SuperCDMS: Recent results on low-mass WIMPs

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We present the first search for weakly interacting massive particles (WIMPs) using the background rejection capabilities of SuperCDMS [1]. A blind analysis of data from an exposure of 577 kg-days leads to an upper limit on the spin-independent WIMP-nucleon cross section of 1.2×10^{-42} cm^2 at 8 GeV. This result probes new parameter space for WIMP-nucleon scattering cross section for light WIMPs with masses < 6 GeV/c^2 and is in tension with WIMP interpretations of recent experiments.

The detection and identification of the dark matter in the Universe constitutes one of the greatest challenges in modern Physics. A generic weakly interacting massive particle (WIMP) is a well motivated candidate, as it can be produced in the right amount and searched for in direct and indirect detection experiments. Recent excesses of events reported by CDMS II (Si)[2], CoGeNT [3], CRESST-II [4], DAMA [5], and possible indirect evidence from gamma rays from the galactic centre [6], can be interpreted in terms of WIMPs with mass in the 6–30 GeV/c^2 range. Various theoretical constructions also provide WIMP candidates in this mass range [7,8,9,10,11].

The direct search for light WIMPs is extremely challenging, since they produce only low-energy nuclear recoils, forcing experiments to lower their analysis energy thresholds [12,13,14,15,16]. Following this approach, low-energy recoils in the range 1.6–10 keV$_{\mathrm{nr}}$ (nuclear-recoil equivalent energy) from the SuperCDMS experiment at the Soudan Underground Laboratory [17] have been analysed, exploiting the excellent background discrimination capabilities of the new detectors [1].

SuperCDMS at Soudan is an upgrade to the Cryogenic Dark Matter Search (CDMS II) [18] with new detector hardware, operating in the same location with the same low-radioactivity setup [19] since March 2012. The target consists of five towers, with three 0.6-kg cylindrical germanium crystals each. These detectors (iZIPs) are instrumented with interleaved ionization and phonon sensors on their flat faces. From the measured ionization and phonon energy, we derive the recoil energy and the "*ionization yield*," the ratio between ionization and recoil energy. This is a key quantity to discriminate nuclear recoils (expected from WIMP interactions) from electron recoils (expected from most backgrounds), since nuclear recoils exhibit a reduced ionization yield compared to electron recoils. Moreover, the iZIP sensor layout greatly improves the determination of a fiducial volume in the bulk, designed to reject events in the peripheral regions of the detectors (which present a reduced ionization yield and pollute the signal region) [20]. The fraction of the total phonon or ionization energy measured by the guard sensors is encoded in "*radial partition*" parameter through which radial fiducialization is defined. Similarly, a "*z partition*" parameter is constructed from the fraction measured by the sensors on each face and used to define the z fiducialization.

The data presented here was recorded between October 2012 and June 2013 using the seven detectors with the lowest trigger thresholds. The remaining detectors are used to reject events which deposit energy in more than one detector (incompatible with WIMP interactions). Periods of abnormal detector behavior and elevated noise are removed from the analysis. After accounting for these losses, the exposure is 577 kg-days. To prevent bias when defining the event-selection criteria, all single-detector hits with recoil energies between a time-dependent noise threshold and 10 $\mathrm{keV_{nr}}$, and with ionization energy consistent with nuclear recoils, were removed from study, i.e. blinded. A distinct open set of data, containing 97 kg-days of exposure, was constructed from periods following ^{252}Cf calibrations.

The relation between the total phonon energy and the mean ionization energy of nuclear recoils for each detector, as determined from ^{252}Cf calibration data, is consistent with Lindhard's model. The nuclear-recoil band is defined by accepting events within 3σ of the mean ionization energy. The nuclear-recoil equivalent energy is constructed from the total phonon energy by subtracting the contribution of Luke-Neganov phonons corresponding to the mean nuclear-recoil ionization response for the respective total phonon energy.

Hardware trigger thresholds for each detector were adjusted several times during the WIMP search. For each period of constant trigger threshold, the trigger efficiencies as functions of total phonon energy were measured using ^{133}Ba calibration data. Analysis thresholds are set to be 1σ below the energy at which the detector trigger efficiency is 50% in periods of time for which this quantity is above the noise threshold used in the data blinding, and equal to such threshold otherwise. The combined efficiency is an exposure-weighted sum of the measured efficiency for each detector and period, and is shown in the left-hand side of Figure 1.

