Proposal for PhD Dissertation

Simulation of CDMSlite Detector's Response to Ge-71 Decay and Comparison to Data

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Abstract

The SuperCDMS Soudan experiment searches for dark matter particles via direct detection of weakly interacting massive particles (WIMPs). The primary detector in this thesis is the CDMSlite detector, which is designed for the discovery of low-mass WIMPs but has a sensitivity that is limited by our understanding of its response. Our work focuses on understanding its response using new simulations of the detector and comparing it to Ge-71 calibration data which provides known energies and particles. While we will not use the data to search for dark matter, we show new understanding that will be invaluable for future searches using advanced detectors in the SuperCDMS SNOLAB experiment.

1. Background

1.1. Overview of SuperCDMS Soudan Experiment and CDMSlite

The existence of dark matter has been indicated by astronomical observations in the last few decades. One of the models for dark matter is **W**eakly **I**nteracting **M**assive **P**articles (WIMPs) which predicts that WIMPs can deposit energy by scattering with a nucleus as shown in Fig 1.1.1. The SuperCDMS Soudan experiment searches for WIMPs via direct detection, and the detectors are run in a specific configuration that we refer to as CDMSlite mode to be sensitive to low mass (<10 GeV/c^2) WIMPs whose deposit energies are expected to be less than ~10 keV, as shown in Fig 1.1.2. Since known standard model particles will interact with the detector, and are a background for our search, we must be able to understand them as well. As also shown in Fig 1.1.1, different particles cause different types of interactions. WIMPs and neutrons can scatter on atomic nuclei to cause *Nuclear Recoil* (NR), while photons and electrons can scatter on atomic electrons to cause *Electron Recoil* (ER).

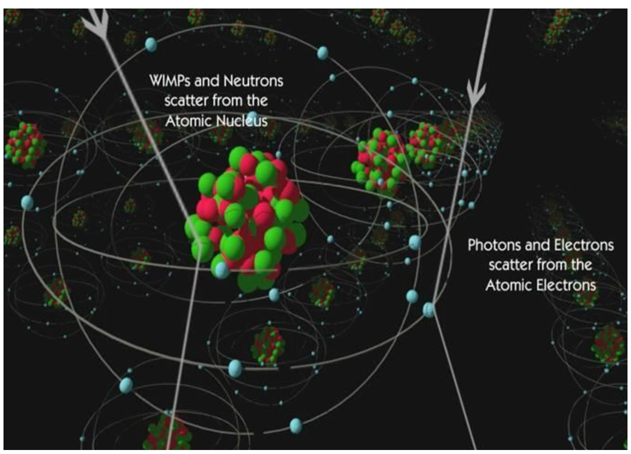


Fig 1.1.1 Different Particles Cause Different Interactions

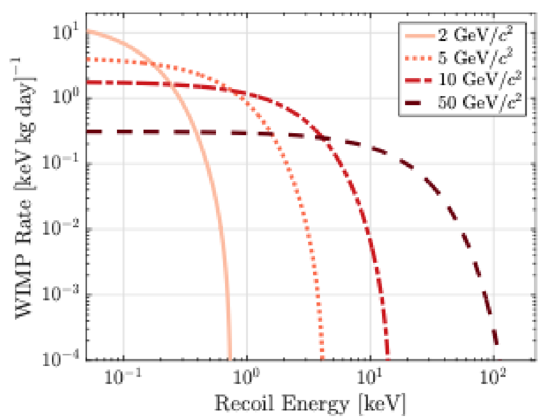
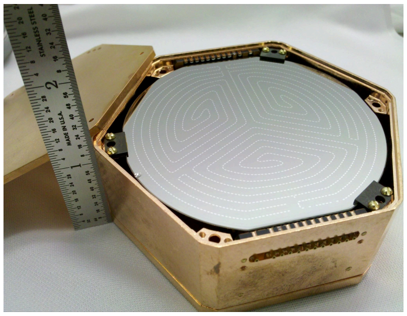
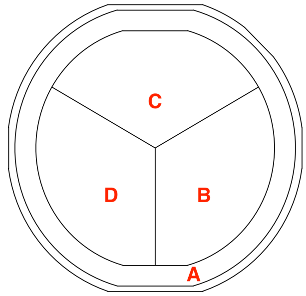


