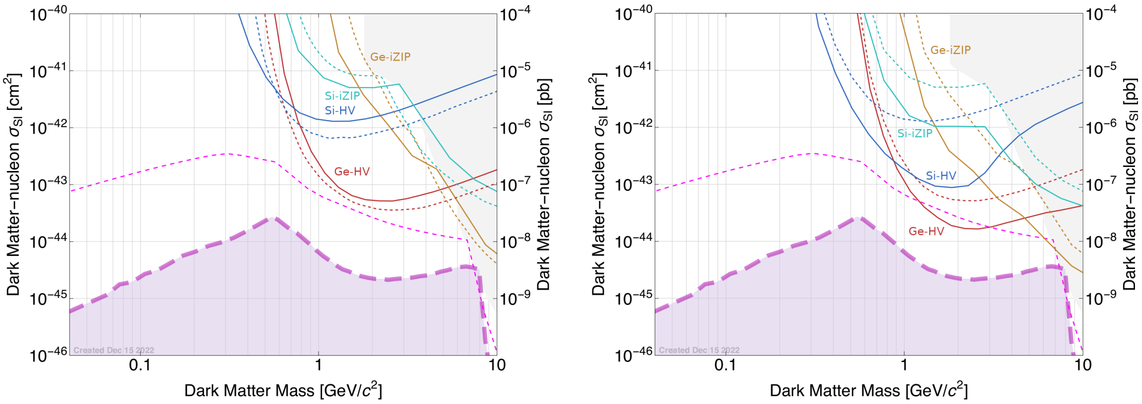

Figure 3: Sensitivity projections at 90% C.L. for SuperCDMS SNOLAB [6]. Left: Comparison of current (solid) and previous OI projections (dashed) [5]. Right: Updated OI (dashed) and PLR projections (solid).

4. Summary and outlook

By combining the strengths of the complementary iZIP and HV detector technologies, SuperCDMS will be able to perform a broadband DM search with world-leading sensitivity below the mass range of 10 GeV/c^2 and the capability to constrain internal and external backgrounds. Moreover, SuperCDMS will perform searches for other DM candidates such as dark photons, axion-like particles and lightly ionizing particles. The experimental infrastructure is well under construction at SNOLAB with important milestones achieved this year. Meanwhile, early science results can be expected from the SuperCDMS production tower testing underway at CUTE and the very successful HVeV R&D detector program [7].

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