

**SuperCDMS Background Models for Low-Mass Dark
Matter Searches**

**A DISSERTATION
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY**

D'Ann Rebekah Barker

**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
Doctor of Philosophy**

Dr. Priscilla Cushman, Advisor

August, 2018

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Acknowledgements

It is impossible to express my gratitude to everyone that has helped me along my journey toward earning this PhD. My love of learning and curiosity has been with me as long as I can remember, and was fostered by many teachers and mentors throughout the years. I have also had the support of family and friends. Thank you.

Foremost, the love and support of my family has been invaluable. You have always encouraged me to do what I enjoy and reminded me that my best is good enough. Impossible was not a word we used; there were no boundaries on my educational options. I could not have made it this far without you.

I am grateful to my advisor Prisca Cushman for saying yes when I asked to join her group. I have learned so much about asking the right questions and getting to the heart of a problem. Your guidance has made me a better, more independent, thinker and researcher. I would also like to thank Vuk Mandic for offering additional perspective and insights. Thank you for encouraging me to speak out and ask questions.

The UMN group has been absolutely amazing. I have enjoyed getting to know each of you. I am exceptionally grateful to Mark Pepin for passing on all his knowledge about CDMS data analysis and backgrounds. Our mutual coffee addiction led us on many adventures over the years. I appreciated the countless conversations about everything under the sun, and I consider you a true friend. Thank you for the encouragement even after your departure from UMN. And to Anthony Villano who has inspired me with your ideas and curiosity; you were always available to talk through problems and offer suggestions and encouragement. I am also grateful to Hannah Rogers, Allison Kennedy, Nick Mast, Matt Fritts, Hassan Chagani, Scott Fallows, and Tommy Hofer; you welcomed me into the group and made my research experience enjoyable.

My first year at UMN would likely have been a disaster without Zach Lesko. You

put up with me for hours on end as we struggled through Quantum, Particle, and GR. Let's not do that again. I am also grateful for the friendship of Karlen Shahinyan and Pat Meyers; the many movie nights and social support at parties made graduate school about more than just physics. Our conversations always meant a lot.

I would also like to thank the SuperCDMS Collaboration for invaluable advice and feedback on my research over the years. I would especially like to thank Ben Loer for mentoring me through all things backgrounds, and Mike Kelsey for promptly answering all my questions about SuperSim. Additionally, Bill Page and the entire CDMSlite analysis team have done tremendous work, and I feel very honored to have been able to work with you over the past few years.

To my many small group friends: Rachel Ball, AnnaLisa Buol, Lindsey Crye, Ian De Silva, Nicole Frikke, Cassie Gold, Dave Marthaler, and David Ruess. You accepted me and offered me your friendship. I am so grateful for our conversations and accountability. You have made my time in Minneapolis a truly wonderful experience.

Molly, I can never say thank you enough for walking with me. I have grown so much and come so far.

“But for me it is good to be near God; I have made the LORD my refuge, that I may tell of all your works.” - Psalm 73:28

To my family

Abstract

An abundance of astrophysical and cosmological evidence indicates the existence of a non-luminous, non-baryonic form of matter, called dark matter, that is approximately a quarter of all energy in the universe. One promising candidate for dark matter is the Weakly Interacting Massive Particle (WIMP) which interacts with baryonic matter at most on the scale of the weak force. The Cryogenic Dark Matter Search (CDMS) experiment aims to detect the nuclear recoils induced by the elastic scattering of WIMPs off of germanium nuclei. This is a rare signal and difficult to detect, especially the low-energy recoils that are produced by low-mass dark matter.

The CDMS project operated at the Soudan Underground Laboratory from 2003–2015, with an upgrade to the SuperCDMS experiment in 2012. The germanium detectors were operated at 50 mK and able to measure both the ionization and athermal phonons produced in a particle interaction. Measuring two signals enables discrimination between electron recoil and nuclear recoil events. An alternative operating mode for the detectors is called the CDMS low ionization threshold experiment (CDMSlite), where a higher bias was applied to the detectors and only the phonon signal analyzed. This method increased sensitivity to low-mass dark matter interactions, but sacrificed discrimination capability.

The CDMSlite spectrum had a large contribution from electron recoil background events. From the information gained during the first two CDMSlite Runs, a background model was developed for the third and final CDMSlite Run. Analytical descriptions were identified for those backgrounds that were theoretically known, e.g. tritium β -spectrum, and GEANT4 simulations were used to understand and predict the low-energy spectra from other sources, e.g. Compton scattering.

Multiple new models were developed for detectors operated in CDMSlite at Soudan. These include the analytical formula for Compton scattering, and empirical models for surface backgrounds from ^{210}Pb contamination of the germanium crystals and detector housing. In order to accurately describe the surface events, a new detector response function was developed that included information about the electric field and energy resolution of the detector. These models were essential to the implementation of a profile likelihood analysis of the CDMSlite Run 3 data, which improved on the sensitivity to dark matter over the Run 2 optimum interval analysis for WIMP masses above $2.5 \text{ GeV}/c^2$. This demonstrated a successful application of a likelihood analysis to the high-voltage operating mode, and the potential for these analyses in the future SuperCDMS SNOLAB experiment.

For the SuperCDMS SNOLAB experiment, the change in background rates from radiogenic neutrons was considered as additional towers of detectors were added, and the feasibility of an active neutron veto as a potential upgrade for large payloads was studied. This veto could be constructed of plastic scintillator with layers of gadolinium resin, and would aid in reducing the nuclear recoil single scatter background that is indistinguishable from the WIMP signal.

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1

Detection of Weakly Interacting Massive Particle Dark Matter

Over the last few decades, scientists' understanding of the universe has greatly increased. It is now established that the universe is composed of dark energy, dark matter, and luminous, baryonic matter. Measurements of the density parameters of these constituents, at the present time in the universe, are: dark energy $69.11 \pm 0.62\%$, dark matter $25.89 \pm 0.57\%$, and baryonic matter $4.86 \pm 0.10\%$ [1]. Not much is known about the two more abundant components, and determining their nature is an active area of research. In contrast, the smallest portion of the universe, baryonic matter, is explained by the Standard Model of particle physics [2].

The model that best describes the changes in the proportions of these constituents is called Λ CDM, where Λ indicates the dominance of dark energy and CDM stands for cold dark matter.¹ Λ CDM describes the evolution of the universe from the Big Bang, through inflation, particle formation, creation of heavy elements (Big Bang Nucleosynthesis), and large scale structure formation, culminating in the expanding universe observed today. In this model, dark matter is a heavy particle that interacts weakly with baryonic matter [2].

Because dark matter interactions are rare, the direct observation of these particles is challenging. Thus, it is beneficial to have a complete characterization of all other

¹ A review of this Λ CDM (also called Big-Bang Cosmology) can be found in Ref. [2].

particle interactions, such that the dark matter signal, if present, can be identified. The properties of dark matter and the expected signature are discussed in this chapter along with methods of detection. Much of the remainder of this thesis describes models developed for representing the undesirable backgrounds and one application in the Cryogenic Dark Matter Search low ionization threshold experiment.

1.1 Weakly Interacting Massive Particles

A historically preferred dark matter candidate, supported by the observational evidence, is the weakly interacting massive particle (WIMP). This is a general class of particles that have an expected mass in the range of $1 \text{ GeV}/c^2$ to $10 \text{ TeV}/c^2$ and interact with luminous matter at most on the scale of the weak force. A family of new particles, where the lowest mass partner provides a dark matter candidate, is postulated in many theories which extend the Standard Model (SM) of particle physics. However, current experiments searching for WIMP dark matter have yet to detect these particles imposing constraints on the existing models and the continual development of new theories [3].

1.1.1 *Properties and Evidence*

There is a wealth of astrophysical and cosmological evidence for the existence of dark matter that extends from single galaxies to the visible universe. All suggest a dominant, non-luminous, non-absorbing component to the matter of the universe that is approximately five times more abundant than baryonic matter. Alternative models of gravity, other than Einstein's theory of general relativity [4], have been proposed such as the well studied class of models called MODified Newtonian Dynamics [5]. Though MOND can explain evidence on the galactic level, it cannot describe observations on larger scales like cluster dynamics. Thus, a particle solution to the dark matter problem is preferred. The observed evidence points to a successful particle dark matter candidate with the following properties [6]: massive, neutral and minimally interacting, stable, and non-relativistic.

Dark matter is observed to have **mass** and interact gravitationally. The idea of dark matter was first postulated to explain the contradictory mass measurements of galaxy clusters. The total mass estimated from the velocities of the constituent galaxies was

several hundred times larger than the mass deduced from the luminous component [7–9]. On the scale of individual spiral galaxies, a massive, neutral halo of density $\rho \propto r^{-2}$ is consistent with measurements of the orbital velocities of material outside the visible disk [10, 11].

Secondly, dark matter has not been detected to interact through any of the mechanisms that make baryonic matter visible, such as the absorption, emission, or scattering of light. Thus, it can be said that the particle is **neutral** and **minimally interacting**. Compelling examples of this property come from the observations of the mass distribution of galaxy clusters. These mass distributions are determined through gravitational lensing maps, optical images, and x-ray emissions of intergalactic gas [12–15]. A famous example is the Bullet Cluster [16]. Here, two clusters collided millions of years ago, and the hot intergalactic medium, which contains most of a cluster’s baryonic mass, stalled in the center of the clusters; this central distribution is identified by x-ray images as the location of greatest mass density. However, measurements of gravitational lensing indicate the majority of matter in the clusters passed through unimpeded and are separated in space. These observations indicate each cluster had a dark matter halo that did not interact whereas the baryonic matter interacted and was left behind [14, 16]. The requirement for a minimally interacting dark matter particle is also evidenced by measurements of the diffuse γ -ray background [17].

The effects of dark matter are detected at the present cosmological time, with the relic density inferred from studies of the anisotropies in the Cosmic Microwave Background (CMB) [17, 18], and the process of Big-Bang Nucleosynthesis (BBN) [19]. Thus, it must be a **stable** particle that does not decay; or if it does, has a half-life on the time scale of the universe.

The temperature of dark matter after leaving the equilibrium of the early universe, and thus the relative time of this decoupling, was important for structure formation. The interplay between the gravitational attraction of dark matter and baryons and the pressure from the baryonic coupling to radiation created density fluctuations. If dark matter were relativistic at structure formation, the density fluctuations would shrink instead of grow [20]. Simulations, such as the Millennium simulation [21], study the growth of Large Scale Structure (LSS) with various relic densities of dark and normal matter. Comparisons between simulations of the LSS in the universe and observations

from the Sloan Digital Sky Survey [21–23] support a **non-relativistic**, or cold, dark matter particle. This type of particle, and the gravitational wells it created would seed structure formation.

1.1.2 *Supersymmetry WIMP Candidates*

WIMPs represent only one of many dark matter candidates², such as Sterile Neutrinos [24] and MACHOs [25, 26]. Others arise from beyond-the-standard-model theories which were originally developed to solve other particle-physics problems. For example, supersymmetry (SUSY) was created to solve the hierarchy problem³ [27, 28], and axion particles were introduced as part of a solution to the strong charge-parity (CP) invariance problem⁴ [29, 30]. A few of the WIMP dark matter candidates arising from SUSY theories are discussed further.

In SUSY, a fermion (boson) superpartner is predicted for every boson (fermion) in the Standard Model [27, 28]. In the minimal supersymmetric extension to the SM (MSSM), an additional symmetry R -parity⁵ is introduced which must be conserved. Thus, the lightest supersymmetric particle (LSP) is stable, electromagnetically neutral, and a possible WIMP dark matter candidate [28]. In the constrained MSSM (CMSSM), the LSP is typically identified as the lightest neutralino χ_1^0 , which is composed of a linear combination of the superpartners of the neutral gauge bosons [31].

Searches for evidence of SUSY have taken place at the Large Hadron Collider (LHC), where the large energy scales allow for the creation of heavy particles. Though searches are continuing, neither ATLAS [32] nor CMS [33] have detected SUSY candidates which could decay to the LSP. These null results place tight bounds on the CMSSM [34]. As such, extensions have been proposed such as the next-to-minimal model (NMSSM) [35]

² There are a number of review articles summarizing candidates for dark matter such as Refs. [2, 3].

³ The hierarchy problem arises from the fact that the measured mass of the Higgs is much smaller than calculated through radiative corrections, unless there is extreme fine-tuning.

⁴ In quantum chromodynamics (QCD), there could be a breaking of CP symmetry in the strong interaction that has not been observed in experiments. This lack of symmetry breaking is known as the strong CP problem and requires fine-tuning of QCD.

⁵ R -parity is a discrete symmetry defined as

$$R = (-1)^{3B+L+2s} \quad (1.1)$$

where B and L are the particle's baryon and lepton number and s its spin. Superpartners have $R = -1$ while SM particles have $R = +1$.

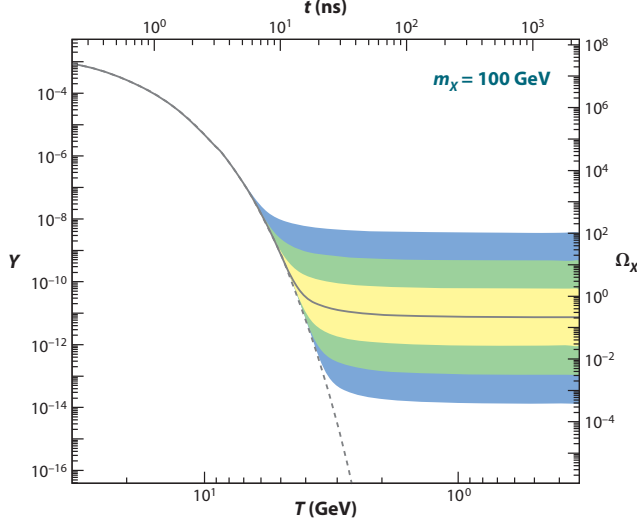


FIGURE 1.1: Possible freeze-out condition for a $100 \text{ GeV}/c^2$ dark matter particle. As time t increases and temperature T decreases, the equilibrium (dashed line) condition for number of particles in a comoving volume Y and the relic density Ω_χ decrease. Once the particle undergoes freeze-out, Y and Ω_χ become constant, leaving equilibrium (solid line). In the particular case shown, the cold dark matter relic density is produced. The bands show differences by a factor of 10 (yellow), 100 (green), and 1000 (blue). Figure from Ref. [37].

and the phenomenological MSSM (pMSSM) [36]. With no evidence of CMSSM, the preferred mass of the neutralino is $m_\chi \sim 1 \text{ TeV}/c^2$.

1.1.3 The “WIMP Miracle”

After a period of rapid inflation, the temperature of the universe was still very hot, with matter and radiation existing in equilibrium. This included any dark matter particles χ . The equilibrium state requires the rate of production and annihilation of particles to be equal. Thus, there is a constant number density of any given particle type. As the universe cooled, the rate of particle production decreases.

Simultaneously, the expansion of the universe lowered the number density of dark matter n_χ , decreasing the annihilation rates. As expansion continued and the universe cooled, the mean-free-path of production and annihilation increased beyond the size of the universe. Thus, the number of dark matter particles in a comoving volume Y became constant. This process is referred to as “freeze-out.” The freeze-out and resulting relic density for a $100 \text{ GeV}/c^2$ dark matter particle is shown in Fig. 1.1.

This process occurs for all particles present in the early universe, and the resulting relic density depends on the coupling $\langle\sigma v\rangle$; as the coupling increases the relic density decreases. Thus, the stronger the coupling the lower the relic density. The predicted

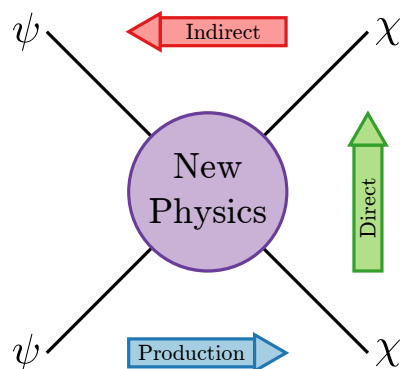


FIGURE 1.2: Cartoon Feynman diagram demonstrating the possible methods of interaction between standard model (SM) ψ and dark matter χ particles through some unknown, new physics process. Collider searches follow the blue arrow attempting to produce χ from ψ . In the opposite direction (red), indirect detection looks for SM particles created in the decay/annihilation of χ . Direct detection (green) seeks to observe the direct interaction of ψ and χ .

relic density is [2]

$$\Omega_\chi h^2 \approx \frac{(10^{-37} \text{ cm}^2)c}{\langle \sigma v \rangle}. \quad (1.2)$$

A thermally produced dark matter candidate should have mass and coupling such that $\Omega_\chi = \Omega_{\text{CDM}} = 0.259 \pm 0.003$ [1].

Incidentally, a particle with interaction cross section on the weak scale (a few picobarns) and a mass above $\sim 2 \text{ GeV}/c^2$ yields the appropriate relic density to account for dark matter [38, 39]. This coincidence is known as “the WIMP miracle.”

1.2 Experimental Direct Detection

Even with the observational evidence and myriad of theories, dark matter has yet to be experimentally observed and its properties measured, specifically its mass m_χ and interaction cross section σ . In essence, the interaction between dark matter χ and standard model (SM) ψ particles must be witnessed. In general, there are three complementary programs to observing dark matter demonstrated in Fig. 1.2: produce dark matter particles in a collider from the high-energy collision of SM particles (collider searches); observe the decay/annihilation products of residual relic dark matter (indirect detection); or measure the scattering between a dark matter particle and a SM particle (direct detection). This thesis will focus on the direct detection of WIMP dark matter.

1.2.1 Expected Event Rate

There are three essential components to the WIMP differential event rate: the astrophysical model of dark matter, the type of dark matter-nucleus interaction, and the properties of the detector target material. Once the differential rate is known, the observed events is calculated as [40]

$$N = \int_{E_1}^{E_2} \frac{dR}{dE_r} \mathcal{E}(E_r) dE_r, \quad (1.3)$$

giving N events with recoil energy E_r in the energy range E_1 to E_2 . dR/dE_r is the differential recoil rate and $\mathcal{E}(E_r)$ the detector exposure.⁶

In order to determine the differential rate of expected events, first consider the differential number density of WIMPs near the detector [41]

$$dn = \frac{n_0}{k} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}, \quad (1.4)$$

where n_0 is the mean dark matter particle density ($\equiv \rho_0/m_\chi$ with ρ_0 the dark matter density), $f(\mathbf{v}, \mathbf{v_E})$ the dark matter velocity distribution, $\mathbf{v}$ the velocity of the WIMPs on the target, v_E the Earth's velocity relative to the dark matter halo, and k a normalization constant such that

$$\int_0^{v_{\text{esc}}} dn \equiv n_0, \quad (1.5)$$

with $v = |\mathbf{v}|$ and v_{esc} the local galactic escape velocity. For a particular target with N_T nuclei per unit mass, the differential event rate per mass is

$$dR = N_T v d\sigma dn = \frac{N_T n_0}{k} d\sigma f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}, \quad (1.6)$$

where $d\sigma$ is the differential WIMP-nucleus cross section.

Generally, a Maxwellian distribution is assumed given by [41]

$$f(\mathbf{v}, \mathbf{v_E}) = \exp \left[-\frac{(\mathbf{v} + \mathbf{v_E})^2}{v_0^2} \right], \quad (1.7)$$

⁶ The detector exposure is related to the mass of the detector, the length of observation time, and the efficiency, or accuracy, of identifying NRs.

where v_0 is the characteristic velocity. Alternative forms exist, such as the empirical model proposed by Mao et. al. [42] which is developed on dark matter halo simulations.

As a cold dark matter candidate, WIMPs have non-relativistic velocities $v \sim 10^{-3}c$. This gives a de Broglie wavelength of $\mathcal{O}(\text{fm})$ for a WIMP $m_\chi = 100 \text{ GeV}/c^2$. Thus, the WIMP will interact with the nucleus as a single target and not the individual nucleons. The kinetic energy of the WIMP can be calculated simply as $E = 1/2mv^2$ where v is the velocity of the WIMP. The recoil energy E_r given to a nucleus of mass m_T is then

$$E_r = \frac{\mu_T^2 v^2}{m_T} (1 - \cos \theta), \quad (1.8)$$

where θ is the recoiling angle in the center of mass frame, and the reduced mass of the system is given by $\mu_T = m_\chi m_T / (m_\chi + m_T)$. The average energy imparted to the target is

$$\langle E_r \rangle = \frac{\mu_T^2 v^2}{m_T}. \quad (1.9)$$

For the WIMP of mass $m_\chi = 100 \text{ GeV}/c^2$ and velocity $v = 10^{-3}c$ scattering on a germanium nuclei of mass $m_T \sim 67 \text{ GeV}/c^2$, the average energy is $\langle E_r \rangle = 24 \text{ keV}$. Alternatively, the same WIMP scattering on an electron $m_T = 511 \text{ keV}/c^2$ gives an average recoil energy of $\langle E_r \rangle = 0.5 \text{ eV}$. This energy is below the reach of modern technology, and therefore most direct detection dark matter experiments search for the nuclear recoils of WIMPs.⁷

There are a range of WIMP energies, and therefore velocities, that can create a recoil of energy E_r , where the minimum is, from Eq. 1.8,

$$v_{\min} = \sqrt{\frac{m_T E_r}{2\mu_T^2}}, \quad (1.10)$$

while the maximum is related to the Galactic escape velocity v_{esc} and Earth's motion in the halo v_E [46]:

$$v_{\max}(\cos \theta) = \sqrt{v_{\text{esc}}^2 - v_E^2(1 - \cos \theta)} - v_E \cos \theta. \quad (1.11)$$

⁷ Many models of dark matter exist by which inelastic scattering off electrons is a viable interaction mechanism. See Refs. [43–45].

Constant	Symbol	Value	Source
Local Dark Matter Density	ρ_0	$0.3 \text{ GeV } c^{-2} \text{ cm}^{-3}$	[2]
Galactic Escape Velocity	v_{esc}	544 km s^{-1}	[47]
Characteristic Velocity	v_0	220 km s^{-1}	[48]
Solar Peculiar Velocity	$v_{\odot}$	12.2 km s^{-1}	[49]
Earth Orbital Velocity	$v_{\oplus}$	29.8 km s^{-1}	[40]

TABLE 1.1: Accepted values for the Standard Halo Model used in direct detection experiments.

The Earth's velocity is given by $\mathbf{v}_E = \mathbf{v}_0 + \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}$, where $\mathbf{v}_{\odot}$ the sun's peculiar velocity and $\mathbf{v}_{\oplus}$ the Earth's orbital velocity around the sun. The values for the Standard Halo Model (SHM) used by the direct detection community are given in Table 1.1. The differential rate with respect to recoil energy of the target dR/dE_r must account for all WIMP velocities $v_{\min} \leq v \leq v_{\max}$, that can impart E_r to the nucleus, and the changing cross-section with recoil energy:

$$\frac{dR}{dE_r} = n_0 N_T \int_{v_{\min}}^{v_{\max}} \frac{d\sigma}{dE_r} \frac{vf(\mathbf{v}, \mathbf{v}_E)}{k} d^3\mathbf{v}. \quad (1.12)$$

As the specifics of dark matter and its interactions with normal matter are unknown, a general calculation of the interaction cross section is used. Interactions are typically categorized as spin-independent (SI) or spin-dependent (SD) [50], but it is also possible to take a more comprehensive effective field theory approach (see, for example, Refs. [51–53]). The interaction Lagrangian for the non-relativistic WIMP can be simplified to include the scalar (SI) and axial-vector (SD) terms. This interaction is characterized by five parameters: wimp mass m_χ , the SI couplings to the proton and neutron f_p and f_n , and the SD couplings a_p and a_n [50]:

$$\mathcal{L} \approx 4\chi^\dagger \chi \left(f_p \eta_p^\dagger \eta_p + f_n \eta_n^\dagger \eta_n \right) + 16\sqrt{2} G_F \chi^\dagger \frac{\vec{\sigma}}{2} \chi \cdot \left(a_p \eta_p^\dagger \frac{\vec{\sigma}}{2} \eta_p + a_n \eta_n^\dagger \frac{\vec{\sigma}}{2} \eta_n \right). \quad (1.13)$$

Additionally, χ is the WIMP wave function, η the neutron and proton Weyl spinors, $\vec{\sigma}$ the spin operator, and G_F is the Fermi constant. Often, special cases are considered where only the left term in Eq. 1.13 is used, which is SI scattering, or solely the right

term in Eq. 1.13, which is SD scattering.

In the SI scenario, at the zero-momentum transfer limit, the scattering amplitudes add in coherence and the standard cross section is given by [54]

$$\sigma_0^{\text{SI}} = \frac{4\mu_{\text{T}}^2}{\pi} [f_p Z + (A - Z) f_n]^2. \quad (1.14)$$

When it is assumed that $f_p \approx f_n$, the cross section is proportional to the square of the atomic mass A . This enhancement is a motivation to use a target composed of heavy nuclei when probing SI interactions. For SD WIMP-nucleon interactions, the zero-momentum transfer limit of the cross section is [54]

$$\sigma_0^{\text{SD}} = \frac{32(J+1)}{\pi J} G_F^2 \mu_T^2 [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2 \quad (1.15)$$

where J is the nuclear spin and $\langle S_p \rangle$ and $\langle S_n \rangle$ are the expectation values of the proton and neutron spins.⁸ In general $a_p \neq a_n$. Only odd numbered nuclei can participate in SD interactions with WIMPs.

It can be shown (see Ref. [54]) that the differential cross section is⁹

$$\frac{d\sigma}{dE_r} = \frac{m_T}{2\mu_T^2 v^2} \sigma_0 F^2(q), \quad (1.16)$$

where $F(q)$ is a nuclear form factor¹⁰ and q the momentum transferred in the scattering. The differential cross section, zero-momentum cross section, and nuclear form factor are all different for SI or SD. The total differential cross section is then

$$\frac{d\sigma}{dE_r} = \frac{d\sigma_{\text{SI}}}{dE_r} + \frac{d\sigma_{\text{SD}}}{dE_r} = \frac{m_T}{2\mu_T^2 v^2} [\sigma_0^{\text{SI}} F_{\text{SI}}^2(q) + \sigma_0^{\text{SD}} F_{\text{SD}}^2(q)]. \quad (1.17)$$

⁸ This is technically a simplification where the proton and neutron couplings should be written in terms of the isoscalar and isovector couplings $a_0 = a_p + a_n$ and $a_1 = a_p - a_n$, where it is also possible for the isovector coupling to include two-body currents such that $a'_1 = a_1(1 + \delta a_1(0))$ [55].

⁹ The differential cross section of Ref. [54] is of the form $d\sigma/dq^2$ which can be transformed from momentum to energy by noting the momentum transferred in the scatter is $q^2 = 2m_T E_r$.

¹⁰ The nuclear form factor $F(q)$ parameterizes the loss in coherent scattering as the energy of the recoil increases and the WIMP begins to probe the internal structure of the nucleus [54]. In the direct detection community, the Helm form factors are most commonly used [56].

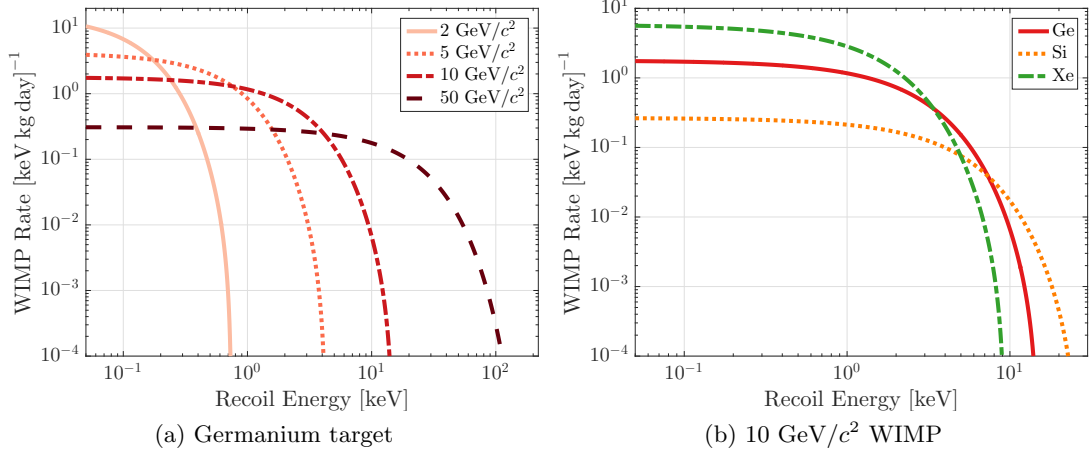


FIGURE 1.3: Differential rate for spin-independent WIMP-proton elastic scattering with cross section $1 \times 10^{-41} \text{ cm}^2$ and various WIMP masses on a germanium target (a) and a $10 \text{ GeV}/c^2$ WIMP on different targets (b). The WIMP masses shown in (a) are 2 (solid), 5 (dotted), 10 (dashed-dot), and 50 (dashed) GeV/c^2 . For (b), prominent experimental targets of germanium (red solid), silicon (orange dotted), and xenon (green dashed-dot) are given. Figures from Ref. [57].

Combining Eq. 1.12 and Eq. 1.17 gives the differential rate

$$\frac{dR}{dE_r} = \underbrace{\frac{N_T m_T}{2m_\chi \mu_T^2}}_{\text{Detector}} \cdot \underbrace{[\sigma_0^{\text{SI}} F_{\text{SI}}^2(q) + \sigma_0^{\text{SD}} F_{\text{SD}}^2(q)]}_{\text{Interaction}} \cdot \underbrace{\rho_0 \int_{v_{\min}}^{v_{\max}} \frac{1}{k} \frac{f(\mathbf{v}, \mathbf{v}_E)}{v} d^3\mathbf{v}}_{\text{Astronomical}}. \quad (1.18)$$

An example of the differential WIMP event rate for the WIMP-proton SI interaction is given in Fig. 1.3 for various WIMP masses in a germanium target, and a comparison of the rates for a WIMP of $10 \text{ GeV}/c^2$ in a few prominent experimental targets. This thesis will focus on the SI interactions of WIMPs with germanium nuclei.

1.2.2 Expected Backgrounds to Direct Detection Dark Matter

In an experimental target of germanium, like those used for the Cryogenic Dark Matter Search (CDMS), the total scattering rate above a 2 keV threshold for a low-mass WIMP of $m_\chi = 5 \text{ GeV}/c^2$ and interaction cross section $\sigma_{\text{SI}} = 10^{-41} \text{ cm}^2$ is $R \approx 0.05 \text{ [kg day]}^{-1}$. This is well below typical background radiation rates and would be impossible

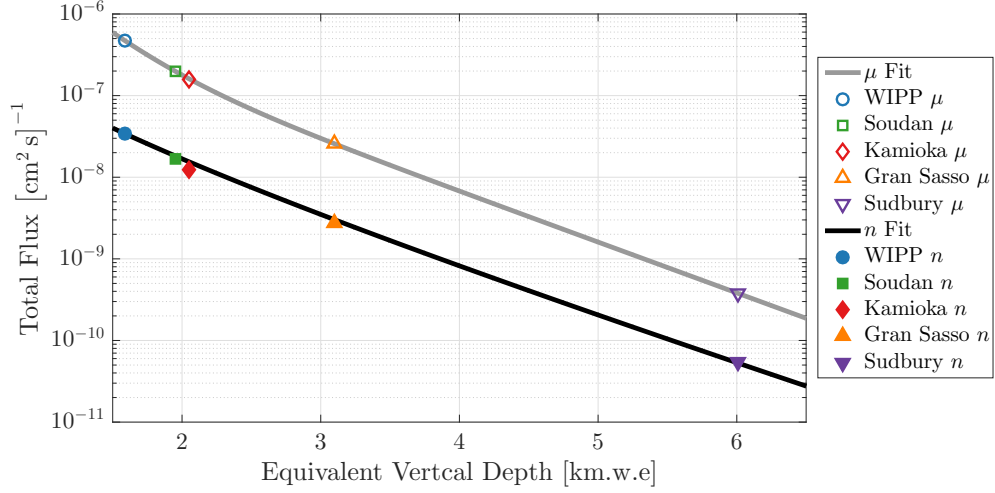


FIGURE 1.4: Flux of cosmic muons and neutrons at various underground laboratories as a function of the overburden depth. The muon fluxes are measurements while the flux for neutrons is derived from a simulation and the muon measurements. Each data set is fit with an empirical model (solid lines). Depth is given in km-water-equivalent. Figure from Ref. [57] with data and fits from Ref. [58].

to detect. Thus, it is imperative that direct detection experiments operate in a low-background environment. This is achieved by establishing the detector facility at an appropriate location, ideally deep underground, and constructing shielding to protect the detector from residual radiation. If possible, the experiment should be designed with the ability to distinguish WIMP signatures from background events. Sources of background common to all experiments, cosmic rays and nearby radioactive matter, are discussed with those specific to CDMS addressed in Chapter 3.

Cosmic rays, the dominant component of which are protons, interact in the atmosphere and often create secondary showers. A variety of particles are created in the secondary showers including, but not limited to, pions, muons, and neutrons. Most of these have small penetration depths in dense material; however, muons of sufficient energy can travel through many kilometers of rock before interacting and creating additional secondaries. The muon itself will deposit energy $\mathcal{O}(\text{MeV})$, but the neutrons produced can appear as WIMP signals. By locating the experiment underground, the flux of muons is reduced as well as the secondary neutrons. Additionally, an active muon veto can be installed. Measurements of the muon flux at a number of under-

ground laboratories are given in Fig. 1.4 along with a parameterization as a function of the overburden. The neutron fluxes are derived from simulation [58].

The radiogenic background is due to materials near the detectors. A low-level, ambient radiation, is constantly present from the decays of long-lived isotopes from the Earth's formation (e.g. uranium or thorium), or by activation of materials on the surface from cosmic rays (e.g. tritium and cobalt in steel). The electromagnetic decay products, β 's and γ 's, external to the experiment are effectively shielded by a material with a high atomic number, such as lead. Those decays internal to the experiment cause electron recoils (ERs) and can be removed if the detector has discrimination capability. Neutrons produced in external decays are mitigated by layers of hydrogenous material, polyethylene or water, whereas internal decays are a source of background. Therefore, experiments use ultra-pure materials to reduce this potential background.

1.2.3 Overview of Experiments

There are a variety of different experimental approaches to directly observe dark matter, though all rely on measuring the energy deposited from the scattering of a nucleus and dark matter particle. In general, there are three different mechanisms of energy collection based on the material type and temperature of the experiment. Devices that are sensitive to phonons, or lattice vibrations, must be cooled to the point that no thermal vibrations are excited in the lattice. Scintillation is the process by which the energy deposited in the material is converted to light and measured by photo-sensitive devices. Finally, a detector can determine the number of electron-hole pairs, or ionization, produced by applying an electric field and collecting the charge carriers.

Many experiments use a combination of these measurement channels as a method of discriminating between ER and NR events. Each technique differs in the amount of NR energy required to create quanta: ~ 100 eV per scintillation photon, ~ 10 eV per electron-hole pair, and ~ 1 meV per phonon [59]. The ratios between the channels enables categorization of individual events as ER or NR. The direct detection experiments, classified by energy measurement technique, are given in the Venn diagram of Fig. 1.5.

Another method of discrimination is a search for annual modulation. As the Earth moves around the Sun through a relatively stationary dark matter halo, it causes an apparent modulation in the kinetic energy of the incoming WIMPs. Thus, a stronger signal

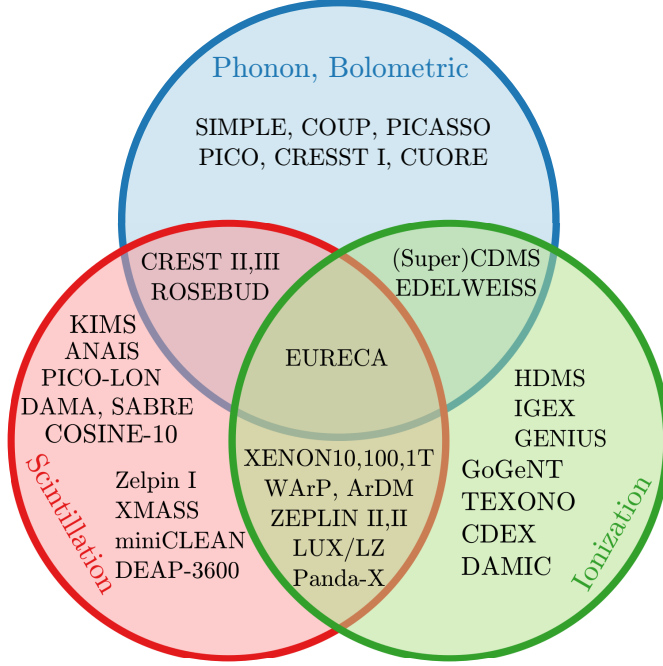


FIGURE 1.5: Venn diagram categorizing the direct detection experiments by the method of energy measurement. The top circle contains experiments which use any type of heat measurement; superheated liquids and cryogenic crystals.

would be observed in June and reach a minimum in December, for energy thresholds >1 keV.

Direct detection experiments represent their results in the WIMP-nucleon cross section σ versus WIMP mass m_χ plane. Exclusion curves are used when no excess above background is observed. These are interpreted as any combination of σ and m_χ parameters above and to the right of the curve are inconsistent with the data. If an excess above background is observed, the 90% confidence level (C.L.) contours give the σ and m_χ for potential candidates.

The direct detection field can be separated into high-mass (WIMPs $\gtrsim 10$ GeV/ c^2) and low-mass (WIMPs $\lesssim 10$ GeV/ c^2) WIMP searches.¹¹ The heavier mass WIMP region contains many of the SUSY candidates, and to date there has been no discovery of these particles. These searches are dominated by the noble liquid detectors with some of the strongest limits set with liquid xenon from the LUX [60], PandaX-II [61], and XENON [62] experiments. Liquid argon is also used by the DarkSide [63] experiment, but because of the lower atomic mass of argon, its sensitivity to spin-independent WIMP-nucleon cross sections is smaller in the high mass region. One benefit to liquid

¹¹ The experiments discussed in this section represent a sample and is by no means exhaustive.

nobles is their ability to scale their detectors to large mass, and thus larger exposure, as well as an exceptional understanding of their backgrounds.

Alternatively, low-mass WIMP searches have historically been dominated by solid state detectors such as DAMIC [64] which uses silicon charge coupled devices (CCDs), CRESST [65] with cadmium-tungstate crystals, and SuperCDMS Soudan [66] with germanium. The low-mass region has gained momentum in recent years with the stringent constraints imposed by the xenon experiments. Hits of possible dark matter signals have been observed in four experiments: the annual modulation searches of DAMA/LIBRA with NaI(Tl) crystals [67, 68], and CoGeNT germanium detector [69]; and the event-by-event discrimination experiments CRESST-II (CaWO_4 target) [70], and CDMS-II silicon analysis [71]. These experiments have observed an excess of events above background that could be interpreted as low-mass dark matter. However, new data from SuperCDMS and CRESST have not observed these WIMP parameters, suggesting complementary target materials are advantageous to determining the properties of dark matter.

A number of experiments are developing new ways to gain access to lower energy thresholds to more effectively search for low-mass WIMPs. SuperCDMS has operated the CDMS low ionization threshold experiment (CDMSlite) measuring only the athermal phonons [72]. The XENON100 experiment utilized the gain in the ionization only signal to perform a low-mass WIMP search [73]. Currently, the DarkSide-50 experiment leads the field in sensitivity to low-mass WIMPs also using only the ionization signal to lower the analysis threshold [74]. The present state of the direct detection dark matter field is shown in Fig. 1.6.