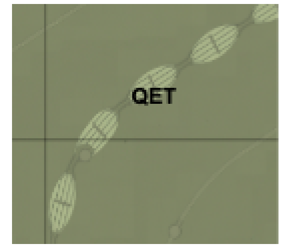
Fig 1.1.2 WIMP Rate vs Recoil Energy

1.2. CDMSlite Detector

The CDMSlite detector is the primary detector in this thesis as shown in Fig 1.2.1 which is roughly cylindrical with a ~76 mm diameter, ~25 mm height, and ~600 g mass and made of a single semiconductor crystal, Germanium. The detector is set to 0 volts on the top side and -70 volts on the bottom side. There are four separate channels on, as shown in Fig 1.2.2, on each side of the detector. Channel A is the outer channel and Channel B, C, D are the inner channels. These channels are instrumented with the same number, 400+, of **Q**uasiparticle Trap Assisted **E**lectrothermal Feedback **T**ransition Edge Sensor (QET) units that collect, transport and read out energy.







(zoom-in of the detector surface)

Fig 1.2.1 CDMSlite Detector   Fig 1.2.2 Diagram of Four Phonon Channels   Fig 1.2.3 QET unit

Particle interactions in the crystal ionize electrons to produce electron-hole pairs as well as cause lattice vibrations (phonons), as shown in Fig 1.2.4. When a voltage is set across the crystal, electrons and holes will accelerate and bounce into the lattice to produce more phonons, as shown in Fig 1.2.5. This effect is Neganov-Trofimov-Luke (NTL) Effect and the extra phonons produced on the tracks of electrons and holes are called Luke phonons. When phonons hit the QET units in each of the four phonon channels, a signal is produced and recorded by electronics. More phonons, the bigger the signal.

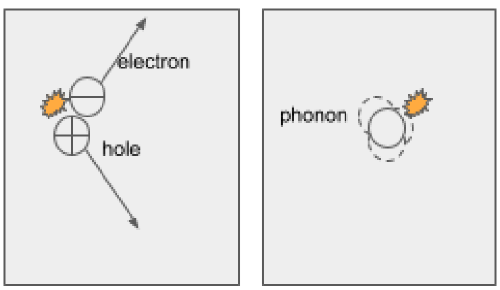


Fig 1.2.4 Particle Interactions Produce Electron-Hole Pairs and Phonons

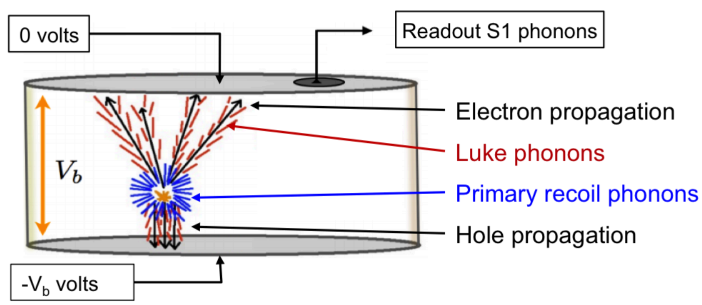


Fig 1.2.5 Neganov-Trofimov-Luke (NTL) Effect and Luke Phonons

1.3. Energy Calibration of CDMSlite Detector and Ge-71 Decay

Since we want to understand how much signal is read out of the detector from a known energy interaction, we use Ge-71 (electron capture) decay for the energy calibration of the CDMSlite detector. Ge-71 is not naturally occurring but can be produced by Ge-70 neutron activation. Calibration runs were performed during which a Cf-252 source which emits neutrons is put near the detector and Ge-70s in the detector can become Ge-71s by capturing neutrons. Ge-71 is an unstable nucleus and will do electron capture decay with 100% branching ratio with a half-life of 11.43 days. In the process, the Ge-71 captures an orbital electron to become a Ga-71 and the binding energy of the electron releases by emitting photons and/or electrons. The K-, L- and M- shell binding energies of Ga-71 are 10.37, 1.3 and 0.16 keV, which are used for the energy calibration of the detector with fractions of 87.60%, 10.48% and 1.919%.