Three levels of data-selection criteria have been used to identify triggered events as WIMP candidates. A first data-quality cut rejects poorly reconstructed and noise-induced events, removing also periods of abnormal noise and spurious triggers (for which the pulse shape is inconsistent with that expected for real events). The second level (preselection) singles out event configurations consistent with WIMPs, requiring single-scattered events that feature energies within the 3σ nuclear-recoil band and phonon partitions consistent with bulk nuclear recoils. A loose fiducial volume, constructed from the ionization partitions, further restricts events to be consistent with bulk nuclear recoils. Similarly, events near the detectors' sidewalls are rejected by requiring the guard electrodes on both faces to be within 2σ from the mean of the baseline noise. Events coincident with the muon veto are also rejected. The final level of event-selection (discrimination) uses a boosted decision tree (BDT) with four discriminators: the total phonon energy, ionization energy, phonon radial partition and phonon z partition. A BDT was trained for each detector using simulated background events and nuclear recoils from ^{252}Cf calibration weighted to mimic a WIMP energy spectrum, accounting for the selection criteria acceptance. The BDT discrimination thresholds for individual detectors were chosen simultaneously to minimize the expected 90% confidence level (C.L.) Poisson upper limit of the rate of passing events per WIMP exposure. The BDT was trained and optimized separately for 5, 7, 10, and 15 GeV/c^2 WIMPs. Events that pass any of the four WIMP-mass optimizations are accepted into the signal region as candidates. The left-hand side of Figure 1 shows the cumulative efficiency after applying each level of selection criteria and the analysis thresholds.

A background model was developed that includes Compton recoils from the gamma-ray background; 1.1–1.3 keV X-rays and Auger electrons from L-shell electron-capture (EC) decay of ^{65}Zn, ^{68}Ga, ^{68}Ge and ^{71}Ge; and decay products from ^{210}Pb contamination on the detectors and their copper housings. The right-hand side of Figure 1 shows the individual components of the background model as a function of the 10 GeV/c^2 BDT discrimination parameter after applying the preselection criteria. This background model was finalized prior to unblinding and predicted $6.1^{+1.1}_{-0.8}$ (stat.+syst.) events passing the BDT selection. Simulations of radiogenic and cosmogenic neutrons predict an additional 0.098 ± 0.015 (stat.) events. These estimates included only known systematic effects. Because the accuracy in background modeling required for a full likelihood analysis is difficult to achieve in a blind analysis of this type, the decision was made before unblinding to report an upper limit on the WIMP-nucleon cross section.

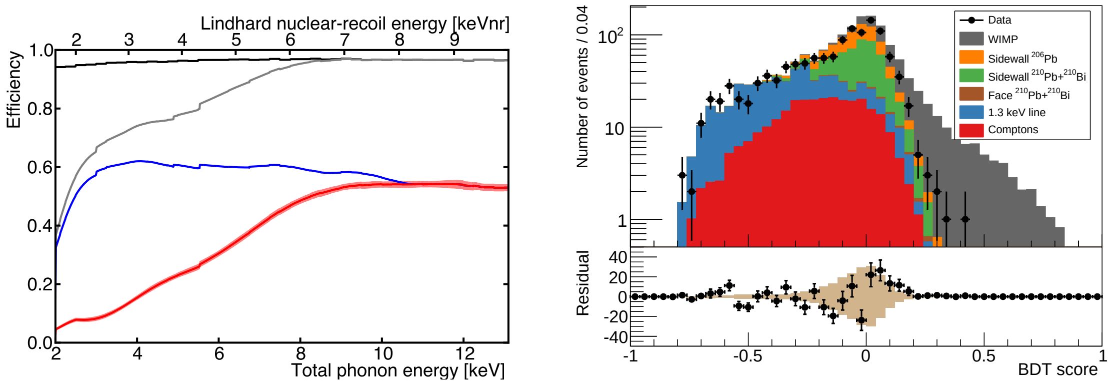

Figure 1 – Left) Cumulative efficiencies after sequential application of each stage of event selection. From top to bottom, these are data-quality criteria, trigger and analysis thresholds, preselection criteria, and BDT discrimination with 68% C.L. (stat. + syst.) uncertainty band. Right) Components of the background model passing the preselection criteria, summed over all detectors. For comparison, a 10 GeV/c^2 WIMP with cross section 6×10^{-42} cm^2 is shown on top of the total background. Events passing preselection criteria are overlaid showing the statistical errors. The bottom plot shows the difference between the data and the background expectation. Tan bars indicate the systematic uncertainty (68% C.L.) on the background estimate.

