SuperCDMS SNOLAB: status and prospects for measuring the coherent neutrino scattering

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Abstract. SuperCDMS SNOLAB is a low-background experiment that will use semiconductor germanium and silicon detectors to search for galactic dark matter. In addition the experiment has potential to measure the coherent scattering of solar $^8$B neutrinos. This process will dominate some parts of the spectrum between 1 and 10 keV in the detectors with full background rejection capabilities. However the total number of events from coherent neutrino scattering is expected to be $\sim 1$ if the experiment is assumed to operate five years with an 80% live time, and therefore not sufficient to provide a significant observation of this process. Upgrades to the experiment are planned to extend the sensitivity down to the limit set by the coherent neutrino scattering.

1. Introduction

A neutrino is predicted to interact coherently with all the nucleons contained in an atomic nucleus via neutral current if the exchanged momentum $q$ satisfies $q \lesssim 1/R$, where $R$ is the radius of the nucleus considered [1]. For typical values of $R$ and for neutrino energies between 1 and 100 MeV this condition implies that the recoiling nucleus should have energies of few keV or below. The cross-section of this process has been calculated with a $\sim 5\%$ precision in the Standard Model (SM), but to date no experiment has reached the sensitivity needed to validate it.

Given that the coherent neutrino scattering produces a recoiling nucleus this process is expected to eventually become an irreducible background for the direct searches of weakly-interacting massive particles (WIMPs) that may constitute the galactic dark matter (DM) halo [2][3][4]. This fact motivates the study of the coherent neutrino scattering in such experiments.

The technology used in direct DM searches is determined by the necessity of reducing the background from environmental radiation, that produce abundant events in the keV range in comparison with those from coherent scattering of neutrinos or WIMPs. These background events are mostly caused by either 1) atomic electrons recoiling after a gamma-ray interaction, 2) charged particles from nuclear decays, or 3) atomic nuclei recoiling after a neutron interaction. The particular choice of SuperCDMS SNOLAB in order to address such backgrounds is to use semiconductor detectors.
2. Semiconductor detectors

Part of the recoil energy deposited in semiconductor crystals, $E_R$, is used to produce electron-hole pairs. The ratio between the energy used to produce electron-hole pairs, $E_Q$, and $E_R$ is called ionization yield, $Y \equiv E_Q/E_R$, and depends on the type of the recoiling particle. For a recoiling atomic electron $Y \simeq 1$, while for a recoiling atomic nucleus $Y \simeq 0.3$. Therefore the measurement of this quantity would allow to identify the recoiling particle. The number of charge carriers $N_q$ produced by the recoiling particle is equal to $E_Q/\epsilon$, where $\epsilon = 3.0$ eV for germanium. The rest of the recoil energy is released as lattice vibrations, called phonons.

In absence of applied electric fields the electron-hole pairs recombine shortly after their production, releasing all the energy used to create them as additional phonons. Therefore all the recoil energy is eventually released as phonons, and hence $E_P = E_R$. Note that by measuring both $N_q$ and $E_P$ the equations $N_q = YE_R/\epsilon$ and $E_P = E_R$ can be inverted in order to determine $E_R$ and $Y$, thus giving information on both the energy and the type of the recoiling particle.

By applying an external electric field the charge carriers drift along the field lines. This mechanical work done on the electron-hole pairs by the external field is also released to the lattice as phonons [5] [6], called Neganov-Trofimov-Luke phonons. This contribution to the total phonon energy is equal to $E_{P,NTL} = q_eVN_q$, where $V$ is the external voltage difference, and therefore the total phonon energy in presence of an applied electric field is

$$E_P = E_R(1 + Y q_eV/\epsilon)$$

Note that in this case it is still possible to determine $E_R$ and $Y$ by measuring $N_q$ and $E_P$. For later purposes, note also that the total phonon energy is greater than $E_R$ by a factor that linearly increases with $V$.

3. The SuperCDMS SNOLAB experiment

The design of SuperCDMS SNOLAB [7] includes 24 monocrystalline germanium and silicon detectors, arranged in four stacks of six detectors each. The mass of each germanium and silicon detector is 1.39 and 0.61 kg respectively, and the nominal operation temperature is planned to be $\sim 15$ mK. According to their design the detectors are classified in two exclusive categories as explained below.

Ten germanium detectors and two silicon detectors will be instrumented to measure both $N_q$ and $E_P$, and therefore will allow to determine both $E_R$ and $Y$. In addition to the background discrimination that will be provided by the knowledge of $Y$, the applied electric field and the segmented read-out configuration will enable complete fiducialization.