2. Motivation/Problems

The CDMSlite detector is designed for the discovery of low-mass WIMPs but has a sensitivity that is limited by our understanding of its response. Data taking using the CDMSlite detector was performed shortly after calibration runs when the Cf-252 source is removed so there are no neutrons but many Ge-71 decays occuring. There are three data taking runs and the data from Run 2 is used in this thesis. The two figures below show the energy distribution that the detector recorded. Fig 2.1 includes all events and Fig 2.2 is a zoom-in of Fig 2.1 that shows more details in the energy range of 0.01 - 12 keV. As shown in Fig 2.2, the data clearly shows the three peaks from Ge-71 decay. However, in both Fig 2.1 and 2.2, we also see a lot of other events, large energy (>10 keV) events, low energy (<0.1 keV) events and events between the peaks. As low-mass WIMPs deposit energies are expected to be less than ~10 keV (as shown in Fig 1.2) and the lowest energy events are dominated by noise, this thesis focuses on data in the peaks from Ge-71 decay and the events between the peaks to allow us better understand how the CDMSlite detector respond to Ge-71 decay.

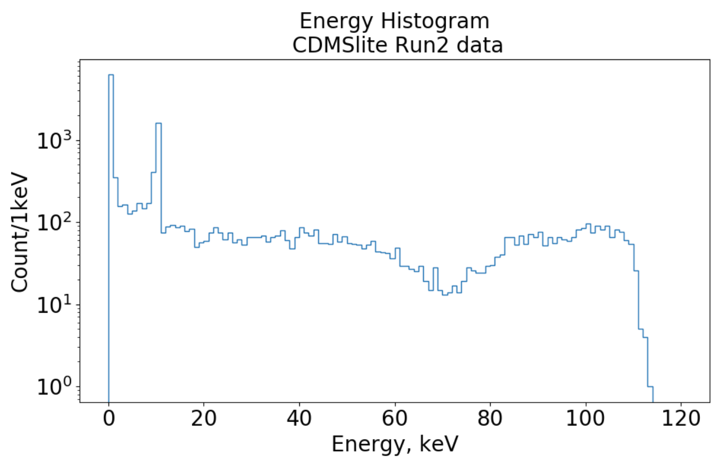


Fig 2.1 Energy Histogram (Full Range), CDMSlite Data

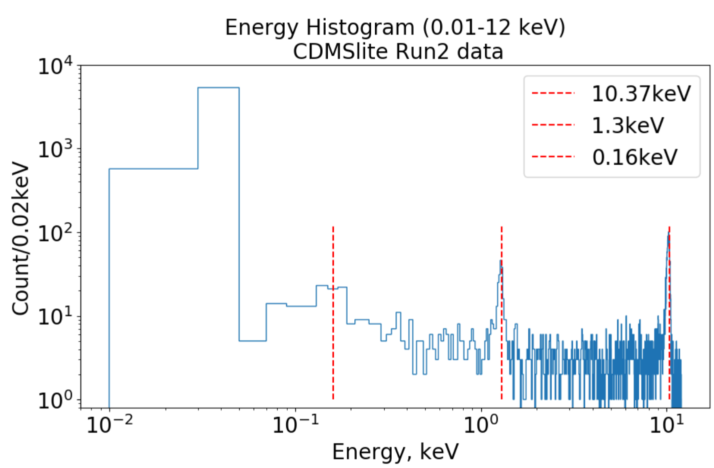


Fig 2.2 Energy Histogram (Zoom-in, 0.01 - 12 keV) with Ge-71 Decay Lines, CDMSlite Data

3. Proposal / Work Plan

The proposed work plan is to better understand the experiment via simulations of how the CDMSlite detector responds to Ge-71 decay and comparisons to the data. This will be done using a series of simulations using the new SuperCDMS Simulation to build up our understanding. The Simulation has two parts, simulation of the interactions with the detector (Source Simulation or SourceSim) and simulation of how the detector responds to the interactions (Detector Simulation or DetectorSim). The simulation will produce data that can be analyzed and/or sent to Data Reconstruction. We will run three different types of SourceSim configurations through the same DetectorSim configuration with increasing sophistication to build up from the simplest interactions to the full Ge-71 decay. Descriptions of the three SourceSim configurations are shown in Table 3.1.