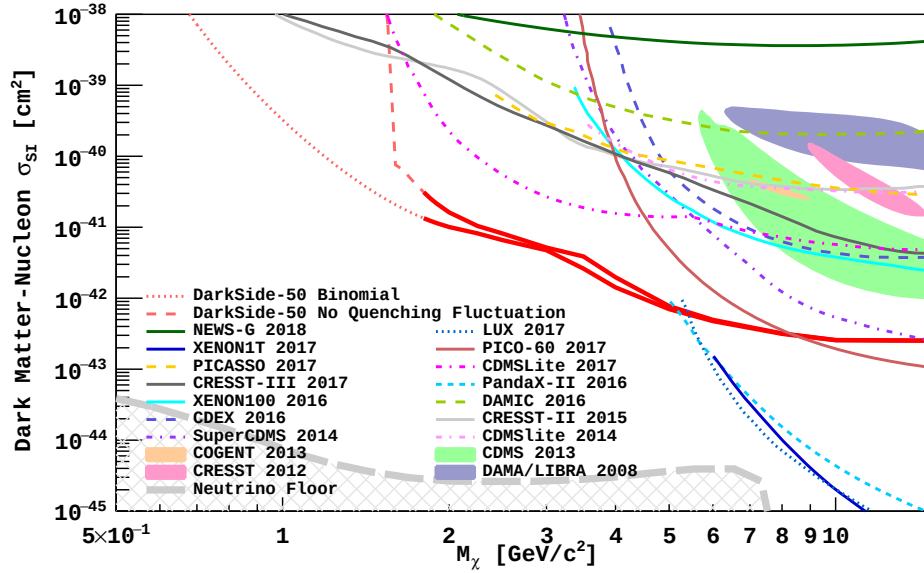


FIGURE 1.6: Current state of the direct detection dark matter field in the WIMP-nucleon cross section vs WIMP mass plane. Exclusion curves do not favor mass and cross sections above and to the right. These are given for DarkSide-50 [74] (red), NEWS-G [75] (dark green), Xenon1T [62] (dark blue), PICASSO [76] (yellow dotted), CRESST-III [65] (dark grey), Xenon100 [73] (cyan), CDEX [77] (dark blue dash), SuperCDMS [66] (purple dot-dash), LUX [60] (blue dot), PICO-60 [78] (brown), PandaX-II [61] (cyan dashed), DAMIC [64] (green dash), CRESST-II [79] (light grey), and CDMSlite [80] (purple dot-dash). The 90% confidence level (C.L.) contours are for potential candidates. These are CoGeNT [69] (orange), CRESST [70] (pink), CDMS-II [71] (green), and DAMA/LIBRA [67] (purple). Figure from Ref. [74].

2

The SuperCDMS Experiment

The Cryogenic Dark Matter Search (CDMS) is a direct detection dark matter experiment designed to identify the interaction of a dark matter particle with a germanium or silicon target. The detector technology of CDMS is able measure both electron-hole pairs (ionization) and lattice phonons (heat) for every event. This is achieved with the interleaved Z-sensitive Ionization and Phonon (iZIP) detectors. The measurement of two signals allows SuperCDMS the ability to discriminate electron recoil (ER) events, such as γ 's and β 's, from nuclear recoil (NR) events, such as WIMPs and neutrons. An alternative running mode, called the CDMS low-ionization threshold experiment (CDMSlite), accesses lower energies through the use of Neganov-Trofimov-Luke phonons, but sacrifices the ability to discriminate ER and NR events.

The SuperCDMS Soudan experiment operated from 2012 - 2015 using the same infrastructure as the previous CDMS II experiment which took data from 2003 - 2008. The experiment was located in the old Soudan iron ore mine in northern Minnesota which was converted into a science laboratory in the early 1980s, called the Soudan Underground Laboratory (simply referred to as Soudan). SuperCDMS was located on the 27th level which is 713 m below ground. SuperCDMS plans to continue the effort at the SNOLAB facility in Sudbury, Ontario with first data expected in 2020. This chapter describes the facilities that allow SuperCDMS to search for dark matter and the detector technology.

2.1 Soudan Operations

Many of the details of the experimental infrastructure and data acquisition will be discussed, with more information described in Ref. [81].

2.1.1 Facility

The facility that housed the detectors was located in a radio-frequency shielded room (RF room) that was also a class-10,000 clean room when occupied, and a class-1,000 clean room during off-hours. The detectors were situated in a copper cryostat (known as the icebox), which was cooled by a dilution refrigerator, and surrounded by layers of shielding to protect the detectors from many sources of radiation.

The detectors were cooled to operating temperature with an Oxford Instruments Kelvinox 400-S ^3He - ^4He dilution refrigerator. There were six stages of cooling to bring the temperature from room temperature to base temperature: 300 K (room temperature), 77 K (nitrogen shield), 4 K (helium bath), 600 mK (still), 50 mK (cold plate), 10 mK (mixing chamber). These stages are shown with the full fridge schematic in Fig. 2.1. Each copper cryostat can, held at one temperature, was connected by a copper tube to the corresponding stage in the fridge. This set of connections was called the cold stem (C stem) and penetrated the shielding. With no load, the base temperature of the cryostat was $\lesssim 10$ mK. This gave sufficient cooling power as the detectors were designed to be operated at ~ 50 mK.

There was a small gap between the helium and still cans in the cryostat that accommodated the detector electronics which were thermally coupled at 4 K. All the electronics cabling necessary to read-out the detectors was threaded through a second set of tubes called the electronics stem (E stem) to the front-end electronics boards, also located in the RF room (the right side of Fig. 2.1).

Mounted to the E stem opposite the fridge, a secondary cooling system was installed that helped bear the thermal load of the full set of five towers and reduced live time loss from liquid helium transfers to the fridge. This system was a Giffords-McMahon cryocooler, and was thermally coupled at the 4 K and 77 K stages. The cryocooler was driven by expansion and contraction of helium gas by a mechanical piston, which introduced some external vibration and was a source of low frequency noise. Both

cryo-cooler systems were from commercial manufacturers and therefore not constructed from high-purity materials. The layers of shielding located between the fridges and the cryostat protected the detectors from their radiation.

2.1.2 *Shielding*

The CDMS shield was designed to reject external backgrounds from cosmic rays and cavern rock radioactivity, as well as offer some protection from the internal radioactive decays of the apparatus. By locating the experiment underground at Soudan, the mine overburden of 713 m greenstone rock (2090 meters water equivalent (m.w.e) depth) reduced cosmic ray muon flux in the laboratory by a factor of 5×10^4 with respect to the surface.

The cosmic muons that manage to penetrate to experimental depth had higher overall energies, and thus greater possibility of creating secondary particles in the cavern rock, like neutrons and γ 's. The layers of shielding were designed to protect against those secondary particles. There was also an active muon veto around the experiment to improve the rejection of cosmic backgrounds by identifying muons. Forty, 5 cm thick, panels of Bicron BC-408 ($\text{H}_{11}\text{C}_{10}$) plastic connected to photomultiplier tubes (PMTs) made up the outer layer of shielding. These panels overlapped in order to avoid line-of-sight for any muon to the detectors. Any event in the detectors that was coincident with an energy deposit exceeding a given threshold in the veto panels was rejected. The veto panels are shown as the blue rectangles connected to the black PMTs in Fig. 2.2.

Within the active muon veto were alternating passive layers of neutron and γ shielding. Working inward, the outer layer consisted of 40 cm thick polyethylene (H_2C_1 chains) bricks which served to moderate neutrons. The electromagnetic particles, primarily γ 's, were shielded by two sequential layers of lead, 22.5 cm total thickness, with the inner 4.5 cm made of ancient lead. Finally, there was an inner layer of polyethylene, 10 cm thick, between the lead shield and cryostat which shielded against any neutrons created in the outer polyethylene and lead shields. All these layers are shown in Fig. 2.2 with the polyethylene layers in green, the lead in gray, and the ancient lead in light gray.

The ^{210}Pb isotope is found in trace amounts in natural lead. With a half-life of 22.3 years, if present in the apparatus materials, it will decay throughout the life time

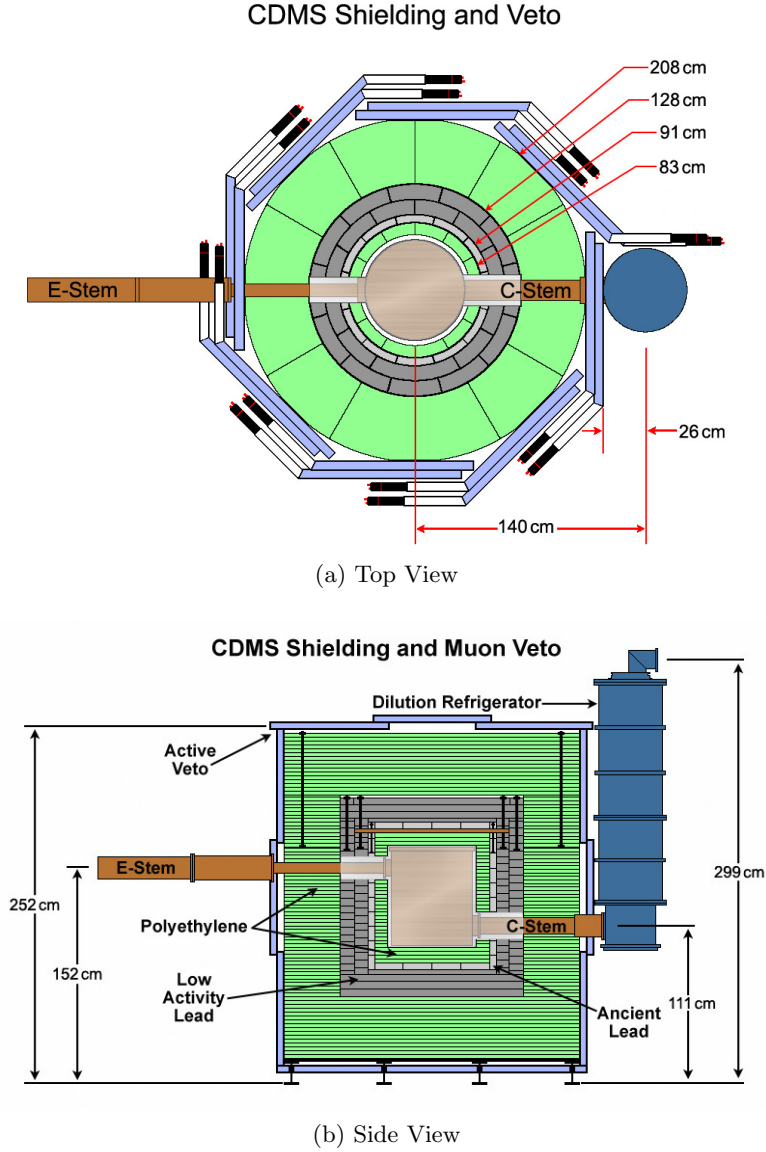


FIGURE 2.2: Cross-sectional diagrams of the CDMS shielding as viewed from the top down (a) and the side (b). The outermost layer consisted of the active muon veto panels (light blue) connected to PMTs (white and black). The passive layers of shielding, from outermost to innermost are: 40 cm polyethylene (green), 18 cm lead (gray), 4.5 cm ancient lead (light grey), and 10 cm polyethylene (green). In the center is the cryostat (light brown) which provided another 1.9 cm of shielding. The E stem and C stem are shown in brown in their relative locations. On the right, in blue, is the dilution refrigerator. Figures courtesy A. Villano and J. Sanders.

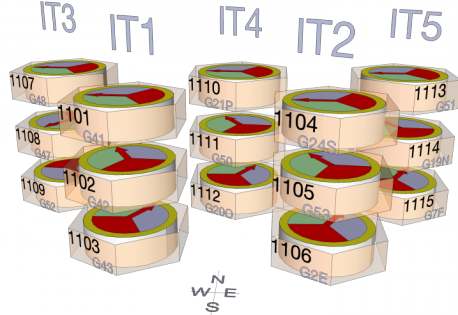


FIGURE 2.3: Layout of the SuperCDMS Soudan detector array. The detectors were arranged in five towers of three, with detectors in the same tower rotated with respect to one another (orientation given by red arrows). Detectors are named based on their tower and location in the stack from top to bottom.

of the experiment. The decay products of ^{210}Pb create substantial bremsstrahlung which could be a large electromagnetic background. The ancient lead layer was formed from a ballast of a sunken Roman ship found in the Mediterranean and was depleted of ^{210}Pb . By adding the layer of ancient lead inside the natural lead, it acted as a shield for any bremsstrahlung radiation.

Additionally, there was a 0.381 mm thick mu-metal (81 % Ni, 19 % Fe) shield inside the inner polyethylene layer which served to block any spurious magnetic fields that could have interfered with detector electronics operations (specifically the superconducting quantum interference devices, or SQUIDS). The gap between the mu-metal and cryostat was flushed with a dry nitrogen purge to avoid contamination of ^{222}Rn , a source of ^{210}Pb from mine air. The cryostat cans were made of radio-pure copper, each 0.125 in thick, which provided an additional ~ 1.9 cm of γ and β shielding for the detectors.

Through the combination of shielding and iZIP detector technology, SuperCDMS Soudan estimated a background of ~ 0.1 neutrons total in ~ 500 days of data [83].

2.1.3 Data Accumulation and Processing

SuperCDMS Soudan consisted of five towers of three iZIPs each for a total payload of ~ 9 kg. Figure 2.3 shows the arrangement of iZIPs at Soudan. They were named based on the tower number and location in the tower starting at the top. For example, T2Z1 was the top detector in tower 2 (also labeled 1104 in Fig. 2.3).

Data Divisions

Data taken during a period in time where the cryogenics were continuously stable is called a run. In total, SuperCDMS Soudan had three runs:

- **Run 133** was the first science run which lasted from March 2012 to July 2013. The run was forced to end because a ^{133}Ba calibration source became trapped in the shield. Removing the source required a warm-up and partial shield deconstruction.
- **Run 134** lasted from July 2013 to July 2014 when the experiment was purposefully warmed-up to perform standard maintenance on the cryocooler.
- **Run 135** was the last run from September 2014 to November 2015, at which time the experiment was decommissioned.

During SuperCDMS Soudan, there were three separate CDMSlite runs: the first occurred during Run 133, the second overlapped Runs 134-135, and the third and final occurred during the final stage of the experiment in Run 135. The CDMSlite runs will be discussed in more detail in Chapter 5.

The data were organized by series, with each series lasting roughly 3 hours. This duration was determined as the time that the detectors could remain neutralized in order to maintain full collection of charge [84].

There were three main data types in SuperCDMS Soudan:

- **Low-Background/WIMP Search** data were used for science results. There were no intentional sources placed near the detectors; only the natural radioactivity of the experiment and other physics events that deposited energy in the detector were recorded. The majority of data were taken in this mode in order to maximize the WIMP search exposure.
- **^{133}Ba Calibration** was the ER, or electromagnetic, calibration method. When taking data in this mode, two ^{133}Ba sources were placed in source tubes along the E and C stems. These tubes ended at the edge of the cryostat, such that the sources were located inside the lead and polyethylene shields. ^{133}Ba decays to ^{133}Cs via γ and conversion electron channels, with the most prominent peaks, in order of probability, at 356.0, 81.0, 302.8, and 383.8 keV [85]. This source was

used to define the energy scale and the ER band. In order to monitor the energy scale, five ^{133}Ba calibration series were taken each week.

- **^{252}Cf Calibration** was the NR calibration mode. A single ^{252}Cf source was placed in the source tubes, alternating between the E and C stems. ^{252}Cf decays via α emission generating γ 's, but spontaneous fission also occurs with a $\sim 3\%$ probability. When ^{252}Cf undergoes spontaneous fission, it produces 3–4 neutrons with energies up to 10 MeV, but with the most probable occurring at ~ 1 MeV [86]. This source was used for NR calibration and defining the NR band. Data were only taken in this mode a few times per calendar year, in a few series, in order to avoid neutron activation of the detectors.

Triggering

Data collection did not occur continuously. Rather, a sufficient signal was required for the experiment to issue a hardware trigger and record the traces of detector channels. The condition for determining whether a signal was adequate was controlled by five user-defined settings: charge low/high (Qlo/Qhi), phonon low/high (Plo/Phi), and phonon ultra low (Pwhisper). A single trigger-control board had access to four phonon and two charge channels per detector, performed the analog sum of individual charge/phonon traces, and compared this sum to the user-set values for each trigger setting. The user also specified the trigger condition which was used to determine when to record current data. This was almost exclusively set such that the sum of the phonon trace exceeded Plo. When the condition was met, the detector trigger occurred and the detector traces saved. Since SuperCDMS Soudan had four phonon and two charge channels on each side of the detector, two trigger-control boards were needed per detector. To evaluate whether to issue a trigger, the logical OR of each trigger setting was used, unless there was a problem with a channel.

For a given event, it was possible that more than one detector could surpass trigger settings. In that case, the first detector to exceed its trigger condition issued the global trigger. The recorded traces of all detectors were aligned such that the time of the global-trigger was always given in the same bin. When a detector triggered in low-background data, the entire iZIP array was read-out. For calibration data, only the

tower containing the initiating trigger was read-out.

There was also a mode such that the data acquisition system (DAQ) could prompt a random trigger and the system recorded the current channel traces regardless of content. If there was no coincident particle event, the traces were a good indicator of the primarily electronics noise in the detectors. These random triggers are separated into two categories:

- **Beginning-/End-Of-Run Randoms** were taken at the start/end of each series. In this mode, 500 random triggers were issued in succession.¹ These tell the quality of the noise surrounding a series.
- **In-Run Randoms** were initiated during the course of a series. These random triggers occurred approximately every tenth event and monitored the noise throughout the data series.

Processing

To extract information from the data traces recorded for an event, each trace was processed by an optimal-filter (OF) algorithm. The OF algorithm modeled a signal trace $S(t)$ as linear combination of a template $A(t - t_0)$, that can be shifted by some time delay t_0 , and Gaussian noise $n(t)$:

$$S(t) = aA(t - t_0) + n(t), \quad (2.1)$$

where the template is scaled by the amplitude a . The algorithm determined the optimal value of a and t_0 given the average signal noise. The amplitude of the signal was estimated by maximizing the signal-to-noise ratio of the fit. In order to avoid time-domain correlations with non-white noise, the algorithm was performed in frequency space.

The frequency-domain goodness-of-fit χ^2 of each pulse depended on the amplitude of the template and the time delay; those values which gave the lowest χ^2 were the global best-fit. The value of χ^2 determined whether the event trace was significantly different than the template, i.e. a non-physical event. A larger value of χ^2 indicated a

¹ There are some series in the beginning of CDMSlite Run 3 where 500 end-of-run randoms were not taken due to a mistake in the run configuration file.

bad fit. The amplitude a was proportional to the energy absorbed by a sensor, and the delay gave information about the position of the event in the detector. For more details see Refs. [59, 87, 88].

A few of the basic algorithms are:

- **OF**, or standard optimal-filter, fit a single template to a trace. It was used for individual channels and, after applying relative normalizations, the combined total trace.
- **NSOF**, sometimes referred to as just NF, was the non-stationary optimal-filter. It removed the position dependence of the OF and gave the best energy reconstruction. Because of the time intensive nature of this algorithm, it was only run on the total phonon trace.
- **OF0/NSOF0** forced the time delay t_0 of the fit to zero. This algorithm was important for randoms, as the OF and NSOF showed a preference for noise fluctuations and thus biased toward non-zero amplitudes. Without using the zero-delay, the distribution of randoms were centered away from 0 keV.

The output of the filtering algorithms retained the units of the circuit, volts for charge channels and amperes for phonon. To convert the amplitudes to physical units of energy, a standard of calibration was necessary. The energy calibration was performed using the higher statistics ^{133}Ba data that had prominent ER peaks at known recoil energies.

The individual phonon channels underwent a relative calibration process before they were added together for the total phonon energy. This relative calibration was performed using the tails of the phonon traces as these consisted of the ballistic phonons which illuminate the detector uniformly; in other words, all channels collect the energy equally. To determine the total phonon energy, the relative calibration of individual phonon traces was applied, then the individual channel traces were summed to create a total phonon trace, PT. After the sum was performed, the OF and NSOF algorithm were run.

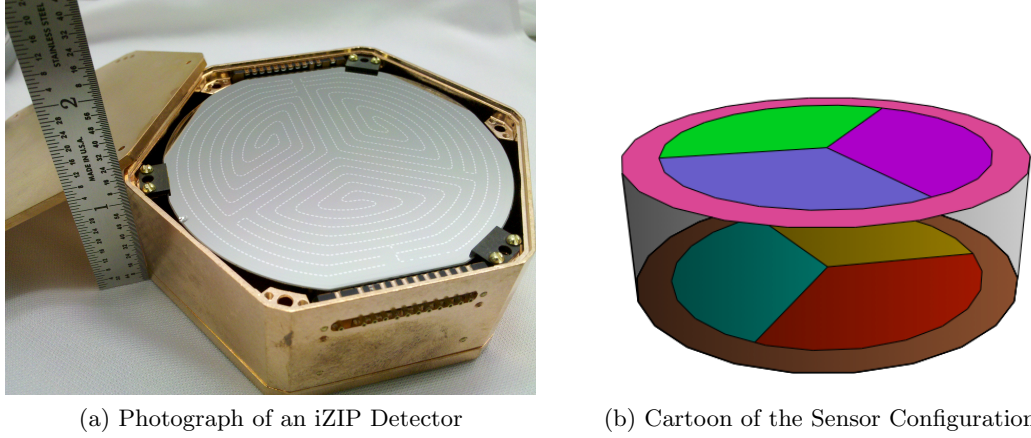


FIGURE 2.4: Photograph of an iZIP mounted in its copper housing (a) and a cartoon of the channel layout (b) for the SuperCDMS Soudan detectors. The phonon sensors in (a) are visible on the face of the crystal, though the charge rails are too thin to be seen by eye in the photograph.

2.2 iZIP Detectors

2.2.1 Physical Description

SuperCDMS Soudan used cylindrical iZIPs of diameter 76 mm and height 25 mm with a mass of ~ 600 g. These detectors were made of ultra-pure germanium (Ge) with dislocation impurity density on the order of $\sim 10^{10} \text{ cm}^{-3}$. Both top and bottom faces of the detectors were photolithographically patterned with alternating ionization rails and phonon sensors. During operation, there was an applied bias potential of ± 2 V resulting in a $V_b = -4$ V total. Bias was applied to the charge rails and the phonon lines were grounded. The phonon sensors can be seen on the photograph of a fabricated detector in Fig. 2.4a.

The phonon sensors were arranged into four channels: an outer channel A configured as a ring, and three inner channels B - D that were wedge shaped. A cartoon of the phonon channel pattern is give in Fig. 2.4b. The phonon channels on the bottom face were rotated by 60 degrees with respect to the top face in order to give finer position information for the event. Roughly speaking, the inner charge channel covered the three inner phonon channels and the outer charge channel was co-located with the A phonon channel.

2.2.2 Ionization Measurement

If the energy deposited in a germanium detector from an incident particle is greater than the band gap energy $E_{\text{gap}} = 0.74$ eV [89], some of the energy goes into exciting electrons into the conduction band. However, on average, an amount of energy greater than E_{gap} must be deposited in the crystal to liberate a single electron/hole pair; this energy is $\epsilon_\gamma = 3.0$ eV for Ge [90]. Thus, $\sim 25\text{-}30\%$ of the energy deposited is used to excite electrons across the band gap. The remainder of the energy goes into the creation of optical phonons, satisfying conservation of momentum [91]. It is easier for a recoiling nuclei to excite phonons, creating fewer charge carriers for NRs. This process is called quenching [92].

A bias voltage V_b is applied across the detector to drift liberated carriers to the surface. Because of the topology of the crystal, electrons and holes propagate differently. Electrons have an anisotropic effective mass; thus, they do not follow along the field lines but have oblique propagation. Alternatively, the mass of the hole is approximated by a scalar, and its velocity vector is aligned with the field [93]. As described by the Shockley-Ramo theorem, image charges are induced in the ionization sensors as the carriers are drifted to the surface [94]. It is these image charges that are collected by the amplifier, with the amount equal to the number of original carriers generated.

The main feature of the charge amplifier circuit is the Junction gate Field-Effect Transistor (JFET) operated in negative feedback mode. A simplified schematic of this amplifier is shown in Fig. 2.5, where the detector is represented by the capacitor C_d . After a particle interaction, the induced charge is collected into the feedback capacitor C_f causing a voltage spike at the output V_o . A large biasing resistor R_b is located between the biasing source and detector which prevents the induced current from shorting on time scales less than $R_b C_d = 40 \text{ M}\Omega \cdot 50 \text{ pF} = 2 \text{ s}$. The feedback capacitor drains through the feedback resistor R_f with a time constant of $\tau = R_f C_f \approx 40 \text{ }\mu\text{s}$. This feedback loop is protected from the biasing source through the coupling capacitor C_c . Any stray capacitance in the circuit is represented by C_s .

Since the propagation time of charges through the detector is nanoseconds, but the digitization rate is $0.8 \text{ }\mu\text{s}$ per sample, the rising edge of the signal is nearly instantaneous. The falling edge of the signal is controlled by the time constant of the feedback loop. Thus, the only variable of the ionization measurement is the amplitude which

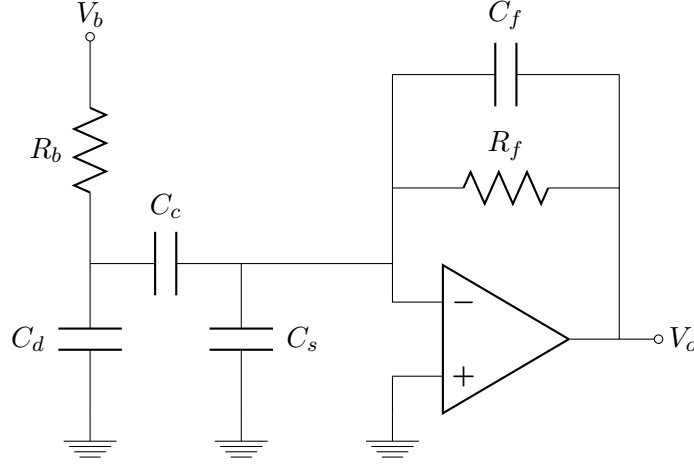


FIGURE 2.5: A simplified schematic of the CDMS charge amplifier. The detector is represented by $C_d \approx 50$ pF, which is connected to the source V_b through the biasing resistor $R_b = 40$ M Ω . The coupling capacitor $C_c = 300$ pF protects the feedback loop which consists of the amplifier, feedback resistor $R_f = 40$ M Ω , and feedback capacitor $C_f \approx 1$ pF. Stray capacitance in the circuit is $C_s \approx 75$ pF. The signal is digitized at 1.25 MHz such that there are 2048 samples per event. Figure from Ref. [57].

is proportional to the collected charge, or the number of electron-hole pairs generated $N_{e/h}$.

The energy measured in the charge signal, called the ionization energy E_Q , is the recoil energy from carriers assuming the interaction was an ER with 100% charge collection efficiency. The ionization energy is proportional to the number of electron-hole pairs as

$$E_Q = N_{e/h} \epsilon_\gamma. \quad (2.2)$$

Thus, the recoil energy for completely collected ERs is $E_r = E_Q$. Since carrier production is quenched in an NR, a quantity called ionization yield (or just yield for short) is defined that gives the relationship between the recoil energy of the interaction and the ionization produced as $Y(E_r) \equiv E_Q/E_r$. By definition, $Y(E_r) = 1$ for an ER. A NR, or an event that has incomplete charge collection, has $Y(E_r) < 1$. Using the definition for yield and the relationship between ionization energy and the number of carriers, it is

possible to define the number of electron/hole pairs in terms of yield

$$N_{\text{e/h}} = Y(E_{\text{r}})E_{\text{r}}/\epsilon_{\gamma}. \quad (2.3)$$

2.2.3 Phonon Measurement

The power of the iZIP technology is in its ability to detect and measure athermal phonons. Roughly 70% of the deposited energy in a particle interaction facilitates the generation of phonons.

Phonon Generation

There are three distinct points at which phonons are created: the primary recoil, during carrier relaxation, and by the Neganov-Trofimov-Luke mechanism. Each will be discussed briefly as well as the energy in that channel.

Primary phonons are created at the initial scatter site from the direct recoil of an electron or nucleus. The energy of these phonons E_P is proportional to the total energy deposited in the interaction minus the energy that is expended in the creation of electron-hole pairs:

$$E_P = E_{\text{r}} - N_{\text{e/h}}E_{\text{gap}}. \quad (2.4)$$

These primary phonons are initially created with frequency $\mathcal{O}(10 \text{ THz})$ [89], but quickly down-convert via quasi-diffusion through two processes. First, anharmonic decay occurs when the phonon divides into two phonons of roughly the same frequency. The decay rate of this process is $\tau_{\text{D}} \propto (1 \text{ THz}/\nu)^5$, where the proportionality constant is $\mathcal{O}(\mu\text{s})$ [95]. This mechanism occurs very close to the initial interaction site. Secondly, primary phonons undergo elastic scattering on the various isotopes that are present in a crystal of natural germanium. If the germanium detector was isotopically homogenous, this process would not occur. The scattering rate for this mechanism goes as $\tau_{\text{S}} \propto (1 \text{ THz}/\nu)^4$, where the proportionality constant is dependent on isotope mass [96].

Originally, the primary phonons have very short mean-free-paths ($< 1 \text{ mm}$), but after a few microseconds of quasi-diffusion, the mean-free-path of down-converted phonons is on the order of the detector size ($\sim 1 \text{ cm}$), and the phonons propagate homogeneously throughout the crystal with frequency $\nu \lesssim 1 \text{ THz}$. At this stage the phonons are called

ballistic. The phonon sensors mainly collected ballistic phonons.

Conservation of energy requires that the energy from liberating carriers across the band gap must be returned to the crystal. When the charges reach the surface, they relax back into the Fermi level, and any remaining kinetic energy E_{KE} must also be transferred to the lattice. This process produces high energy relaxation phonons that quickly interact with the sensors due to their proximity to the surface. The sensor over the deposition site will give a pulse with a faster rise-time as compared to the other three phonon sensors. The energy released in the relaxation process is

$$E_R = N_{\text{e/h}} E_{\text{gap}} + E_{\text{KE}}. \quad (2.5)$$

Neganov-Trofimov-Luke (NTL) phonons [97, 98] are created when drifting carriers across the crystal and add additional energy to the system beyond the initial deposition. As the electric charges are accelerated to the surface by the applied field, they advance between lattice sites. Energy is transferred to the lattice because of conservation of momentum. After carriers reach terminal velocity, any additional work that is done on the charges initiates phonons. This process is very important for CDMSlite operations and is covered in great detail in the theses of R. Basu Thakur [88] and M. Pepin [57].

To determine the energy contribution from NTL phonons E_{NTL} , consider the energy from a single charge carrier q over a distance d_q

$$E_q = e |\mathbf{E}| d_q - E_{\text{KE};q}, \quad (2.6)$$

where e is the elementary charge of an electron, $|\mathbf{E}|$ is the magnitude of electric field, and $E_{\text{KE};q}$ is the kinetic energy of a charge carrier for some amount of work done in initial acceleration. The total NTL phonon energy is a sum over the charges generated such that

$$E_{\text{NTL}} = \sum_q E_q = e \sum_q |\mathbf{E}| d_q - E_{\text{KE}}, \quad (2.7)$$

where E_{KE} is the total kinetic energy of carriers which is returned during the relaxation process. Considering an interaction that occurs in the bulk of the detector, the electric field is constant giving $|\mathbf{E}| = V_b/d_0$, with d_0 the thickness of the detector. Using this

relationship in Eq. 2.7 gives

$$E_{\text{NTL}} = eV_b \sum_q \frac{d_q}{d_0} - E_{\text{KE}}. \quad (2.8)$$

In the case of full charge collection, each charge pair travels the total distance of the crystal, so the sum becomes

$$E_{\text{NTL}} = eV_b N_{\text{e/h}} - E_{\text{KE}}, \quad (2.9)$$

which represents the full energy produced by NTL phonons.

The total phonon energy E_t in the system is the sum of primary, relaxation, and NTL phonons assuming they are all collected at equal rates:

$$E_t = E_P + E_R + E_{\text{NTL}} \quad (2.10)$$

$$= (E_r - N_{\text{e/h}} E_{\text{gap}}) + (N_{\text{e/h}} E_{\text{gap}} + E_{\text{KE}}) + (eV_b N_{\text{e/h}} - E_{\text{KE}}) \quad (2.11)$$

$$= E_r + eV_b N_{\text{e/h}}. \quad (2.12)$$

Using the relationship for the number of electron-hole pairs from Eq. 2.2,

$$E_t = E_r + \frac{eV_b}{\epsilon_\gamma} E_Q, \quad (2.13)$$

which relates the total, ionization, and recoil energy of an interaction. Alternatively, substituting Eq. 2.3 for the ionization energy gives

$$E_t = E_r \left(1 + \frac{Y(E_r) eV_b}{\epsilon_\gamma} \right). \quad (2.14)$$

This relates the total phonon energy to the recoil energy deposited by the particle where the total amplification of E_r is $(1 + Y(E_r) eV_b / \epsilon_\gamma)$.

From the energy relationship defined in Eq. 2.14, three energy scales are defined based on the type of recoil: **Total Phonon Energy** assumes no recoil type, but gives the measured E_t in units of keV_t; **Electron Equivalent Energy** assumes ER with a yield of one, and calculates electron-equivalent recoil energy $E_{\text{r,ee}} = E_t / (1 + eV_b / \epsilon_\gamma)$, with units of keV_{ee}; and **Nuclear-Recoil Equivalent Energy** assuming an NR and

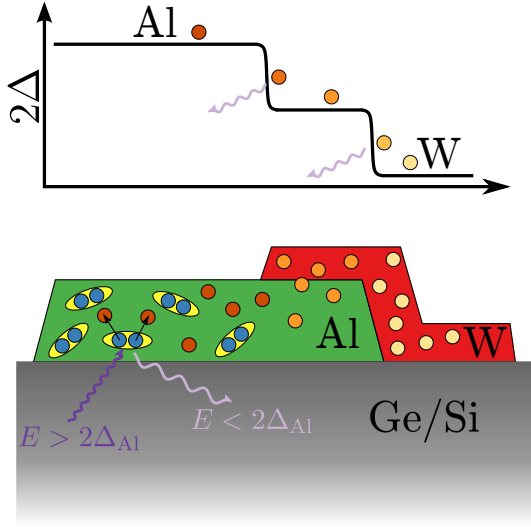


FIGURE 2.6: Cartoon depiction of the physics of quasiparticle trapping in a QET. Phonons with sufficient energy $E > 2\Delta_{\text{Al}}$ (dark purple) can break Cooper pairs (blue circles enclosed by yellow oval) within the Al fin and create quasiparticles (dark orange). These diffuse from regions of higher to lower energy (top graph), eventually reaching the W TES. As they diffuse, the quasiparticles lose energy (represented by the color gradient from dark orange to light yellow). It is possible for phonons to be created with $E < 2\Delta_{\text{Al}}$ (light purple) which cannot break Cooper pairs and are considered lost energy. Figure courtesy of M. Pepin [57].

a model for yield such that the nuclear-recoil equivalent energy is given by $E_{\text{r,nr}} = E_{\text{t}} / (1 + Y(E_{\text{r}})eV_b/\epsilon_{\gamma})$, with units of keV_{nr} .

Phonon Detection

The phonons that are generated in an event are detected through the use of Quasiparticle-trap-assisted Electrothermal-feedback Transition-edge-sensors (QETs). These are photolithographically patterned aluminum (Al) fins connected to a narrow tungsten (W) film, where the larger aluminum coverage acts as an antenna to direct phonons toward the tungsten. The detector is cooled to a point where both the aluminum ($T_c = 1.2 \text{ K}$) and tungsten ($T_c \sim 80 \text{ mK}$) are superconducting, approximately 50 mK . The tungsten is held in the normal conducting/superconducting transition by electrothermal feedback.

The mechanism of quasiparticle trapping was first suggested by N. Booth [99], and is shown pictorially by the cartoon in Fig. 2.6. Only phonons that interact with the aluminum fins can be collected. As such, ballistic phonons will reflect in the detector until they are absorbed by the aluminum. If the energy of the phonon is greater than the superconducting gap of aluminum, $2\Delta_{\text{Al}} = 340 \mu\text{eV}$, it will break a Cooper pair and create quasiparticles. Observe that this is more energy than typical thermal energies, $k_B T = 3.4 \mu\text{eV}$, and as such, only athermal phonons will be detected. Inside the

aluminum, the absorbed phonons will create more phonons. If these newly created phonons are of sufficient energy, they will break more Cooper pairs.

The aluminum overlaps with the tungsten in a region called the bi-layer which reduces the probability of phonon reflection. In tungsten, the gap energy required to break a Cooper pair is smaller at $2\Delta_W \sim 20 \mu\text{eV}$, but still greater than thermal energies. Quasiparticles will diffuse through the aluminum on timescales $\mathcal{O}(\mu\text{s})$ until they reach the bi-layer, creating more quasiparticles if their energy is sufficient. As they propagate and move from aluminum to bi-layer to tungsten, the quasiparticles lose energy becoming trapped in the tungsten layer (demonstrated in the top panel of Fig. 2.6).

The tungsten is held in transition between superconducting and normal conducting by Joule heating in what is called a transition-edge-sensor (TES). The TES is kept at a constant voltage V_b by an external circuit. When the phonon energy is absorbed in the tungsten, it causes an increase in the temperature of the TES which causes a large change in the TES resistance pushing it toward the normal conducting region. This change in resistance can be measured by an amplifier, of which a simplified version is shown in Fig. 2.7. When the resistance in the TES increases, it causes more current to flow through the shunt resistor R_{sh} which causes a change in the current through the input inductor L_i . This changing current is observed as a change in the magnetic flux through the SQUID-array. These SQUIDs (superconducting quantum interference devices) are sensitive magnetometers which detect the changing magnetic flux in L_i ; the voltage across the SQUID responds to the change in magnetic flux and is registered by the amplifier. When the flux is altered due to the changing current through L_i , the feedback inductor L_{fb} receives a current. The relationship between the input inductor and the feedback inductor is $L_{\text{fb}} = 0.1L_i$, amplifying the change in current by a factor of 10. The signal is read-out at V_o and digitized at a rate of $1.6 \mu\text{s}$ per sample. The feedback circuit is configured in negative feedback mode to keep the flux through the SQUID constant.

The QETs are in thermal contact with the crystal substrate which cools the TES back to the equilibrium point. Configuring the QETs in EFT allows for much quicker TES response than if self-heated. There are 1820 QETs per face which corresponds to a surface coverage of $\sim 5\%$. This low surface coverage and the circuit response causes

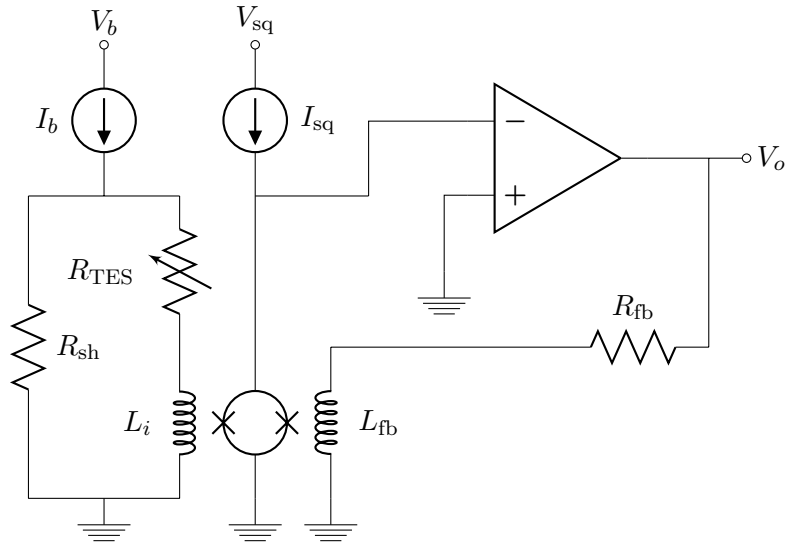


FIGURE 2.7: A simplified schematic of the CDMS phonon amplifier for a single channel. The TES of variable resistance $R_{\text{TES}} \approx 100 - 200 \text{ m}\Omega$ is held at bias V_b . When the resistance of the TES changes, more current will flow through the shunt resistor $R_{\text{sh}} \approx 25 \text{ m}\Omega$. This causes a change in current, and thus flux, through the inductor $L_i = 250 \text{ nH}$, which is coupled to the feedback circuit through the SQUID-array with $L_{\text{fb}} = 0.1L_i$. The feedback resistance is $R_{\text{fb}} = 1 \text{ k}\Omega$. The signal is digitized at a rate of 0.625 MHz such that there are 4096 sample per event. Figure from Ref. [57].

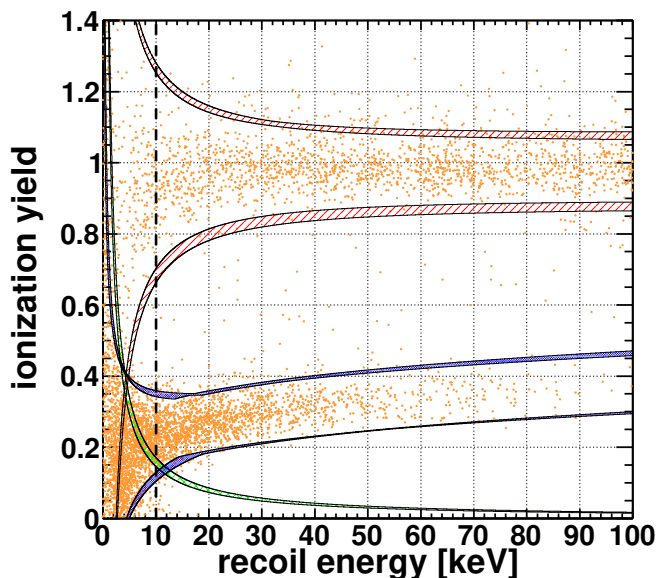


FIGURE 2.8: Ionization yield as a function of recoil energy for ^{252}Cf data (yellow points). The ERs occupy a band at $Y(E_r) \sim 1$ (red band), while NRs have a lower yield of $Y(E_r) \sim 0.3$ (blue band). The width of the yield bands are tuned on known-recoil-type calibration data. Also shown in green is a typical charge threshold band, and recoil energy threshold (black dotted). Figure courtesy of A. Villano.

two distinct characteristics of the phonon signal. The peak of the trace is rather sharp and contains information about the location of the event. The tail is characteristic of a slow delay and contains the information about the energy of the event.

