PROCEEDINGS OF SCIENCE

Investigating Compton steps in SuperCDMS Si HVeV detectors

Sudipta Das[1,2,*] **on behalf of the SuperCDMS collaboration**

[1] *School of Physical Sciences, National Institute of Science Education and Research, Jatni, 752050, India*

[2] *Homi Bhabha National Institute, Training School Complex, Anushaktinagar, Mumbai 400094, India*

E-mail: sudipta.das@niser.ac.in

SuperCDMS is constructing its next generation experiment at SNOLAB to detect dark matter candidates with masses ≤ 10 GeV/c^2 using pure Ge and Si detectors operated at cryogenic temperature. These detectors are of two types. The interleaved Z-sensitive Ionization and Phonon (iZIP) detectors can differentiate between nuclear and electron recoils, providing effective background rejection, while the High Voltage (HV) detectors use high voltage bias to attain excellent energy resolution and low energy threshold. To analyze dark matter search data, an accurate energy calibration of these detectors is necessary. Unlike in Ge detectors, there are no activation lines in Si that can be used for low energy calibration ($\leq \mathcal{O}$(keV)). However, Si Compton steps can serve as an alternative for energy calibration in this region. The SuperCDMS Si HVeV detectors, with their energy resolution of $\mathcal{O}$(eV) and energy thresholds of $\mathcal{O}$(10 eV), are the perfect instruments to study the Compton steps. This work aims to investigate the K shell Compton steps at 1.8 keV for Si HVeV detectors and compare them with a calibration derived from optical photons. The understanding of Compton steps for these detectors will aid in calibrating the larger SuperCDMS SNOLAB Si HV detectors.

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

[*] Speaker

PoS(TAUP2023)077

Introduction

The next generation SuperCDMS experiment, SuperCDMS SNOLAB, is dedicated to the search for low-mass dark matter candidates with masses $\leq$ 10 GeV/c^2 [1], employing cryogenic Ge and Si detectors. Interactions of such dark matter particles with the detectors are anticipated to generate low-energy recoils, yielding signals within the energy range of O(0.1-100 keV). An accurate energy calibration of the detectors within this range is important for the analysis of dark matter search data. This calibration is achieved by exploiting known features in the energy spectrum. In the case of Ge detectors, neutron activation lines of ^{71}Ge (K-, L-, and M-shell lines at 10.37 keV, 1.30 keV, and 160 eV, respectively) serve as reference points for the low energy calibration. However, for Si detectors, the absence of suitable low-energy activation lines make the low-energy calibration challenging. An alternative approach could be the use of Si Compton steps, such as the 1.8 keV step for the K shell and the 0.15 keV and 0.1 keV steps for the L shells, which are observable in the Compton spectrum. The scattering cross-section for the Compton process decreases below the atomic binding energies, resulting in the formation of step-like structures known as Compton steps [3]. These step positions are material-dependent, and the relative heights of the steps are proportional to the number of electrons present in the atomic shell.

In this study, our primary focus is on investigating the K shell's Compton step at 1.8 keV in prototype gram-scale SuperCDMS Si HVeV detectors.

Calibration data analysis

Data were taken with four Si HVeV (High Voltage eV resolution) detectors. HVeV detectors [2] are gram-scale ($\approx$ 1g) phonon-sensitive detectors with a dimension of 10 mm $\times$ 10 mm$\times$ 4 mm. They have an excellent energy resolution (O(eV)) and a broad dynamic range up to O(100 keV).

Two separate sets of calibration data were acquired for the investigation of Compton steps. A ^{137}Cs ($\approx$ 662 keV gamma) source was used to study the Compton steps and a Light Emitting Diode (LED) ($\approx$ 2 eV optical photons) was used to study the non-linearity of the detector response at keV energies and perform cross-calibration at low-energies. A Geant4 simulation [5] was conducted using a single HVeV detector to model the detector's response. The resulting energy spectrum in the low-energy range (O (keV)) obtained from the simulation is illustrated in Fig. 1 (left). Notable features in this spectrum include a Cu X-ray photo peak at 8.1 keV (due to the Cu housing of the detector) and a Si K shell Compton step at 1.8 keV. The detector response to 662 keV gammas from ^{137}Cs was obtained at 0 V bias voltage experimentally. This spectrum is investigated for Compton steps in the O(keV) range and is shown in Fig. 1 (right).

To estimate the recoil energy, a pulse-integral-based energy estimator was employed, which calculates the area of the pulse within an analysis window of $\approx$ 13.1 ms. This method was chosen due to its broad dynamic range O(100 keV). The distinct e^-h^+ pair peaks obtained from an LED run can be seen in Fig. 2 (left). These e^-h^+ peaks are used for the energy calibration at ~keV energies (Fig. 2 (right)). The current scale, measured as the position of the first e^-h^+ pair peak in the spectrum in current units, was changed due to the inclusion of the LED source in the detector payload. The current scale can be varied by changing the detector Working Points (WPs) along the R-T transition curve (Fig. 3 upper left) of the Transition Edge Sensors (TES). The closest current

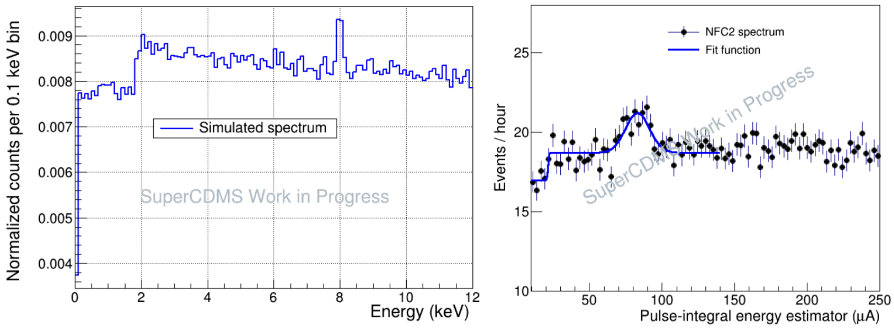

Figure 1: (left) Simulated detector response to 662 keV gammas from a ^{137}Cs source, featuring Cu X-ray photo peak and K shell Compton step. (right) Experimental spectrum showing a distinct peak and a step-like structure.