- SourceSim: 1) Pure Energy Deposit; 2) Photons; 3) Ge-71 Decay
- DetectorSim: CDMSlite Detector

Table 3.1 Description of Three SourceSim Configurations

1) Pure Energy Deposit	• Electron Recoil (ER) and Nuclear Recoil (NR) • Only a single hit in the detector, the simplest case
2) Photons	• Carry majority of the energy released in a Ge-71 decay event • Interact multiple times inside the detector, each with ER interaction • Sometime leave the detector
3) Ge-71 Decay	• Both ER and NR are involved • Multiple particles are involved, photons, electrons, and a Ga-71 nucleus that recoils

4. Simulation Objectives

- How does the CDMSlite Detector respond to the known energies from Ge-71 Decay?
    - Do we get back the interaction energy from a known interaction energy deposit? What is the resolution?
- Does the CDMSlite Detector provide a good measurement of the energy?
    - Are there regions of the detector which provide a good measurement and which don't? (Yes)
    - What causes bad measurements?
- Can we use the full set of energy measurements to help determine if an event is well measured?
    - Can we use the full set of energy measurements from the four channels to tell us where an interaction occurs, and therefore likely to be well-measured?
    - Can we model the relationship between energy and position?

5. Current Status

We have run the simplest case, ER 10keV + CDMSlite Detector, which has an energy closest to the largest expected peak (10.37 keV) from Ge-71 decay and the hits are uniformly distributed in the detector. The full simulation, taking into account the phonons produced and the QET response, produces an energy measurement for each of the four phonon channels, which we will refer to as E_A, E_B, E_C and E_D. The sum of these four variables, E_{Total}, provides a measurement of the full interaction.

$$E_{Total} = E_A+E_B+E_C+E_D$$

According to the theory of NTL Effect, as we described in *1.2 CDMSlite Detector*, we expect the total energy measurement, E_{Expect}, to be 123.24 keV. We found that E_{Total} is only a fraction of E_{Expect}, which we refer to as the Collection Efficiency.

$$\text{Collection Efficiency} = E_{Total}/E_{Expect}$$

Figure 5.1 shows the distribution of Collection Efficiency. We note two distributions: a peak at ~87%, where we get as much as we are going to get, and a set of events with a value of <80% which are due to mis-measurements. We define events with collection efficiency >=80% as good measurement events and those <80% as bad measurement events. We plot collection efficiency in the Z-R plane (Fig 5.2) and compare it to CDMSlite Field Map (Fig 5.3). The comparisons show energy mismeasurement in a region of the detector that doesn't have the full voltage. The region where bad measurement events occur is consistent with the region that has voltage of <70V (the green region in Fig 5.3 below)

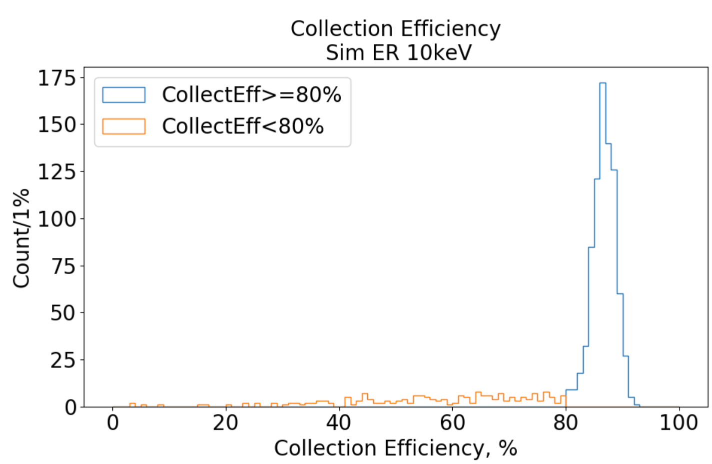
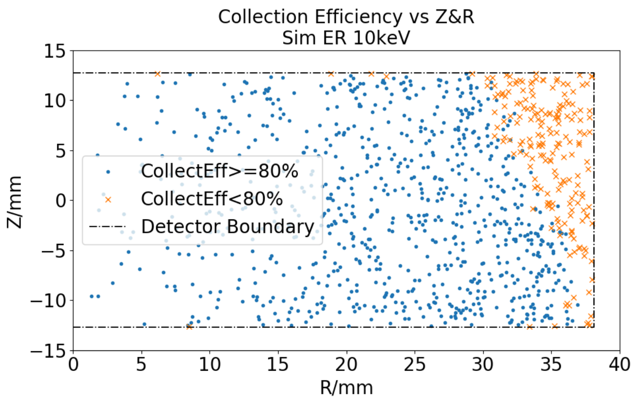