2.2.4 Yield Discrimination

The concept of yield was introduced in Sec. 2.2.2 and defined as the ratio between ionization energy and recoil energy. Since NRs produce fewer electron/hole pairs, this quantity is a way to discriminate between NRs and ERs. This discrimination capability is important for a direct detection dark matter experiment because WIMPs produce NRs at a much lower rate than the ER background events.

Yield can be defined on an event-by-event basis if Eq. 2.14 is rearranged and the relationship $E_r = E_Q/Y(E_r)$ is used. Thus, yield can be written in terms of total phonon energy and ionization energy as

$$Y(E_r) = \frac{E_Q}{E_t - \frac{eV_b}{\epsilon_\gamma} E_Q}, \quad (2.15)$$

where E_Q and E_t are directly measured by the experiment. An example of the yield verses recoil energy for calibration data is shown in Fig. 2.8. The yellow data points are

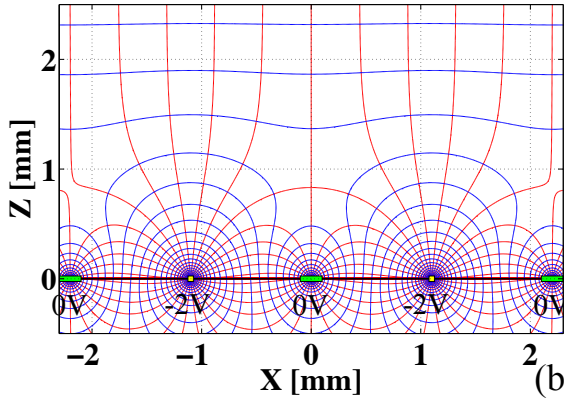


FIGURE 2.9: Field lines near the surface of an iZIP. Here, the charge rails are at -2 V and the phonon sensors at 0 V. The electric field lines are given in red and the equipotential contours in blue. For an event that occurs within ~ 1 mm of the surface, both the electrons and holes will be collected on the same surface. A bulk event has a charge signal shared by both surfaces. Figure from Ref. [100].

γ 's and neutrons from a ^{252}Cf neutron source. Photons and electrons populate the band at $Y(E_r) = 1$, whereas NRs, represented by the neutrons in this figure, are located at $Y(E_r) \sim 0.3$. The red and blue curves outline the 3σ ER and NR bands respectively. Also pictured is the charge threshold which has a $1/E_r$ dependence shown by the green curve in Fig. 2.8. The ER and NR bands flare at low energy due to larger noise in the charge read-out circuit for small ionization energies. Thus, the bands can no longer be separated at ~ 5 keV, which is the point where the bands overlap at the 3σ level. This implies that the power of yield decreases for low energy recoils. To avoid this region, analysis thresholds are often set at 10 keV (vertical dotted line in Fig. 2.8). This type of analysis is known as a high-threshold analysis and is free of ER backgrounds. However, sensitivity to low-mass WIMPs is sacrificed.

There is a small population of events in Fig. 2.8 between the two bands that are ERs with reduced ionization energy because of scattering in the dead layer (the region a few μm from the surface). These so called “surface events” are formed by scattered β 's or γ 's. Surface events were a major background for the CDMS II experiment, which prompted the detector design improvements for SuperCDMS Soudan. The interleaved patterning of the charge and phonon sensors provided the iZIPs excellent rejection of these surface events. A section of an instrumented surface of an iZIP is shown in Fig. 2.9. For events in the bulk, electrons and holes that were liberated in an interaction drifted to opposite faces. By contrast, surface events followed the field lines to the same side of the detector. An event was required to have signal on both sides of the detector. This charge symmetry cut defines an event as bulk rather than surface.

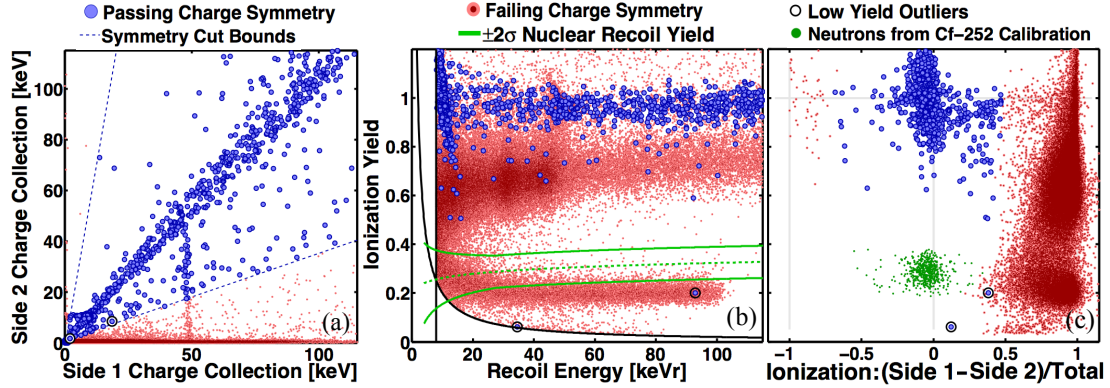


FIGURE 2.10: Data from ~ 900 live hours of detector T3Z1 with the ^{210}Pb source facing side 1. (a) Ionization signal on both sides of the detector where good bulk events (blue dots) share an almost equal signal between the two sides while the surface events (red dots) do not. The 46.7 keV γ line is clearly visible. (b) Ionization yield as a function of recoil energy with the 2σ NR band outlined in green. There are no blue events within this band. Two low yield events are present (circled), but they are outside of the NR band. (c) Ionization yield verses the difference in ionization energy collected on the two sides. Also included in this subfigure are the neutrons from ^{252}Cf used to define the NR band. Bulk ER and NR events have a symmetric signal and are centered around zero. Figure from Ref. [100].

In order to determine the surface rejection of the iZIP, two surface sources were installed in a tower at Soudan. One was placed above T3Z1 and the other below T3Z3 (see Fig. 2.3 for the location of these detectors). These sources were silicon wafers that had been exposed to ^{222}Rn ; the ^{210}Pb daughter was implanted into the silicon. ^{210}Pb has low-energy γ 's and β 's as well as the recoiling ^{206}Pb nuclei that interacted primarily on the surface of the detector opposite the source plate.² The data from ~ 900 live hours taken with this source is shown in Fig. 2.10. No surface events were found in the NR band between 8 - 115 keV_{nr}, which corresponds to the true recoil energy of the event. Thus, an upper limit on surface-event leakage fraction, or the percent of events passing the charge symmetry cut that also are within the NR band, was set at 1.7×10^{-5} [100].

² A very detailed treatment of the ^{210}Pb background for the CDMSlite detectors is the subject of Chapter 7.

2.3 CDMSlite

The technique developed by SuperCDMS Soudan to search for low-mass dark matter is called the CDMS low ionization threshold experiment, or CDMSlite. Recall, the relationship between total phonon energy E_t and recoil energy E_r is given by

$$E_t = E_r \left(1 + \frac{Y(E_r)eV_b}{\epsilon_\gamma} \right). \quad (2.16)$$

If $eV_b \gg \epsilon_\gamma$, then the scale factor for the recoil energy is dominated by the applied voltage. This amplification is from the NTL phonons, and, since this term is proportional to the ionization signal, $E_Q = E_r Y(E_r)$, the ionization energy is amplified. This ability to read-out ionization with phonons was first demonstrated by Luke in 1988, as well as the scaling of the amplitude of the signal with applied bias voltage [98]. It was also shown that the noise remained constant with increasing voltage until breakdown occurred [101].

To operate in this mode, a larger bias of 70–75 V is applied to an iZIP by grounding one side of the detector and applying a negative bias V_b to the other side. Only signal on the grounded side of the detector was recorded. With a single phonon signal and no ionization measurement, it was impossible for CDMSlite to reject surface events. Also, through NTL amplification, the ER/NR discrimination capability is lost. However, it is possible to attain a lower energy threshold and gain access to low-mass WIMPs.

2.4 Future SNOLAB Operations

The next generation SuperCDMS experiment will be located at the SNOLAB facility in Sudbury, Ontario, with first data anticipated for 2020. It is expected to reach smaller WIMP-nucleon cross sections using increased shielding, larger, more sensitive detectors, and improved read-out hardware. A brief description is presented here with full details of the upcoming experiment given in Ref. [102].

2.4.1 Facility and Shielding

The SNOLAB laboratory is located approximately 2 km underground in the Creighton nickel mine operated by Vale. At this depth, the total overburden is equivalent to

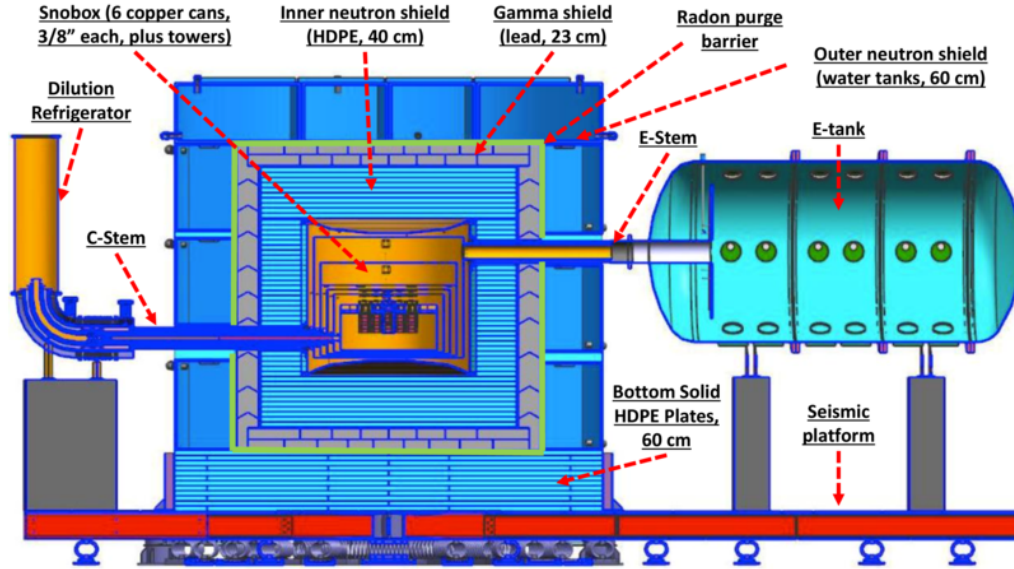


FIGURE 2.11: Schematic of the planned SuperCDMS SNOLAB experiment. The shielding will consist of layers of purely passive material which are, from outer to inner: 60 cm of water (top and sides) or polyethylene (bottom), 23 cm of lead, 40 cm polyethylene, and six 0.325 in copper cryostat cans (called the Snobox). The Snobox is thermally coupled to the various stages of the dry dilution refrigerator through the C stem (left), and the electronics for the towers will be fed through the E stem to the E tank (right). The entire apparatus is seismically isolated from the cavern floor, as the mine is still active. Figure from Ref. [102].

6010 m.w.e [103]. This depth reduces the cosmic muon and neutron flux by an additional factor of 2.5 from the Soudan levels. Thus, it is not necessary to install an active muon veto for the first, smaller payload.

The proposed purely passive shield for SuperCDMS SNOLAB is shown in Fig. 2.11 along with the entire experimental apparatus. The outer neutron veto will consist of 60 cm of water (top and sides) and polyethylene (bottom). Within this layer will be a ^{222}Rn shield constantly flushed by N_2 to mitigate contamination of atmospheric ^{222}Rn . The inner layers of shielding will be made of a 23 cm layer of low-activity lead to protect against γ 's, and an additional 40 cm of polyethylene for further neutron reduction. The Creighton mine is still operational, and so the experiment will be placed on a seismic platform to isolate it from the cavern floor.

The cryostat, referred to as the Snobox, will have six cans of 0.325 in copper. These will be thermally coupled to the dry dilution refrigerator through copper tubes that make up the C stem. Inside the Snobox there is space for a 31 tower payload, but the first stage of the experiment will only deploy four towers. As at Soudan, the cold electronics are thermally coupled to the 4 K stage, and the cables threaded out of the Snobox through the E stem. At SNOLAB, the detectors are designed to operate in the 15–30 mK range as opposed to the ~ 50 mK at Soudan. The colder base temperature should lead to a better energy resolution.

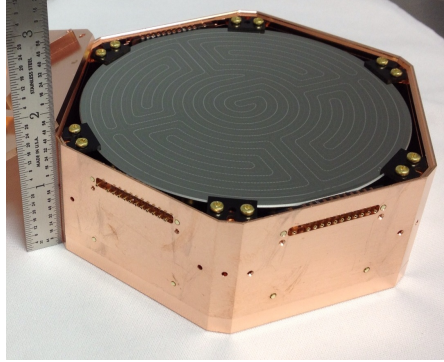
Two possible upgrade options for the experiment after the first phase of operations are adding additional towers and replacing the inner polyethylene shield with an active neutron veto. Some design possibilities for the active neutron veto are discussed in Chapter 8 as well as the expected changes in detector rates with varying configurations of towers.

2.4.2 *Detector Design and Layout*

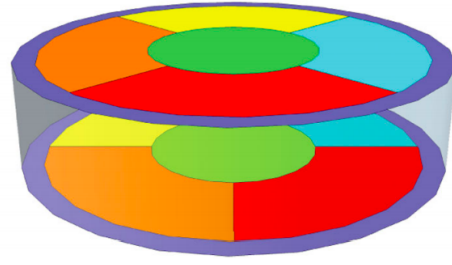
The towers of SuperCDMS SNOLAB are designed to contain six detectors each. Thus, in the initial payload of four towers, there will be a total of 24 detectors. These detectors are larger than at Soudan, with a diameter of 100 mm and thickness of 33.3 mm. Additionally, silicon detectors will be deployed together with the germanium.

A set of 12 iZIPs will continue to use both ionization and phonon signals to search for NR dark matter signatures. A photograph of the new iZIP detectors is shown in Fig. 2.12a with the phonon channel configuration given in the cartoon of Fig. 2.12b. The phonon channels will consist of one outer ring and one central circle, with the remaining four channels as the other four quadrants. As with the Soudan iZIPs, the outer charge channel approximately covers the outer phonon ring, and the inner charge channel covers the inner phonon channels. The applied bias on the ionization channels will total 6 V for Ge and 8 V for Si; the phonon rails will remain grounded.

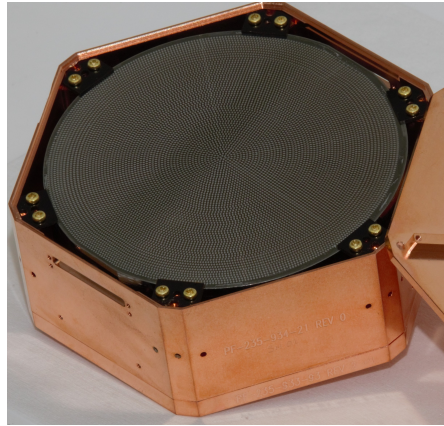
Accompanying the improved iZIPs, SuperCDMS SNOLAB will employ specialized high voltage (HV) detectors. These will build on the success of CDMSlite, and are part of the directive of SuperCDMS SNOLAB to search for low-mass dark matter. The HV detectors will be phonon only and have been optimized for collecting NTL phonons by redesigning the TESs and increasing the aluminum coverage. The added aluminum will



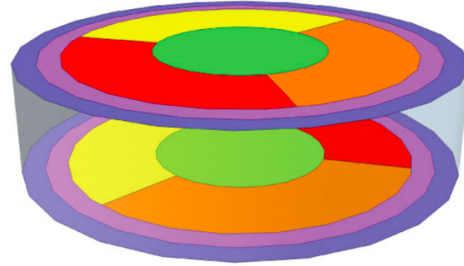
(a) Photograph of SNOLAB iZIP



(b) Cartoon of iZIP Sensors



(c) Photograph of SNOLAB HV



(d) Cartoon of HV Sensors

FIGURE 2.12: Photograph of SuperCDMS SNOLAB iZIP (a) and HV (c) detectors mounted in their copper housing, and a cartoon of the channel layout for iZIP (b) and HV (d). The HV devices measure purely phonons. Only the phonon channels are shown in (b), but the outer charge channel roughly follows the outer phonon ring, and the inner charge channel covers the inner five phonon channels.

augment phonon absorption, collecting more of the primary phonons in addition to the ballistic [104].

The 12 HV detectors will be operated with a large bias of 100 V; however, unlike CDMSlite, the bias will be applied symmetrically. This change will give the HV detectors a more uniform electric field and allow both sides of the detector to be read-out [104]. A photograph of the HV detector design is shown in Fig. 2.12c with the sensor schematic shown in Fig. 2.12d. Like the iZIP, the HV detector has six phonon channels on each side, but with two outer rings allowing for better identification of events at high radius. This sensor configuration will potentially improve the HV detector's ability to reject surface events and events that experience reduced NTL amplification due to electric field asymmetries.

The initial SNOLAB payload will have 10 Ge iZIPs, 2 Si iZIPs, 8 Ge HV, and 4 Si HV. For each detector type, the projected sensitivity given the optimum interval limit setting framework [105] is shown in Fig. 2.13. They are compared with two previous SuperCDMS Soudan analyses, CDMSlite Run 2 [106] and the Low Threshold (LT) analysis [66], each of which had world leading limits at the time of their publication. The HV detectors are expected to reach sub-GeV/c² dark matter masses, and will be the most sensitive designed by SuperCDMS.

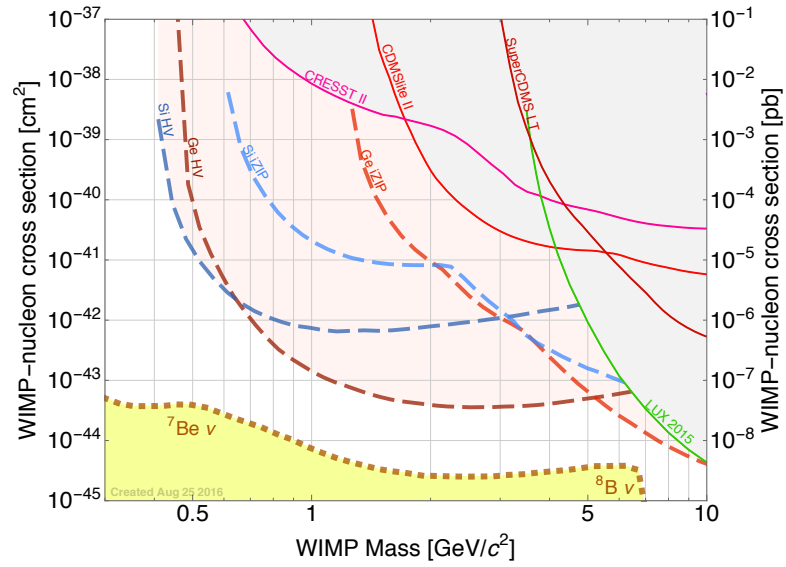


FIGURE 2.13: Projected sensitivity for the SuperCDMS SNOLAB experiment in the spin-independent WIMP-nucleon cross-section plane. Shown in the dashed curves are the sensitivity estimates, determined with the optimum interval method [105], of the Ge HV (dark red), Ge iZIP (red), Si HV (dark blue), Si iZIP (light blue). They are compared to a selection of the current limits in the field (solid lines): CRESST-II (pink) [79], CDMSlite Run 2 (red) [106], SuperCDMS LT (dark red) [66], and LUX (green) [107]. The neutrino floor is given by the orange dashed/yellow shaded region. Figure from Ref. [102].

3

Background Sources in SuperCDMS

The term “backgrounds” is used to refer to any event in a detector that mimics or masks a potential dark matter signal. In Sec. 1.2.2, some common backgrounds to all direct detection dark matter experiments were discussed. This topic will now be revisited but in the specific context of the SuperCDMS experiment, both the past Soudan operation and the future SNOLAB venture.

Radiogenic backgrounds are events from radioactive isotopes that originate from the cavern that contains the experiment, or the apparatus itself. The daughters of these decays are generally separated into particles which cause electron recoils (ERs), for example β 's and γ 's, and those which cause nuclear recoils (NRs), for example neutrons. These can be further subdivided into events which deposit energy in a single or multiple detectors; i.e. single or multiple scatters. WIMPs are classified as a NR single-scatter event, thus, if an experiment has ER/NR discrimination capability, NR single-scatters are the critical background to consider. Without discrimination power, ER single-scatter events become equally important.

SuperCDMS is designed with layers of shielding that prevent against nearly all external sources, such as the γ 's and neutrons from the cavern walls. Thus, the radioactivity of the shielding and the other apparatus materials become the dominant source of the radiogenic background. The exact method of interaction in the detectors can be difficult to predict, so a Monte Carlo simulation can be used to aid in understanding these

backgrounds.

3.1 Sources of Environmental Radiation

The environmental radiation that cause backgrounds in SuperCDMS originate from three sources: primordial, cosmogenic, and anthropogenic [108]. The primordial and cosmogenic will be discussed in greater detail as they are a focus of many of the background studies in this thesis. A common anthropogenic source is ^{137}Cs , a fission product of ^{235}U which was used in nuclear reactors and weapons. ^{137}Cs has a half-life of 30.1 years and is water soluble; thus, it is found in many materials. ^{137}Cs decays via beta-decay with an 85% probability of 662 keV γ emission [85].¹

3.1.1 *Primordial*

Isotopes are considered primordial if their half-lives are $\geq 10^9$ years, implying they were generated in the Earth's formation. Two of the most important neutron producing primordial sources are ^{232}Th (99.98% natural abundance, half-life 14.1 Gyr) and ^{238}U (99.27% natural abundance, half-life 4.5 Gyr). ^{40}K (0.012% natural abundance, 1.3 Gyr) is an additional primordial isotope that produces γ 's and can be a dominant source in the ER spectrum as $^{\text{nat}}\text{K}$ is prevalent in the environment.

^{238}U and ^{232}Th are the first isotopes in a long decay chain as shown in Fig. 3.1. They undergo many α - and β -decays before reaching the stable ^{206}Pb (^{208}Pb) for ^{238}U (^{232}Th). Accompanying the decay are a number of strong γ emissions that are labeled in the figure along with their relative intensities. These γ 's, and those produced from ^{40}K , are the primary contributor to the ER Compton background (see Chapter 4).

Because the half-lives of the daughter isotopes are considerably shorter than the parent, secular equilibrium is often assumed. This implies the rate of decay for each isotope is constant. There are a few places along the chain where the assumption of secular equilibrium can break, namely at the noble gas radon, which can easily escape material [108]. The γ and β production in the primordial decays are well studied and easy to implement as a source in a Monte Carlo simulation.

¹ All the decay information in the remainder of this chapter is from the National Nuclear Data Center, NuDat 2.7 [85].

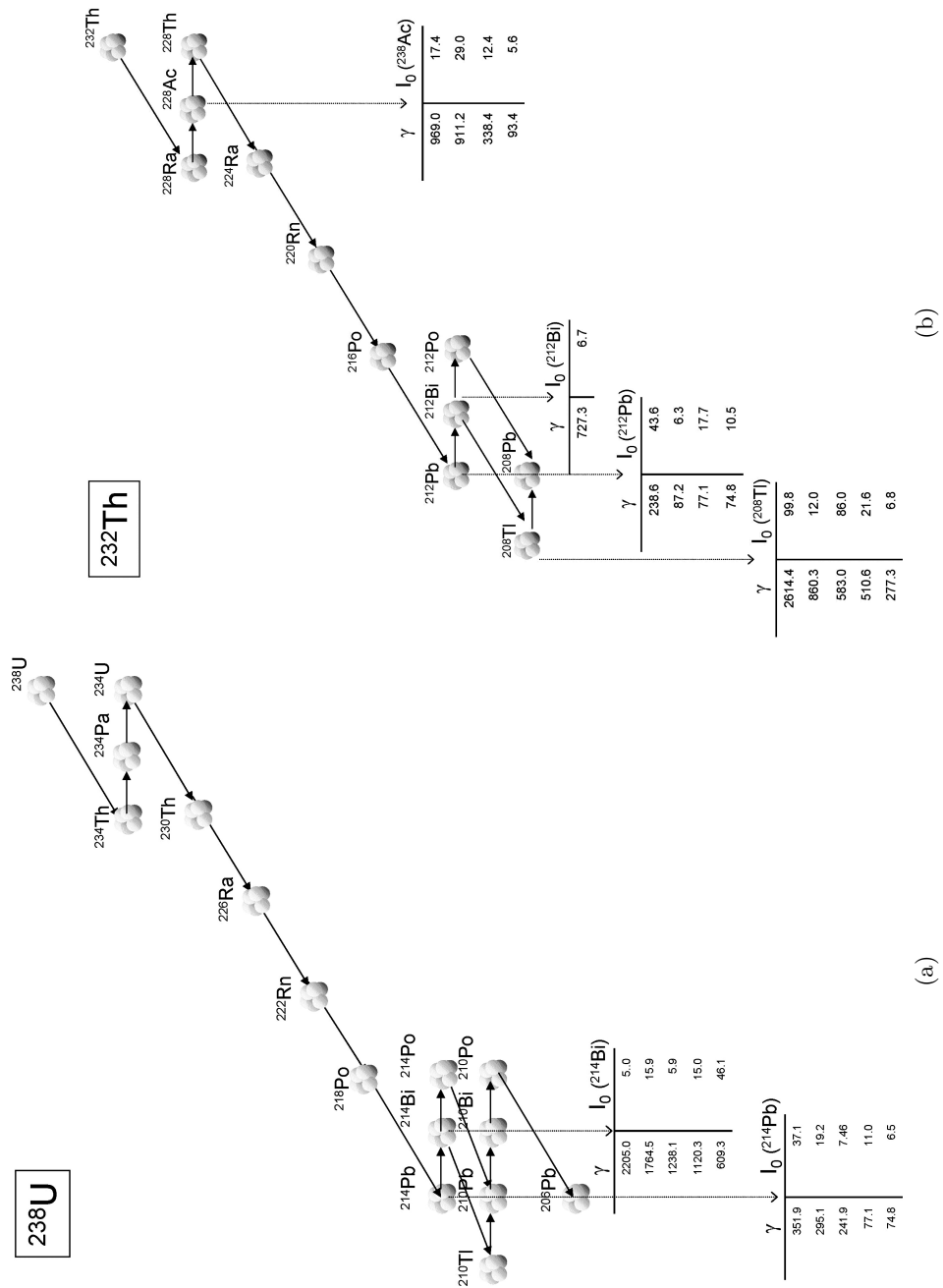


FIGURE 3.1: Decay chains of ^{238}U (a) and ^{232}Th (b) which are neutron producing backgrounds to the SuperCDMS experiment. The $\swarrow$ implies an α -decay and the $\rightarrow$ represent β -decays. Prominent γ energies are also indicated along with their intensities. Figures from Ref. [109]. For more information about the half-lives of the decays, the reader is directed to Ref. [85].

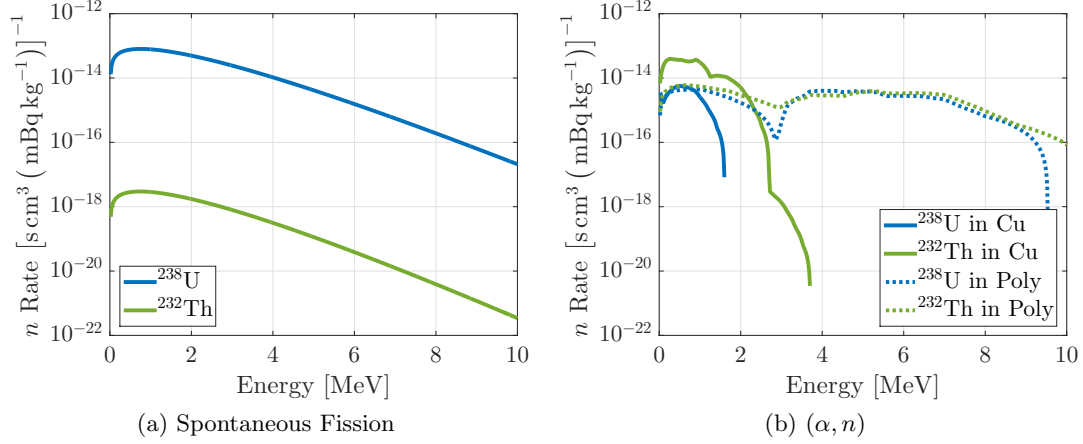


FIGURE 3.2: Energy spectra of neutrons produced through spontaneous fission (a) and (α, n) (b) processes in the decays of ^{238}U (blue) and ^{232}Th (green). The dependence of material on the (α, n) process is demonstrated in (b) by considering copper (solid) and polyethylene (dotted) which are common materials used in the construction of SuperCDMS. Figures from Ref. [57].

Neutrons are produced through spontaneous fission (SF) and (α, n) processes during the course of the decay of ^{238}U and ^{232}Th . The resulting spectra of neutrons can depend on the material where the impurity is contained. Of the primordial isotopes, the primary source of SF is ^{238}U with a branching fraction of 5.45×10^{-7} [109], though SF has been observed in ^{232}Th (branching fraction $\sim 10^{-11}$) [110]. The spectra of neutrons produced are independent of the material. Alternatively, (α, n) occurs when the energetic α 's created through the various decays of Fig. 3.1 interact with the surrounding material. The energies of the neutrons produced vary between decay chain and material, though no α created in the decays of ^{238}U or ^{232}Th has the ability to create neutrons in lead. The spectra of neutrons is determined through a simulation with the SOURCES4C package [111, 112]. Figure 3.2 shows the spectra of neutrons produced via SF and (α, n) from ^{238}U and ^{232}Th in copper and polyethylene, common materials in SuperCDMS. These spectra determine the distribution of neutrons for a Monte Carlo simulation.

Radon is produced in both the decays of ^{238}U and ^{232}Th . As a noble gas, it has the ability to diffuse out of the surrounding material. ^{220}Rn from ^{232}Th has a half-life of 55.6 s and consequently a low probability of escape. However, ^{222}Rn from ^{238}U has a

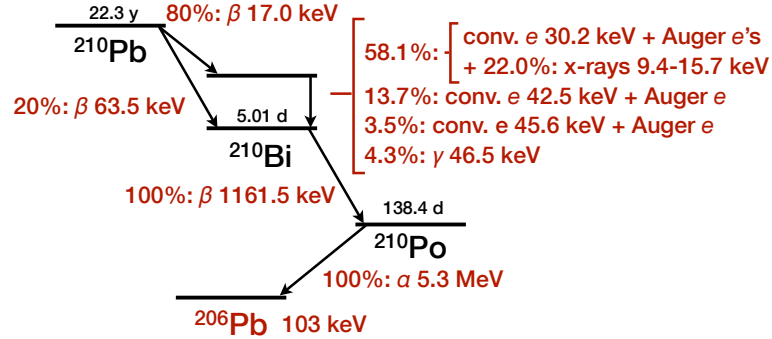


FIGURE 3.3: Decay chain for ^{210}Pb and its daughters. The plethora of low energy β 's and γ 's produced are a known source of surface events. Figure from Ref. [113].

half-life of 3.82 days allowing plenty of time to propagate into the environment. Radon, in its gaseous form, will attach itself to exposed surfaces in a process called plate-out. Thus, exposure to air contaminated with radon will cause the surfaces of material to become radioactive; for example, radon plate-out on the surfaces of the SuperCDMS detectors and housings causes surface events in the experiment. This background is the subject of Chapter 7.

^{210}Pb follows in the decay of ^{222}Rn and has a half-life of 22.2 years. If present as a contamination, it will decay throughout the life time of the experiment producing many low energy β 's and γ 's as well as an α and the final, stable ^{206}Pb nucleus. This decay process is illustrated in Fig. 3.3. ^{210}Pb is also found in natural lead, and the β 's can create bremsstrahlung and x-rays. In SuperCDMS Soudan, a layer of ancient lead, depleted of ^{210}Pb , was added as a shield for this undesirable effect. When ^{210}Pb is close to detectors, as when ^{222}Rn contaminates the surfaces during processing and fabrication, all the decay products will remain close to the surfaces. The α produced in the decay of ^{210}Po can have reduced yield and look like an NR. Also, the low energy β 's and γ 's are surface events and difficult to reject in CDMSlite.

3.1.2 Cosmogenic

Activation occurs when external radiation induces new radioactive isotopes into a material. One example is cosmogenic activation. Protons and neutrons in cosmic rays can cause spallation in the crystals and apparatus materials during their lives above ground

(fabrication, storage, transportation, etc.), or produce isotopes in the atmosphere that can contaminate the source material.

Of the many contaminants that can be produced in copper, ^{60}Co is the most important. It is relatively long-lived with a half-life of 5.3 days, and undergoes β -decay primarily with a β of endpoint 95.8 keV and a very high probability of emitting two high-energy γ 's at 1173 and 1333 keV. Copper is used in SuperCDMS for the construction of the detector towers and cryostat cans. Minimizing storage at the Earth's surface mitigates this background.

The detector materials of germanium and silicon, which will accompany the SuperCDMS SNOLAB payload, have contamination from the β -emitter tritium with 18.6 keV endpoint energy. An additional β -emitter in silicon is ^{32}Si (227.2 keV endpoint). Both are expected to be a dominant source of background for silicon [102]. ^{32}Si is produced in the atmosphere and contaminates the ore due to contact with surface water. Though at a much lower probability, it can also be introduced into the material through the refinement process [114].

Germanium, which was the only material in the SuperCDMS Soudan payload and will dominate the detector contingent at SNOLAB, also has other isotopes besides tritium that decay either by β -decay or electron capture (EC). The additional cosmogenically produced isotopes that undergo β -decay have endpoints $\mathcal{O}(\text{MeV})$ and relatively small production rates. These can generally be ignored in SuperCDMS. The isotopes that undergo EC give discrete lines in the detectors below ~ 10 keV and were seen in the CDMSlite Run 2 spectrum [115]. As both tritium and a number of the EC peaks are a major background source with known analytical descriptions, their models are described as used in SuperCDMS analyses.

Tritium

Tritium is modeled according to the non-relativistic β -decay theory as the endpoint, or Q -value, satisfies the relationship $Q \ll m_e c^2$. The relative probability as a function of the kinetic energy of the electron $N(E_{\text{KE}})$ is described by

$$N(E_{\text{KE}}) = C \sqrt{E_{\text{KE}}^2 + 2E_{\text{KE}}m_e c^2} (Q - E_{\text{KE}})^2 (E_{\text{KE}} + m_e c^2) F(Z, E_{\text{KE}}), \quad (3.1)$$

	<i>K</i>		<i>L</i> ₁		<i>M</i> ₁	
	μ [keV]	<i>A</i>	μ [keV]	<i>A</i>	μ [keV]	<i>A</i>
⁶⁸ Ge	10.37	1.0	1.30	0.1202	0.160	0.0203
⁶⁸ Ga	9.66	1.0	1.20	0.1107	0.140	0.0183
⁶⁵ Zn	8.98	1.0	1.10	0.1168	0.122	0.0192
⁵⁵ Fe	6.54	1.0	0.77	0.1111	0.082	0.0178

TABLE 3.1: Cosmogenic isotopes that decay via electron capture and are present in the SuperCDMS germanium detectors. The shell energies μ are from Ref. [118]. The amplitudes *A*, from Ref. [119], are normalized with respect to the *K* shell.

where *C* is a normalization constant, the kinetic energy and mass of the electron are E_{KE} and $m_e c^2$ respectively, *Q* is the *Q*-value or endpoint energy, and $F(Z, E_{\text{KE}})$ is the Fermi function [116]. The non-relativistic approximation for the Fermi function is given by

$$F(Z, E_{\text{KE}}) = \frac{2\pi\eta}{1 - e^{-2\pi\eta}}, \quad \text{with } \eta = \frac{\alpha Z E}{pc}. \quad (3.2)$$

Z is the atomic number of the daughter nucleus, α is the fine structure constant, $E = E_{\text{KE}} + m_e c^2$ is the total energy of the electron, and *p* is the momentum of the electron [117].

The contribution of tritium can be determined for the Ge/Si detector if the production rate is known as well as the detector history. Alternatively, the spectral shape can be fit to the data in a maximum likelihood type analysis [115]. In either case, the analytical description given by Eqs. 3.1 and 3.2 is necessary to model the background.

Electron Capture Peaks

The cosmogenic isotopes that decay via EC with the largest production probability in the SuperCDMS germanium detectors are listed in Table 3.1 with their shell energies and relative amplitudes, normalized to the *K* shell.

Because there are predetermined ratios of the probability of EC between shells, it is easy to relate the expected number of events in each shell peak through this probability. The amplitude for the Gaussian that represents the shell peak is given by the EC rate, and the sum of the three peaks describes the background from one EC isotope. Thus,

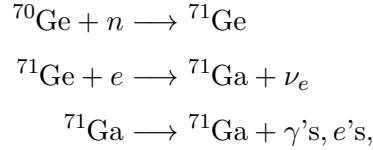
the EC background is modeled as a sum of Gaussians:

$$f_{\text{ECpeaks}}(E) = \sum_{i=K,L,M} \frac{A_i}{\sigma_i \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{E - \mu_i}{\sigma_i} \right)^2 \right], \quad (3.3)$$

where A_i is the amplitude of the shell normalized to the K -shell peak, and μ_i is the energy, both of which are given in Table 3.1. The width of the peak σ_i is determined by the detector performance (see Sec. 5.4). Additional shells, for example the L_2 , can be added if the EC contribution from a single isotope is large. By modeling the EC peaks with Eq. 3.3, the relative amplitude of the K shell is the only free parameter in a maximum likelihood type fit, reducing the complexity of the algorithm.

3.2 Electron Capture of ^{71}Ge

Neutrons from the ^{252}Cf calibration source can capture on ^{70}Ge creating ^{71}Ge which undergoes EC. This process is summarized as



where the last line represents the reordering of ^{71}Ga into a stable state. The half-life of ^{71}Ge is 11.43 days [120]. A thorough description of the process and the energies of the decay products can be found in Ref. [57].

The distinct peaks created in this neutron activation of germanium are required for calibrating the energy scale of CDMSlite and future HV detectors. Unlike the high-energy γ 's from the ^{133}Ba calibration that produce saturated events, the ^{71}Ge peaks are in the energy range of interest for the low-threshold detectors, and give three distinct lines well separated in energy.

As a background, it is modeled similarly to the cosmogenic EC peaks:

$$f_{^{71}\text{Ge}}(E) = \sum_{i=K,L_1,L_2,M} \frac{A_i}{\sigma_i \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{E - \mu_i}{\sigma_i} \right)^2 \right]. \quad (3.4)$$

	K		L_1		L_2		M_1	
	μ [keV]	A	μ [keV]	A	μ [keV]	A	μ [keV]	A
^{71}Ge	10.37	1.0	1.30	0.1202	1.14	0.0011	0.160	0.0203

TABLE 3.2: Shell energies [118] and relative amplitudes [57] for the electron capture of ^{71}Ge . The amplitudes have been normalized with respect to the K shell.

The variable definitions are identical to Eq. 3.3. Because of the large number of events in the detector, even with a small capture probability, the L_2 shell can no longer be ignored. The energies and relative amplitudes are given in Table 3.2.

3.3 Monte Carlo Simulations

For backgrounds that do not have known analytical descriptions, for example, Compton scattering and the surface events from ^{210}Pb , a sophisticated simulation can aid in characterizing the contribution in SuperCDMS. The GEANT4 particle simulation toolkit is used to simulate the passage of particles through matter and understand the interaction of sources in the experiment through Monte Carlo methods [121]. GEANT4 was the primary simulation package for background studies, though a couple supplementary Monte Carlos were utilized, such as one developed in Chapter 6 that describes the detector response of CDMSlite.

GEANT4 allows the user to define an experimental geometry specifying the location, shape, size, and material properties of different components. In order to track the particle interactions, such as the energy deposited in one part of the geometry, that particular volume is made “sensitive” to record the particle information. The details of the propagation of the particles is managed by physics libraries which contain lists of processes for the particles simulated. For example, if the incident particles are γ -rays, the physics list will contain modules for Compton scattering, photoelectric effect, etc. Some particular GEANT4 physics lists are studied in Chapters 4 and 7. How far a particle propagates through the material, as well as the potential for secondary particle generation, is controlled by the physics processes and a random-number generator.

