# Photo-neutron Calibration of SuperCDMS Detectors

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## SuperCDMS detector physics

Super Cryogenic Dark Matter Search (SuperCDMS) [1] is a direct dark matter search experiment that makes use of low temperature solid state detectors to search for rare scattering of Weakly Interacting Massive Particles (WIMPs) with atomic nuclei. The SuperCDMS Soudan experiment consisted of 15 germanium detectors arranged in five towers of three detectors each with a total mass of 9 kg and an operating temperature of 50 mK.

WIMPs elastically scatter off a nuclei causing nuclear recoils (NR) while generating $e^-/h^+$ pairs during this process. Gamma-rays and beta-rays scatter off electrons, producing electron recoils (ER). A bias voltage ($V$) applied to the detector makes the charge drift along the electric field lines. The mechanical work done on the $e^-/h^+$ pairs by the field is released to the lattice as Neganov-Trofinov-Luke (NTL) phonons [2] with an energy $E_{\rm NTL}=qVN$ where $q$ is the charge of an electron and $N$ is the number of $e^-/h^+$ pairs created by the scatter event. All of the energy associated with a scatter event is eventually released in the form of phonons. $E_{\rm total}$ is the sum of recoil energy, $E_R$, and NTL phonon energy ($E_{NTL}$) that we measure in our detectors. The ionization yield ($Y$) is a relative measure of the number of $e^-/h^+$ pairs created compared to the ER process. It is possible to write the total phonon energy as $E_{\rm total}=E_R(1+qVY/\epsilon)$ where $\epsilon$ is the average amount of recoil energy to create an $e^-/h^+$ pair in the ER case (3.0 eV in Ge). NRs produce fewer $e^-/h^+$ pairs than ERs and thus have $Y$ less than 1. SuperCDMS detectors measure $N$ and $E_{\rm total}$.

The SuperCDMS Soudan detectors were operated in two modes, the interleaved Z-sensitive Ionization and Phonon detectors (iZIP) operated at 4V and the CDMS low ionization threshold experiment (CDMSlite) detectors which were operated at higher voltages between 25V and 70V. The $E_{\rm total}$ produced from an event can be amplified by the applied voltage. The higher the bias voltage, the more the contribution from $E_{\rm NTL}$ per electron-hole pair. This reduces the recoil energy threshold, but sacrifices the ability to distinguish between ER and NR that iZIP mode retains. Hence a direct measurement of $Y$ is not possible for CDMSlite detectors.

## Motivation for calibration

The motivation for a dedicated calibration of the SuperCDMS detectors comes from the fairly wide uncertainty in the exclusion curve of WIMP interaction cross-section and mass [1] using CDMSlite data shown in Fig. 1. The uncertainty comes from limited precision in determining the nuclear recoil energy scale. This stems from the inability of the CDMSlite detectors to measure the ionization yield as described in the previous section. An accurate understanding of the nuclear recoil energy scale is necessary for establishing the WIMP mass scale. CDMSlite makes use of the Lindhard model to predict the yield. The yield can be written as follows [3]:

$$Y = \frac{k \cdot g(\varepsilon)}{1 + k \cdot g(\varepsilon)}$$
$$g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon$$
$$\varepsilon = 11.5 E_R / Z^{7/3}$$

Here $Z$ is the atomic number of the recoiling nucleus, $\varepsilon$ a reduced energy term, $E_R$ is the recoil energy and $k$ describes the electronic energy loss. The value of $k$ is fixed at 0.157 for Ge using the original Lindhard theory. We treat $k$ as a free parameter in this analysis. The model works reasonably well at recoil energies greater than 10 keV, as seen in Fig 2. More data below 1 keV are needed to ascertain the reliability of this model at lower recoil energies. The photo-neutron calibration will provide data as low as $\sim 1$ keV.

## Photo-neutron Calibration

The calibration technique here uses a high rate $^{88}$Y or $^{124}$Sb $\gamma$-source placed next to a Be absorber. The $\gamma$-source and Be wafer were placed above the detector. $^{124}$Sb and $^{88}$Y emit $\gamma$s of 1.69 MeV and 1.84

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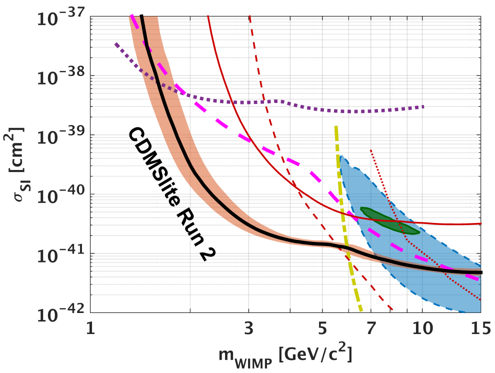


FIG. 1: Exclusion curve in the WIMP interaction cross-section and WIMP mass plane from CDMSlite Run 2 (black solid curve with associated uncertainty band) [1].

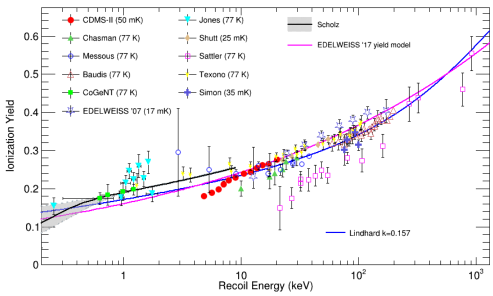


FIG. 2: Ionization yield obtained by various experiments in germanium as a function of nuclear recoil energy [3] [4] [5].

MeV respectively. Following a $^{9}$Be($\gamma$,n) reaction the $^{124}$Sb+Be and $^{88}$Y+Be sources produce neutrons between 22.8-24.1 keV and 151-159 keV, respectively. In case of $^{124}$Sb the maximum recoil of the Ge nucleus is around 1.3 keV and for $^{88}$Y around 8.1 keV. By studying the recoils of Ge nuclei from these quasi-monoenergetic neutrons, the measured total phonon energy $E_{\text{total}}$ of our detectors can be calibrated to the recoil energy $E_R$.

## Analysis

Data was taken with the $\gamma$+Be source(neutron on) and with just the $\gamma$-source(neutron off). Data selection was done by subjecting the it to several quality checks to remove electronic glitches, low frequency noise, poorly reconstructed events and bad periods of data. The next step of the analysis is simulating the expected $E_R$ spectrum in the detector using GEANT4. The final step of the analysis is to compare the simulated neutron on $E_{\text{total}}$ spectrum to the measured neutron on $E_{\text{total}}$ spectrum. We determine the best fitting simlated spectrum to data using a negative log likelihood function. We modify the Lindhard formalism such that the k value can be a single parameter or a linear combination of two parameters with a dependence on $E_R$. Statistical uncertainty on the simulated data is calculated by repeating the procedure with 500 simulated data samples of equal statistics and calculating the standard deviation of the best fit value of $k$ in each case. Systematic uncertainty in the energy-dependent neutron-nucleus scattering cross section in germanium detector is accounted for by obtaining cross-section files for all the stable isotopes of Ge from the TENDL-2017 [6] nuclear database and repeating the NLL method to show the deviation in the best fit values of k.

## Summary

The Lindhard model is known to have limited accuracy at low recoil energies and no dependence on temperature. The results from this work will be helpful in understanding our ionization yield and putting more precise limits on SuperCDMS dark matter search results as they probe into lower dark matter masses [7].

## References

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