Fig 5.1 Collection Efficiency, ER 10keV Sample



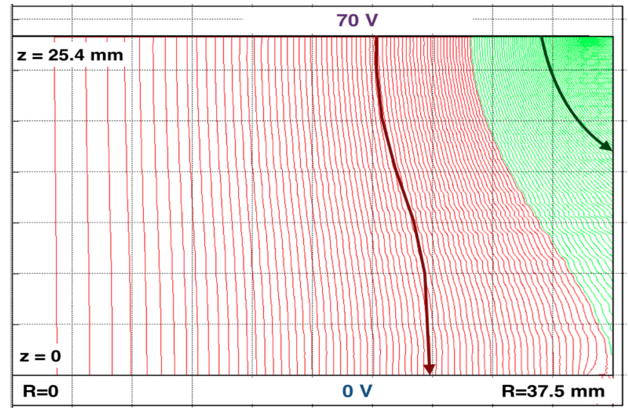


Fig 5.2 Collection Efficiency vs Z&R, Sim ER 10keV

Fig 5.3 CDMSlite Field Map

Since we see a clear correlation between energy measurements and position, but we do not have a measurement of the position in the real data, we developed a simple cut to remove the bad measurement events that have collection efficiency less than 80%. As those events almost occur at high radius (>~30 mm), we are able to remove them if we can find a variable that is well correlated with the radius. As Fig 1.2.5 shows, phonons are produced at the interaction position and/or along the tracks of electrons and holes. Therefore, we expect that Channel A, the outer channel as shown in Fig 1.2.2, will collect more phonon energy if an event occurs at higher radius and less if at lower radius. We define the fraction of the energy collected by Channel A, $Fraction_A$, as:

$$Fraction_A = E_A/E_{total}$$

The value of $Fraction_A$ versus true radius is shown in Fig 5.4.

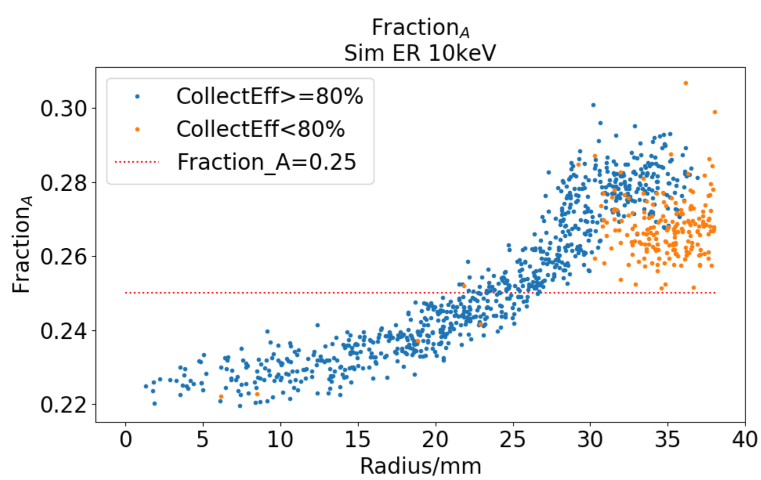


Fig 5.4 $Fraction_A$ vs Radius.

We can successfully remove the bad measurement events with a cut $Fraction_A$ <0.25, though a large portion of the good measurement events are also removed. To see how well this cut might work with real data, and understand if our simulation approximates reality, we select a sample of events with an energy very close to the 10.37 keV line of Ge-71 decay since we expect each to be well measured, as shown in Fig 5.5.