The remaining detectors, namely eight germanium detectors and four silicon detectors, will be instrumented to measure $E_P$ only. They will operate at higher voltage bias in order to amplify the phonon signal above the baseline noise threshold. This approach uses the fact that additional phonons are produced in the presence of external electric fields. From Eq. 2 the total phonon energy $E_P$ is greater than $E_R$ by a factor linear on $V$, therefore operating the detectors with increased voltage $V$ would allow to effectively explore lower recoil energies [9]. Note however that only the phonon signal can be amplified using this method. As $N_q$ is not available in these detectors the particle identification and the fiducialization are compromised, and the reconstruction of $E_R$ requires assumptions on the value of $Y$.

The detectors will be shielded from environmental radiation by covering the full solid angle with layers of lead and high-density polyethylene. In addition the structures within the shielding will mostly use radiopure copper. The experiment will be deployed at SNOLAB (6010 m.w.e.) in order to suppress the impact of the cosmogenic radiation.
The funding for the SuperCDMS SNOLAB project has been already approved by agencies from US and Canada. The experiment is planned to operate between 2020 and 2014 with an 80% live time.

4. Projected sensitivity of SuperCDMS SNOLAB

The projected sensitivity of direct DM searches is usually given as the region of the WIMP parameter space that would be excluded by the experiment in absence of signal. Nominally a two-dimensional parameter space is used, that considers the WIMP mass and the WIMP-nucleon cross-section. Such study has been already carried out for SuperCDMS SNOLAB [7], and it allows to obtain conclusions on the sensitivity of this experiment to measure the coherent neutrino scattering.

The current calculation of the projected sensitivity of SuperCDMS SNOLAB to detect DM includes a simulation of all the relevant expected backgrounds: 1) recoiling electrons from beta decays of $^3$He and $^{32}$Si present in the detectors; 2) recoiling electrons from Compton scattering of external gamma-rays interacting in the detector; 3) surface events from nearby beta decays and recoiling $^{206}$Pb nuclei; 4) recoiling nuclei from neutron scattering; and 5) recoiling nuclei from coherent neutrino scattering.

![Figure 1. Energy spectrum of the simulated background events in the detectors measuring both $E_P$ and $N_q$, for germanium (left) and silicon (right). Extracted from [7], Fig. 7. The contributions shown are recoiling electrons from beta decays of $^3$He and $^{32}$Si present in the detectors, and from Compton scattering of external gamma-rays interacting in the detector (red), surface events from nearby beta decays (green) and recoiling $^{206}$Pb nuclei (orange), recoiling nuclei from neutron scattering (blue), and recoiling nuclei from coherent neutrino scattering (cyan). The recoiling electrons from electron capture on activated germanium are also included (grey).](image)

Selection cuts are applied to the simulated background events. The detectors measuring both $E_P$ and $N_q$ use that information to identify the recoiling particle and to enable complete fiducialization. The high-voltage detectors are assumed to operate at 70 V, and only include fiducialization along the radial direction, based on the phonon signal. The energy spectra that results from applying these requirements are shown in Figs. 1 and 2.

The simulated background events that satisfy the selection requirements are used to obtain the exclusion limit at 90% C.L. expected for five years of data taking (2020-2024) with an 80% live time. This calculation is based on the optimal interval method [8], and therefore no background subtraction is performed. The result of this calculation is shown in Fig. 3.
Figure 2. Energy spectrum of the simulated background events in the high-voltage detectors, for germanium (left) and silicon (right). Extracted from [7], Fig. 6. The contributions shown are recoiling electrons from beta decays of $^3$He and $^{32}$Si present in the detectors, and from Compton scattering of external gamma-rays interacting in the detector (red), surface events from nearby beta decays (green) and recoiling $^{206}$Pb nuclei (orange), recoiling nuclei from neutron scattering (blue), and recoiling nuclei from coherent neutrino scattering (cyan). The recoiling electrons from electron capture on activated germanium are also included (grey).

Figure 3. Projected sensitivity of SuperCDMS SNOLAB for five years of data taking (2020-2024) with an 80% live time. Extracted from [7], Fig. 8. For comparison the results from SuperCDMS Soudan [9][10], CRESST-II [11] and LUX [12] are also shown. The dotted orange line is the expected dark matter discovery limit from coherent neutrino scattering [13].

5. Implications for the measurement of the coherent neutrino scattering
Figs. 1 and 2 indicate that the coherent scattering from solar $^8$B neutrinos will dominate some parts of the spectrum between 1 and 10 keV in the detectors measuring both $E_P$ and $N_q$. 
However the total number of events from coherent neutrino scattering is expected to be \( \sim 1 \) if the experiment is assumed to operate between 2020 and 2024 with an 80% live time, and therefore not sufficient to provide a significant observation of this process. Upgrades of the experiment are planned to extend the sensitivity down to the limit set by the coherent neutrino scattering.

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