It is helpful to define a few important GEANT4 terms:

- **Primary:** the initial particle created by the simulation.
- **Secondary:** any successive particles created as the primary propagates through the geometry.
- **Sensitive Volume:** specified by the user, these volumes have any interaction saved as output for offline analysis.
- **Event:** the highest level of classification. An event begins when a primary is created; all the interactions of the primary and secondaries, in any sensitive volume, are given the same event number.
- **Step:** the process that takes a particle from one state to another. The state, and how the change occurs, depends on the physics processes defined in the physics list.
- **Hit:** each interaction of a particle in a sensitive volume is a hit, and the information, such as energy deposition and position coordinates, are recorded.

The output given by GEANT4 requires additional analysis and processing to match physical data from the experiment. Since, the individual hits cannot be resolved in a detector, all energy deposited in a single detector over $1 \mu\text{s}$ is summed into a single recoil energy. This recoil is classified as an ER or NR depending on the amount of energy that is deposited through electromagnetic E_{EM} and nuclear E_{nuclear} processes, designated by the particle type. ER and NR recoils are defined as

$$\text{ER if: } 0.05E_{\text{EM}} > E_{\text{nuclear}} \quad (3.5)$$

$$\text{NR if: } 0.05E_{\text{nuclear}} > E_{\text{EM}}. \quad (3.6)$$

Is necessary to classify events as single or multiple scatters as dark matter is expected to interact once in the SuperCDMS detector array per event; thus, WIMPs are single-scatter NRs. This determination is based on the number of detectors with energy depositions. For iZIPs, a multiple scatter is defined as an event in which more than one detector has a total recoil energy greater than 2 keV. However, the energy condition is

relaxed for CDMSlite due to the lower threshold; an event in CDMSlite is considered a multiple scatter if any other detector has a total recoil energy greater than 2 keV.

3.3.1 *The “Classic” CDMS GEANT4 Monte Carlo*

The stand-alone GEANT4 simulation is called the “classic” CDMS GEANT4, or classic MC. The current iteration contains the SuperCDMS Soudan construction according to Fig. 2.2 in every aspect except the cryostat and PMTs. Not pictured in Fig. 2.2 are the calibration source tubes that follow the C and E stem, but have been added to the classic MC. Many particle generators have been written that describe a variety of radioactive sources: for example, γ ’s and neutrons from ^{232}Th and ^{238}U ; and γ ’s from ^{133}Ba , ^{40}K , ^{60}Co , etc. Any piece of the experimental apparatus, in the bulk or on a surface, can be contaminated with radioactive sources. However, only the array of detectors are sensitive volumes and record hits.

The classic MC was used for the Compton scattering background in Chapter 4. Particularly, ^{133}Ba was simulated from the source tubes to mimic the ^{133}Ba calibration configuration at Soudan. This output was compare to SuperCDMS Soudan data. The second simulation placed γ ’s from ^{238}U in the bulk of the cryostat cans. Since Compton scattering in the detectors is primarily from the radiogenic contamination in the apparatus materials, this simulation was used to construct the final background model.

3.3.2 *SuperSim*

SuperSim is the new, versatile CDMS-specific GEANT4 simulation framework and is the sanctioned Monte Carlo for the Collaboration.² Many predefined geometries exist, for example, the Soudan experiment with either the CDMS II or SuperCDMS detector configuration, and SuperCDMS SNOLAB. These geometries are not static, but the user can change the materials of any component or number of detectors, to name a few options. The particle generator for SuperSim is broader than the classic MC as SuperSim accesses new features of GEANT4 such as the decay of any radioactive particle. Like with the classic MC, these sources can be placed within the bulk, or on the surface, of any of the experimental components. However, any part of the experiment can be a

² The primary developer and maintainer of SuperSim is M. Kelsey.

sensitive volume with the detector array always sensitive.

Taking advantage of the configurability of SuperSim, it was used in the ^{210}Pb background study of Chapter 7 to construct a single SuperCDMS Soudan tower geometry. The surfaces of the copper housing and germanium detectors were contaminated with ^{214}Po to understand the implantation of ^{210}Pb , and the expected background from this source in CDMSlite.

The other set of simulations that relied heavily on the SuperSim framework were devoted to exploring the potential backgrounds of SuperCDMS SNOLAB and possible mitigation strategies. These studied the expected effect of an active neutron veto on the background from radiogenic neutrons in the bulk of the cryostat cans. SuperSim's flexibility allowed a variety of veto designs to be easily modeled. These simulations are discussed in Chapter 8.

G4DMC

An extension of SuperSim is the GEANT4 Detector Monte Carlo (G4DMC). This simulation uses a condensed matter package, G4CMP, to model the propagation of phonons and charges in a crystal. Originally a separate GEANT4 simulation, the G4DMC will be merged with SuperSim in order to understand the detector response to a simulated background. Work is ongoing to complete the integration, but is expected to support the analysis efforts of SuperCDMS SNOLAB.

The G4DMC was used to understand the electric-potential map of the CDMSlite detector by simulating the propagation of single electron hole pairs uniformly distributed throughout the crystal. This map was integral to the development of the detector response function in Chapter 6.

4

Compton Scattering at Low Energies in Germanium

Underlying radioactivity in the experiment's materials is the dominant source of the γ background in SuperCDMS Soudan. These γ 's contribute to the electron-recoil spectrum in the form of Compton scattering.

Unlike with the backgrounds of Secs. 3.1.2 and 3.2, a GEANT4 simulation was necessary to model Compton scattering. This was done by validating low-energy electromagnetic physics lists in GEANT4, specifically the Monash University Compton Model, with SuperCDMS Soudan data. The simulation spectra for the CDMSlite detectors were fit with a sum of error functions to determine the model parameters. This chapter describes the construction of the model for Compton scattering in CDMSlite at low energies.

4.1 Basic Compton Scattering Theory

In his seminal paper in 1923, Arthur Compton determined the increase in wavelength for hard x rays and γ rays scattered off electrons in light elements to be [122]

$$\lambda' - \lambda_0 = \frac{h}{m_e c} (1 - \cos \theta), \quad (4.1)$$

where λ_0 and λ' are the incident and scattered γ wavelength respectively, h is the Planck constant, m_e the mass of the electron, c the speed of light, and θ the angle between

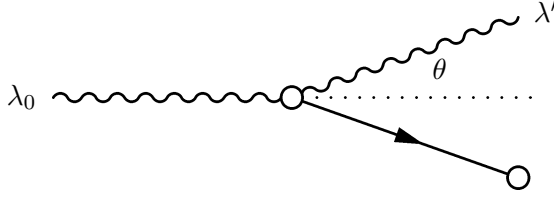


FIGURE 4.1: Diagram showing the kinematics of Compton scattering where λ_0 is the incident γ wavelength, λ' the scattered γ wavelength, and θ the angle between the incident and scattered γ . The open circle represents the electron initially at rest and then given energy E_r .

the incident and scattered γ (see Fig. 4.1 for a pictorial representation of Compton scattering). For light elements, one can make the assumption that the initial electron is at rest. This modified the classical Thomson cross section σ_T [123] by a factor inversely proportional to the energy of the incident γ .

It was not until Dirac published his relativistic quantum theory of the electron in 1928 [124] that a complete treatment of the problem of a scattered photon off a single free electron was developed by Klein and Nishina [125]. In this work, the average intensity of scattered light $\bar{I}$ was calculated as

$$\bar{I} = \frac{I_0}{r^2} \frac{e^4}{2m_e^2 c^4} \frac{1 + \cos^2 \theta}{(1 + \epsilon(1 - \cos \theta))^3} \left(1 + \epsilon^2 \frac{(1 - \cos \theta)^2}{(1 + \cos^2 \theta)(1 + \epsilon(1 - \cos \theta))} \right). \quad (4.2)$$

I_0 is the intensity of incident radiation, e the charge of the electron, r the radius vector from the electric potential field to the point of scattering, and $\epsilon = \frac{E_0}{m_e c^2}$. The average intensity is related to the differential cross section such that

$$\frac{d\sigma}{d\Omega} \propto \sigma_T \frac{1 + \cos^2 \theta}{(1 + \epsilon(1 - \cos \theta))^3} \left(1 + \epsilon^2 \frac{(1 - \cos \theta)^2}{(1 + \cos^2 \theta)(1 + \epsilon(1 - \cos \theta))} \right) \frac{E_0}{E'}, \quad (4.3)$$

where E_0 and E' are the energies of the incident and scattered γ , respectively. If the relationship between energy and scattering angle given in Eq. 4.1 is used, the differential cross section can be rewritten in the familiar form of the Klein-Nishina equation [126]:

$$\frac{d\sigma}{d\Omega} \propto \sigma_T \left(\frac{E'}{E_0} \right)^2 \left[\frac{E'}{E_0} + \frac{E_0}{E'} - \sin^2 \theta \right]. \quad (4.4)$$

The absolute normalization is unimportant for the discussion in this chapter.

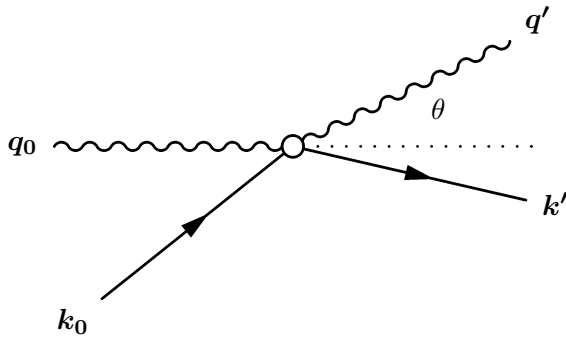


FIGURE 4.2: Representation of the three-dimensional scattering of a γ of four-vector $\mathbf{q}_0$ scattering off an electron with initial four-vector $\mathbf{k}_0$. The scattered γ and recoiling electron have four-vectors $\mathbf{q}'$ and $\mathbf{k}'$ respectively. θ is still the angle between the incoming and scattered γ . This represents just one plane of the scattering; all but the incident γ can have components perpendicular to the plane. Figure modified from Ref. [130].

Using conservation of energy, $E_0 = E' + E_r$, Eq. 4.4 can be rewritten in terms of the recoiling energy of the electron

$$\frac{d\sigma}{dE_r} \propto \sigma_T \left[2 + \frac{x}{1-x} \left(x - \frac{2}{\epsilon} \right) + \frac{x^2}{\epsilon^2 (1-x)^2} \right], \quad (4.5)$$

with $x = E_r/E_0$, and E_r the recoil energy of the electron. This can now be directly related to the measured energy in the CDMSlite detectors.

4.2 Scattering for Bound Electrons

Since the initial Klein-Nishina derivation, there have been a number of attempts to expand the simple, free-electron, theory to include scattering from a bound electron, as would occur in a solid [127, 128]. One such expansion is the Relativistic Impulse Approximation (RIA) as proposed by Ribberfors [129]. A group from Monash University used the RIA to derive, from first principles, a relativistic, three-dimensional, two-body scattering model which they called the Monash University Compton Model [130]. Figure 4.2 gives a representation of the three-dimensional Compton scattering. This initial work also developed an implementation of the model in GEANT4 called `G4LowEPComptonModel`. This physics list is one of many low-energy electromagnetic physics lists in `G4EmStandardPhysics_option4` specifically designed for energies below a few keV [121, 131]. These models consider the atomic structure of the atom, atomic de-excitation, and properties of the bound electron.

The Monash University Compton Model calculates properties of the scattered γ and recoiling electron by modifying the standard assumptions of Compton scattering: the initial electron is not at rest and the final state products are not confined to a two dimensional plane. This more complete treatment is necessary to replicate the phenomenon of “Compton steps”: discontinuities created in the low-energy spectrum at the location of each electron binding energy level. For example, the electrons in the K shell of germanium have a binding energy of 11.1 keV. This energy is deposited in the detector due to the reorganization of the electron shells, along with any additional energy that is given to the freed electron by the incident γ . Thus, an electron from the K shell can never deposit less than 11.1 keV in the detector, and likewise for electrons in the other atomic shells. Naïvely, the expectation is that the number of electrons in each shell determines the relative size of the steps; however, details of the electron wave functions can also effect the size. The Compton steps have been directly observed in silicon detectors [132].

4.3 Simulation of Mono-energetic γ 's with the Monash University Compton Model

With this more detailed physics list, a simulation was created and executed in GEANT4 with 356 keV γ 's incident on germanium. This energy was chosen because it is the most prominent energy of γ 's from the ^{133}Ba decay, which is the primary electron-recoil calibration source for SuperCDMS Soudan. These γ 's were incident isotropically on a germanium cylinder the size of a SuperCDMS iZIP (76.2 mm in diameter and 25.4 mm in height). The effect of the Monash University Compton Model can be seen in Fig. 4.3. The simulation spectrum was compared to the Klein-Nishina equation given in Eq. 4.5, modified to emulate the Compton steps using the naïve assumption that the step height is proportional to the number of electrons available in a shell. This simple change was implemented as:

$$\frac{d\sigma}{dE_r} \propto \left[2 + \frac{x}{1-x} \left(x - \frac{2}{\epsilon} \right) + \frac{x^2}{\epsilon^2 (1-x)^2} \right] \cdot \sum_i c_i \Theta(E_r - e_i), \quad (4.6)$$

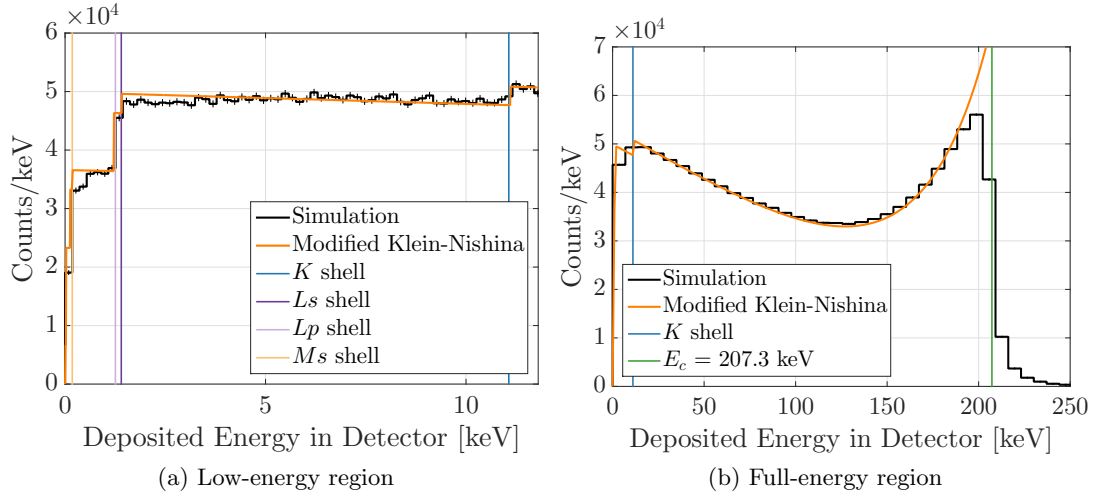


FIGURE 4.3: Simulation from incident γ 's of 356 keV on a germanium target compared to a modified Klein-Nishina theoretical model. (a) The low-energy region demonstrating the structure from the Compton steps. (b) The entire range of energy deposition where the tail above the Compton edge is visible.

where i is the various shells for a given atom (K , L , etc.), c_i are the weights for the steps, and e_i are the binding energies. This equation works reasonably well to model most aspects of the resulting spectra from a mono-energetic incident γ as evidenced by Fig. 4.3.

Figure 4.3a shows that low energy steps appear at the binding energies of germanium. The theoretical description approximately matches the simulation in this energy range; the discrepancies are mainly due to the negative slope of the Klein-Nishina, which is not reproduced in simulation, and the naïve step size. A high-energy tail is visible in Fig. 4.3b above the Compton edge.¹ If the momentum direction of the bound electron and the direction of the incident γ are aligned, it is possible for the electron to have more kinetic energy than is predicted by the calculation with the electron at rest. The theoretical calculation matches the full energy range to about 200 keV, beyond which events are smeared due to the momentum of the bound electron. This interpretation was verified by calculating the bound electron momentum from the simulation and using this distribution in a simple reconstruction of the `G4LowEPComptonModel`.

¹ Recall, in the simple theory [122], the maximum energy transferred to the recoiling electron occurs at $\theta = 180$ in Eq. 4.1.

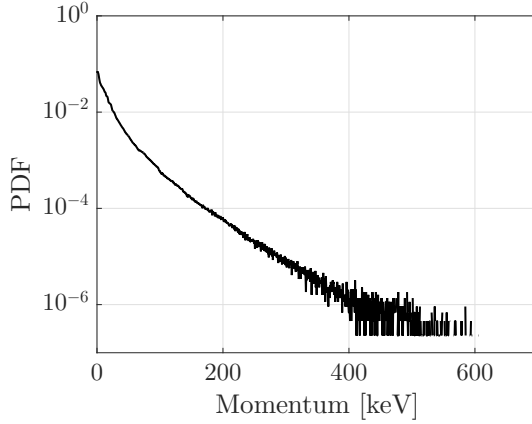


FIGURE 4.4: Average momentum PDF of the bound electron from all atomic shells in germanium (assuming natural units).

Two outputs of the GEANT4 simulation are the kinetic energy and the momentum unit vector for the incident γ , recoiling electron, and scattered γ . With this data, the energy and momentum of the bound electron can be reconstructed. The kinetic energy, E_B , can be found simply by conservation of energy

$$E_B = E' + E_r - E_0, \quad (4.7)$$

where E_0 and E' are the energies of the incident and scattered γ respectively, and E_r is the energy of the recoiling electron. The momentum of the bound electron is

$$\mathbf{p}_B = E' \mathbf{p}' + \sqrt{E_r^2 + 2m_e E_r} \cdot \mathbf{p}_r - E_0 \mathbf{p}_0. \quad (4.8)$$

Here, the momentum unit vectors are $\mathbf{p}_B$, $\mathbf{p}'$, $\mathbf{p}_r$, and $\mathbf{p}_0$ for the bound electron, scattered γ , recoiling electron, and incident γ , respectively. The average momentum, $p_B = |\mathbf{p}_B|$, from the simulation is shown in Fig. 4.4.

Following a prescription similar to that of `G4LowEPComptonModel`, the effects of the momentum of the bound electron on the recoiling electron were considered. The average momentum PDF, Fig. 4.4 was used. For simplicity, the binding energy of the electron was assumed to be zero. This removed the need to calculate the probability that an electron was located in a particular shell and had a negligible effect on the high-energy region under consideration.

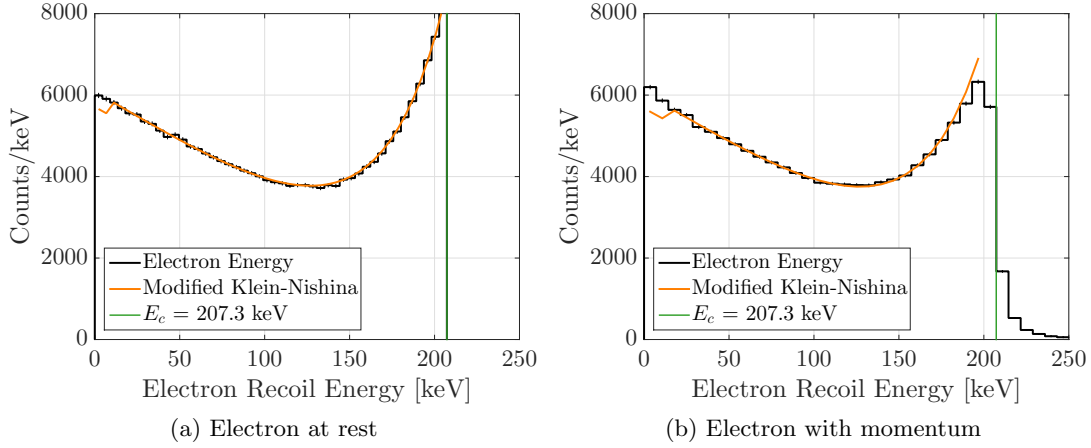


FIGURE 4.5: Energy deposited by the recoiling electron when the bound electron is at rest (a) or has momentum (b). The high energy tail about the Compton edge (vertical line) is clearly visible when momentum is included. This can be compared to Fig. 4.3b.

The steps are as follows:

1. Select a scattered γ angle from the Klein-Nishina cross-section (from Eq. 4.3)

$$\frac{d\sigma}{d(\cos \theta)} = \frac{1}{2 \cdot (1 + \epsilon(1 - \cos \theta))^2} \cdot \left[\frac{1}{1 + \epsilon(1 - \cos \theta)} + \left(\frac{1}{1 + \epsilon(1 - \cos \theta)} \right)^{-1} - 1 + \cos^2 \theta \right]. \quad (4.9)$$

2. Select the momentum from the average momentum CDF (created from Fig. 4.4).
3. Select angles for the bound electron; $0-\pi$ in the plane of the incident γ and $0-2\pi$ in the perpendicular plane (see Fig. 4.2).
4. Calculate the energy of the scattered γ using the momentum of the bound electron, the angles of the bound electron and scattered γ , and the energy of the incident γ (derivations for this equation comes from Ref. [130]).
5. Calculate the energy of the recoiling electron.

Figure 4.5 compares the energy of the recoiling electron with and without the momentum of the bound electron. It is clear that including momentum for the bound

electron results in the high-energy tail above the Compton edge. This is demonstrated by comparing Figs. 4.3b and 4.5b where the tail is similar in shape and magnitude. The differences near the Compton edge caused by leaving out the electron binding energy are small, as expected.

4.4 Verification with SuperCDMS Soudan ^{133}Ba Data

The previous section explored the phenomena of Compton steps in simulated data, however, a verification of their existence and magnitude in physical data was also desired. SuperCDMS Soudan ^{133}Ba -calibration data were used as it was γ -dominated data and exists in abundance.

4.4.1 *Description of the Data Set*

A set of ^{133}Ba high-statistics data was collected during Run 135 over the course of about a month from late-December 2014 to mid-January 2015. From this data, the region below 20 keV_{ee} was considered for each detector. Of the fifteen detectors, only the six detectors with the best low-energy behavior and without any channel shorts were considered: T1Z1, T2Z1, T2Z2, T4Z3, T5Z2, and T5Z3. Both the charge and phonon energy estimators were used in this analysis; specifically, the maximum of the charge-energy measured on either side of the detector (qsummaxOF), and the phonon-energy reconstructed with a non-stationary optimal filter algorithm (ptNF).

Basic quality cuts were applied to the data to remove anomalous events, and it was required that the detector issue the trigger (see Sec. 2.1.3). Figure 4.6 shows an example spectrum in both ionization- and phonon-energy estimators from T4Z3. In Figs. 4.6a and 4.6c the effect from applying the basic quality cuts is considered. These removed little data above the noise² and show essentially perfect passage of data. The passage fraction is calculated on a binned basis as

$$\text{Passage Fraction} = \frac{\text{Ba events with quality cuts}}{\text{Ba events}}. \quad (4.10)$$

The passage fraction as a function of energy is also shown in Fig. 4.6. In ionization

² The noise, colloquially referred to by CDMS as the noise wall, was the sharpe rise in the energy spectrum at low energies, predominately due to low-frequency and electronics noise.

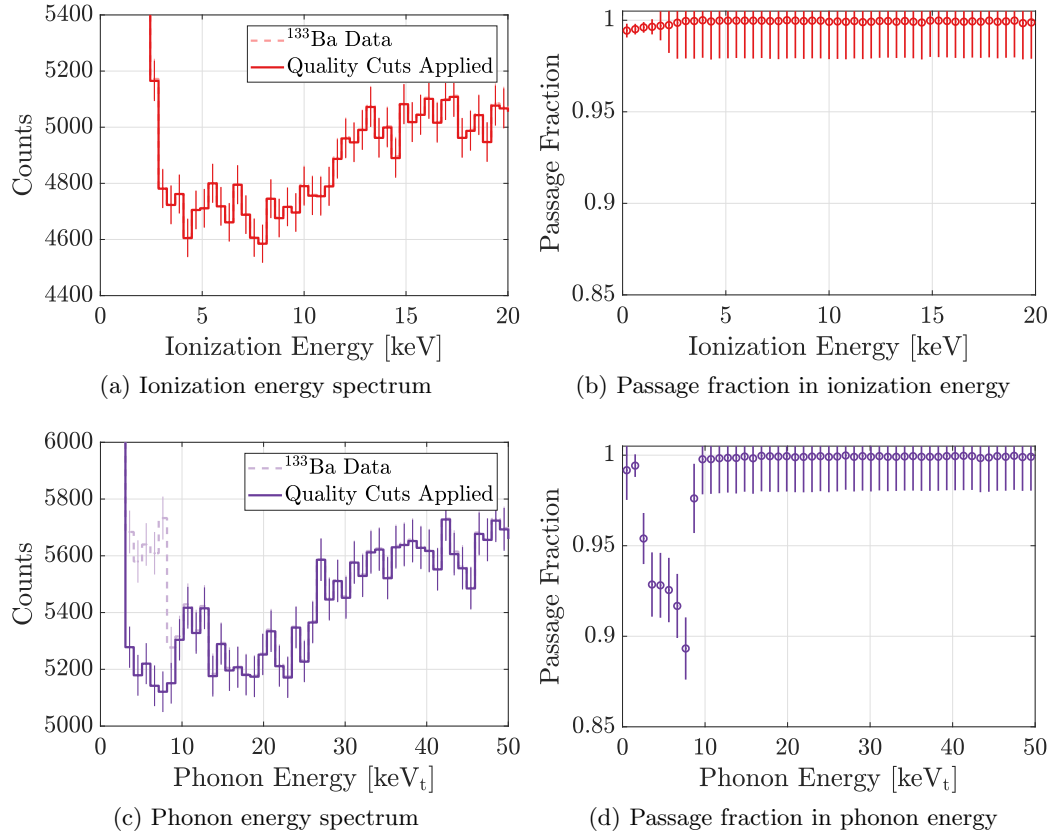


FIGURE 4.6: Spectrum from ^{133}Ba data from T4Z3 in ionization (a) and phonon (c) energy estimators and passage fraction after applying basic quality cuts for the ionization (b) and phonon (d) energy estimators. An increase in the event count can be seen in (a) around 11 keV_{ee} and in (b) around 25 keV_t showing indications of the K -shell Compton step. The passage fraction is essentially unity above 3 keV_{ee} in (b) and 10 keV_t in (d).

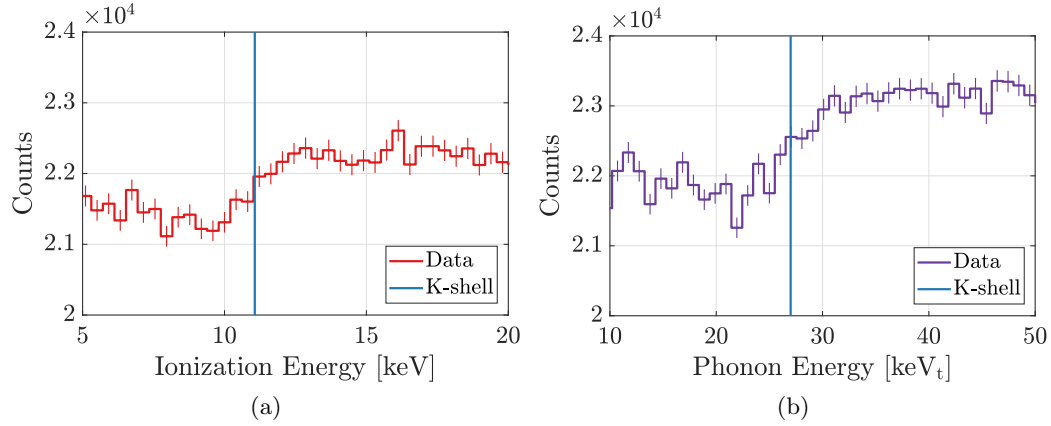


FIGURE 4.7: Spectra of ^{133}Ba data after summing the data from the six detectors used in this analysis in terms of their ionization (a) and phonon (b) energy estimators. The energy range was chosen for which the detectors had constant passage fractions. Also indicated as the vertical line is the location of the K shell in the two energy estimators.

energy, the passage fraction reaches unity at $\sim 3 \text{ keV}_{\text{ee}}$ (Fig. 4.6b), and for phonon energy at $\sim 10 \text{ keV}_{\text{t}}$ (Fig. 4.6d).

4.4.2 Analysis of the K -shell Step

The data from all six individual detectors was combined for further study of the spectrum. Figure 4.7 shows the data used in both ionization- and phonon-energy estimators. The analysis was bounded below by a threshold of $5 \text{ keV}_{\text{ee}}$ in ionization-energy and $10 \text{ keV}_{\text{t}}$ in phonon-energy. Above these thresholds all detectors had constant passage fractions. This also avoided the low-energy noise wall.

The K shell of germanium at 11.1 keV is indicated by the blue vertical line in Fig. 4.7. There are two plateaus, one above 11.1 keV and a second below 11.1 keV . The observed deviations on the plateaus are consistent with statistical fluctuations of a flat distribution. It is evident by eye that there is a distinct difference in the number of counts above and below the K shell. By taking the average number of counts below the K shell and comparing to the average number of counts above the K shell, the relative step size was calculated to be $3.7 \pm 0.2\%$ in ionization energy and $5.4 \pm 0.2\%$ in phonon energy.

To determine if the step was a real effect or fluctuation, a scan over the spectrum

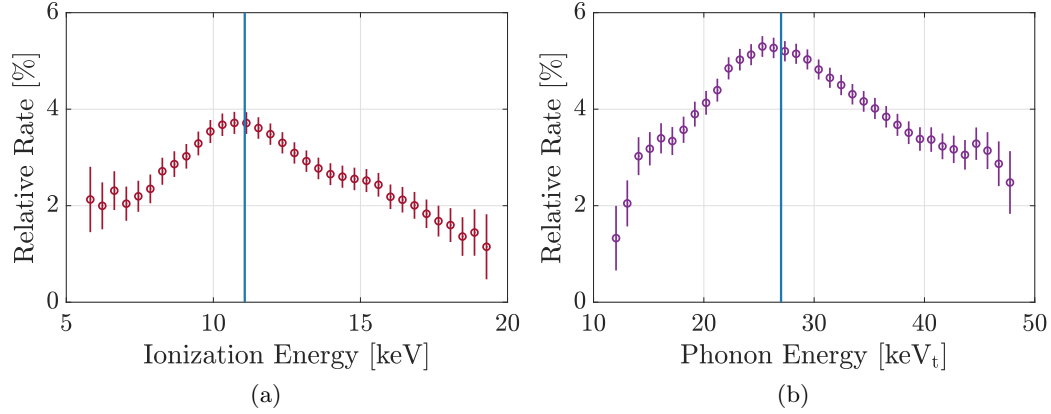


FIGURE 4.8: Relative step size rate of the ^{133}Ba data as a function of ionization (a) and phonon (b) energy estimators. The vertical line indicates the energy of the K shell. There is a clear peak within a couple bins of this location in both energy estimators.

was completed and the average number of counts below the moving reference point were compared to the average number of counts in the bins above that reference point:

$$\text{Relative step size} = \frac{\text{average counts}(E > E_i) - \text{average counts}(E < E_i)}{\text{average counts}(E > E_i)}, \quad (4.11)$$

where E_i indicates the reference energy. This can be seen in Fig. 4.8. There is a clear peak within a couple bins of where the K shell is indicated (vertical blue line). Thus, there is clearly a change in the rate above and below the K shell in germanium. This method of measuring the relative step size agrees to the calculation using $E_i = 11.1$ keV: $3.7 \pm 0.2\%$ in ionization energy and $5.4 \pm 0.2\%$ in phonon energy. Since there was no defined fiducial volume for the detectors, there was some incomplete signal collection causing a decrease in the observed energy and a peak in the relative rate that was slightly less than the expected K shell.

Another test to determine if the increase in count rate at the K shell was real consisted of fitting the spectrum with various functional forms. Figure 4.9 shows the resulting fits to the ^{133}Ba spectra and Tables 4.1, 4.2, and 4.3 give the functional form, resulting fit parameters, and their goodness of fit. It is clear a simple linear function does not describe the data well. There are reasonable agreement to the data for both the error function and the combination function. Also, the relative step size from the functional

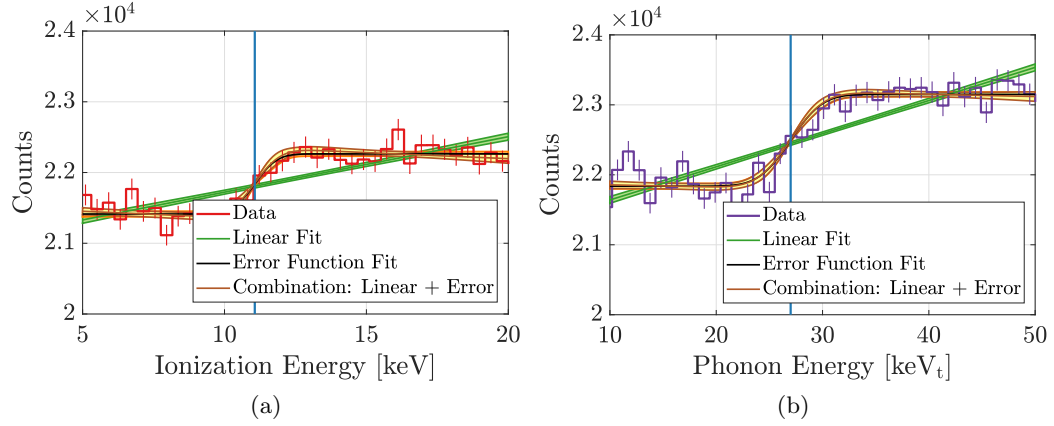


FIGURE 4.9: Fits of the linear, error, and combination equations to the ^{133}Ba spectra in ionization (a) and phonon (b) energy estimators. The vertical line indicates the K -shell energy. Both the error-function and combination-function fit the data well in both energy estimators.

Linear: $m_L E + b_L$			
	b_L [Counts]	m_L [Counts/keV]	χ^2/ndf
Ionization	$2.1\text{E}4 \pm 73$	78 ± 6	3.01
Phonon	$2.1\text{E}4 \pm 67$	47 ± 2	5.13
Simulation	$1.0\text{E}4 \pm 52$	57 ± 4	2.94

TABLE 4.1: Fit parameters for a linear equation to the ionization- and phonon-energy estimators and a GEANT4 simulation. The linear fit function does not represent the spectra as reflected in the high χ^2/ndf .

Error Function: $0.5A_E \left[1 + \operatorname{erf}\left(\frac{E-\mu}{\sigma_E}\right) \right] + b_E$				
	b_E [Counts]	$S_E = \frac{A_E+b_E}{b_E}$ [%]	σ_E [keV]	χ^2/ndf
Ionization	$2.1\text{E}4 \pm 40$	3.82 ± 0.25	0.62 ± 0.25	1.02
Phonon	$2.2\text{E}4 \pm 40$	5.67 ± 0.25	2.36 ± 0.52	1.98
Simulation	$1.1\text{E}4 \pm 27$	5.21 ± 0.32	0.23 ± 0.12	1.07

TABLE 4.2: Fit parameters for an error function to the ionization- and phonon-energy estimators and a GEANT4 simulation. The values of S_E can be compared to the relative step size: $3.71 \pm 0.23\%$, $5.27 \pm 0.21\%$, and $5.16 \pm 0.31\%$ for ionization, phonon, and simulation respectively. All are within the 1σ error. The χ^2/ndf indicate good agreement between the fit function and spectral shape.

Combination: $0.5A_C \left[1 + \operatorname{erf}\left(\frac{E-\mu}{\sigma_C}\right) \right] + m_C E + b_C$					
	b_C [Counts]	$S_C = \frac{A_C+b_C}{b_C}$ [%]	σ_C [keV]	m_C [Counts/keV]	χ^2/ndf
Ionization	$2.2\text{E}4 \pm 110$	4.44 ± 0.66	0.72 ± 0.27	-17 ± 14	1.00
Phonon	$2.2\text{E}4 \pm 110$	5.98 ± 0.75	2.50 ± 0.64	-3.2 ± 6.4	2.03
Simulation	$1.1\text{E}4 \pm 70$	5.21 ± 0.67	0.23 ± 0.13	0.0 ± 8.3	1.11

TABLE 4.3: Fit parameters for a combination of an error function and linear equation to the ionization- and phonon-energy estimators and a GEANT4 simulation. The values of S_C can be compared to the relative step size: $3.71 \pm 0.23\%$, $5.27 \pm 0.21\%$, and $5.16 \pm 0.31\%$ for ionization, phonon, and simulation respectively. All are within the 1σ error. The χ^2/ndf indicate good agreement between the fit function and spectral shape.

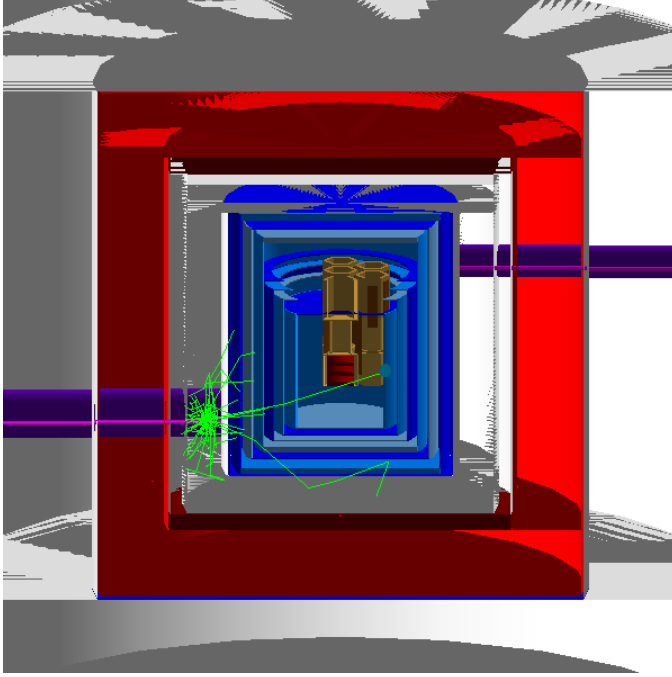


FIGURE 4.10: Cross-sectional view of the SuperCDMS Soudan geometry in GEANT4. The layers are structured as (from outer most to inner) outer-poly (white/gray), lead (red), inner-poly (white/gray), cryostat cans (blue), and towers with detectors (copper with red cylinders). Horizontal penetrations for the E-stem (top right purple) and C-stem (bottom left purple) are given with their source tubes (magenta). The tracks originating from the C-stem source tube are the ^{133}Ba γ 's (green).

fits agree within statistical errors to the relative step size calculated from the scan over energy. It is important to note that relative step size for the energy estimators is always smaller than the naïve assumption, where only the number of available electrons in the K shell is considered, which gives 6.25%. The phonon fits generally have lower χ^2/ndf because the phonon measurement is not as clean as the ionization, especially when combining detectors.

4.4.3 Comparison to GEANT4 Simulation

Finally, the data from the detectors was compared to a GEANT4 simulation³ of the SuperCDMS Soudan experiment during ^{133}Ba calibration. The geometry of the simulation is shown in Fig. 4.10. The energy deposited from the simulation in the same six detectors as the SuperCDMS Soudan data were considered individually, in order to apply a detector dependent energy resolution [133], and then combined. The simulation is compared with the ionization-energy estimator in Fig. 4.11, where the blue vertical line again indicates the K -shell energy. The χ^2/ndf for the simulation and ionization

³ GEANT4.10.01.p02 was used with the classic GEANT4 Monte Carlo.

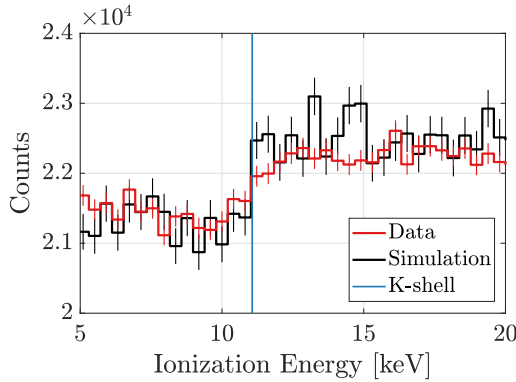


FIGURE 4.11: Comparison between the GEANT4 simulation and SuperCDMS Soudan ionization-energy estimator data using the ^{133}Ba source. The vertical line indicates the K -shell energy. It is clear that the simulation has a larger relative step size, though around half the bins are within the statistical uncertainties. The χ^2/ndf between the two histograms is 1.54.

energy is 1.54.

The relative step size of the simulation was calculated with an energy scan (Eq. 4.11) and was found to be $5.2 \pm 0.3\%$. Additionally, the simulation spectrum was fit with the same functional forms as the data and the results are given in Tables 4.1, 4.2, and 4.3. The agreement between the simulation and data gives confidence to the use of `G4LowEPComptonModel` and `G4EmStandardPhysics_option4` for SuperCDMS studies. A comparison with phonon energy was not considered since no phonon physics was included in the simulation, and the energy deposited in GEANT4 was representative of the ionization energy.