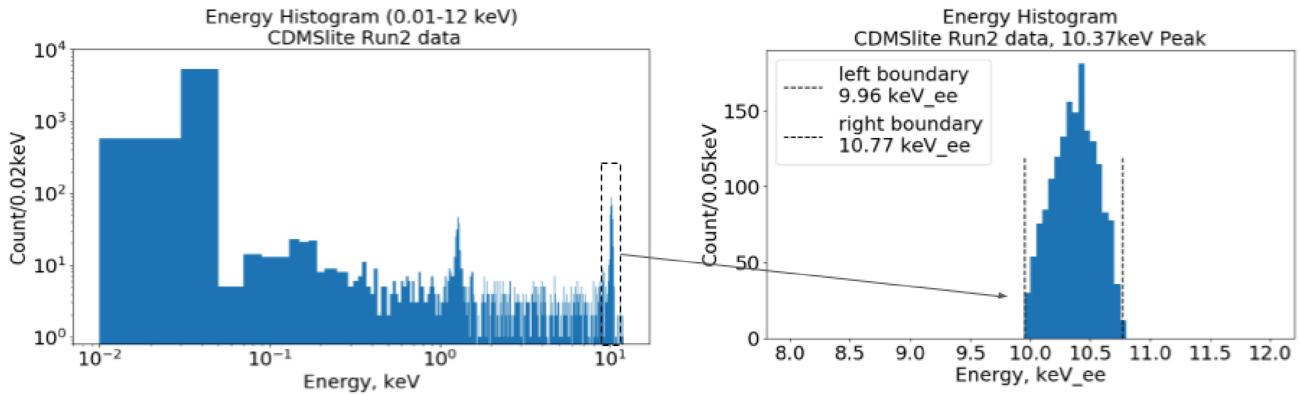


Fig 5.5 Selection of Well Measured Events, 10.37 keV Peak

We can compare them to the simulation which we know are well measured to those in data. The results for the energies in each of the four channels are shown in Fig 5.6.1 - 5.6.8. We observe both qualitative agreement and quantitative disagreement when comparing the measured energy of the four channels (E_A, E_B, E_C and E_D). Left column is for CDMSlite Run2 data (10.37keV line) and the right column for simulation (ER 10keV where we have normalized to 10.37keV for comparison). In particular, comparing the side by side plots, they mostly have the same shape which suggests that our simulation is approximating reality. Similarly, since we expect the events to be uniformly distributed, this is consistent with the three inner channels being approximately equal. We note that B, C and D are very similar in the simulation as expected, but C is very different from the similar B and D in real data. This may be a detector calibration problem.