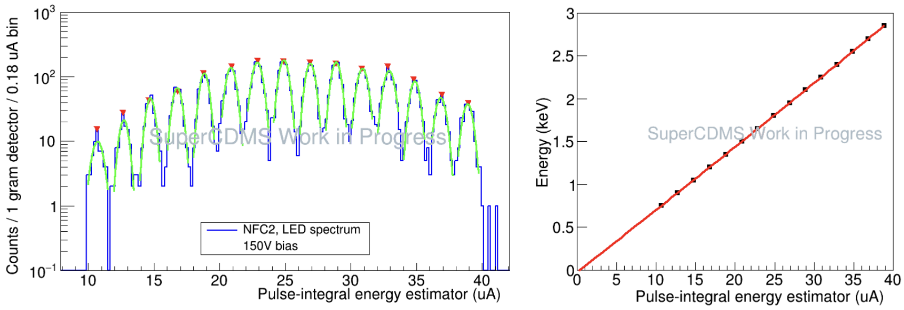

Figure 2: (left) LED spectrum obtained at a bias voltage of 150 V in the Integral-based energy estimator. (right) Energy calibration for the Integral based energy estimator.

scale in the LED data compared to the ^{137}Cs data is achieved by performing a scan on the detector WPs. In order to match the current scale, a linear working point correction was implemented in addition to the WP scan. LED data at three different WPs (WP1, WP2, WP3) (Fig. 3 upper left) were taken where WP3 gives the closest current scale to the ^{137}Cs data. The peak energies were determined by using the LED calibration at WP3 and the differences between the energies give an estimate of the differences in current scale (Fig. 3 upper right). The variation of peak energies for each value of n_{eh} (order of the e^-h^+ peak) after the WP correction is shown in Fig. 3 (bottom). The residual plot, indicating differences of less than 1%, suggests that a linear correction is sufficient.

Summary and outlook

In the ^{137}Cs spectrum, we observe evidence of a K shell Compton step. Our subsequent objective is to apply the WP correction to the LED calibration data and conduct cross-calibration to validate the K shell Compton step. The L shell Compton step study is also ongoing using pulse amplitude based energy estimator which provides better energy resolution at the cost of reduced dynamic range. The insights gained from studying the Compton steps in gram-scale Si HVeV detectors will be applied to the larger kg-scale Si HV detectors in the SNOLAB experiment.

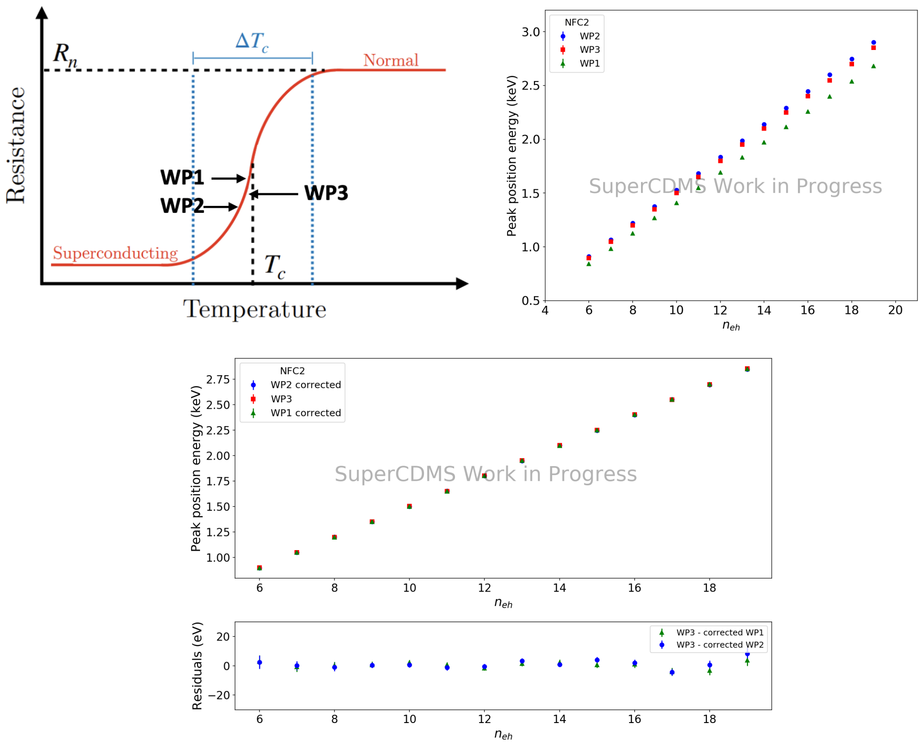

Figure 3: (Upper left) Different TES WPs in the R-T transition curve based on the current scale [6]. Energies for n_{eh} peaks for three different WPs before (upper right) and after (lower) the linear WP correction.

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