4.5 Radiogenic Compton Background in SuperCDMS Soudan

The dominant contributor to the Compton background for SuperCDMS Soudan data is the radiogenic γ 's from trace amounts of contamination in the experimental materials. These originate from the shield materials (polyethylene and lead) as well as the cryostat and towers (copper).

4.5.1 Description of the Simulation

A major effort was completed by E. Lopez Asamar to simulate the components of the radiogenic γ 's and match the spectra in the SuperCDMS Soudan detectors above 300 keV; this type of analysis is called a Global Gamma Monte Carlo (GGMC) [134]. The γ backgrounds from contamination due to ^{40}K , ^{222}Rn , ^{232}Th , and ^{238}U were used in the GGMC. They were uniformly distributed through the bulk of the inner layers of

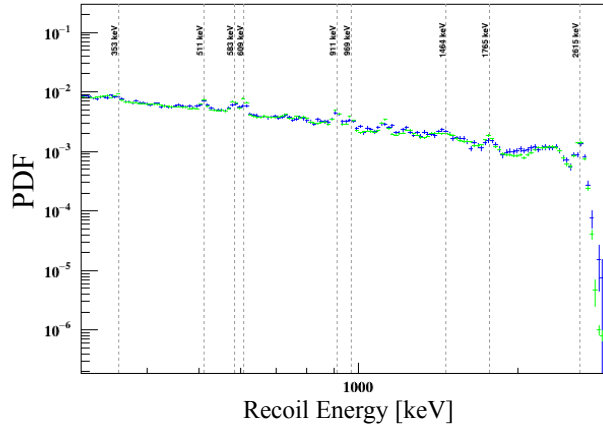


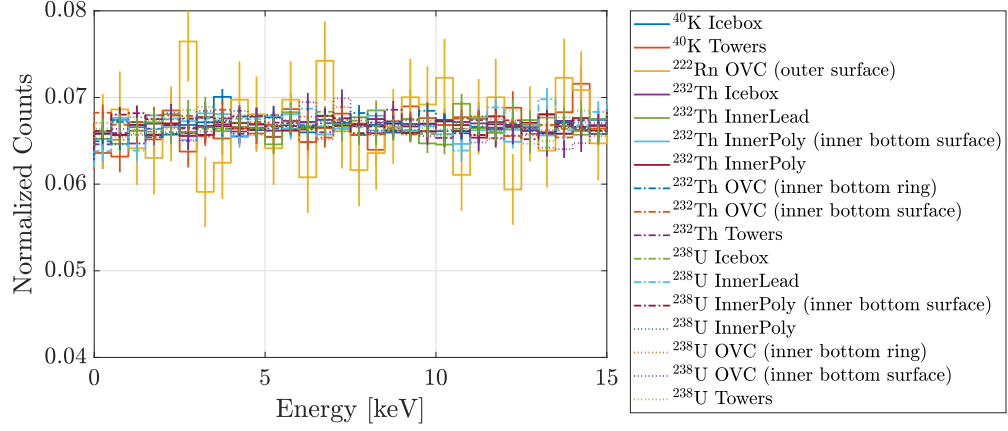
FIGURE 4.12: Example fit of the Global Gamma Monte Carlo (green) to the electron recoil spectrum (blue) in T4Z3. The dashed vertical lines indicated peaks from the radioactive sources. Figure from Ref. [134].

shielding (inner polyethylene and lead), the cryostat cans, and detector towers. Additionally the surface of the inner polyethylene and outer cryostat can were contaminated. Figure 4.12 gives an example of the agreement between Monte Carlo and data in the electron recoil spectrum of T4Z3.

As the intent of the GGMC was to determine the areas of the experiment with the highest level of radioactivity by comparing the high-energy portion of the electron recoil spectrum, the low-energy electromagnetic GEANT4 physics list was not used. Therefore, it was necessary to redo all or part of this simulation with the improved physics list validated in Sec. 4.4. To determine how many components to simulate, a skim of the GGMC was taken below a total deposited energy of 15 keV in order to compare the various γ sources and locations of contaminants in various combinations of the detectors. All this was necessary to determine if a targeted high statistics simulation could be completed of one contaminant, or if the entire GGMC would need to be redone.

4.5.2 Spectral Comparisons

Figure 4.13 shows all the possible sources of contamination from the GGMC. The energy from all detectors has been coadded together to improve statistics. For each contamination source, though there are statistical fluctuations, the spectra are flat in energy. To quantify the agreement between the various spectra, the χ^2/ndf was calculated between each pair of contamination (here, seventeen choose two). The distribution of χ^2/ndf



(a) All GGMC contaminants

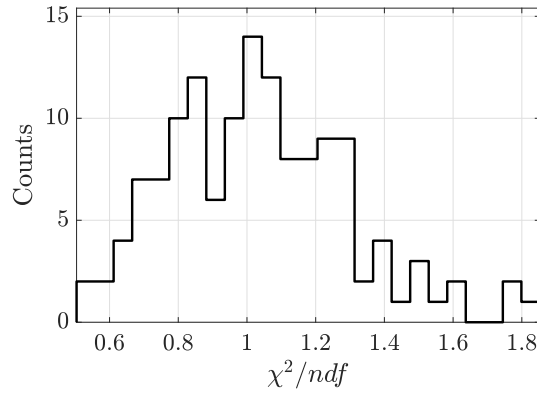
(b) Distribution of χ^2/ndf

FIGURE 4.13: All the possible sources of contamination from the GGMC (a) and the distribution of the χ^2/ndf between the sources (b). Each spectra is shown as a PDF to aid comparison. The spectra appear flat by eye and consistent within statistical fluctuations. The χ^2/ndf between each pair of spectra is peaked at one indicating good agreement.

can be seen in Fig. 4.13b and is peaked around one, indicating the spectra agree with one another within statistical error.

Several contaminations were grouped together to further investigate the consistency between radiogenic γ 's and originating location. It was determined that all ^{238}U contamination from all materials gave compatible spectral shapes. This is seen in Fig. 4.14a. Additionally, the spectra from ^{40}K , ^{232}Th , and ^{238}U originating in the bulk of the cryostat cans are flat in energy (Fig. 4.14b). This is characteristic of all contaminants in the material bulk. Finally, considering the differences in location within the cryostat, Fig. 4.14c demonstrates that a bulk source deposits energy at the same rate in all detectors.

A final check on the location of the events in the detector was completed. For the event location, the energy weighted position was used rather than the individual hits which more accurately represents the response expected from an iZIP detector. The energy weighted position of an event, $\vec{x}_{weight}$, is calculated by

$$\vec{x}_{weight} = \frac{\sum_i \epsilon_i \cdot \vec{x}_i}{\sum_i \epsilon_i}, \quad (4.12)$$

where the sum is over the number of GEANT4 hits, ϵ_i is the energy of the hit, and $\vec{x}_i$ is the position of the hit. The ^{238}U from the cryostat was considered in T2Z1 and T5Z2 and is shown in Fig. 4.15. Since T2Z1 is the top detector in the tower, there are slightly more events at high values of Z . Also, due to the external nature of the source, there is a larger number of events around the edges of the detector, at high Z and R^2 . These distributions were typical of the bulk sources studied from the GGMC.

All the tests presented in this section indicate that one contamination could be chosen in order to do a high-statistics simulation with the low energy physics list `G4EmStandardPhysics_option4`. The γ source chosen was ^{238}U as it has multiple energies in its decay, but is otherwise a relatively simple source. These were simulated originating from the geometrical source of the cryostat. This is a bulk source, and with all the cans of the cryostat considered, there is varying amounts of attenuation for the gammas creating a broader spectrum emulating a variety of radiogenic backgrounds.

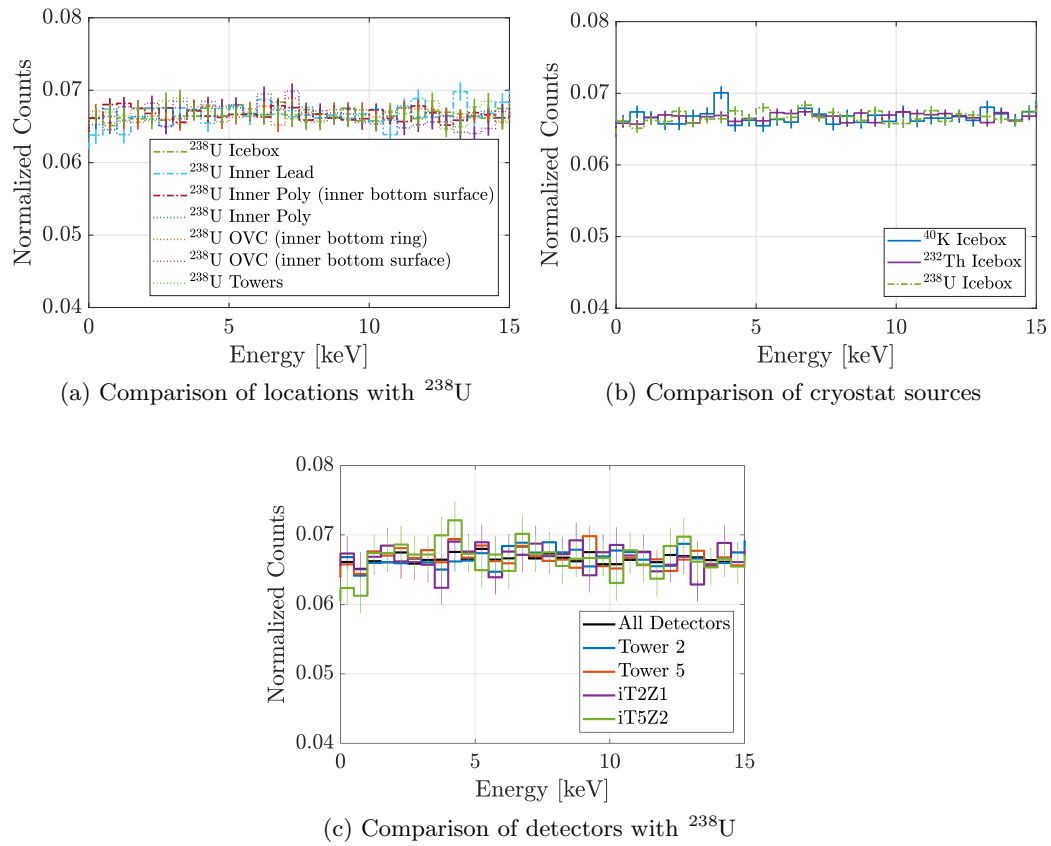


FIGURE 4.14: Comparison of GGMC between locations of ^{238}U contamination (a), the contamination from the cryostat (b), and the ^{238}U cryostat contamination of various detector arrangements (c). All comparisons are consistent with flat spectra in energy.

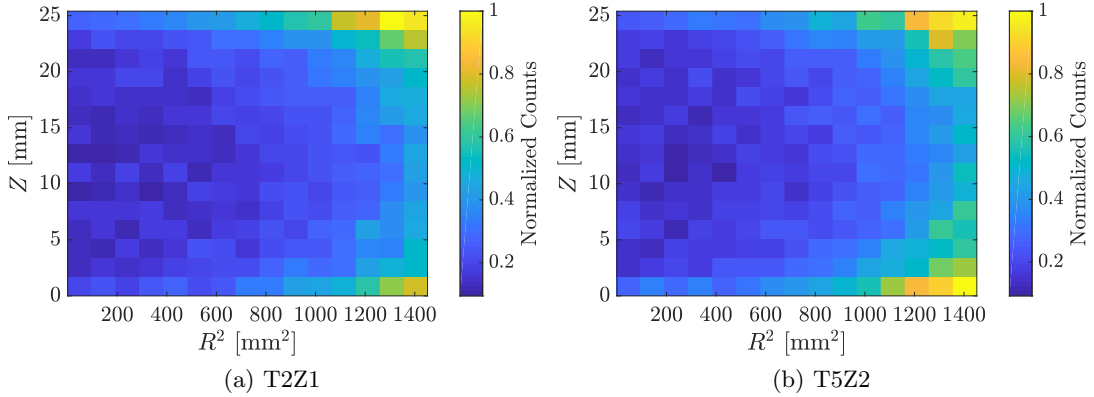


FIGURE 4.15: Distribution of events in the CDMSlite detectors T2Z1 (a) and T5Z2 (b). They have been normalized such that the highest number of counts is set to 1. There is a slightly higher population of events on the surfaces on the detector, but in general the distribution is fairly uniform. Note also the modest increase in events at the top (high Z values) of T2Z1 as it is located at the top of the tower.

4.6 Model for CDMSlite

A high-statistics simulation of ^{238}U from the cryostat cans was completed with the same geometry as used for the ^{133}Ba study and shown in Fig. 4.10. The number of primaries simulated from each cryostat can was normalized by the volume of the can removing the need to normalize the output of the simulation. The ^{238}U source has two main γ contributors, ^{214}Bi and ^{214}Pb , which were generated in equal number. For this analysis, all detectors were needed in order to identify multiple scatters, but the model was only constructed for the two CDMSlite detectors, T2Z1 and T5Z2.

4.6.1 Theoretical Expectation

The modified Klein-Nishina equation Eq. 4.6, described the simulation well for a mono-energetic source of incident γ 's, but was very difficult to modify for multiple energies, especially when the γ 's travel through material that changes their profile before interacting in the detectors. Thus, similarly to the SuperCDMS Soudan ^{133}Ba data analysis, an analytic model based on error functions was constructed to fit to the simulation.

	μ_i [keV]	A_i	A_i/N_1
K	11.1	$2/32 = 0.0625$	0.0029
L	1.26	$8/30 = 0.2667$	0.0123
M	0.13	$18/22 = 0.8182$	0.0376
N	0.04	$2/4 = 0.5$	0.0230

TABLE 4.4: Theoretical parameters of the first four steps for the analytical Compton model given in Eq. 4.13. The location of each step μ_i is the binding energy of the germanium shells. The amplitudes A_i are calculated based on the ratio of electrons in the shell to the number of available electrons at the shell energy. N_1 is calculated from 0–20 keV.

	σ_K [eV]	σ_L [eV]	σ_M [eV]	σ_N^* [eV]
Run 2 (T5Z2)	101 ± 1	31.0 ± 0.2	18.4 ± 4.2	11 ± 4
Run 3 (T2Z1)	108 ± 2	36.3 ± 2.0	13.9 ± 2.0	13 ± 2

TABLE 4.5: Resolution of the ^{71}Ge activation peaks. Data for Run 2 is from Ref. [72] and Run 3 were obtained in Sec. 5.4. *Calculated from data-driven resolution model, not measured.

This will take the form

$$f_C(E) = \frac{1}{N_1} \sum_{i=K,L,\dots} 0.5A_i \left[1 + \operatorname{erf}\left(\frac{E - \mu_i}{\sqrt{2}\sigma_i}\right) \right], \quad (4.13)$$

where N_1 is a normalization factor so that the function integrates to one. The approximate location of each step is given by μ_i and the resolution by σ_i . A_i , or the amplitude of the error function, is the relative step size.

Theoretically motivated parameters for the first four steps are found in Tables 4.4 and 4.5 which were used as starting points for the model development. Table 4.4 gives the expected location of the steps μ_i and the naïve amplitudes. The L - and M -shell μ_i are the energy for the p-orbital. Since the p-orbital has a larger number of electrons than the s-orbital, it was expected that the step would align with this energy. The amplitudes A_i are based on the number of available electrons. For example, A_K is calculated as the electrons in the K shell over the total number of electrons in the germanium atom:

$2/32 = 0.0625$. Though the remainder of the shells are more complicated, it is simplified for these approximations such that the subshells are all considered as one. The ratios of electrons are also given in Table 4.4. The resolutions σ_i in Table 4.5 are from the ^{71}Ge activation peaks located near each step. For Run 2, the values are from Ref. [72]. The Run 3 resolutions are derived in Sec. 5.4.

4.6.2 *Simulation Event Selection*

There were many pathologies in physical data removed by quality cuts that were irreproducible in the GEANT4 simulation. However, there were two cuts applied to CDMSlite data that need special consideration: these were the multiples cut and radial cut. The multiples cut identifies events that have energy deposited in more than one detector and was straightforward to implement in the simulation analysis as GEANT4 gives information about the energy deposited in all detectors during an event. The radial cut was more difficult to apply because there is no clear relationship between physical detector coordinates and the CDMSlite radial parameter, but some simplified versions were examined. Both of these cuts were important to consider when developing a model for CDMSlite data.

For each event, the energy deposited in each detector was summed. An event was considered a multiple scatter if any other detector has more than 2 keV of energy deposited. Both detectors T2Z1 and T5Z2 were considered. The analysis region of interest for this study was 0–20 keV.

4.6.3 *Fitting the Simulation and Building the Model*

A consistency check was performed on the K shell by comparing the relative step size from the ^{238}U simulation with the ^{133}Ba analysis in Sec. 4.4. Since the step is a function of material only, the same relative step size was expected regardless of the energy spectrum of the incident γ 's. Figure 4.16 shows the K -shell steps from the total energy deposited for the radiogenic simulation in T2Z1. As in the previous analysis, the energy range from 5–20 keV was fit with an error function. The result of the fit on the spectra from the total energy deposited is directly comparable with the ^{133}Ba simulation result of $5.3 \pm 0.3\%$. For T2Z1, the relative step size of the K shell is $6.1 \pm 0.5\%$, and in T5Z2 $5.4 \pm 0.5\%$. All are consistent within the 1σ statistical uncertainties.

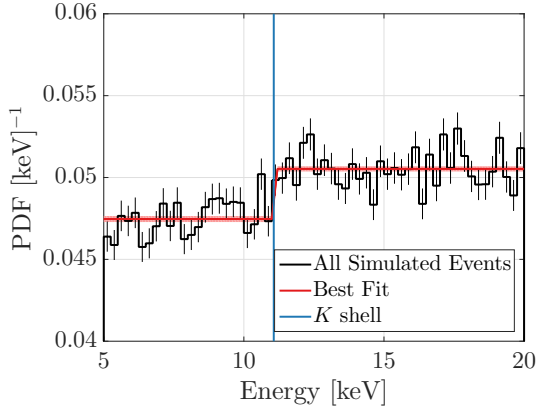


FIGURE 4.16: Fit to the K shell in T2Z1 for the total energy deposited from ^{238}U gammas originating in the cryostat. The relative step size when considering the total energy deposited is $6.1 \pm 0.5\%$ and is directly comparable to the ^{133}Ba simulation which gave $5.3 \pm 0.3\%$. These are consistent within the 1σ statistical errors.

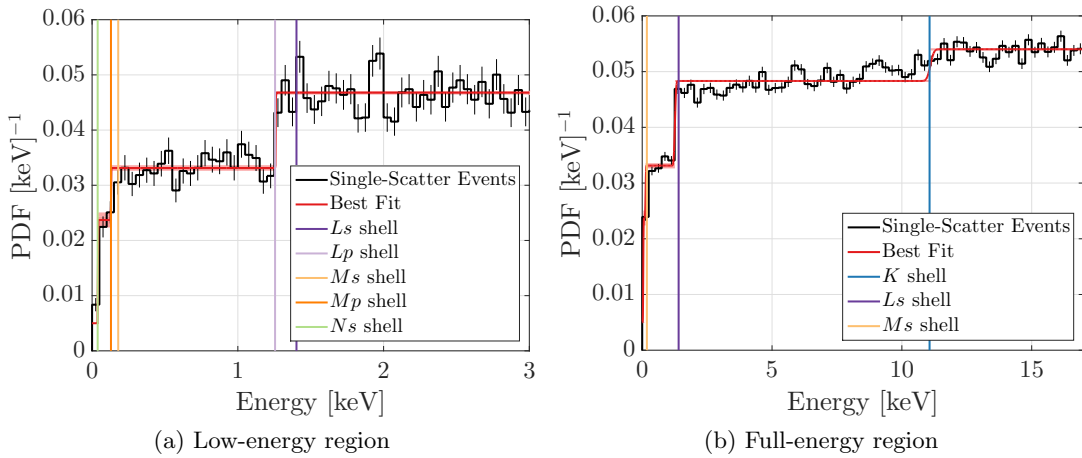


FIGURE 4.17: Compton model fit to T2Z1. (a) Low energy fit showing the L , M , and N shells. (b) Full energy range. The shaded region gives the 1σ error on the fit result. The slight positive slope in (b) is a geometric effect (see text).

	A_K/N_1	A_L/N_1	A_M/N_1	A_N/N_1	χ^2/ndf
Run 2 (T5Z2)	9.22 ± 0.46	15.7 ± 0.8	10.5 ± 2.1	15.3 ± 2.0	1.37
Run 3 (T2Z1)	5.7 ± 0.3	15.2 ± 0.5	9.43 ± 1.40	18.7 ± 1.3	1.4

TABLE 4.6: Compton model parameters for CDMSlite normalized over the energy range 0–20 keV. The values are multiplied by 10^3 . All shells but the K shell are within the 1σ errors indicating the decrease in probability as a function of energy below 11 keV is constant in both detectors. The χ^2/ndf indicate reasonable fits to the spectra.

The singles spectrum from 0–20 keV in both T2Z1 and T5Z2 were fit with a slightly modified Eq. 4.13. Due to the binned nature of the fit, only the amplitudes of the first four steps could be accurately determined. To keep the function from evaluating to zero before 0 eV, a constant value was added. The final analytical expression is

$$f_C(E) = 0.005 + \frac{1}{N_1} \sum_{i=K,L,M,N} 0.5A_i \left[1 + \operatorname{erf}\left(\frac{E - \mu_i}{\sqrt{2}\sigma_i}\right) \right]. \quad (4.14)$$

Figure 4.17 shows the final fit to T2Z1, and the normalized step amplitudes are given in Table 4.6. The relative amplitudes for all shells, except the K shell, are within 1σ errors. The slight positive sloping in Fig. 4.17b is also present in T5Z2 and related to the singles cut: the probability decreases for a single scatter as the energy deposited in the detector of interest decreases. Additionally, the difference in K -shell amplitudes of the singles spectrum is due to the relative location in the towers. There are fewer singles in T5Z2, since it is in the center of the tower, which increases the apparent size of the K -shell step. The χ^2/ndf for the final fits are 1.4 and 1.37 for T2Z1 and T5Z2 respectively and give in Table 4.6.

Moreover, the effects of the fiducial-volume cut was considered on the singles spectrum. Because the radial parameter does not correspond to physical radius, two simple cuts were defined for good events: 1) those with $R < 30.5$ mm, and 2) those in regions which could experience a reduced voltage (roughly following Fig. 6.2). Figure 4.18 compares the fiducial volume cuts for T5Z2. The straight cut removes more volume of the detector and a greater percentage of data (60% compared to 40%) increasing the statistical fluctuations observed in Fig. 4.18a. However, the differences in the fit parameters are within the 1σ errors.

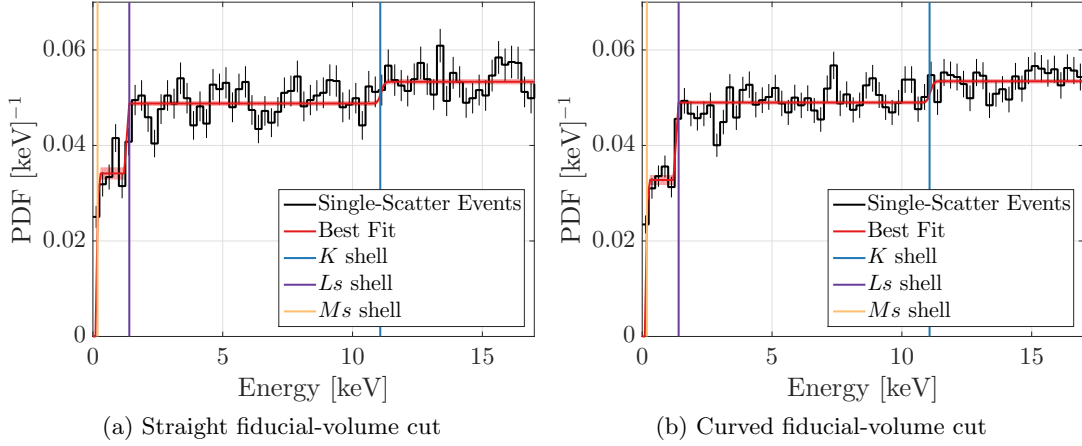


FIGURE 4.18: Consideration of straight (a) and curved (b) fiducial volume cuts on the singles spectrum in T5Z2. The curved cut removes the “corners” of the detector which could experience reduced voltage. Differences in the fit parameters are within the 1σ errors. The straight cut removes more of the detector volume and thus more events increasing the amount of fluctuations observed in (a).

The final Compton spectrum due to the radiogenic contamination of the apparatus materials is modeled by Eq. 4.14. For CDMSlite Run 2 and Run 3, the normalized amplitudes are given in Table 4.6. The width of the steps σ_i are determined by the resolution model of the detector.

5

CDMSlite Run 3 Analysis

There were three separate periods of data taken in the CDMSlite operating mode. Run 1 was the first science run at Soudan in 2013 where T5Z2 was biased at -69 V with a final livetime of 10.32 days. This demonstrated the viability of the technology and set world-leading limits on spin-independent WIMP-nucleon cross sections for WIMP masses from 2.8–6 GeV/ c^2 [80, 88]. The success of Run 1 prompted a second, longer run, CDMSlite Run 2. Data were taken from February through November 2014 with T5Z2 at -70 V and a final livetime of 115.6 days [57, 106]. For the final run of CDMSlite, a different detector was operated, T2Z1, from February to May 2015 at -75 V with a final livetime of 60.9 days. This chapter discusses the Run 3 analysis program, data quality cuts, and the energy resolution model developed on the final data.

5.1 Overview of Run 3

Between Run 1 and Run 2, changes were made to the read-out electronics, and noise monitors were added to the experiment to characterize vibration. Noise was also reduced at the beginning of each data series by pre-biasing the detector. This removes trapped charge by operating the detector at a higher voltage for 10 min prior to each data series. Additional analysis improvements were made, such as the introduction of a radial fiducial volume cut [57, 72, 106]. Run 2 reached the lowest threshold of a CDMS detector at 56 eV_{ee} and set world leading limits for spin-independent cross sections for

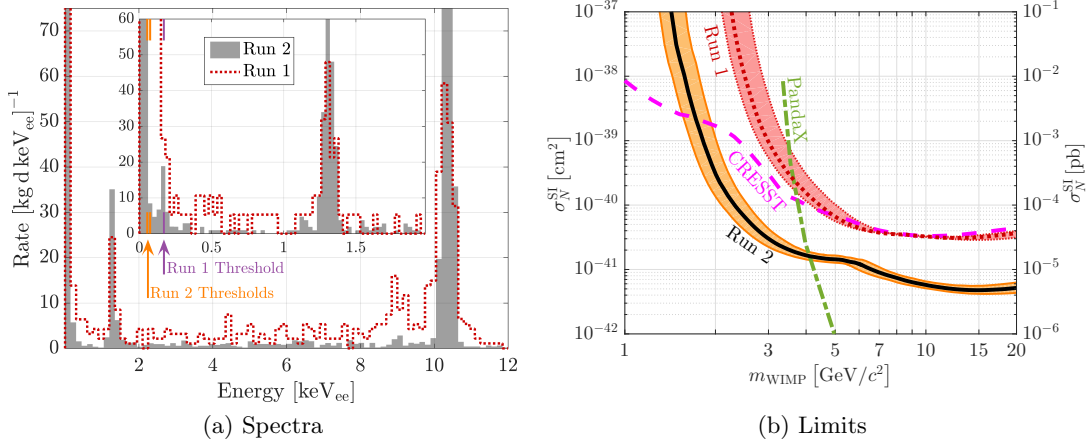


FIGURE 5.1: Comparison of the final energy spectra (a) and resulting spin-independent WIMP-nucleon cross-section limits (b) for CDMSlite Run 1 and Run 2. The inset in (a) is a zoom of the energy range 0–2 keV_{ee} . The improvements to the Run 2 analysis are seen by the lower rate of events between the activation peaks as compared to Run 1. Also note the lower threshold achieved by Run 2. Both of these factors contribute to the improved limit of Run 2. The two additional limits in (b) are from CRESST-II (pink dashed) [79] and PandaX (green dot-dashed) [135]. Figures from Ref. [72].

WIMP masses of 1.6–5.5 GeV/c^2 [106]. The effect of these modifications on the Run 2 analysis are demonstrated in Fig. 5.1a, and were subsequently incorporated into Run 3. Figure 5.1b shows the optimum interval limits [105] of CDMSlite Run 1 and Run 2 compared with other experiments. Both Run 1 and Run 2 were unblind analyses; all the data were available to the analyzers and used to determine quality cuts.

Two factors contribute to low analysis thresholds and the choice of detector for CDMSlite: stable operation at high bias, and good phonon energy resolution. Both were satisfied by T2Z1 during Run 3 commissioning. It was observed in SuperCDMS Soudan Run 133 that T2Z1 had a better noise environment than T5Z2, and, consequently, a better phonon energy resolution [136]. Of the detectors tested, it was shown that T2Z1 had the lowest leakage current [137], as demonstrated in Fig. 5.2 where the yellow points represent the measured current on T2Z1. Low leakage current at high bias implies stable detector operation. Though T5Z2 satisfied the same two conditions, successful application of the CDMSlite technique to a different detector demonstrated reproducibility. A final change to the configuration of Run 3 was made which operated

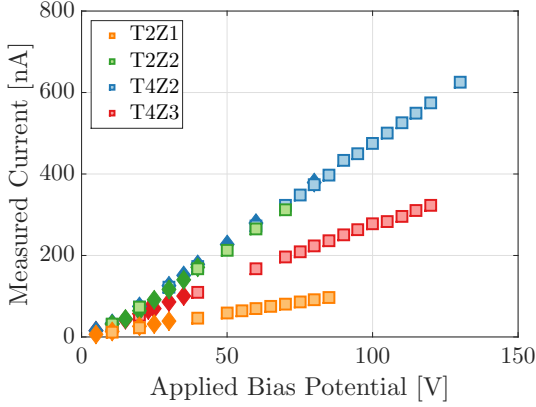


FIGURE 5.2: Measured current as a function of the applied bias voltage for the detectors tested during the commissioning of Run 3. Both are plotted in terms of the absolute value of the measurement. The squares represent negative applied bias and the solid dark diamonds positive applied bias. Of the detectors measured, T2Z1 had the lowest measured current (orange data points). Data from Ref. [137].

the experiment in single-tower read-out such that only events in Tower 2 were recorded.

5.1.1 Operations

Significant deviations from the $V_b = -75$ V applied bias were observed over the course of Run 3 from the small change in parasitic resistance R_P with time and temperature [138]. This is illustrated by the schematic of the HV biasing scheme of CDMSlite in Fig. 5.3 which shows the effect of R_P on the detector voltage. Nominally, zero current I_{HV} is drawn from the power supply because of the effectively infinite resistance of the detector. However, changes in the resistance of R_P result in a small current, with the maximum value measured at 120 nA. The large bias resistor R_b protects current flow into the cryostat in the event of a detector short, but can cause a significant decrease in the voltage at the detector:

$$V_{\text{det}} = V_b - R_b I_{HV}, \quad (5.1)$$

where V_{det} is the voltage at the detector.

The changing detector voltage effects the NTL amplification (see Eq. 2.14) and the total phonon energy scale. A maximum variation of 30 % in the measured K -shell energy was observed. In April 2015, the air handlers in the RF room were turned off in a successful attempt to stabilize the operation of T2Z1 [139]. Because of the different physical and noise environment of the detector pre- and post-April, the data set was divided into two portions, Run 3a and Run 3b.

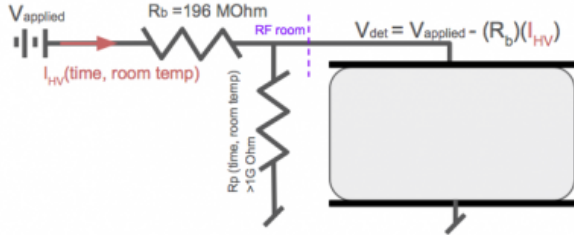


FIGURE 5.3: Simplified schematic of the HV biasing scheme of CDMSlite. Nominally, because of the effectively infinite resistance of the detector, the current from the power supply I_{HV} would be zero; however, a small parasitic resistance R_p enables a small current to be drawn. The large bias resistor R_b protects current flow into the cryostat in case of a detector short. Figure courtesy of W. Page.

5.1.2 Blinding

Run 3 was a blind analysis and provided a test for future runs at SuperCDMS SNOLAB. The technique of “salting” was implemented, where a particular signal distribution of fake events were injected into the data. This fake signal was indistinguishable from the remainder of the data to ensure the analyzers did not know if an event was real or fake. The added signal was not a WIMP distribution of a single mass and cross section, because that could cause bias if there were to be another WIMP signal in the data. This approach has been successfully demonstrated by SNO, a solar neutrino experiment [140], and LUX [60].

Salting was a new approach for SuperCDMS; all previous blind analyses used box blinding. The box blinding approach hides nuclear recoil single-scatter events, i.e. potential WIMP signal, until after all analysis cuts have been developed. Once the box is opened, candidate events are investigated and the results reported. Without electron recoil/nuclear recoil discrimination, this approach is not viable for the CDMSlite-style analyses. The successful first implementation of salting in CDMSlite is reported in Ref. [141].

5.2 Data Quality Cuts

The quality of the data is assessed in a number of different ways to determine when the experiment was behaving anomalously. Some examples include multiple events in a single trace, periods with high trigger rate, or strange pulse shapes. Populations of

events are also removed from the data if they are deemed not-WIMP-like, i.e. good single-scatter physics events in the bulk of the detector. All quality cuts for CDMSlite Run 3 data are briefly reviewed, but only the cuts developed for this thesis are discussed in detail in the following sections (contributed cuts are underlined). Generally, cuts are classified by those that specifically remove livetime from the experiment, and those that effect the efficiency of accepting WIMP-like events.

Livetime Cuts

- **Bad GPS Time**: Events that did not have GPS time recorded, or the difference between the recorded event-time and GPS time were separated by more than 17 s were removed.¹
- **Bad Series**: A number of data series were removed due to large bursts in the trigger rate of the detector.
- **Bad Trigger Rate**: If only a portion of the events in a series suffered from trigger bursts, they were removed with this cut.
- **Charge χ^2** : Though the charge measurement was not used in CDMSlite data analysis, the traces were still recorded in the data stream. This cut removed events where glitches, pulses with sharp rise- and fall-times, were found in the charge data. The origin of these glitches is unknown [142].
- **High Voltage**: This cut simply required that the voltage power supply had a recorded output of -75 V.²
- **Multiply-triggered Glitches**: These multiply-triggered glitches had the same general shape as the charge glitches, but were found in the phonon channels and were correlated across detectors.
- **NuMI**: The Main Injector Neutrino Oscillation Search (MINOS) [143] experiment was located in the cavern next to SuperCDMS at Soudan. Times that correspond to neutrino beam spills for MINOS were removed from the data [144].

¹ This simple cut is not discussed further.

² Ibid.

- **Pre-pulse Baseline:** This cut evaluated the portion of the trace before the global trigger and determined if the mean value of this baseline was too high. Increased baselines are indicative of excessive noise in the event [145].
- **T2Z1 Triggered:** It was required that the CDMSlite Run 3 detector issue the global trigger.

Efficiency Cuts

- **Good Phonon Start Time:** The optimal filter (OF) had a finite time window, -200 μs to 100 μs , around the global trigger in which to locate the pulse within the channel trace. Events with start times at the extremes of this window were removed.
- **Low-frequency Noise:** Low-frequency (LF) noise induced from vibrations of the cryo-cooler dominated the events at low energy. This cut utilized two new techniques to identify and remove these events: two uncorrelated boosted-decision trees (BDTs) which differentiated signal and LF noise, and a bifurcated analysis with the BDTs. It is expected that less than one LF noise event remained in the data set after this cut [146].
- **Muon Veto:** If the active muon veto triggered, the event was removed [147].
- **Phonon χ^2 :** This cut assessed the goodness-of-fit of the non-stationary optimal filter (NF) algorithm and removed events with poor fits.
- **Pulse-shape Glitches:** These glitches were removed based on pulse shape and comparing goodness-of-fit parameters from templates representative of a good, physics event and a glitch-like event [148].
- **Radial Fiducial Volume:** The fiducial volume cut for CDMSlite was based on a radial parameter designed to identify events at large radii in the detector by the ratio of pulse shapes in the outer phonon channel to the inner phonon channels. Improvement in the understanding of the electric field in Run 3, which had a region at high radius where the events experienced a voltage smaller than -75 V, allowed less than one event with reduced voltage to pass this cut [149].

- **Single Scatters:** This single scatters cut was the logical negative of the multiples cut. The multiples cut identified events where more than one detector has an event above threshold. Though singles were technically different than not-multiples, this definition was conservative.
- **Square Pulses:** Similar to the pulse-shape glitches, this cut removed events that had strange square pulses based on the goodness-of-fit parameters of a good, physics event and a square template [150].

5.2.1 *Multiply-Triggered Glitches*

Electronic noise that was correlated across detectors could cause nearly simultaneous triggers in multiple detectors. These events, called glitches, had abnormally fast rise- and fall-times when compared to a physics event. It is generally thought that these occur because of voltage spikes in the TES-biasing lines. If the voltage spike is large enough, it will cause heating in the TESs across multiple detectors. This heating created the correlated glitch events in the phonon channels. The charge signal, however, was consistent with noise. By contrast, a good physics event created both a charge and phonon signal in the detector.

Traditionally, these events are identified by comparing the total number of phonon and charge triggers issued by the detector-interface-boards (DIBs) for every event [151]. If any charge/phonon channel has a signal above threshold, the DIB will record a charge/phonon trigger. In single-tower read-out mode, there are two DIBs for each iZIP and one DIB for the CDMSlite detector, for a total of five charge and five phonon triggers. However, there was an issue with the trigger data; specifically, the sum recorded more triggers than available DIBs, indicating additional triggers from non-active DIBs had been added into the total.

To bypass the trigger issue, the cut was developed on just the Tower 2 phonon triggers. If more than four phonon triggers were recorded, the event was considered a trigger glitch. It was unlikely that a good physics event would cause all detectors to trigger at once creating five phonon triggers. For this criteria, 99.97% of data passed the cut.

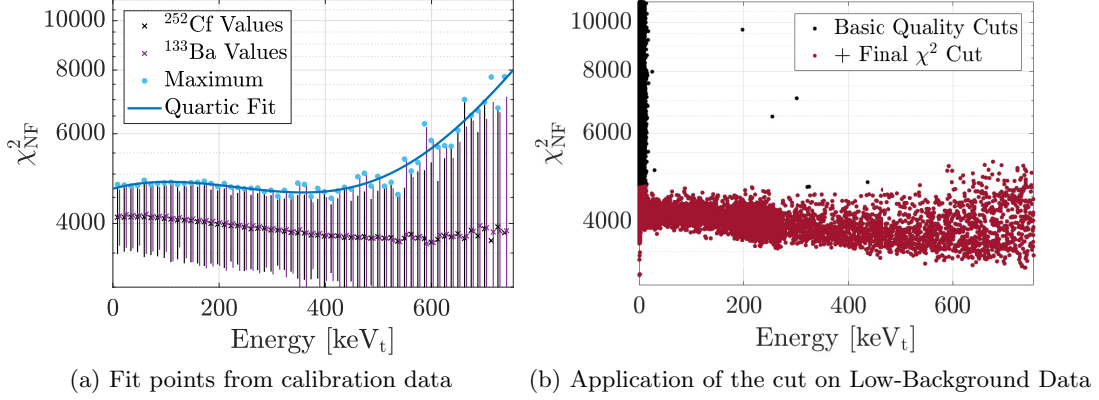


FIGURE 5.4: Phonon χ^2_{NF} as a function of energy. (a) The binned calibration data used as the input to the quartic fit. (b) Final cut on the low background data.

5.2.2 Phonon χ^2_{NF}

This selection identifies events that were poorly fit by the non-stationary optimal filter (NF) algorithm like pile-up and saturation events, and events with very high noise (see Sec. 2.1.3). Because of the poor fits, these events will have high χ^2_{NF} values. Since, the phonon signal is digitized into 4096 bins, good events in the linear response region of the detector have values of $\chi^2_{NF} \sim 4100$.

This cut was designed to follow the distribution of good events in the χ^2_{NF} verses energy plane. Both ^{133}Ba and ^{252}Cf calibration data were shown to accurately describe the distribution of low background data in this plane; thus, it was used to develop the cut. To define the cut boundary, the events were binned in energy and a histogram of the values of χ^2_{NF} was created. This histogram was fit with a Gaussian to extract the μ and σ of the distribution, which was used in defining the fit.