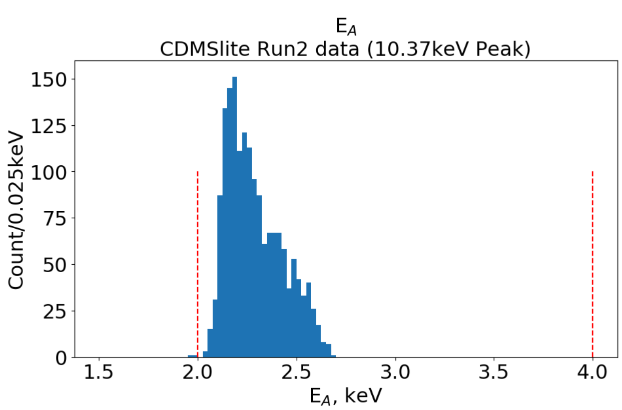


Fig 5.6.1 E_A, CDMSlite Data

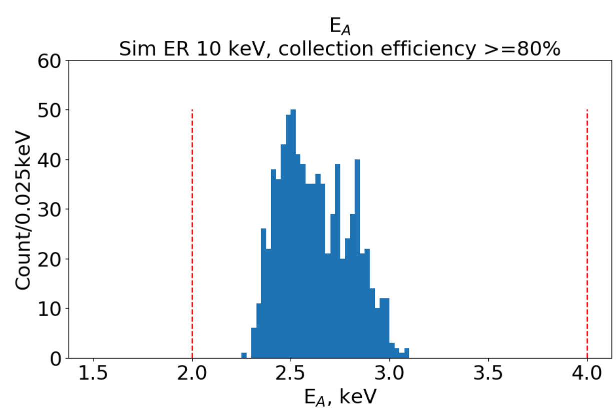


Fig 5.6.2 E_A, Simulated Data, ER 10keV

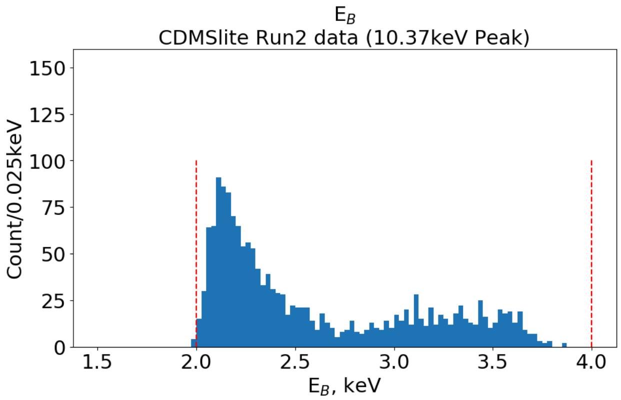


Fig 5.6.3 E_B, CDMSlite Data

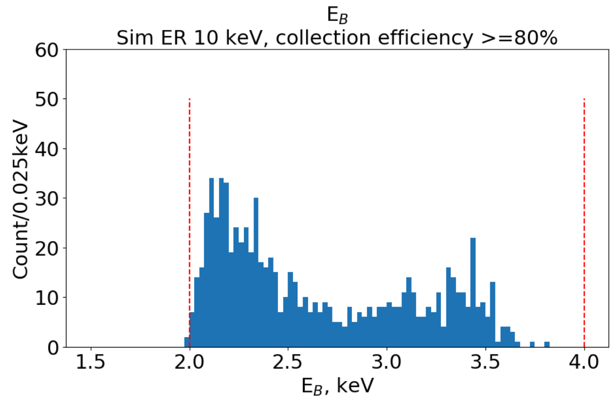


Fig 5.6.4 E_B, Simulated Data, ER 10keV

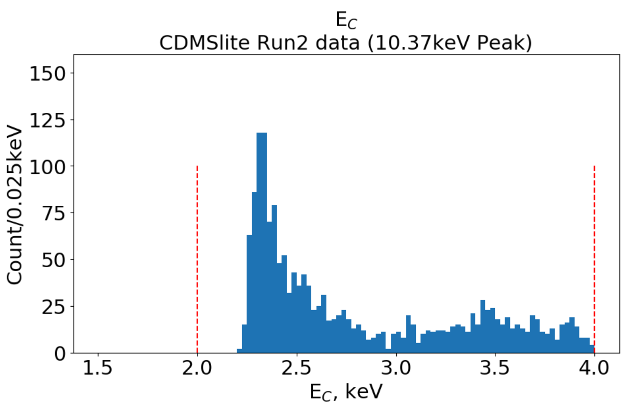


Fig 5.6.5 E_C, CDMSlite Data

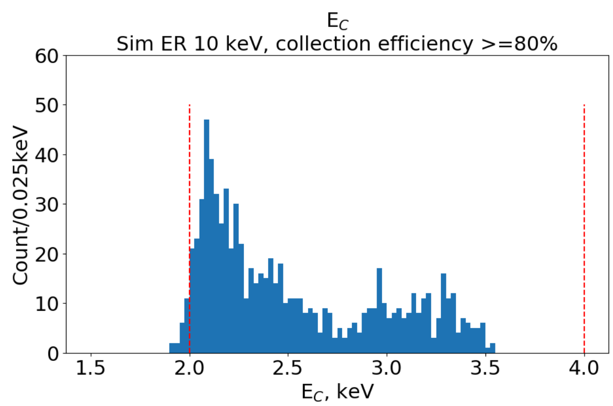


Fig 5.6.6 E_C, Simulated Data, ER 10keV

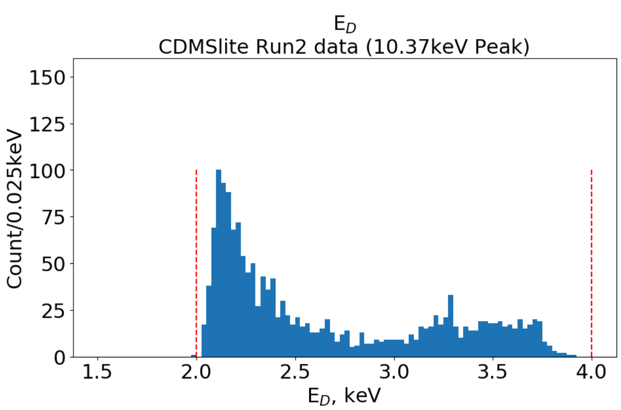


Fig 5.6.7 E_D, CDMSlite Data

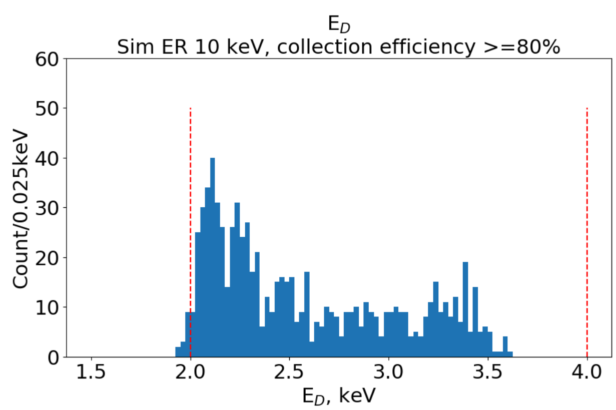


Fig 5.6.8 E_D, Simulated Data, ER 10keV

6. Next Steps

We will add more sophistication to the simulation and simulate the CDMSlite detector's response to photons and Ge-71 decay.