Upon unblinding, eleven candidates were observed, which are shown on the left-hand side of Figure 2. This is consistent with the background prediction for most detectors, except for the three high-energy events in detector T5Z3 (for which there is a probability of only 4×10^{-4} to observe this many background events). However, this detector has an ionization guard electrode shorted to ground and, although the background model was developed to account for this, the altered electric field may have affected the selection of background model templates, and thus the background estimate. Otherwise, the background model has been found to reproduce correctly most features of the true background, as evidenced in the right-hand side of Figure 1. The systematic uncertainty is dominated by the uncertainty of the expected ionization of sidewall events originating from ^{210}Pb and ^{210}Bi. P-value statistics comparing the data passing the preselection criteria with the blind background model prediction range from 8–26% for the BDTs trained to each of the four WIMP masses.

On the right-hand side of Figure 2 we show the 90% C.L. upper limit on the spin-independent WIMP-nucleon cross section, calculated using the optimum interval method without background subtraction for standard halo assumptions. Statistical and systematic uncertainties in the fiducial-volume efficiency, the nuclear-recoil energy scale, and the trigger efficiency were propagated into the limit by Monte Carlo and are represented by the narrow gray band around the limit. The limit is consistent with the expected sensitivity for masses below 10 GeV/c^2 as shown by the green band in Figure 2. The discrepancy above 10 GeV/c^2 is due to the three high-energy events in T5Z3, which are in tension with the background expectation. These results strongly disfavour a WIMP interpretation of the CoGeNT excess, which also uses a germanium target. Similar tension exists with WIMP interpretations of several other experiments, including CDMS II (Si), assuming spin-independent interactions and a standard halo model. New regions of WIMP-nucleon scattering for WIMP masses below 6 GeV/c^2 are excluded. This constitutes the first search for WIMPs exploiting the full background rejection capability of SuperCDMS.

Acknowledgments

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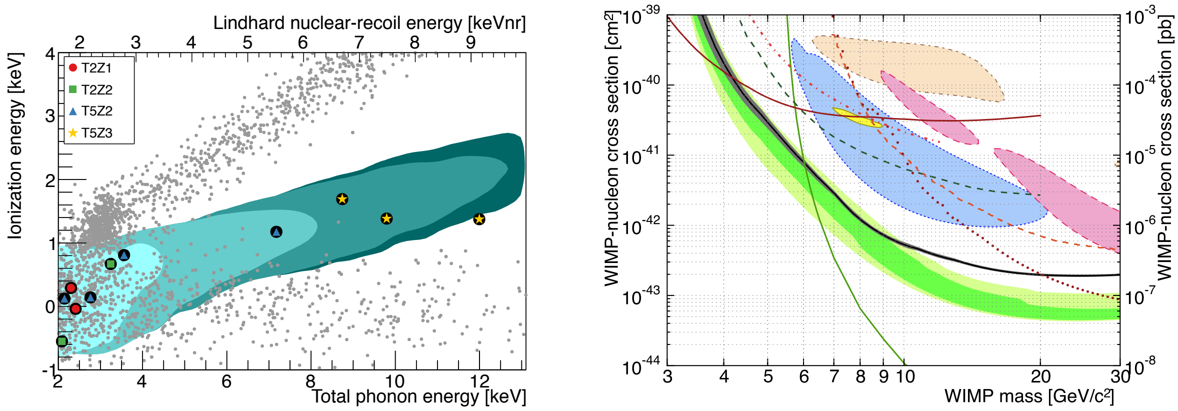

Figure 2 – Left) Veto-anticoincident single-scatter events within the ionization-partition fiducial volume that pass the data-quality selection criteria. Large encircled shapes are the 11 candidate events. Shaded regions (from light to dark) are the 95% confidence contours expected for 5, 7, 10 and 15 GeV/c^2 WIMPs. The band of events above the expected signal contours corresponds to bulk electron recoils, including the 1.3 keV activation line at a total phonon energy of ∼3 keV. High-radius events near the detector sidewalls form the wide band of events with near-zero ionization energy. For illustrative purposes, an approximate nuclear-recoil energy scale is provided. Right) The 90% confidence upper limit (solid black) based on all observed events is shown with 95% C.L. systematic uncertainty band (gray). The pre-unblinding expected sensitivity in the absence of a signal is shown as 68% (dark green) and 95% (light green) C.L. bands.

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