A quartic polynomial described the data well as it remained relatively flat in the region where the detector had a linear response, and flared at high energy where it was expected that the events would be poorly fit by the NF algorithm. The $\mu + 3.5\sigma$ of each bin were used as inputs to a quartic fit. Figure 5.4a shows the bins from the calibration data and the final fit. The performance on the background data is shown in Fig. 5.4b.

5.3 Multiples Cut

The multiples cut was defined to identify multiple-scatters, or events where a particle passing through the experiment deposits energy above the noise threshold in more than one detector. These types of events cannot be WIMP-like dark matter because it is expected that WIMPs will only interact in one detector at a time. In the WIMP search data only non-multiple events were selected.

The basic principle is as follows: to identify a multiple-scatter event on the detector of interest, consider all the other detectors active in the analysis, the veto detectors, and determine if any of the veto detectors also contain an event above the noise threshold. However, the event above threshold cannot be a low-frequency (LF) noise or pulse-shape glitch event. If the event on the veto detector is such an event, then the event in the detector of interest is not a multiple.

Random triggers were an estimate of the energy distribution of the noise for a given series, or set of series, and used to define this cut (see Sec. 2.1.3). The energy of the random events was determined with the total phonon energy reconstructed with the NF algorithm (ptNF). A loose cut was applied on these randoms, selecting events when the energy was less than 25 keV_t . This energy restriction was to prevent any pulse that occurred at the same time as the random, either a good physics pulse or LF noise, from artificially inflating the noise threshold.

From the distribution of randoms, the mean energy μ of the noise was determined. The threshold was then chosen by optimizing between two semi-conflicting goals: setting the value such that an event was easily classified as a real event, but still reasonably close to μ in order to avoid misidentifying multiples. For Run 3, thresholds were determined in the same manner as previous SuperCDMS Soudan analyses after first grouping data series into time blocks in order to avoid individual series fluctuations and lack of statistics [152, 153].

5.3.1 Time Blocks

Time blocks of series were first introduced in order to study the time variation of the noise on the detectors and to assist in the blinding of WIMP like events. Consequently, it was useful in defining the noise thresholds of the multiples cut. The methodology

was developed by E. Lopez Asamar and was used to create time blocks for Run 3 [154]. The general procedure using the best determined method is as follows:

1. Calculate, series-by-series, the thresholds t_s that exclude noise at the 1σ level.
2. Group a minimum of n_0 series into clusters.
3. Create time blocks by grouping consecutive clusters such that

$$\max(T) - \min(T) < \epsilon \min(T) \quad (5.2)$$

where T is the set of all series thresholds t_s in the cluster.

Additional restrictions were imposed such that clusters, and time blocks, must not contain series that span a ^{252}Cf calibration, or Run 3a and Run 3b. These conditions created four data “chunks” in which to determine time blocks.

The distribution of random triggers was non-Gaussian and had a tail toward high energies. Thus, setting a threshold of $t_s = \mu + \sigma$ based on a Gaussian fit would not properly capture the higher tails. Instead, a CDF of the distribution was created and t_s set at the 1σ equivalent value, i.e. where the CDF reaches 0.84. Thresholds were also defined using in-run randoms which best determine the noise of a given series.

There were a few outlier series identified with very large thresholds either due to low statistics or high noise. Thus, before time blocks were created, the mean of all series in a data chunk μ_c was determined and any series with a threshold more than three standard deviations above μ_c were removed from the process. In all chunks, on all detectors, fewer than five series were determined to be outliers.³

Figure 5.5 shows the time blocks defined with $n_0 = 20$ and $\epsilon = 0.1$ which were determined such that a minimum number of blocks were defined, but sufficient to follow the noise variations. There were 15, 19, and 17 time blocks for T2Z1, T2Z2, and T2Z3, respectively. Correlations were also observed in the pattern of noise across detectors.

³ Series identified as outliers were included in the time blocks in order to determine the multiples thresholds.

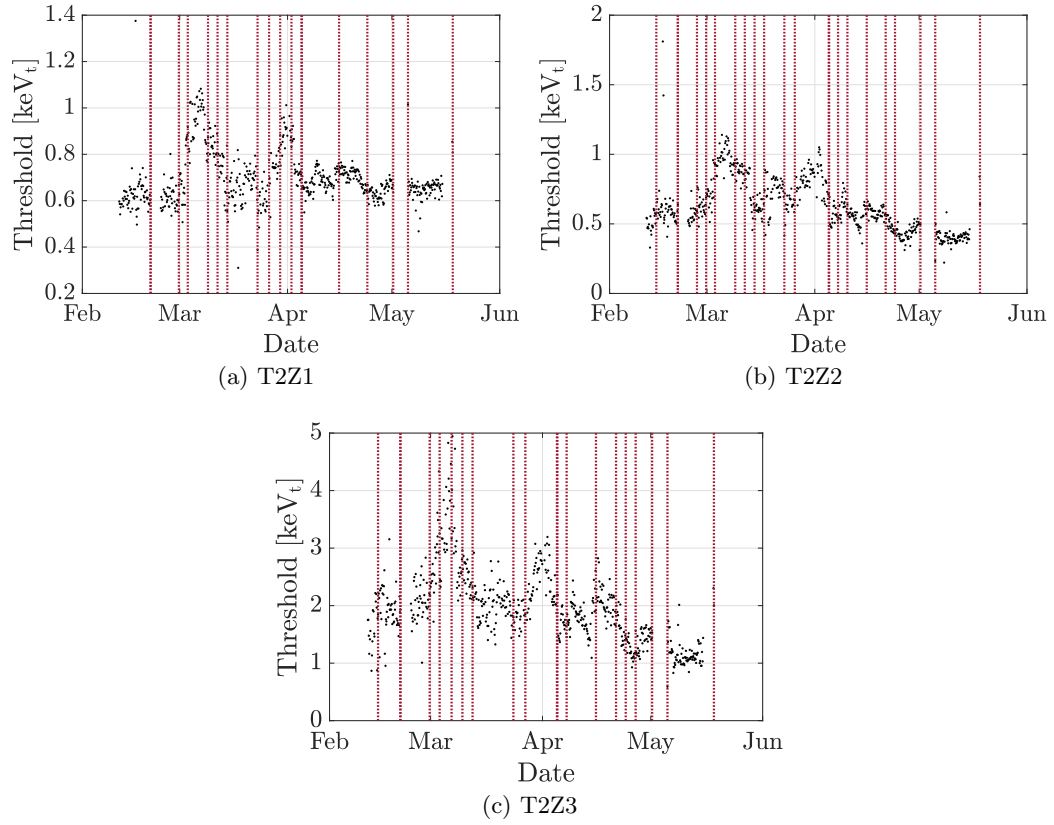


FIGURE 5.5: Series-by-series thresholds determined from in-run randoms with time block indicated for T2Z1 (a), T2Z2 (b), and T2Z3 (c). Note the similarity in noise patterns across the detectors revealing the correlation in noise. Time blocks were defined such that there was a minimum of $n_0 = 20$ series per cluster, and $\epsilon = 0.1$. There are 15, 19, and 17 time blocks for T2Z1, T2Z2, T2Z3 respectively.

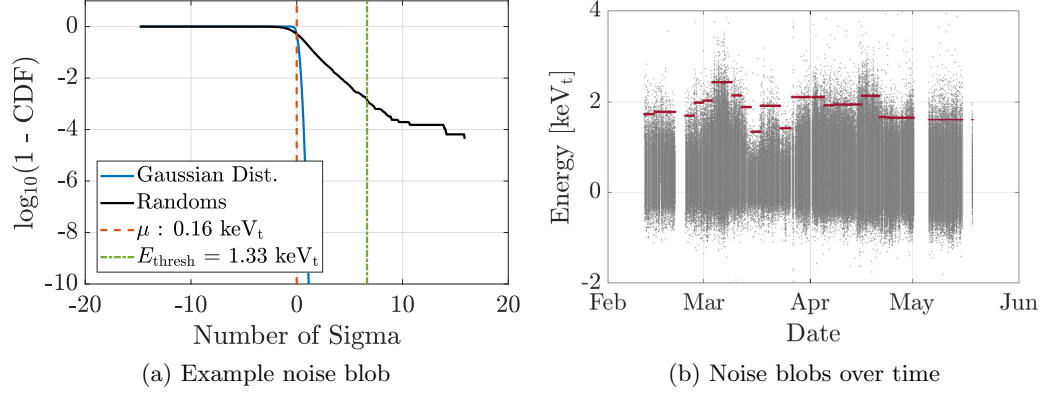


FIGURE 5.6: Example noise distribution in a time block for T2Z2 in the $\log_{10}(1 - \text{CDF})$ plane (a) and time evolution of T2Z2 thresholds over Run 3 (b). The high-energy tail of the randoms is visible in (a) and compared with a Gaussian (blue) for the same μ and σ equivalent values. The green dotted vertical line indicates the threshold at the 3σ equivalent value on the CDF.

5.3.2 Noise Thresholds

Within a time block, the random triggers from all series were combined. Even with the increased statistics, these noise distributions were not Gaussian, so a CDF of the distribution was constructed. The threshold of the time block was set to the 3σ equivalent value such that 99.87% of all randoms were below this threshold.

An example of a noise distribution on T2Z2 is given in Fig. 5.6a. It is shown in the $\log_{10}(1 - \text{CDF})$ plane in order to demonstrate the high-energy tail of the distribution. Also shown for comparison in the blue curve is a true Gaussian with the same μ and σ equivalent values. The green dotted vertical line indicates the threshold for the time block. The time evolution of the thresholds over Run 3 for T2Z2 is shown in Fig. 5.6b. The thresholds for each time block on each detector in Tower 2 was determined in this manner.

5.3.3 Constructing the Cut

If an event was found above threshold in a veto detector, it must also be verified that it was not a LF noise or pulse-shape glitch event. Therefore, it was necessary to define criteria that classified an event as LF noise or pulse-shape glitch. Similarly to the templates

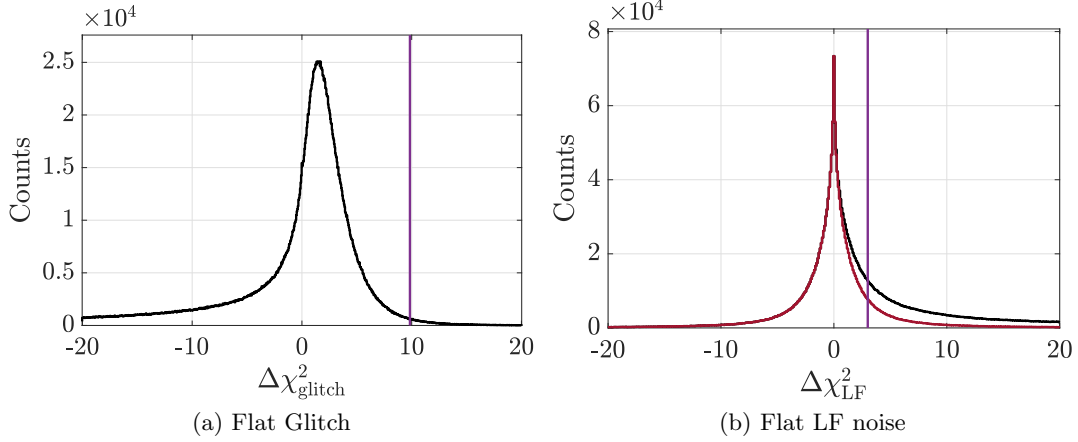


FIGURE 5.7: $\Delta\chi^2_{\text{glitch}}$ (a) and $\Delta\chi^2_{\text{LF}}$ (b) distributions for randoms in T2Z3 used to define the pulse-shape glitch and LF noise cut, respectively. Since randoms can be contaminated with LF noise, the randoms with $\Delta\chi^2_{\text{LF}} < 0$ are reflected to create a symmetric distribution of randoms on which to define the cut. The cut value is shown in both figures as the purple vertical line.

defined that identify good physics events, additional templates were constructed that describe the general shape of LF noise and pulse-shape glitches. These are described in detail in Refs. [155, 156].

Each event in the data set was fit with all three templates (good pulse, LF noise, and pulse-shape glitch) with the OF algorithm to determine the goodness-of-fit χ^2 . The difference between the good template fit χ^2_{OF} and the LF/glitch fit $\chi^2_{\text{LF/glitch}}$ was defined as the $\Delta\chi^2$ of the event, where

$$\Delta\chi^2_{\text{LF/glitch}} = \chi^2_{\text{OF}} - \chi^2_{\text{LF/glitch}}. \quad (5.3)$$

LF/glitch type events have higher positive values of $\Delta\chi^2$ whereas good events have more negative values of $\Delta\chi^2$. The random triggers were also fit with these templates, and the $\Delta\chi^2$ of randoms provided a baseline for defining the cut value. Events with $\Delta\chi^2$ greater than the constant value defined on the randoms were considered LF noise or pulse-shape glitches. All the randoms were used, and a cut was defined for each detector.

The cut for the pulse-shape glitches was defined such that 99% of the randoms pass the cut [155]. Figure 5.7a shows the random distribution in $\Delta\chi^2_{\text{glitch}}$ for T2Z3 with the

value of the cut shown as the green vertical line.

The population of random triggers was more likely to be contaminated with LF noise than glitches. Thus, when defining the cut for LF noise, the randoms with negative $\Delta\chi_{\text{LF}}^2$ were reflected across zero forming a symmetric distribution. The cut was then placed so that 90 % of the symmetric randoms were below the cut value [156]. Figure 5.7b shows a comparison of the distributions of randoms and the reflected negative randoms, as well as the final cut value for T2Z3.

Along with the pulse-shape glitches, it was also important to remove the multiply-trigger glitches discussed in Sec. 5.2.1. The same definition for this population of events was used in the multiples cut; namely, if more than four DIBs on Tower 2 issue a phonon trigger the event was classified as a glitch.

Though the multiples cut was defined generically such that any of the three detectors in Tower 2 could be the detector of interest, the performance on T2Z1 was of importance for the Run 3 analysis. Recall, the cut searches for multiple-scatters as defined, and so it was the not multiples that were considered WIMP-like events. On the random triggers, the negative of the multiples cut had an efficiency of 99.95 %.

5.3.4 *Checks on the Efficiency*

Noise Correlations

The thresholds for the time blocks were set such that the fraction of random triggers above threshold is $F = 1 - 0.9987$. If the noise on the detectors was perfectly correlated, then the fraction of randoms above the threshold F would be equal to the fraction of randoms that were categorized as multiples M , and the singles efficiency is $1 - M = 0.9987$. Instead assuming the noise is perfectly independent on the vetoing detectors (the number of which is given by n_V), then the randoms identified as multiples would be $M = n_V F(1 - F)^{n_V - 1}$ or $M = 2F(1 - F)$ for Run 3, and the singles efficiency is $1 - M = 0.9974$.

However, this is a slight oversimplification as the multiples cut additionally depends on LF noise and glitch cuts. Between the LF noise and glitches, the LF noise was stricter, passing anywhere in the range 50–85 % of randoms, depending on the detector. Thus, it was possible to ignore the effect of the glitch cuts, and the efficiency of the

	Correlated LF Noise	Uncorrelated LF Noise
Correlated Thresholds	0.9988	0.9991
Uncorrelated Thresholds	0.9978	0.9978

TABLE 5.1: Table of possible correlations between thresholds and noise for determining the reasonableness of the singles efficiency

multiples cut depends on whether both the random triggers and the LF noise were correlated or independent.

Recall, an event is a multiple if there is an event on a veto detector that is above threshold and not LF noise. Taking the smaller fraction of LF noise events, the probability of identifying an event as LF noise is $N = 0.15$. Then, the probability of a single detector random identified as a multiple from the LF noise cut is $P = F(1 - N)$. If P was uncorrelated across all detectors, the the probability of observing one multiple in two vetoing detectors is $M = 2P(1 - P)$ giving a singles efficiency of $1 - M = 0.9978$. Alternatively, the LF noise could be perfectly correlated as well as the noise thresholds, i.e. if one detector identified a random as a multiple it would be identified on all detectors, which gives a singles efficiency of $1 - P = 0.9988$.

There are additional cross terms in the matrix of correlated/uncorrelated noise such that the thresholds were correlated but the LF noise was not, or the LF noise was correlated but the thresholds were not. The first, correlated thresholds and uncorrelated LF noise gives the fraction of randoms identified as multiples as $M = F(1 - N)^2$ and a singles efficiency of $1 - M = 0.9991$. Finally, uncorrelated thresholds and correlated LF noise gives $M = 2(1 - F)(1 - N)$ and a singles efficiency of $1 - M = 0.9978$.

The range of possible efficiencies from these simple arguments is 99.74 - 99.91 %. The actual singles efficiency was higher, 99.95 %, but within reason of those calculated above. The matrix of efficiencies is give in Table 5.1.

Single-scatters from Radiogenic γ 's

The final check on the singles efficiency compared the ratio of single scatters to all events in the low background data with the same ratio calculated from the Global Gamma Monte Carlo (GGMC) completed by E. Lopez Asamar [134]. This simulation included

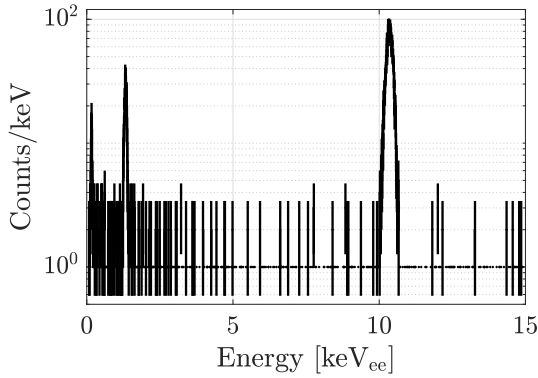


FIGURE 5.8: Final energy spectrum for CDMSlite Run 3. The characteristic features of the ^{71}Ge activation peaks on a relatively flat background is seen and can be compared to the previous CDMSlite runs in Fig. 5.1a.

only the radiogenic γ backgrounds to the experiment (see Sec. 3.1). The expected ratio from this study is singles/events = 0.5841.

To calculate the ratio from data, a clean sample was prepared by applying a complete set of quality cuts, as well as a simple radial fiducial volume cut. The ^{71}Ge activation lines were removed from the data since they were not included in the simulation. However, it was still necessary to estimate the flat background rate that existed under these peaks. To predict this rate, an energy range above the peak equal to that removed was used to calculate the expected events. The resulting ratio from data is singles/events = 0.7149.

There are many reasons this ratio was higher by $\sim 10\%$ in data than simulation. For example, the GGMC does not consider any additional sources of background other than the radiogenic, which contributes exclusively to Compton scattering. This assumes that all the background in the detector was from Compton scattering, whereas tritium and cosmogenic activation peaks also contributed to the background [115].

5.4 Resolution Model

After the application of all quality cuts, the resulting energy spectrum is given in Fig. 5.8. The same features are observed as in Fig. 5.1a, namely the ^{71}Ge activation peaks on a relatively flat background.

An important characterization of the Run 3 data set was constructing the energy resolution model. This was also necessary for aspects of the spectral shapes of the backgrounds. The energy dependent resolution model describes the expected spread

in energy for a mono-energetic γ incident on the detector. The physics behind the construction of such a model is discussed in Chapter 6, but it is generally described as the sum of three terms: the energy independent noise from the electronics σ_E , the linear in energy fluctuations from the discrete nature of charge or the Fano resolution σ_F , and effects from the physical location of the event in the detector which is quadratic in energy σ_{PD} :

$$\sigma_T^2(E_{r,ee}) = \sigma_E^2 + \sigma_F^2(E_{r,ee}) + \sigma_{PD}^2(E_{r,ee}) \quad (5.4)$$

$$= \sigma_E^2 + BE_{r,ee} + (AE_{r,ee})^2. \quad (5.5)$$

The expected width, assuming a Gaussian response, at a given energy from a mono-energetic γ source is σ_T . A , B , and σ_E are free parameters of the model. In order to determine the resolution model for Run 3, four measurements were used: the widths/resolution of the ^{71}Ge activation peaks and a measure of the zero-energy noise of the detector.

The main ^{71}Ge activation peaks are located at 10.37 keV, 1.3 keV, and 0.16 keV (see Fig. 5.8). Each peak was modeled with a combination of a Gaussian and linear background in order to determine the width of the peak. The fit equation is given by

$$f(E) = \frac{a}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{E-\mu}{\sigma}\right)^2\right] + (mE + b) \quad (5.6)$$

where the parameters of the Gaussian are its amplitude a , the location in energy μ , and the resolution or width σ ; the linear portion of the model is described by the slope m and the offset b . All were free parameters of the fit. The resolutions of the activation peaks were determined using all the available data as the change in the noise environment between the two portions of Run 3 have small effects at those energies. Table 5.2 gives the locations μ and resolutions σ of the ^{71}Ge peaks.

The zero-energy noise distribution was measured from the random triggers. For this study, the end-of-run (EOR) randoms were used as they were relatively free of LF noise. The total phonon zero-delay optimal filter energy estimator, ptOF0, was used,

Peak	Location		Resolution
	μ [keV _{ee}]		σ [eV _{ee}]
<i>K</i> shell	10.35 ± 0.002		108 ± 2
<i>L</i> shell	1.33 ± 0.003		36.3 ± 2.0
<i>M</i> shell	0.162 ± 0.002		13.9 ± 2.0
Baseline	3a	0.0	9.87 ± 0.04
	3b	0.0	12.7 ± 0.04

TABLE 5.2: Location and resolution of the ^{71}Ge activation peaks and baseline noise in CDMSlite Run 3.

converted to electron equivalent energy⁴

$$E_{\text{r,ee}} = \frac{E_{\text{t}}}{1 + eV/\epsilon_{\gamma}}. \quad (5.7)$$

However, since the bias changed frequently over the course of the run, the mean bias voltage V for each series was used for the conversion. For each series, the EOR randoms were fit with a Gaussian to determine the resolution. Figure 5.9a shows an example fit to the EOR randoms of a single series. Unlike in Run 2, the distribution of randoms was well described by a Gaussian [57]. The variation in zero-energy resolutions over the course of Run 3b is demonstrated in Fig. 5.9b. To determine one baseline resolution for each of Run 3a and Run 3b, the live-time weighted average was used. These are 9.87 ± 0.04 eV and 12.7 ± 0.04 eV for Run 3a and Run 3b respectively, and are also given in Table 5.2.

A resolution model was created for each portion of Run 3 by fitting Eq. 5.5 to the resolutions of the three activation peaks and baseline noise. The fit was weighted by the error of the measurements, and all parameters were free. The final best fit to Run 3b is shown in Fig. 5.10 by the black curve with the 1σ uncertainty band. The measurements are also overlaid. All are within the uncertainty band of the fit except the *M* shell which is slightly lower. This is also seen in Run 3a.

Table 5.3 gives the best fit values to the model of Eq. 5.5. The energy independent

⁴ Since the conversion was to electron equivalent energy, the yield was given as $Y(E_{\text{r}}) = 1$ for every event.

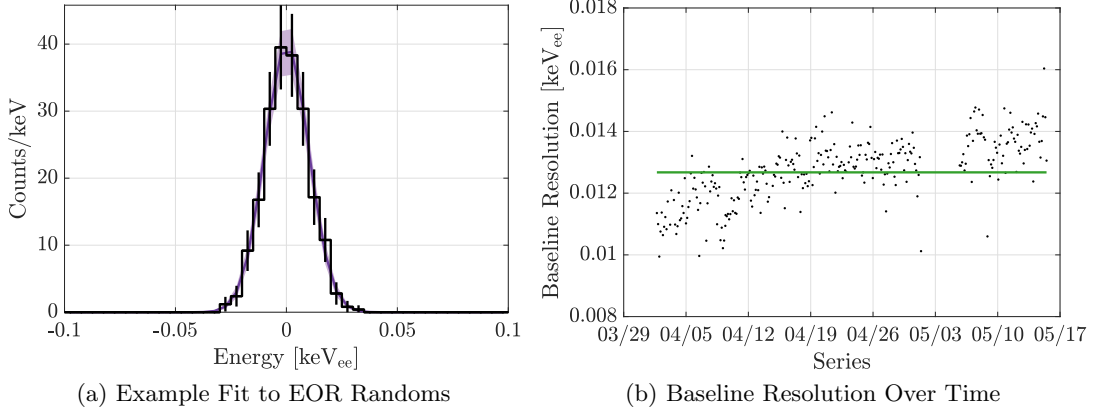


FIGURE 5.9: Example baseline resolution fit (a) and the time dependence of the resolution (b) for CDMSlite Run 3b. The baseline resolution is determined from the total phonon zero-delay OF energy estimator on the EOR randoms corrected for the average voltage of the series and is fit well with a Gaussian. The clear change in resolution as a function of time indicative of the changing noise environment is demonstrated in (b). The live-time weighted average of the baseline resolutions for Run 3b is 12.7 ± 0.04 eV_{ee} (green horizontal line).

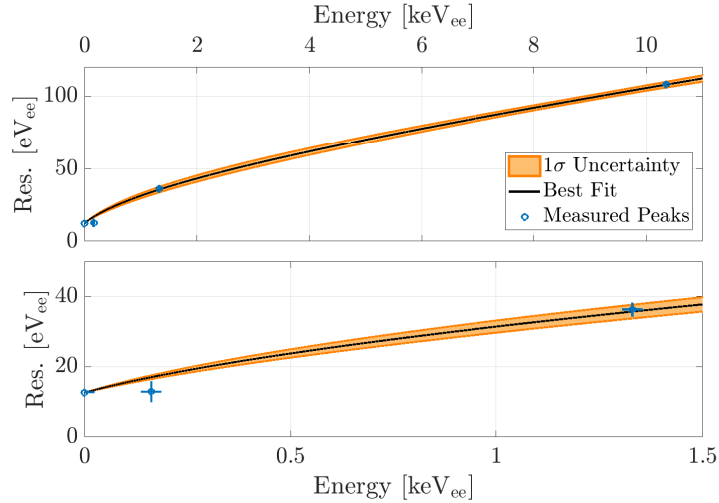


FIGURE 5.10: Measured resolution (blue points) for each of the three ^{71}Ge activation peaks and the baseline noise of Run 3b along with the best fit (black curve) and 1σ uncertainty band (orange shaded) for the model in Eq. 5.5. The fit was weighted by the uncertainty of the measurements, and the all parameters of the model were free. The bottom frame is a smaller energy range showing the three lowest measurements.

	σ_E [eV _{ee}]	B [eV _{ee}]	A ($\times 10^3$)
Run 3a	9.87 ± 0.04	0.87 ± 0.12	4.94 ± 1.27
Run 3b	12.7 ± 0.04	0.80 ± 0.12	5.49 ± 1.13

TABLE 5.3: Best fit energy resolution parameters to the model in Eq. 5.5 for CDMSlite Run 3a and 3b. The energy independent term σ_E is identical to the baseline resolution of each portion of the run. The coefficient B is consistent between the runs, but is larger than the theory which gives $B = 0.39$ [90, 157]. The values of A are within the 1σ error for each run.

term σ_E is identically the baseline resolution of each portion of the run. This is due to the very small errors on the measurements. The coefficient B is consistent between the runs, but is larger than Fano theory which gives $B = 0.39$ [90, 157]. It is also not compatible with the Run 2 value of 0.64 ± 0.11 [57, 72]. It is likely that, with the more volatile noise environment of Run 3, there was an additional contribution that was linear in energy besides just the Fano resolution. The values of A are within the 1σ error for each run and consistent with the Run 2 value of $A = (5.68 \pm 0.94) \times 10^{-3}$ [57, 72].

6

CDMSlite Detector Response Function

Many of the backgrounds described in Chapter 3 can be approximated with a uniform distribution in the detector. Thus, a simple resolution model developed on the ^{71}Ge activation peaks can be applied to the analytical energy spectrum due to background events. However, surface events and other non-uniform populations are not described by the simple resolution model, and a more complete model was developed.

An important feature of CDMSlite is its ability to access low energies through the NTL effect [97, 98] which is directly related to the voltage. The model outlined in this chapter will also incorporate the voltage profile of CDMSlite as part of the response function of the detector.

6.1 Generic Energy Resolution

When a particle interacts in the detector it deposits energy E_r . In a perfect detector, this amount of energy would be exactly measured by the electronics forming a very narrow peak at E_r . Instead there is some amount of fluctuation in the energy recorded by the detector which is the detector's response function. The Gaussian created by the fluctuations is the energy resolution, and the width, or σ , is a measure of how well the detector performs. This width is energy dependent. Some sources of fluctuation causing imperfect energy resolution are: change in operating conditions (bias voltage, electronics, etc.), random noise in the detector and/or electronics, and statistical noise

from the discrete nature of carrier generation. This final component, the discreteness of signal, contributes an irreducible minimum amount of fluctuation to the signal and will set a limit on the detector performance [158].

A discrete number of charges N are generated in an interaction, thus, if the same amount of energy is deposited in the detector, there will be some random fluctuation as the number of generated charges changes. If the carrier generation process is governed by a Poisson distribution, it is expected that the deviation of the fluctuations is $\sigma = \sqrt{N}$. Measurements have shown that the resolution is lower by a factor of two or three than these simple statistical arguments. Thus, the Fano factor F , is introduced to account for these deviations, and the resolution occurring from the creation of charge carriers is [159]

$$\sigma_F = \sqrt{FN}. \quad (6.1)$$

All other sources of fluctuation combine with the fluctuations due to the creation of charge carriers giving the total, or overall, energy resolution which tends toward a Gaussian shape. Thus, the total energy resolution is a quadrature sum of the various components [158]:

$$\sigma_T^2 = \sigma_{\text{noise}}^2 + \sigma_{\text{drift}}^2 + \sigma_F^2 + \dots \quad (6.2)$$

In SuperCDMS, the electronics noise and/or drift in the operating conditions is generally summed up in the energy-independent term σ_E . A third term σ_{PD} is introduced which considers the position dependence of the event within the detector due to the electric field, sensor TES response, etc., and is energy dependent. Thus, the total energy resolution model is

$$\begin{aligned} \sigma_T^2(E_{r,ee}) &= \sigma_E^2 + \sigma_F^2(E_{r,ee}) + \sigma_{PD}^2(E_{r,ee}) \\ &= \sigma_E^2 + BE_{r,ee} + (AE_{r,ee})^2, \end{aligned} \quad (6.3)$$

where A is an experimentally determined coefficient and theoretically $B = \epsilon_\gamma F$ (the relationship between charge and energy is given in Equation 2.3).

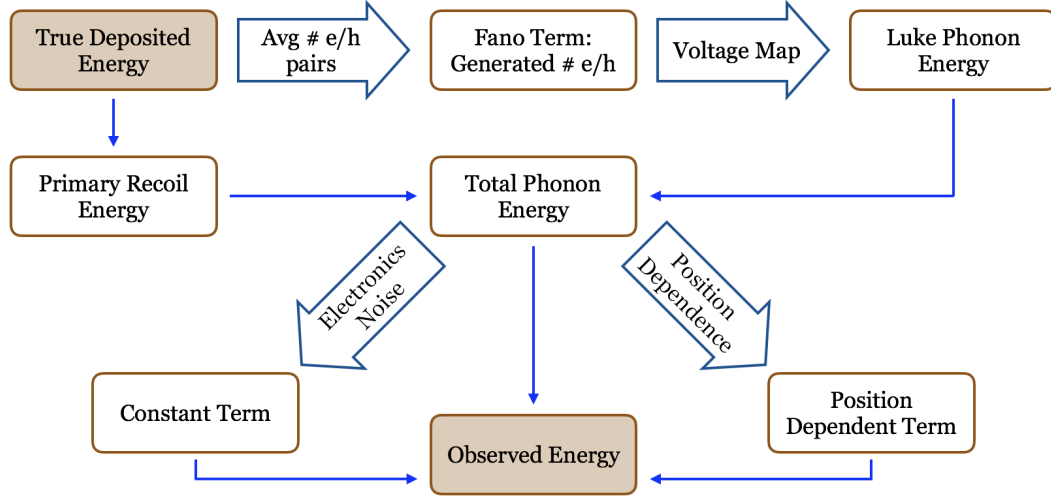


FIGURE 6.1: Flow chart representing the steps of the implementation of the detector response function. The boxes denote energy quantities, and the thick arrows represent important calculations. Thin arrows are simple arithmetic calculations.

6.2 Implementing the Components of Resolution

Each component of the resolution must be modeled properly and then combined to build the full resolution function. Simulation of particle interactions (GEANT4 in this case) model energy depositions in multiple small, localized steps and steps well separated in space. These small, localized steps will be referred to as micro-hits, and groups of steps separated by more than a millimeter will be called hits. The set of all hits that occur in a detector within a microsecond constitute a single event. The following steps outline the conversion from true simulation energy to total phonon energy, illustrated in Fig. 6.1:

1. All micro-hits within a millimeter are summed into a single hit:
 - (a) The summed energy is the primary recoil energy E_r for that hit.
 - (b) To determine the location of the hit, the energy weighted position of the micro-hits is calculated as

$$\bar{x} = \frac{\sum_i x_i \cdot \epsilon_i}{E_r}, \quad (6.4)$$

where the sum is from 1 to the number of micro-hits, x_i is the location in

space (can be the x , y , or z coordinate), and ϵ_i is the energy deposited in the micro-hit.

- (c) The voltage of the hit $V(x, y, z)$, which informs the NTL gain, is determined with the energy weighted position of the hit. (Further discussion of the voltage profile can be found in Sec. 6.2.1.)

2. For each hit, the NTL contribution to the phonon energy E_{NTL} must be calculated:

- (a) A hit is classified as an electron recoil (ER) or nuclear recoil (NR) based on the particle ID of the micro-hits. This classification is used to determine the yield Y and the Fano factor F of the hit.
 - i. $Y = 1$ for ERs and is calculated based on Lindhard [160] for NRs
 - ii. $F = 1$ for NRs [102] and theoretically $F = 0.13$ for germanium ERs [157, 161].
- (b) The average number of electron/hole pairs is calculated as $N_{\text{avg}} = Y \cdot E_{\text{r}}/\epsilon_{\gamma}$, where $\epsilon_{\gamma} = 3 \text{ eV/pair}$ for germanium.
- (c) The actual number of electron/hole pairs is calculated based on the Fano resolution; N is selected from a Gaussian centered at N_{avg} of width $\sigma_{\text{F}} = \sqrt{FN_{\text{avg}}}$.
- (d) The NTL energy for the event is $E_{\text{NTL}} = V(x, y, z) \cdot Ne$, where e is the electric charge.

3. The constant resolution from noise σ_{E} and any additional position dependent resolution A' is calculated and added to the total phonon energy giving the observed energy in the detector E_{t} in eV_t.

To compare to the physical data in electron-equivalent energy, the total phonon energy is converted as

$$E_{\text{r,ee}} = E_{\text{t}}/(1 + eV_{\text{b}}/\epsilon_{\gamma}) \quad (6.5)$$

where V_{b} is the applied bias to the detector.

6.2.1 *CDMSlite Voltage Map*

CDMSlite was operated by applying a large negative bias to one face of the crystal with the other face grounded and instrumented for signal read-out. It is known that operating with an asymmetric bias creates distortions in the electric field such that some of the field lines terminate on the crystal side-walls rather than a face [72]. To study this effect in detail, the GEANT4 Detector Monte Carlo (G4DMC) tool, under development for SuperCDMS, was used [162].

The G4DMC can currently simulate the propagation of charge and phonon physics for very low energy events. It uses electric-potential files created with COMSOL¹ to guide the propagation of charges. If just the charge physics is enabled in the G4DMC, it can be used to determine the effective potential difference an electron/hole pair will experience at a given location in the crystal. An initial electron/hole pair is generated with a very low energy and allowed to propagate along the field lines until the carriers terminate on the detector boundary. The initial and final positions of the carriers are recorded as well as the voltage at the final location of the electron and hole. The difference in the electric potential at the final locations gives the change in voltage experienced, δV . This procedure can be repeated for electron/hole pairs generated uniformly throughout the detector volume in order to create a voltage map that gives the difference in electric potential of the carriers as a function of the initial position in the detector. R. Agnese performed these simulations for CDMSlite Run 2, and the map developed for those studies was utilized in the Run 3 analysis [72].

Figure 6.2 shows the difference in electric potential as a function of initial position (henceforth referred to as the voltage map) for a 70 V applied bias viewed in two different planes. There are noticeable differences at high radius as the $X = 0$ plane is near the detector DIBs and thus much more prominent distortions. Below $R^2 = 800 \text{ mm}^2$, all locations experience the full bias voltage.

Since the electric potential file was generated with the housing surrounding the detector at ground, this voltage map can be scaled to any applied voltage by simply multiplying the points on the map by $V_b/70$. This voltage map was used to calculate the NTL phonon energy. Due to the noticeable variations in the map with position seen

¹ COMSOL MULTIPHYSICS® software (COMSOL, Inc., Burlington, MA)

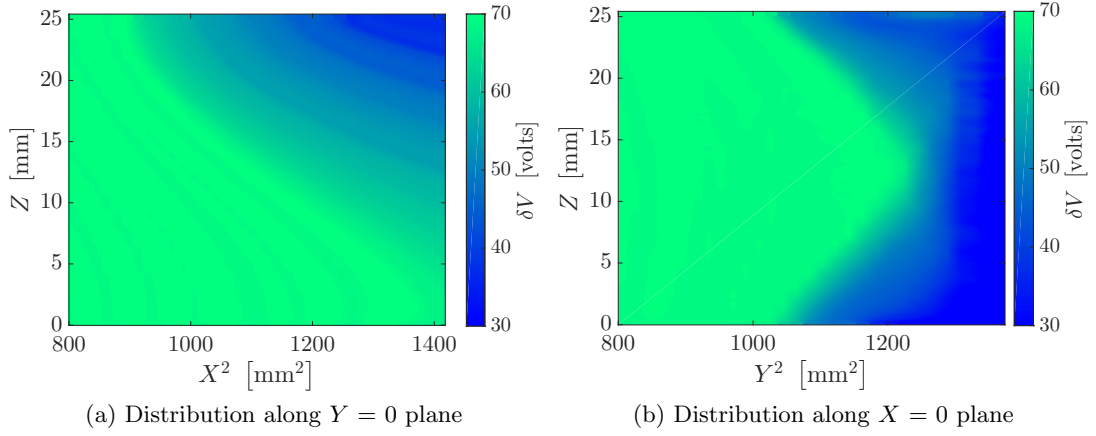


FIGURE 6.2: Voltage profile in CDMSlite that shows the difference in electric potential δV between the final point of collection for the electron and hole as a function of initial position. Here, the top of the detector is biased at +70 V and the bottom is grounded. A grounded cylindrical housing surrounds the detector with a small gap between the detector and housing. The two views show the distributions along the $Y = 0$ plane (a) and $X = 0$ plane (b). Note, the DIBs are located in the $X = 0$ plane which adds to the distortions in (b). Below $R^2 = 800 \text{ mm}^2$ the charge carriers experience the full bias voltage.

Detector	Ref.	σ_E [keV _t]
T2Z1 (Run 3a)	Sec. 5.4	0.209 ± 0.001
T2Z1 (Run 3b)	Sec. 5.4	0.326 ± 0.001
T2Z2	[133]	0.203 ± 0.0002
T2Z3	[133]	0.329 ± 0.0003
T5Z1	[133]	0.702 ± 0.0007
T5Z2	[72]	0.225 ± 0.001
T5Z3	[133]	0.217 ± 0.0002

TABLE 6.1: Baseline resolution values.

in Fig. 6.2, all three coordinates are needed to calculate the voltage at a given location.

The voltage map of the iZIP was required to model energy depositions in the other detectors to determine if an event was a multiple scatter. It consisted of two regions: the scalloped field lines reduced the voltage within 2 mm of the faces of the detector to 2 V and the remainder were at a constant 4 V.

6.2.2 Baseline Resolutions

The baseline resolutions of the detectors is a proxy for the energy-independent noise resolution, σ_E . This was calculated for Run 2 [72] and the iZIP detectors [133]. The Run 3 baseline resolution was calculated in Sec. 5.4. Table 6.1 summarizes these values for the detectors of interest. Only Tower 2 and 5 are considered as they contain the CDMSlite detectors.

6.2.3 Check of Implementation

To test the implementation of this detector response function, simple Monte Carlo events were generated to mimic the CDMSlite Run 2 spectrum. The main features were delta functions of the ^{71}Ge activation peaks according to their branching ratio, and a flat background over the energy range of 0–15 keV. All these events were uniformly distributed throughout the detector volume. Figure 6.3 compares the initial input energies with the output of the detector response function. The activation peak locations are the same, but they have a more Gaussian distribution with an increased low-energy tail.