We will investigate the quantitative disagreement between real and simulated data and re-calibrate the real data as we guess the real data were not calibrated correctly.

Thesis Outline

1. **Introduction**
    - 1.1. Evidence for the Existence of Dark Matter and its Properties
        - 1.1.1. Observations of Dark Matter
          (Galaxy Rotation Curve, Gravitational Lensing)
        - 1.1.2. Evidence that Indicates Dark Matter is Non-Baryonic Particles
          (Gravitational Microlensing, CMB, Bullet Clusters, N-Body Simulation)
    - 1.2. A Candidate for Dark Matter Particles: Weakly Interacting Massive Particles(WIMPs)
    - 1.3. A Strategy for Dark Matter Particle Search: Direct Detection
        - 1.3.1. Overview of Direct Detection Method
        - 1.3.2. Overview of Current Direct Detection Experiments and Their Results
    - 1.4. Overview of SuperCDMS Soudan Experiment and CDMSlite Mode
    - 1.5. Overview of this Thesis

2. **Physics of Ge-71 Production and Decay**
    - 2.1. Physics of Ge-71 Production: Neutron Source (Cf-252) and Ge Excitation
    - 2.2. Physics of Ge-71 Decay

3. **Detector Physics and Interactions Inside It**
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    - 3.2. Physics of the Single Crystal Germanium
        - 3.2.1. Conduction and Valence Band
        - 3.2.2. Lattice Structure
    - 3.3. Charge and Phonon Creation and Propagation inside Germanium Crystal
        - 3.3.1. Physics of Electron-Hole Pair (Charge) Creation
        - 3.3.2. Physics of Lattice Vibration (Phonon) Creation
        - 3.3.3. Phonon Amplification When There is a Voltage Across the Crystal:
          Neganov-Trofimov-Luke Effect
    - 3.4. Phonon Energy Collection and Transportation: Quasiparticle Trap Assisted Electrothermal Feedback Transition Edge Sensor (QET)
    - 3.5. CDMSlite Detector and Interactions Inside it

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        - 4.1.2. CDMSlite Apparatus (Cryogenics, Shielding, etc)
        - 4.1.3. Data Acquisition(DAQ) for SuperCDMS Soudan Experiment
    - 4.2. Calibration Run and Data Taking
    - 4.3. Electronic Noise During Data Taking
    - 4.4. Expected Sources of Events
        - 4.4.1. Ge-71 Electron Capture Decay in Fiducial Volume
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4.4.3. Other Possible Sources
4.4.4. Noise and Signal Saturation

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5.2. Overview of Optimal Filter and Non-Stationary Optimal Filter
5.3. Signal Template Construction
5.4. Noise PSD
5.5. Converting Readout Signals to Energy Measurements and Calibration
5.6. Phonon Energy Measurement and Recoil Energy

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6.3.2. Peak Locations
6.3.3. Peak Width
6.3.4. Full Sets of Energy Measurements

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8.3.3. Impact of adding TES, DAQ and Noise on the resolution
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9. Simulation of CDMSlite Detector's Response to Ge-71 Decay and the Results
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9.3. Results out of Full Simulation

9.3.1. Energy Spectrum
9.3.2. Peak Locations
9.3.3. Peak Widths
9.3.4. Full Sets of Energy Measurements
9.3.5. Events that Pass/Fail the Analysis Cut

10. Comparison of the Simulated Data to Real CDMSlite Data
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(ptNF, ptOF, psumOF, paOF, pbOF, pcOF, pdOF, conversion to keV_ee)
10.2. Peak Locations of Ge-71 Electron Capture Decays Before and After the Analysis Cut
10.3. Peak Widths of Ge-71 Electron Capture Decays Before and the After Analysis Cut
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10.3.3. Comparison of with-Noise Simulation and Real Data
10.4. Further Analysis of Events that Pass and Fail the Analysis Cuts
(Further subchapter will be added as analysis proceeds)

11. Future Planes after This Thesis
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11.1.1. Simulation of CDMSlite Detector’s response to WIMPs
11.1.2. Simulation Upgrades: TESSim_template to TESSim_ODE
11.2. Detector Upgrades for SNOLAB and the Vision for Analysis for Simulation

12. Conclusion