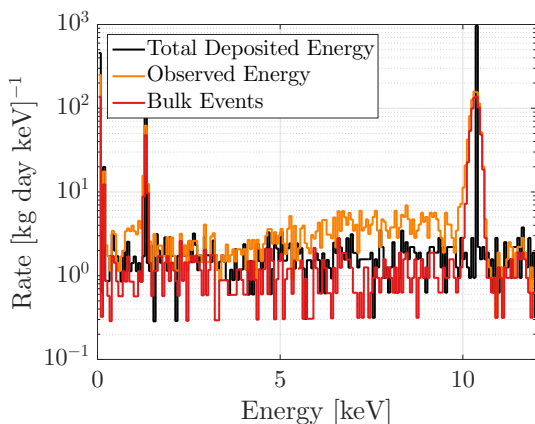


FIGURE 6.3: Demonstration of the detector-response function on a Monte Carlo of uniformly distributed ^{71}Ge activation peaks on a flat background. The increase in events below the activation peaks are events with true energy of, for example, 10.37 keV, that experience less than the full voltage as they are located in the regions of the distortions. The smaller voltage values reduces their NTL energy, and they are reconstructed to lower energies in the detector.

This tail is from events that have, for example, 10.37 keV of energy but are located in a region of the detector that does not experience the full bias voltage and thus have a smaller NTL gain. The energy for these events are reduced when observed by the detector.

6.3 Fiducial Volume Cut Model

The radial cut is very important in CDMSlite as a method of fiducialization [72, 106]. Though there is no direct correspondence between the radial parameter used in the radial cut and position space, it has been developed to preferentially select events that exist in the bulk of the detector and removes those that have reduced NTL gain. With these assumptions, the voltage profiles in Fig. 6.2 were used to determine the relationship between position and voltage for the detector response function. Developing a complicated position cut to proxy the radial cut is equivalent to a simple cut on the voltage of the event. The remainder of this section considers one method for determining this voltage value.

To look in more detail at the relationship between voltage and position, consider the quantity $\Delta V = V_b - \delta V$. This is the deviation of the experienced voltage δV from the applied bias voltage V_b (for Fig. 6.2, $V_b = 70$ V). ΔV as a function of radius is considered for different sections of the detector. Figure 6.4 shows an example of this relationship. As expected, at high radius ΔV increases as the field lines begin to terminate on the detector side walls. The particular example of Fig. 6.4 includes the plane with the DIB.

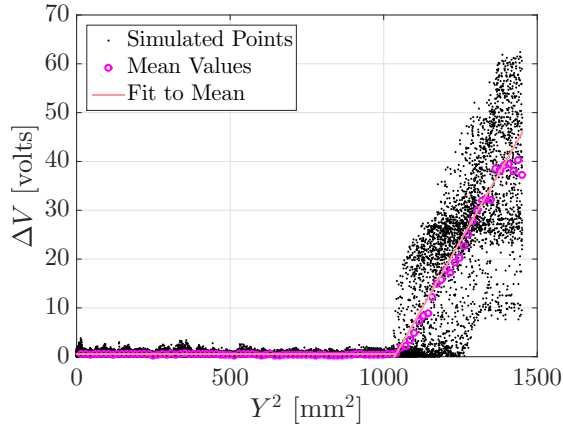


FIGURE 6.4: Example of the relationship between the deviations in voltage from the applied bias, ΔV , and the radius in the detector. This particular section looks at events in the $X = 0$ plane within 8.5 mm of the bottom face. Distortions from the DIBs are clearly seen at high radius. The open circles represent the average ΔV at a given bin in radius. A linear fit to these values is also shown.

The approximate value at which ΔV begins to increase was identified by determining the average value of the voltage deviations from bias; this radius is denoted R_0 . At $R < R_0$, the value of ΔV requires no corrections. For larger radius, the mean values were fit with a simple linear function. The piecewise function is

$$\Delta V_{\text{corr}} = \begin{cases} \Delta V & R < R_0 \\ a\Delta V + b & R > R_0 \end{cases} \quad (6.6)$$

where a is the slope and b the offset. The fit for the example is shown as the pink line in Fig. 6.4. These fit values were used to correct the voltage as a function of radius. A total of six sections were used as a representative sample. Each had the ΔV values corrected in this manner.

The natural log of the corrected voltage ΔV_{corr} was taken as a final, empirical correction, and is shown in Fig. 6.5 along with the Run 2 radial parameter both as a function of total phonon energy E_t . Events in Fig. 6.5a are from the same Monte Carlo as Fig. 6.3. Both planes look very similar. The populations of the ^{71}Ge activation peaks, though at a slightly different calibrated E_t , are independent of “radius.” There is also an increase in events at high “radius”, positive $\ln(\Delta V_{\text{corr}})$ and radial parameter, and a clear separation of the events, $\ln(\Delta V_{\text{corr}}) = 1$ and -4×10^{-5} in radial parameter. There are more events at high “radius” in the radial parameter plane.

As briefly discussed, there was some distinction between the bulk events (negative $\ln(\Delta V_{\text{corr}})$) and the events that experience lower voltage and thus low NTL gain. From

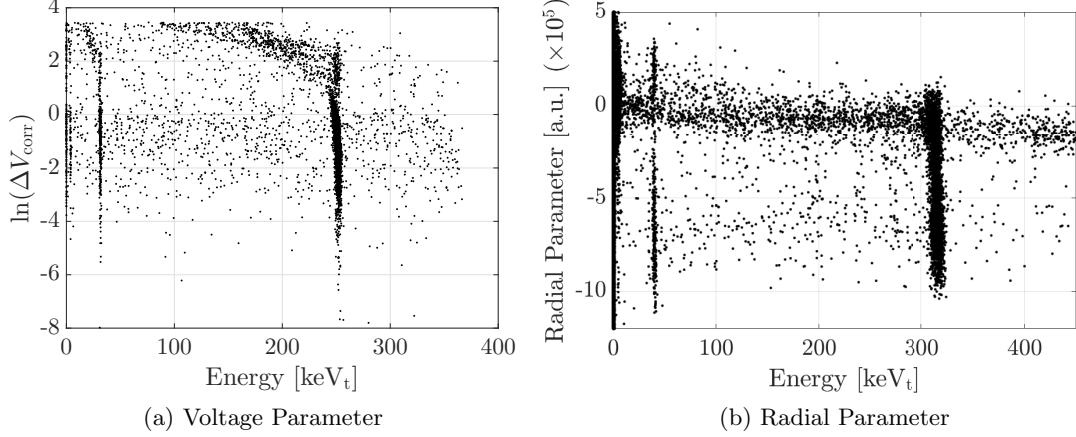


FIGURE 6.5: Comparison between the voltage parameter, $\ln(\Delta V_{\text{corr}})$ (a) and the CDMSlite Run 2 radial parameter (b) as a function of total phonon energy. The large populations of events are the ^{71}Ge activation peaks where the differences in locations and widths between the two figures are due to a difference in calibration. In both planes the peaks are mostly constant in energy and there is a larger distribution of events at the top.

the assumption that the Run 2 radial cut removes all events with low NTL gain, it was used to inform the location of the voltage cut in $\ln(\Delta V_{\text{corr}})$ for this detector response function. The amount of allowed drift in energy from the Run 2 activation peaks was determined and used to calculate the appropriate location of the voltage cut in the $\ln(\Delta V_{\text{corr}})$ plane. The maximum variation in energy for events that pass the radial cut is 1%, thus, events in the $\ln(\Delta V_{\text{corr}})$ plane should not vary in energy more than 1%. The associated value is $\ln(\Delta V_{\text{corr}}) = 0$.²

6.4 Validation of the Response Function

6.4.1 Simple Resolution Model

As there were many different components to this detector response function, it was important to test that the input parameters were recoverable. Using a simple Monte Carlo, it was trivial to create a population of known energy and determine if the output

² An alternative method to set the voltage cut in the $\ln(\Delta V_{\text{corr}})$ plane would be to use the radial cut passage fraction of Run 2.

energy was equivalent (mean of the peak) as well as consider the width of the Gaussian that was created.

Events were uniformly generated in the detector volume at a single energy, and the detector response function was used to convert the energy from true deposited energy to total phonon energy (in keV_t). For the moment, all events were assumed to be ER, and the “theoretical” Fano factor was used. The other free parameters were set to $\sigma_E = 9.25$ eV and $A' = 0$. Events were generated from 0-5 keV in 0.1 keV steps and from 6-30 keV in 1 keV steps. Figure 6.6 shows an example of the generated events in various planes where the input energy is 300 eV. The final conversion was as given in Eq. 6.5.

It is clear from Fig. 6.6 that the low-energy tail was removed by the voltage cut, and that the bulk events fit nicely to a Gaussian. The mean μ of the peak is almost exactly at the simulated input energy. There is a small amount of leakage past the voltage cut (Fig. 6.6a). This is from Fig. 6.4 where correcting the voltage parameter for the cut does adjust some voltage values such that they have a higher apparent voltage and pass the cut. The percentage is $\mathcal{O}(1\%)$. Comparing the determined resolution as a function of energy with the Run 2 values (Fig. 6.7), there is a clear underestimate of the resolution. Thus, the parameters were adjusted.

6.4.2 *Reproducing CDMSlite Run 2*

To compare more accurately with Run 2, another Monte Carlo was generated to mimic the CDMSlite Run 2 data set as in Fig. 6.3. The baseline, constant term remained fixed at $\sigma_E = 9.25$ eV, but F and A' were empirically tuned to $F = 0.19$ and $A' = 5.3 \times 10^{-3}$. To remove some of the variation due to the low statistics of the CDMSlite-like simulation, 200 Monte Carlos were performed. The activation peaks and zero-energy noise were fit with Gaussians as when determining the data driven resolution model (see Sec. 5.4). The distribution of energy and resolution values from the 200 sets were fit with Gaussians to determine the mean and width of the energy and resolution distributions. These were fit with Eq. 6.3 to determine the components of the resolution model. The values from the fit are given in Table 6.2 and compared with the Run 2 data [72]; all are within the 1σ errors. Figure 6.8 compares the Monte Carlo simulations of Run 2 with the mean values of the Run 2 resolution model. The error on the activation peaks as well as the

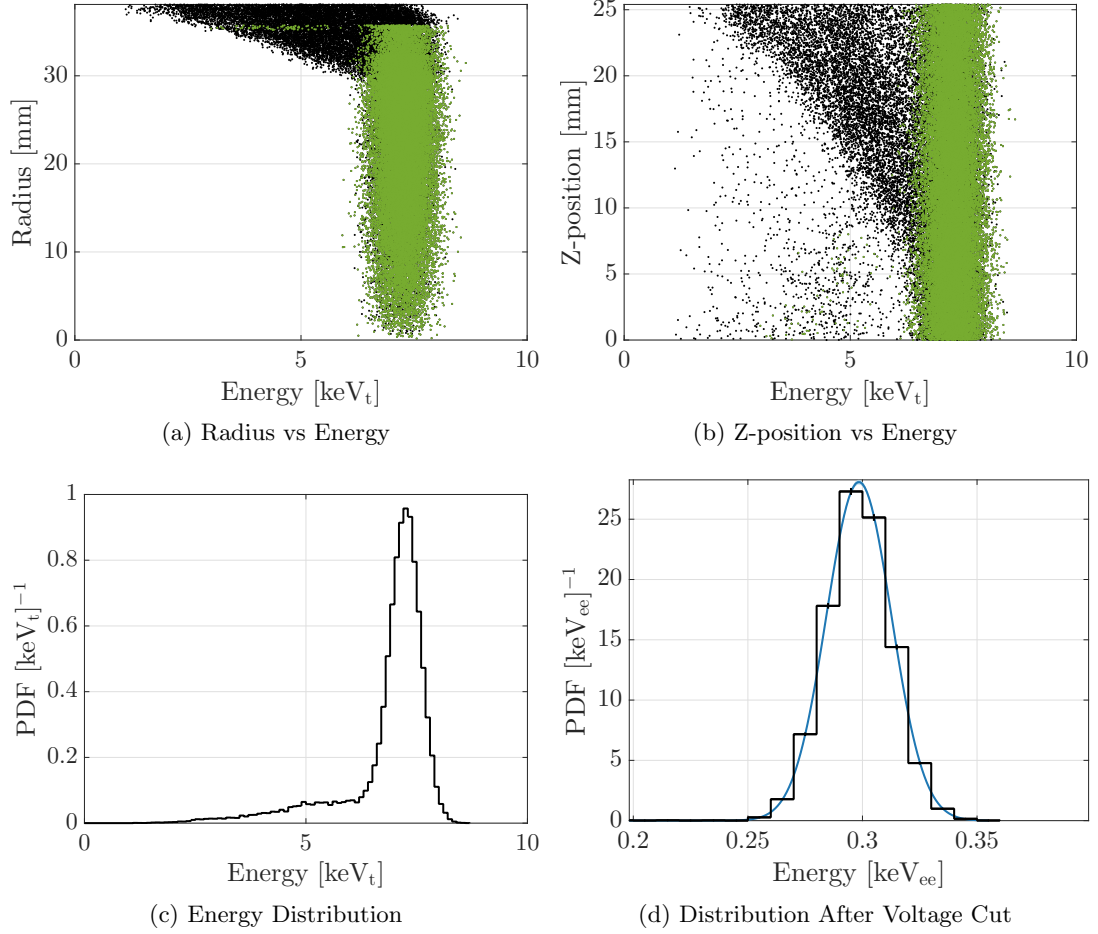


FIGURE 6.6: Example of 300 eV events as a function of radius (a) and z-position (b) where the selected green events pass the voltage cut. The distributions in energy show the low energy tail due to the voltage map (c) and the final fits after the voltage cut (d) where the events are well fit with a Gaussian. Note the small amount of leakage at high radius in (a) which is caused by correcting the voltage; these types of events are also assumed to exist in the CDMSlite radial parameter plane.

	σ_E [eV]	B [eV]	A ($\times 10^3$)
Run 2	9.26 ± 0.11	0.64 ± 0.11	6.12 ± 0.89
Monte Carlo	9.93 ± 0.91	0.57 ± 0.10	6.12 ± 0.89

TABLE 6.2: Comparison of the fits from the resolution model to Run 2 Monte Carlo and data [72]. All are within 1σ errors.

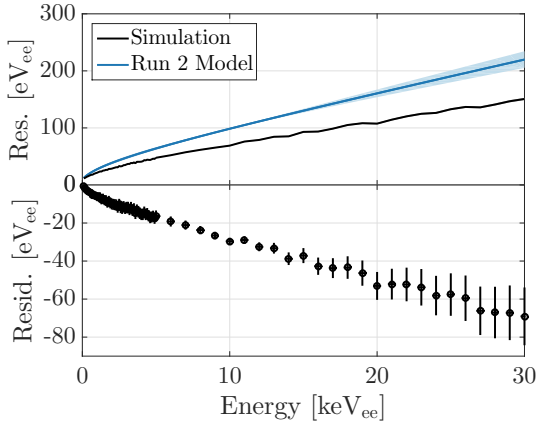


FIGURE 6.7: Comparison of the resolution model from the detector response function (black) with the resolution model from CDMSlite Run 2 (blue). With the theoretical Fano factor and no additional position dependent resolution, the detector response function underestimates the resolution. The bottom panel the residual between the two models.

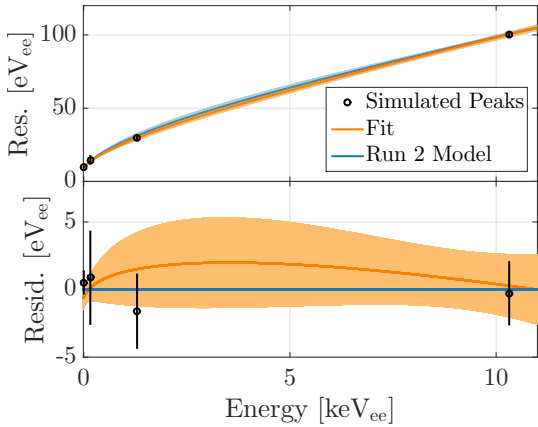


FIGURE 6.8: Comparison of the resolution model from 200 Monte Carlo sets of CDMSlite Run 2 simulations. Distributions of the energy and resolution of the activation peaks and zero-energy baseline were fit to Eq. 6.3. The errors on the individual peaks as well as the 1σ band contain the mean values from the Run 2 resolution model.

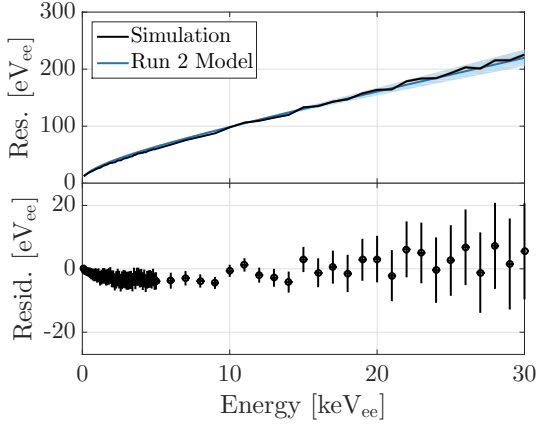


FIGURE 6.9: Resolution scan in energy using the detector response function parameters determined for CDMSlite Run 2. The simulation resolution model falls within the Run 2 error band over the majority of the energy range. The residual is consistent with 0 eV for the majority of the energy range.

	V_b [V]	σ_E [eV]	F	$A'(\times 10^3)$
Run 2	70.0	9.25	0.19	5.3
Run 3a	57.9	9.87	0.27	4.5
Run 3b	73.3	12.7	0.25	5.0

TABLE 6.3: Detector response function parameters to reproduce CDMSlite data.

1σ error on the fit both contain the mean Run 2 model values.

The scan in energy, as performed in Sec. 6.4.1 was completed using the determined model parameters for Run 2. This was a higher statistics Monte Carlo which reduced the errors on the simulation resolution such that the error is driven by the error on the Run 2 resolution model. This comparison is shown in Fig. 6.9. The simulation is contained within the Run 2 error band for the majority of the energy range indicated by the residual consistent with 0 eV.

The detector response function developed in this Chapter is a very powerful tool for comparing simulation with CDMSlite data. Each parameter, V_b , σ_E , F , and A' , can be tuned for a particular run of CDMSlite. The values for CDMSlite Run 2 and Run 3 are given in Table 6.3. It is also possible to exchange the voltage map for an alternative detector configuration or use a yield model other than Lindhard. This flexibility makes the developed detector response function a great tool for future SuperCDMS analysis.

Background Model of Surface Events for CDMSlite

One of the more problematic backgrounds for SuperCDMS is surface events; these are primarily due to the decay of ^{210}Pb which is the long-lived daughter of ^{222}Rn . ^{210}Pb can become implanted into the surfaces of the copper housing and detectors. The events from the decay are dominantly β 's, Auger-electrons, and α 's which have small mean free path and will deposit the majority of their energy within a few millimeters of the detector surfaces (see Fig. 3.3). The development of the iZIPs provided a way to reject these events, but without the interleaved electric field pattern and two sided read-out, CDMSlite lost this ability. To understand this background, and build a model of the expected distribution in energy, a GEANT4 simulation and the detector response function developed in Chapter 6 were used.

7.1 Decay and Implantation of Heavy Nuclei

GEANT4 [121] was used to study the ^{210}Pb decay as was done for the Compton background, because there is no data from CDMSlite from which to build the model. Improvements in GEANT4.10 have made it reliable for correct handling of intricate radioactive decay chains [131]; it can correctly reproduce the complicated branching fractions and Auger-electron cascades expected for the de-excitation of ^{210}Bi shown in Fig. 3.3.

Similarly to previous published CDMS analyses [163, 164], the Screened Nuclear Recoil Physics List (SNRPL) was implemented. SNRPL models the implantation of ions

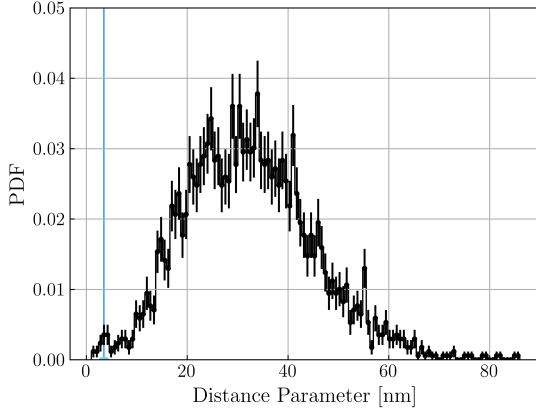


FIGURE 7.1: Implantation profile of ^{210}Pb in germanium. The distribution is Gaussian as expected from SRIM studies. The average depth is about 30 nm with a width of 10 nm, compared to an average depth of 58 nm and a width of 13 nm in silicon [169]. It is expected that the implantation depth of germanium would be smaller as it is a larger nuclei and has more Coulomb screening.

using screened Coulomb interatomic scattering [165]. The default physics for multiple scattering of hadrons in GEANT4 attributes the global effects of the collision (displacement, energy loss, and direction) to a single track step. Thus, nuclei will only travel a limited distance based on the mean free path [166]. With the screening effects of the Coulomb interaction properly taken into account, a more realistic (larger) stopping range is obtained [165].¹

It was necessary to confirm the behavior of the GEANT4 output, particularly the implantation of ^{210}Pb and decay of all isotopes in the chain. This was investigated by allowing ^{214}Po nuclei² to decay isotropically at the surface of the germanium detector. The α -decay of ^{214}Po gives 146.6 keV of energy to the ^{210}Pb nucleus [85] which implants into the surface of the detector. Figure 7.1 shows the implantation profile for the ^{210}Pb nuclei in germanium. From Stopping Range of Ions in Matter (SRIM) [167] simulations by P. Redl, it is known that the average depth of ^{210}Pb in silicon follows a Gaussian distribution centered at 58 nm with a width of 13 nm [169]. In germanium, the depth is expected to be smaller because the Coulomb screening would increase with a heavier

¹ SNRPL was validated against the SRIM software [167] when modeling the ^{210}Pb implantation in the ^{210}Pb silicon source plates installed in tower 3 of SuperCDMS Soudan [113].

² ^{222}Rn decays via α -decay to ^{218}Po which has a half-life of ~ 3 min [85] (see also Fig. 3.1a for the decay of ^{222}Rn). This begins the “plate-out” process by which the radon daughters attach themselves to surfaces in the radon environment. ^{218}Po decays to ^{214}Pb via α -decay which can also cause implantation prior to the ^{214}Po decay. The differences in the GEANT4 simulation beginning the decay chain with ^{218}Po or ^{214}Po were studied by A. Anderson with negligible effect on the resulting energy spectrum [168]. Thus, it was decided to simplify the simulation and reduce computation time by using ^{214}Po as the primary particle.

nucleus (the ratio of the number of protons between germanium and silicon is about a factor of two). This is demonstrated in Fig. 7.1; the average depth is 30 nm and the width is 10 nm.

The energy deposited in GEANT4 from the decays of ^{214}Po to the stable ^{206}Pb are shown in Fig. 7.2 for events where the ^{210}Pb nuclei have implanted into the germanium detector. The β -decay of ^{210}Bi in Fig. 7.2c is featureless, as expected, with the endpoint at 1.2 MeV [85]. There is an increase in number of events at low energy due to the β depositing a small fraction of its energy as it leaves the detector. In the polonium decays of Figs. 7.2a and 7.2d, both the α and lead nucleus are seen as sharp features of the spectrum. The decay of ^{210}Pb is more complicated as in 7.2b (see also, Figs. 3.3), but many features can be identified such as the 46.5 keV γ and the 30.2 keV conversion electron.

Unlike with the Compton background, it is difficult to validate the physics at low energies. There are no expected features in the spectrum at energies <10 keV, and there are more dominant characteristics of both the iZIP and CDMSlite spectrum that mask this background. Figures 7.1 and 7.2 show that the output of GEANT4 agrees with expectations of the implantation and decay based on prior knowledge of the physics lists. The presented high-energy validation combined with the success of previous published CDMS analyses [163, 164] creates confidence in the simulation.

7.2 Simulation of the ^{210}Pb Contamination in SuperCDMS Soudan

With certainty in the specifics of the decay and the implantation profile, a comprehensive simulation was completed.³ A single SuperCDMS Soudan tower geometry, as shown in Fig. 7.3, was used as the probability of ^{210}Pb decay products from one tower depositing energy in the detectors of another tower is low.⁴ The surfaces of the copper housing and germanium detectors were contaminated with ^{214}Po . It is helpful to refer to the locations with their SuperSim volumes: the detectors are denoted Zip and the copper housing is split into the Housing (sidewalls), TopLid, and BottomLid. Each of these volumes of interest were contaminated and analyzed separately unless otherwise stated.

³ This simulation used GEANT4.10.03.p02 and supersim-V03-02-00.

⁴ Cross-contamination is unlikely between towers because the two layers of 3 mm copper housing is thick enough to stop almost all decay particles.

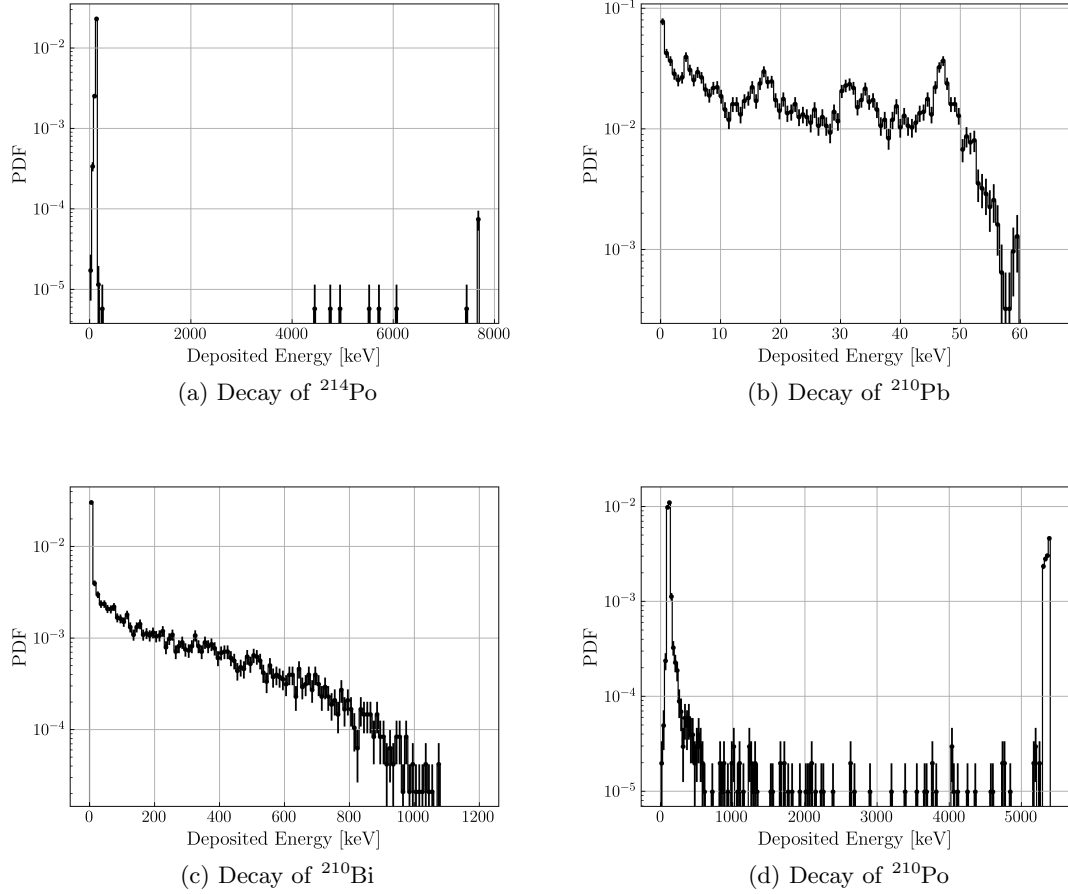


FIGURE 7.2: Energy deposited from the decay of ^{214}Po (a), ^{210}Pb (b), ^{210}Bi (c), and ^{210}Po (d), when ^{210}Pb has been implanted into germanium. In both (a) and (d), which show the decays of polonium, the peaks of the α and lead nuclei are visible. The decay of ^{210}Bi (c) is a smooth β -decay spectrum with endpoint of 1.2 MeV [85]. The increase at low energy is due to events where the β escape the detector, but deposit a few keV or less. In (b), many prominent features of the de-excitation of ^{210}Bi are seen, such as the 46.5 keV γ and 30.2 keV conversion electron (see Fig. 3.3).

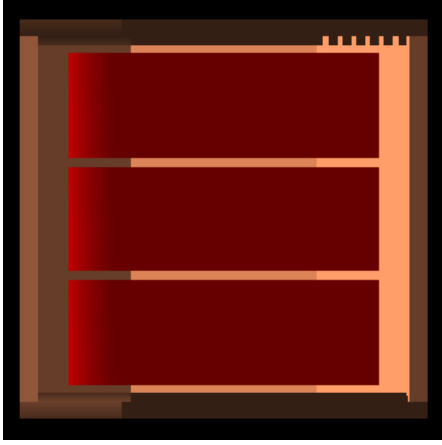


FIGURE 7.3: Single tower geometry used to study the decay of ^{214}Po and the resulting surface events in CDMSlite. The maroon rectangles represent the three germanium detectors in a tower. They are labeled Z1, Z2, and Z3 from the top down. The housing (copper colored) is separated into the TopLid and BottomLid, the cylinders directly above and below the detectors, and the Housing, wall encasing the three detectors.

7.2.1 *Event Processing and Individual Decay Spectra*

GEANT4 events are indexed by the primary particle. Thus, in the output of this simulation, the decay of ^{214}Po to the stable ^{206}Pb was considered one event. iZIPs, on the other hand, index an interaction, or signal, by time. The full decay of ^{214}Po to ^{206}Pb should never be considered an individual iZIP event because of the large times between energy deposits (decays). Thus, it was necessary to process the simulation output such that the energy from the decay of each nuclei was considered separately. The events that deposited energy in the iZIPs were sorted into the four decay chains by the time of the hit rounded to the nearest $0.1 \mu\text{s}$. The events selected were also required to have the ^{210}Bi and ^{210}Po nuclei in the volume of interest, thus ensuring that the ^{210}Pb was successfully implanted into the volume. Labeled by parent nuclei, The decay of ^{214}Po does not contribute to the surface background in CDMSlite whereas ^{210}Pb , ^{210}Bi , and ^{210}Po do.

The simulation output was passed through the detector response function outlined in Chapter 6. Events were also classified as a single- or multiple-scatter. A multiple-scatter was an event that deposits energy in the detector of interest as well as greater than 2 keV_t in another detector. Example spectra from the simulation of the Housing contamination in Z1 with the detector response function of CDMSlite Run 3a are shown in Fig. 7.4 for an energy range of $0\text{--}30 \text{ keV}_{ee}$.

The spectra in Fig. 7.4 are representative of the energy deposited in the CDMSlite detectors from any of the contamination volumes. Figures 7.4a and 7.4b show the

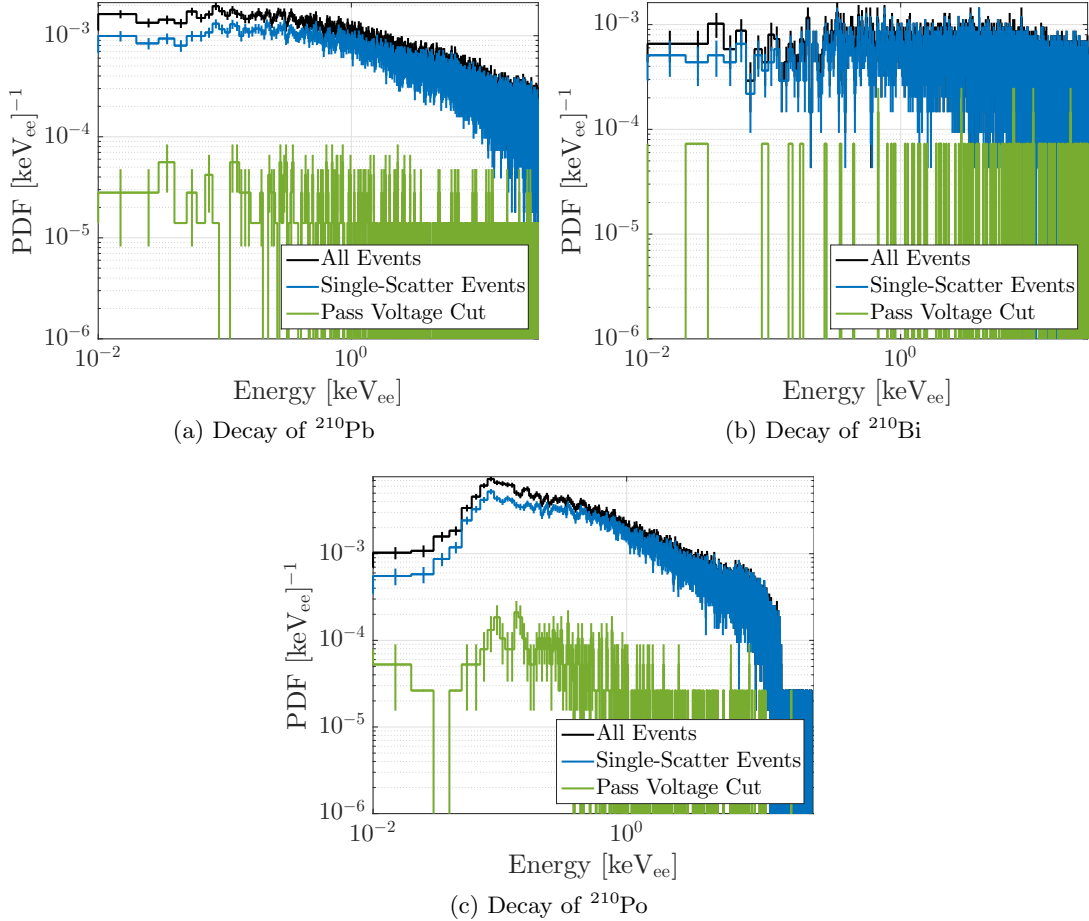


FIGURE 7.4: Example spectra of energy deposited in Z1, from ²¹⁰Pb (a), ²¹⁰Bi (b), and ²¹⁰Po (c) when the ²¹⁰Pb was implanted in the surface of the Housing. The detector response function according to CDMSlite Run 3a has been applied. The three curves on each figure are for all energy deposited (black), only singles (blue), and singles that also pass the voltage cut (green). As this source is from the Housing, most events are removed by the voltage cut. The energy deposited from ²¹⁰Pb (a) and ²¹⁰Bi (b) are featureless, as expected. There are two noticeable aspects of the ²¹⁰Po decay: the sharp drop in events around 15 keV_{ee} from the recoiling ²⁰⁶Pb nucleus, and the peak at 700 eV_{ee}. The low energy peak is less understood, but inspection of the simulation indicates these events are primarily sputtering of germanium and copper nuclei.

relatively featureless β -decay spectra of ^{210}Pb and ^{210}Bi respectively. Any characteristics from the de-excitation of ^{210}Bi in the decay of ^{210}Pb , shown in Fig. 7.2b, are smoothed by the application of the detector response function. The resolution of the detector is $\mathcal{O}(10\text{-}100\text{ eV})$ in this energy range which causes a reduction in features from the raw GEANT4 output due to smearing. One difference between the Housing and Zip volumes is an exponential rise at low energies when ^{210}Pb is implanted into a Zip. This increase in events is a result of particles depositing some energy as they leave the detector volume.

In the decay of ^{210}Po originating in one of the housing volumes, the ^{206}Pb will always deposit less energy than its full kinetic energy of $103\text{ keV}_{\text{nr}}$. This manifests itself in Fig. 7.4c as a drop-off in events at $\sim 15\text{ keV}_{\text{ee}}$. It reconstructs to a decrease in events rather than a peak as the ^{206}Pb has to leave the Housing material. However, in the Zip, this feature is a peak as the ^{206}Pb deposits all of its energy. There is also a peak at about $700\text{ eV}_{\text{ee}}$ in Fig. 7.4c which is present in all volumes from the sputtering of germanium and copper nuclei. It remains unclear if this is a physically motivated feature or a limitation of the simulation.⁵

The various spectra of each decay in Fig. 7.4 give all events, single-scatter events, and single scatters that pass the voltage cut.⁶ The all events spectra are relatively consistent across all CDMSlite runs, except for the TopLid which has a large effect on Z1 and CDMSlite Run 3 but contributes few events to Z2 for Run 2. The largest difference between Z1 and Z2 is the number of events that pass the singles cut. This fraction is reduced for Z2 which causes fewer events to pass the singles and voltage cuts and contribute to the final spectrum.

7.2.2 *Expected Surface Background*

A dedicated study of the SuperCDMS Soudan Run 133-134 α rates in iZIPs was completed by A. Kubik [170]. This investigation showed that the α -decay rate in the detectors was constant throughout Run 133-134 indicating secular equilibrium for the decay of ^{210}Pb . Thus, the energy deposited from events of each decay that pass the singles and

⁵ Investigation by B. Loer showed material dependence of this low energy peak. It is also conjectured that GEANT4's lack of knowledge of the crystal structure in its material definitions could allow nuclei to be ejected at a much lower threshold than if they were bound in a lattice.

⁶ Recall, the voltage cut is the fiducial volume cut in the detector response function, and is the proxy for the CDMSlite radial cut (see Sec. 6.3).

voltage cut (green spectra in Fig. 7.4) in each volume can be added one-to-one without additional normalization.

An example of the expected background from the various volumes for CDMSlite Run 3b is shown as the black spectra in Fig. 7.5 in the region of interest from 0-30 keV_{ee}. For CDMSlite Run 2, since it was a middle detector, the only volumes of interest are the Housing and Germanium (Zip) as these can be normalized to the Run 133-134 α rates (see Sec. 7.4); any events from the TopLid and BottomLid are added into the Housing spectra. The event profiles of Fig. 7.5 are unnormalized and have not been corrected for efficiency, they merely give the shapes of the surface background. The remainder of this chapter will consider the systematic uncertainties associated with the surface model and the normalization of this background with the Run 133-134 α rates.

7.3 Systematic Uncertainties on Spectral Shapes

There are two main sources of uncertainty that impact the shape of the surface event background and were included as a systematic: the voltage map, and the location of the voltage cut.

7.3.1 Voltage Map

The voltage map that was used for the detector response function was created with a grounded bottom face, a positive bias voltage V_b applied to the top face, and the housing of the crystal at ground. This configuration assumes that there is only one detector in a tower and does not consider effects from biased detectors above and/or below the CDMSlite detector. The bias was also inverted from the true CDMSlite configuration (top face grounded and bottom face at negative V_b), but as the crystal was surrounded by a grounded housing, the electric field created by both arrangements is identical. The simplification of the voltage map is a very good approximation of the bulk electric field, but neighboring detectors had an effect on the top and bottom faces of the detector. As the ^{210}Pb background is found predominately on the detector surfaces, this effect must be studied.

Recall, the iZIP detectors have biased charge rails with +2 V on the top face and -2 V

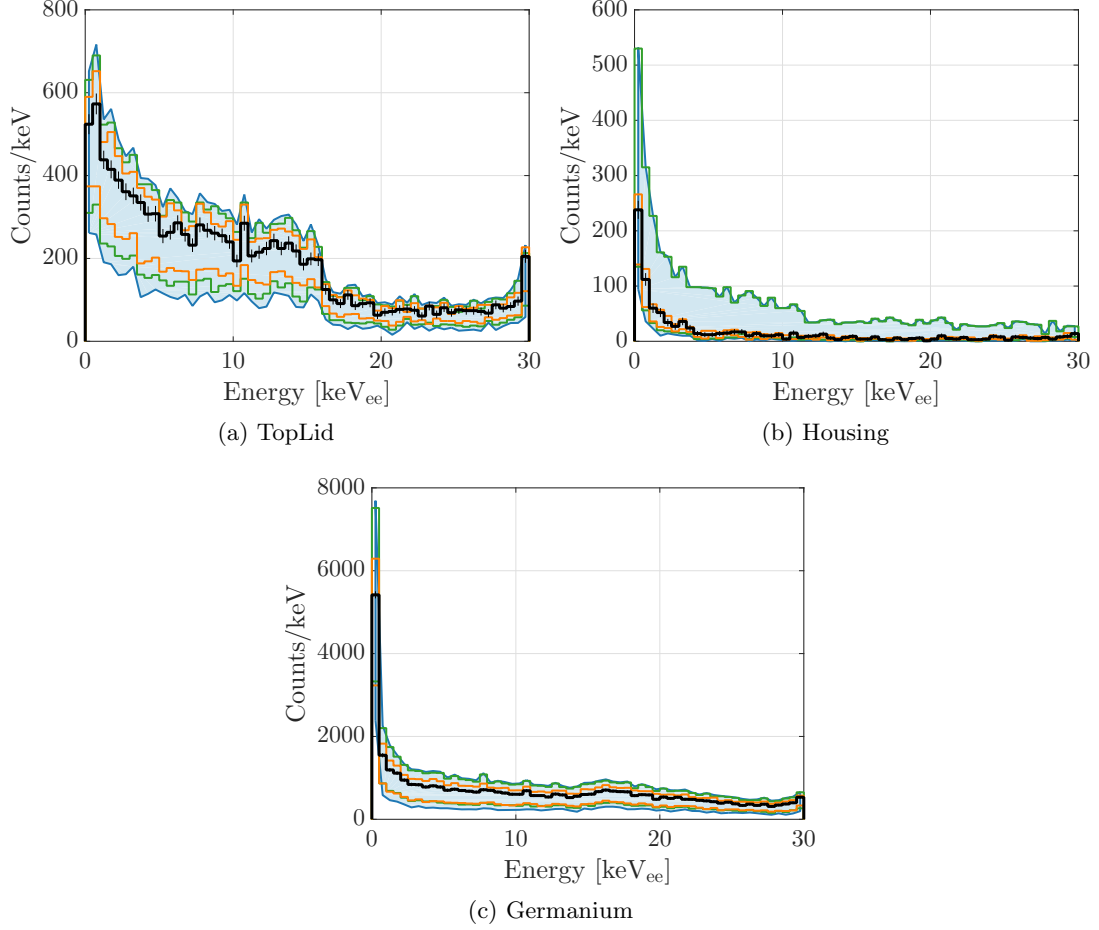


FIGURE 7.5: Final unnormalized surface background spectra from the TopLid (a), Housing (b), and Germanium (c) for CDMSlite Run 3b in detector Z1 from 0-30 keV_{ee} . The black curves show the shape using the best estimate of the voltage cut placement and the standard CDMSlite voltage map. Incorporating the changes in the spectra due to the voltage cut location (green) and possible discrepancies in the voltage map (orange) are also shown (see Sec. 7.3). The voltage cut and map errors are independent and can be added in quadrature to estimate the total systematic errors on the surface background shapes (blue shaded region). Any events from the BottomLid are added into the Housing spectra.

on the bottom face and grounded phonon rails. This is a net ± 1 V on the detector face as seen by a neighboring detector on that face's side. The effects on the surface fields were studied by generating a electric potential file in COMSOL in the actual CDMSlite configuration, and comparing this file with the electric potential file used to create the voltage map.⁷ The bulk region, 10.7–14.7 mm, was assumed to have the least amount of change due to the applied bias and housing (see Fig. 7.6). The flare at large radius, as seen in Fig. 7.6b is due to the detector DIBs and the difference in applying a positive or negative bias to the detector. The behavior is explained well with an exponential as shown by the green curve in Fig. 7.6b.

With this knowledge of the bulk of the detector, the surfaces were analyzed. After inspection, it was decided that the top and bottom 0.1 mm of the detector had the greatest fluctuation above the baseline values. An example near the bottom face is shown in Figs. 7.6c and 7.6d. For CDMSlite Run 3, the voltage map uncertainty included a ± 1 V fluctuation 0.1 mm from the bottom face which was near another detector, and a ± 0.5 V fluctuation on the top face which was under the grounded top lid of the housing. The voltage systematic on the top face were increased to ± 1 V for Run 2 as this face was also adjacent to a detector. The positive (negative) fluctuation was added (subtracted) on both surfaces from the event's δV giving the extreme cases of this uncertainty.

7.3.2 *Voltage Cut Location*

The second source of uncertainty was the location of the voltage cut (see Sec. 6.3). Figure 7.7 shows the various values of this cut that represent the uncertainty from the current inability to map the voltage parameter $\ln(\Delta V_{\text{corr}})$ to the CDMSlite radial parameter. The standard value of $\ln(\Delta V_{\text{corr}}) = 0$ (blue line in Fig. 7.7) is described in Sec. 6.3 and was adjusted by ± 1 as the systematic (red dotted lines in Fig. 7.7).

7.3.3 *Impact of Spectra*

The differences in the electric-potential files and the location of the voltage cut are independent sources of uncertainty, thus, they can be varied one at a time and the corresponding spectra constructed. For the voltage map uncertainty, the standard value

⁷ The new COMSOL files were created by R. Calkins.

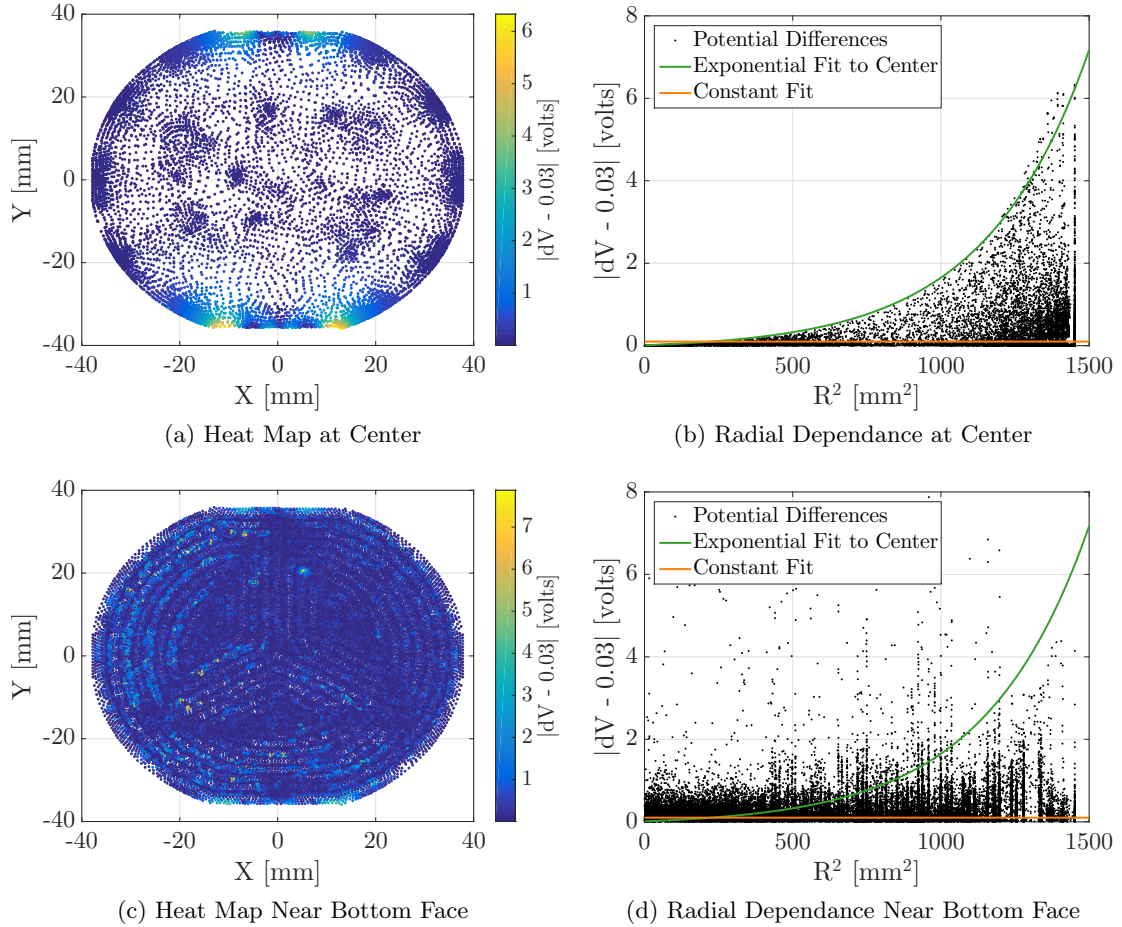


FIGURE 7.6: Comparison of the electric potential files used to create the voltage map and the CDMSlite Run 3 configuration. The difference in the voltage in the bulk of the detector, 10.7–14.7 mm, (a) and (b), are contrasted with the voltage differences near the bottom face, (c) and (d). The heat map in the bulk (a) indicates that there is still difficulty matching at the DIBs (flats at $Y \sim 35$ mm) due to the difference in applying a negative or positive bias voltage. These regions correspond to the flare at high radius in (b). The density of points in (c) is due to the higher mesh used at the surfaces of the detector. There are larger deviations in voltage along the entire surface of the detector, as shown in (d). This suggests at ± 1 V fluctuation at the bottom surface in CDMSlite Run 3.

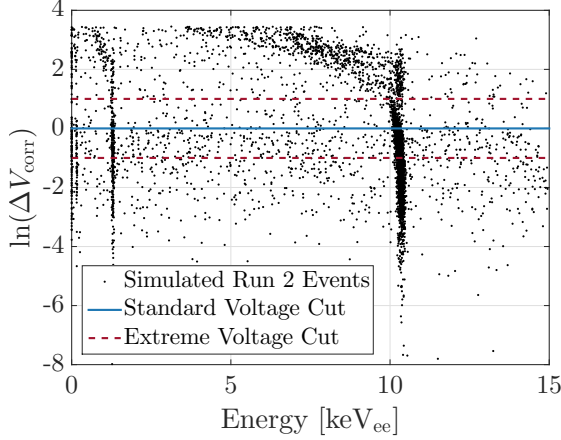


FIGURE 7.7: Various voltage cut locations in the $\ln(\Delta V_{\text{corr}})$ vs energy plane. The black points are a representation of the CDMSlite Run 2 data, with the blue line the standard voltage cut at $\ln(\Delta V_{\text{corr}}) = 0$. The large uncertainty is captured by the ± 1 range in the voltage parameter. This represents the current inability to map the voltage parameter to the CDMSlite radial parameter.

Location	T5Z2	T2Z1
QiS1	17	118
QiS2	18	23
Total	453	1040

TABLE 7.1: Number of α events from SuperCDMS Soudan Run 133-134 in T5Z2 (CDMSlite Run 2) over 170.26 live-days and T2Z1 (CDMSlite Run 3) over 382.48 live-days [170].

of the voltage cut was used. Because they are independent, the quadrature sum can be taken for the final total uncertainty on the spectra. The uncertainty on the voltage map is given by the orange curves in Fig. 7.5, and the variations in the voltage cut as the green curves. The final quadrature sum uncertainty band is shown as the blue shaded region in Fig. 7.5.

7.4 Expected Alphas in the CDMSlite Runs

The SuperCDMS Soudan α study counted the number of α events in each iZIP by selecting energy deposits >3 MeV in low-background search data. The final event numbers, measured with the inner-charge electrodes (QiS1/2) on both sides of the detectors, and the total collected on all sensors, are given in Table 7.1 [170]. The total livetime of the data used for this study was 382.48 days for T2Z1 and 170.26 days for T5Z2. From these event counts, the expected number of α events for CDMSlite were calculated.

7.4.1 Run 2

The CDMSlite Run 2 detector, T5Z2, was the middle detector in the tower. Thus, only the α events from the housing (Housing, TopLid, and BottomLid combined) and germanium detectors (Germanium) are expected. The inner-electrode events, as given in Table 7.1, were directly used to inform the rate of α 's from the Germanium volumes. However, it is important for CDMSlite to have a measure of the expected α 's over the full face (side 1 or side 2) area and not just the inner charge sensor. The Qi events can be scaled by the sensor surface area (the inner charge sensor covers approximately 75% of the surface). Thus, the total number of face α events are $17/0.75 + 18/0.75 = 46.67$. These are events from T5Z2 and any α 's from the neighboring detectors.

Assuming, for the moment, the rate of contamination on the sidewall of the germanium detector is the same as the faces, the number of sidewall events are calculated by scaling the face α counts by the ratio of surface area of face to sidewall:

$$\frac{\text{Face Area}}{\text{Sidewall Area}} = \frac{\pi R^2}{2\pi RH} = \frac{\pi \cdot 38.1^2}{2\pi \cdot 38.1 \cdot 25.4} = 0.75. \quad (7.1)$$

Averaging the QiS1 and QiS2 counts and dividing by two to get the events from only T5Z2, the number of α 's from the germanium sidewall is $11.67/0.75 = 15.56$. The total number of α events from all germanium surfaces of T5Z2 is $46.67 + 15.56 = 62.22$. However, this is a lower bound. The sidewall and face surfaces are known to have an unequal rate of contamination as the faces are repeatedly etched in the fabrication and patterning of the sensors; the difference in rate can be up to a factor of three. To account for this difference, the sidewall number was increased by a factor of two, with the additional counts treated as a systematic such that the upper limit of the sidewall events was a factor of three. This gives a mean value of Germanium α events as 77.78.

The α 's from the housing are calculated as $453 - 46.67 - 15.56 \cdot 2 = 375.22$, where the the face (side 1 and side 2) counts and germanium sidewall events are subtracted from the Total in Table 7.1. All volumes with their errors are listed in 7.2.

7.4.2 Run 3

Since T2Z1 is the top detector in tower 2, α events are expected from the top lid of the housing (TopLid) as well as the housing sidewalls (Housing) and germanium detectors

Volume	T5Z2	T2Z1
TopLid	—	$142 \pm 14.83(\text{stat.})$
Housing	$375.22 \pm 25.02(\text{stat.}), 15.56(\text{sys.})$	$811.11 \pm 36.92(\text{stat.}), 20.44(\text{sys.})$
Germanium	$77.78 \pm 11.87(\text{stat.}), 15.56(\text{sys.})$	$86.89 \pm 11.13(\text{stat.}), 20.44(\text{sys.})$

TABLE 7.2: Number of α events from SuperCDMS Soudan Run 133 - 134 by simulation volume in T5Z2 (CDMSlite Run 2) and T2Z1 (CDMSlite Run 3). The livetime for T2Z1 is 382.48 days, and 170.26 days for T5Z2.

(Germanium). Note that, unlike for Run 2, the α events from Table 7.1 were separated into three volumes. Consider first that the side 2 face of T2Z1 is adjacent to the side 1 face of T2Z2, which are both germanium surfaces. Making the assumption that the rate of α 's from both germanium detectors is equal, the α 's from just T2Z1 germanium QiS2 is $23/2 = 11.5$. Assuming the side 1 contamination is identical to the side 2 contamination, the number of events from germanium in the measured QiS1 value is 11.5 α 's. Subtracting this from the 118 measured α 's, the number of events from the TopLid is 106.5. Scaling by the sensor area, this gives the total number of expected events of $106.5/0.75 = 142$ α 's from the TopLid.

The remainder of the Germanium events were calculated as $11.5/0.75 + 23/0.75 + (11.5/0.75)/0.75 \cdot 2 = 86.89$. Here, the first and second terms give the number of α 's on side 1 and side 2 respectively; the extracted QiS1 and QiS2 α 's scaled by sensor area. Finally, the sidewall α 's are added using the total side 1 events and the known ratio between the area of the face and the area of the germanium sidewall, Eq. 7.1. The extra factor of two in the final term accounts for the detector fabrication differences. Lastly, the α 's from the housing are calculated in the same manner as for Run 2, $1040 - 23/0.75 - 118/0.75 - (11.5/0.75)/0.75 \cdot 2 = 811.11$. The Run 3 volumes are also listed with their errors in Table 7.2.

Lastly, for the values in Table 7.2 to be useful for the CDMSlite background model, they must be scaled from the livetimes of the α study to those of the CDMSlite runs; the Run 2 livetime was 115.6 days, and the Run 3 livetime was 60.9 days.

7.4.3 Calculating Correlations

Since all of the α values in Table 7.1 were calculated from three measure numbers, correlations between these values, and therefore the number of α 's expected from each volume, are anticipated. To determine these correlations, 10^7 random numbers were generated in a normal distribution for each measured value in Table 7.1 with the mean given by the counts and the width by the square root of the counts. These random numbers underwent the prescription outlined above for calculating α 's by volume. The systematic error on the germanium sidewalls was added as a uniform distribution of 10^7 random numbers from, for example, -10.22 to 10.22 in Run 3.

The covariance was calculated from the volume variables as [171]

$$V_{kl} = E[(k - \mu_k)(l - \mu_l)], \quad (7.2)$$

where $E[\]$ denotes the expectation value of the quantity in brackets, k and l represent the distributions from the TopLid, Housing, and Germanium, and μ is the mean of the distribution. Note the variance of a given distribution is $V_{kk} = \sigma_k^2$. The correlation between the volumes is

$$\rho_{kl} = \frac{V_{kl}}{\sigma_k \sigma_l}. \quad (7.3)$$

The number of α 's and their correlations are found in Table 7.3. All the α counts are anti-correlated; increasing the α 's from one volume decreases the expected α 's from another. The correlation between the Housing and Germanium is the strongest as it includes the additional systematic uncertainty on the sidewall events in Germanium.

7.5 Expected Surface Events from the Decays of ^{210}Pb in CDMSlite

The surface event simulation from the decay of ^{210}Po was analyzed to determine the number of α 's detected from the various volumes in Z1 or Z2. No energy resolution was applied and a simple energy selection of $E_{\text{deposited}} > 3$ MeV classifies an event as an α ; recall that this was the same criteria that was used in the original α study [170]. The number of α 's from the ^{210}Po simulation are given in Table 7.4.

These simulation α 's were used with the expected CDMSlite α 's in Table 7.3, and

Volume	Run 2 (T5Z2)		Run 3 (T2Z1)	
	Counts	Correlations	Counts	Correlations
TopLid (T)	—	—	22.61 ± 2.36	$\rho_{TH}^\alpha = -0.27$
Housing (H)	254.76 ± 16.58	$\rho_{HG}^\alpha = -0.49$	129.13 ± 6.39	$\rho_{HG}^\alpha = -0.47$
Germanium (G)	52.81 ± 8.12	—	13.83 ± 3.44	$\rho_{TG}^\alpha = -0.18$

TABLE 7.3: Number of expected α events by volume in the livetime of CDMSlite Run 2, 115.6 days, and Run 3, 60.9 days (N_α^{lite}). There is about a factor of two difference between the livetime of the runs which is reflected in the Housing counts. This study suggests T5Z2 had a higher concentration of ^{210}Pb contamination than T2Z1 as the number of events from Germanium is almost a factor of four higher in T5Z2.

Location	Run 2 (Z2)	Run 3 (Z1)
TopLid (T)	—	8179 ± 90
Housing (H)	23518 ± 153	28620 ± 169
Germanium (G)	117898 ± 343	118205 ± 344

TABLE 7.4: Number of α events by volume from the decay of ^{210}Po in the simulation (N_α^{sim}). The selection criteria for these events mimic the cuts applied in the Run 133 - 134 study [170], and so they can be compared to the values in Table 7.3. The errors are statistical.

Location	Counts		
	Run 2	Run 3a	Run 3b
TopLid (T)	—	12800 ± 113	11639 ± 108
Housing (H)	343 ± 19	1096 ± 33	992 ± 31
Germanium (G)	7343 ± 86	45727 ± 214	41522 ± 204

TABLE 7.5: Total number of events from the simulations of ^{210}Pb in the region of interest for CDMSlite, 0–30 keV_{ee} (N_{ROI}^{sim}). The decrease in events in Run 2 is due to the lower efficiency of the singles cut on a middle detector. To determine the number of events in the entirety of Run 3, Run 3a and Run 3b should not be summed but averaged. All events from the simulation were used to increase statistics rather than a livetime fraction.

the livetime of Run 2 or Run 3, to calculate the corresponding livetime of the simulation:

$$L^{sim} = \left(\frac{N_{\alpha}^{sim}}{N_{\alpha}^{lite}} \right) \cdot L^{lite}, \quad (7.4)$$

where L^{lite} is the livetime of either Run 2 or Run 3, N_{α}^{lite} and N_{α}^{sim} are the expected number of α 's from Tables 7.3 and 7.4 respectively, and L^{sim} is the simulation livetime for the volume of interest (L^{sim} differs by volume).

The ^{210}Pb , ^{210}Bi , and ^{210}Po events with energy deposited in the region of interest (ROI) were counted. Since there were different effective voltage biases and resolution models for the two parts of Run 3 (Run 3a and Run 3b), the number of events in the ROI are different and were considered separately. Run 2 was treated in its entirety for this analysis.⁸ For a ROI of 0–30 keV_{ee}, the total counts from the simulation are given in Table 7.5.

Along with the livetimes, the total number of events in the simulation ROI were used to calculate the expected number of surface events in CDMSlite. The number of

⁸ Run 2 was separated into Run 2a and Run 2b due to necessary cryo-cooler maintenance during the run. The two periods had different radial cut models, but as there is no direct correspondence between the radial parameter and the voltage parameter, the variation in the voltage cut location should encompass this difference. One resolution model was developed for CDMSlite Run 2 [72].

events in the CDMSlite ROI is

$$N_{ROI}^{part} = 3N_{ROI}^{sim} \cdot \left(\frac{L^{part}}{L^{sim}} \right) \quad (7.5)$$

where N_{ROI}^{part} is the expected number of events in the ROI, and L^{part} the livetime, in Run 2, Run 3a, or Run 3b. $N_{ROI}^{sim} = N_{Pb,ROI}^{sim} + N_{Bi,ROI}^{sim} + N_{Po,ROI}^{sim}$ is given in Table 7.5. The factor of three accounts for the fact that, when input into a likelihood-type analysis, one event will be drawn from the surface event distribution by volume, but there are three events that make up the PDF, one for each decay, for every α in the simulation livetime. Combining Eq. 7.4 and Eq. 7.5 gives

$$\begin{aligned} N_{ROI}^{part} &= 3N_{ROI}^{sim} \cdot \left(\frac{L^{part}}{\left(\frac{N_{\alpha}^{sim}}{N_{\alpha}^{lite}} \right) \cdot L^{lite}} \right) \\ &= 3N_{ROI}^{sim} \cdot \left(\frac{N_{\alpha}^{lite}}{N_{\alpha}^{sim}} \cdot \frac{L^{part}}{L^{lite}} \right). \end{aligned} \quad (7.6)$$

For each volume, a N_{ROI}^{part} was calculated. The N_{α}^{lite} are correlated and thus, the N_{ROI}^{part} are expected to be correlated. To simplify the notation for this final portion of the normalization analysis, the variable names are changed as follows: $N_{ROI}^{part} = y_m$, where $m = T, H, G$ for the various volumes, $N_{\alpha}^{lite} = x_{m,1}$, $N_{\alpha}^{sim} = x_{m,2}$, and $N_{ROI}^{sim} = x_{m,3}$. Eq. 7.6 can be rewritten as

$$y_m = 3x_{m,3} \cdot \left(\frac{x_{m,1}}{x_{m,2}} \cdot \frac{L^{part}}{L^{lite}} \right). \quad (7.7)$$

The covariance matrix for the set of functions y_m is [171]

$$U_{kl} \approx \sum_{i,j=1}^n \left[\frac{\partial y_k}{\partial x_i} \frac{\partial y_l}{\partial x_j} \right]_{x=\mu} V_{kl}^{ij}. \quad (7.8)$$

For this study, $n = 3$. When $k \neq l$, only the V_{kl}^{11} terms exist in the covariance matrix V of the x -variables. These terms are given by the correlations in Table 7.3. When $k = l$, only the $i = j$ terms exist in the V_{kl}^{ij} matrix which are the variances; it is assumed there are no correlations between the x_m variables for a given volume m . Thus, nine

V matrices are required to determine the entire correlation matrix U of the expected events in the ROI for Run 3a or Run 3b, and four V matrices are necessary for Run 2.

Two examples are considered. First, $m = T, H$ for the TopLid and Housing volumes. The Run 3 α counts are correlated ($x_{T,1}$ and $x_{H,1}$) with coefficient $\rho_{TH}^\alpha = \rho_{TH}^{11} = -0.27$ from Table 7.3. Thus, V_{TH}^{ij} is given by

$$V_{TH}^{ij} = \begin{pmatrix} \rho_{TH}^{11} \sigma_T^1 \sigma_H^1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \quad (7.9)$$

The covariance for the expected surface counts in Run 3a between the TopLid and Housing is then

$$\begin{aligned} U_{TH}^{R3a} &= \sum_{i,j=1}^3 \left[\frac{\partial y_T}{\partial x_i} \frac{\partial y_H}{\partial x_j} \right]_{x=\mu} V_{TH}^{ij} \\ &= \left[\frac{\partial y_T}{\partial x_1} \frac{\partial y_H}{\partial x_1} \right]_{x=\mu} V_{TH}^{11} \\ &= \left[\frac{\partial y_T}{\partial x_1} \frac{\partial y_H}{\partial x_1} \right]_{x=\mu} \rho_{TH}^{11} \sigma_T^1 \sigma_H^1, \end{aligned} \quad (7.10)$$

where only the non-zero terms are listed. This gives $U_{TH}^{R3a} = -0.59$.

As the second example, consider instead $k = l = G$. Now, all the diagonal terms of V_{GG}^{ij} are non-zero and represent the error on the calculated Run 3 α 's or the simulation counts. This covariance matrix is given by

$$V_{GG}^{ij} = \begin{pmatrix} (\sigma_G^1)^2 & 0 & 0 \\ 0 & (\sigma_G^2)^2 & 0 \\ 0 & 0 & (\sigma_G^3)^2 \end{pmatrix}, \quad (7.11)$$

where the σ_G^i are given in Tables 7.3, 7.4, and 7.5. The covariance for Germanium, or

actually the variance, is

$$\begin{aligned}
U_{GG}^{R3a} &= \sum_{i,j=1}^3 \left[\frac{\partial y_G}{\partial x_i} \frac{\partial y_G}{\partial x_j} \right]_{x=\mu} V_{GG}^{ij} \\
&= \left[\frac{\partial y_G}{\partial x_1} \right]_{x=\mu}^2 V_{GG}^{11} + \left[\frac{\partial y_G}{\partial x_2} \right]_{x=\mu}^2 V_{GG}^{22} + \left[\frac{\partial y_G}{\partial x_3} \right]_{x=\mu}^2 V_{GG}^{33} \\
&= \left[\frac{\partial y_G}{\partial x_1} \right]_{x=\mu}^2 (\sigma_G^1)^2 + \left[\frac{\partial y_G}{\partial x_2} \right]_{x=\mu}^2 (\sigma_G^2)^2 + \left[\frac{\partial y_G}{\partial x_3} \right]_{x=\mu}^2 (\sigma_G^3)^2.
\end{aligned} \tag{7.12}$$

The error on the expected number of events in the ROI of Germanium is $\sqrt{U_{GG}^{R3a}} = 2.1$ events. Thus, the final number of expected surface background events, with error, is 8.3 ± 2.1 for the Run 3a Germanium volume.

This prescription was followed to calculate the covariances for all the expected number of surface events in the ROI. The $y_m = N_{ROI}^{part}$ and correlations are given in Table 7.6a for CDMSlite Run 2 and Table 7.6b for CDMSlite Run 3. The calculated correlations are identical or smaller than the correlations between the α counts give in Table 7.3.

The derived expected events for CDMSlite in Table 7.6b from the Run 133-134 α study were used as constraints, in the likelihood analysis of Run 3 data, on the magnitude of the spectral shapes, such as those given in Fig. 7.5 for Run 3a. The procedure outlined in this Chapter was repeated for the ROI 0–2 keV_{ee}, the range in energy for which CDMSlite is sensitive to WIMP dark matter.

Location	Counts	Correlation
Housing	11.1 ± 0.9	$\rho_{HG} = -0.37$
Germanium	9.9 ± 1.5	—

(a) Run 2

Location	3a		3b	
	Counts	Correlation	Counts	Correlation
Top Lid	54.9 ± 5.8	$\rho_{TH} = -0.22$	46.6 ± 4.9	$\rho_{TH} = -0.23$
Housing	7.7 ± 0.4	$\rho_{HG} = -0.40$	6.5 ± 0.4	$\rho_{HG} = -0.40$
Germanium	8.3 ± 2.1	$\rho_{TG} = -0.18$	7.0 ± 1.8	$\rho_{TG} = -0.18$

(b) Run 3

TABLE 7.6: Expected number of surface events in the ROI 0 - 30 keV_{ee} for CDMSlite Run 2 (a) and Run 3 (b).

Background Studies for the SuperCDMS SNOLAB Experiment Program

SuperCDMS SNOLAB will need to have lower background rates than SuperCDMS Soudan in order to reach the projected sensitivities of Fig. 2.13. For the first payload of 4 towers (10 Ge iZIPs, 2 Si iZIPs, 8 Ge HV, and 4 Si HV), internal sources of radiation, as described in Secs. 3.1.2 and 3.2, are expected to be the dominant background. With the analytical descriptions presented, these can be easily modeled. Additionally, from Sec. 2.4.2, the new HV detectors have phonon measurement on both sides of the crystal, which will give them the potential to have surface event rejection analogous to the iZIPs [102]. Thus, the surface background of Chapter 7 should be of minimal concern.

The remaining known background is the radiogenic γ 's and neutrons described in Sec. 3.1.1. For the environmental γ 's that Compton scatter, the model developed in Chapter 4 can be applied. The radiogenic neutrons are expected to be subdominant for the first phase of the SuperCDMS SNOLAB experiment because of the low levels of material contaminant [102]. However, with increased operating time and additional towers included, i.e. more experimental exposure, this background becomes a concern and potentially limits the future reach of the experiment to dark matter.

This chapter first considers the change in the neutron background with the number of deployed towers, as well as the shift in event categorization (single- or multiple-scatter events). Then, a possible upgrade option to effectively reduce the neutron background,

an active neutron veto, is presented. This veto would replace the existing passive inner-polyethylene shielding layer with a new component sensitive to neutrons. Though not removing the neutron background, this active layer identifies neutrons that single scatter in the detectors. A variety of veto designs are presented and evaluated.

8.1 Relative Background Scaling for Various Payloads

Although the cryostat has capacity for 31 towers [102], the maximum payload considered for these studies was 25 towers. From here, the number of towers was reduced to seven and then five. Also considered was the change in rate with an additional tower from seven to eight.

The neutrons from ^{238}U and ^{232}Th were simulated from the cryostat cans with SuperSim, and the rate of events for each configuration determined. Rather than compare the raw rates, the ratio of rates between payloads was chosen which indicate the increase or decrease in a particular background category. The classifications of significance when simulating neutrons are the nuclear recoil (NR) single scatters, the total NR background, and because neutrons can produce secondary electromagnetic particles, the total electron-recoil (ER) background is of importance.

For dark matter that interacts primarily via NRs, the expected number of NR single-scatters relates to the experiment sensitivity. In iZIP detectors with ER/NR discrimination, the ratio of NR single scatters to all NRs determines their rejection power. The HV detectors are characterized by the ratio of NR single-scatters to all events. For this study, iZIP and HV detectors were not considered separately (effectively, either all detectors are iZIPs or all are HV in the payload). Table 8.1 gives the ratio of the five important categories under review.

First, consider the ratios from seven to eight towers. In all categories, the ratios are very close to unity, though not statistically consistent with one. This indicates that the background rates are not expected to increase with the addition of a single tower. Alternatively, a change in two towers (five to seven), has an almost constant total NR and ER background, but the single-scatter NRs increase. With fewer detectors the probability of a neutron interacting in more than one detector decreases and the number of single-scatter NRs increases for a smaller payload.

	Ratio of Towers		
	5/7	7/8	7/25
single NR	1.11 ± 0.06	1.04 ± 0.01	0.88 ± 0.04
all NRs	0.926 ± 0.003	1.008 ± 0.004	0.65 ± 0.02
all ERs	0.943 ± 0.009	1.022 ± 0.005	1.58 ± 0.08
single NR/all NR	1.20 ± 0.07	1.03 ± 0.01	1.35 ± 0.07
single NR/all events	1.20 ± 0.07	1.00 ± 0.01	0.81 ± 0.07

TABLE 8.1: Ratios of expected backgrounds for various payloads of the SuperCDMS SNOLAB experiment from primordial neutron sources (^{232}Th and ^{238}U) originating in the cryostat cans. The configurations considered were 5, 7, 8, and 25 towers. Important categories of events are the NR single-scatters (single NR), all NRs, and all ERs produced by electromagnetic secondaries. The ratio of single NR or all NRs is important for understanding the WIMP background in iZIPs, and the single NR to all events for the HV detectors. Errors are statistical only.

The change from seven to 25 towers gives about a 40 % increase in the total NR rate. At a payload of 25 towers, the cryostat is almost completely filled giving a large probability of a neutron interacting in one of the 150 detectors. When the towers are confined to the center of the cryostat, there are fewer paths that will result in a NR. Alternatively, the total ER background rate decreases when the payload is expanded. The majority of the events in the 25 tower configuration will be on the outer detectors such that the inner are shielded, having a lower total background rate. These central, self-shielded detectors will be able to set stronger WIMP limits.

Table 8.1 suggests that increasing the first SuperCDMS SNOLAB payload by a few towers from the original four will not cause a large increase in the backgrounds. The rejection power of NR single scatters in iZIPs (ratio of NR single scatters to all NRs) will decrease by about 30 % if more than one additional tower is added. Alternatively, the ability for HV detectors to identify NR single scatters (ratio of NR single scatters to all events) will decrease with the first couple, but then increases by almost 20 %. There appears to be a critical number of towers at which point the backgrounds have a striking increase. However, the NR single-scatter rate will decrease with respect to the total NR background, which is advantageous for iZIPs. Instead, recognizing NR single scatters through an active process can reduce this background almost entirely.

8.2 Motivation for an Active Neutron Veto

It can be useful for an experiment to be able to identify neutrons by capturing them and transforming the nuclear interaction into a high-energy electromagnetic event. This method of neutron detection has been successful for many neutrino experiments [172–175], and is often achieved with a liquid or solid scintillating material doped with metal additives (e.g. boron, gadolinium, and lithium) that have large neutron capture cross sections [176, 177]. After capture occurs the nucleus de-excites, emitting light which is collected by photomultiplier tubes (PMTs) or silicon photomultipliers (SiPMs).

The type of experiment dictates whether to use liquid or solid material for neutron detection. Experiments with simple geometries use a large cylindrical vessel of liquid scintillator [172–175]. In more complicated geometries, many small, radio-pure containment vessels may be required with the attendant risk of leakage. Liquid scintillator is attractive because larger amounts of dopant can typically be suspended in a liquid uniformly rather than homogeneously polymerized. Solid scintillator, on the other hand, can be easily machined, installed, and maintained. Additionally, many of the dopants used in liquid scintillator, for example trimethyl borate (TMB), are dangerous and highly flammable in liquid form, but can be stable when polymerized in a solid [178].

Gadolinium (Gd) has two isotopes with the highest neutron capture cross-section of any naturally occurring element, ^{155}Gd (14.7% natural abundance, cross-section $6.1 \times 10^{-20} \text{ cm}^2$) and ^{157}Gd (15.7% natural abundance, cross-section $2.6 \times 10^{-19} \text{ cm}^2$) [2]. The relaxation process after capture results in internal conversion electrons, Auger electrons, and γ 's. ^{157}Gd emits a cascade of γ 's, on average three, that have a total energy of 7.9 MeV; ^{155}Gd has a total of 8.5 MeV released in the capture process [179].

8.3 Veto Design Requirements

The effectiveness of an active neutron veto of solid scintillator with gadolinium as the primary capture compound was studied for the SuperCDMS SNOLAB experiment. Neutrons produced from internal contamination, specifically those within the layers of shield as with the cryostat cans, that create a single NR in the detectors will often interact in the inner polyethylene. Instead, if this layer were sensitive, the energy from the neutron

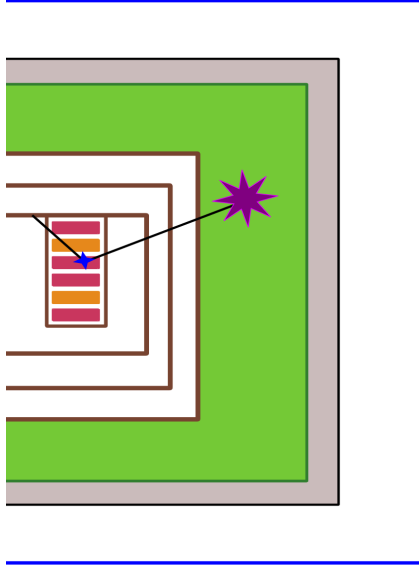


FIGURE 8.1: Cartoon demonstrating the active neutron veto rejecting a nuclear recoil single-scatter event. A neutron from a cryostat can deposit energy in a SuperCDMS SNOLAB tower and then passes into the veto. If the neutron is captured and sufficient energy is collected by the veto, the event can be rejected. The neutron is indicated by the black track. The cryostat cans and tower are in brown containing the germanium (pink) and silicon (orange) detectors; surrounded the cryostat are the active neutron veto (green), lead (gray), and water (white with blue edges) shielding layers. Energy is deposited in the detector (blue cross) and neutron veto (purple star).

capture could be collected and the event rejected. This process is illustrated in Fig. 8.1. Forming an active layer of shielding out of solid, doped scintillator could identify neutron events that also deposit energy in the detector. This increases the possibility of identifying NR single-scatter events that are otherwise indistinguishable from WIMPs.

A good veto would be able to reject 90 % of all NR single-scatter events. This effectiveness is quantized by defining an efficiency as the fraction of NR single-scatter events which also scatter back into the neutron veto and deposit energy above threshold in the scintillator within an integration time. The actual energy threshold will be determined by the light collection efficiency and photodetector threshold. The process of nuclear capture and the subsequent release of capture gammas takes hundreds of microseconds; thus, collecting all the light may require up to a millisecond. However, during that time, electronic noise will be collected along with any signal, making integration time a variable which must be tuned depending on desired dead time and the expected background rate.

During the design phase, many veto configurations were studied; thus, comparisons were benchmarked by the condition of 90 % efficiency at a 50 keV_{ee} threshold and a $100 \mu\text{s}$ integration time. A threshold of 50 keV_{ee} considers both quenching from dopants with products that create NRs (see Sec. 2.2.2)¹ or the potential escape of high energy

¹ Neutron capture on boron creates an α and lithium nuclei of $\sim 2.5 \text{ MeV}$. In boron-loaded linear

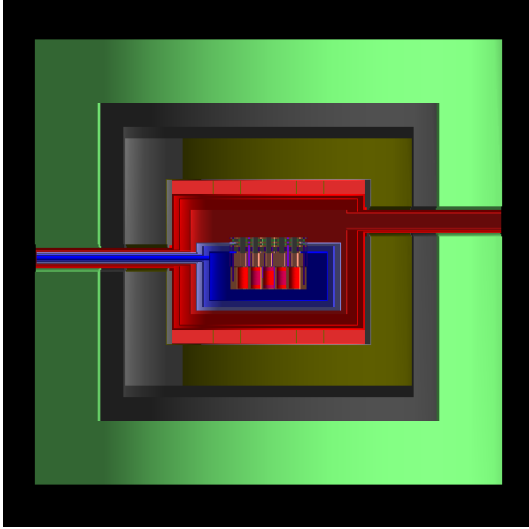


FIGURE 8.2: Cross-sectional view of the SuperCDMS SNOLAB geometry in SuperSim. The shielding layers consist of polyethylene (green), lead (gray), and the active neutron veto (mustard yellow). The outer three cryostat cans are given in red, and the inner three in blue. In the center of the cryostat sit the 25 towers of detectors. The two penetrations are the C stem (left) and E stem (right).

γ 's. In SuperCDMS SNOLAB, the rate of backgrounds above 50 keV_{ee} were projected to be less than 200 Hz ; with a $100 \mu\text{s}$ integration time after an iZIP trigger, less than 2% veto-induced livetime loss is expected [183]. These are referred to as the design parameters.

8.4 Plastic Neutron Veto with Gadolinium

8.4.1 Simulation Description and Analysis Criteria

Simulations were performed with SuperSim² for a geometry based on the October 2013 proposal to the DOE. A cross section is shown in Fig. 8.2. The shielding consists of an outer layer of polyethylene 60.94 cm thick, a 22.86 cm layer of lead, and a 40.64 cm inner active neutron veto. The detector payload investigated consisted of 25 towers of six detectors, containing 70 germanium detectors and 20 silicon detectors distributed throughout the towers for a total payload of 110 kg [183].

Two configurations were studied: scintillator uniformly doped with a variety of loading percentages and azimuthal segmentation where the scintillator is coated in gadolinium resin.³ Primary neutrons were thrown with an energy spectrum corresponding to

alkylbenzene, the measured energy is reduced to $50\text{--}100 \text{ keV}_{ee}$ due to quenching [180–182].

² For these simulations, GEANT4.09.05 and supersim-V00-00-10 versions were used.

³ See Sec. 8.4.2 for the description of the resin compound.

the equilibrium thorium chain and originated from the innermost cryostat can. The thorium spectrum is similar to other potential contaminants and the location is the mostly likely source of shield neutrons that make it to the detectors. The details of the optical photon propagation, the photodetector readout, and the associated backgrounds were not included. Instead, the overall energy deposition as a function of time is presented, to guide further development and to determine feasibility.

For this analysis, an event in the detectors was considered WIMP-like if it deposited energy in the range of 10–100 keV, more than 5% of the energy was in nuclear channels, and no other detector had an energy deposit (NRs or ERs) greater than 2 keV. These conditions were the only requirements imposed.

8.4.2 *Uniformly Doped Neutron Veto*

Initial simulations were completed with uniformly doped gadolinium in polyethylene, with various percentages by weight from 0.1% to 10% [184]. For the quenching of NRs, Birk’s constant for polystyrene was used [92, 185]. At design parameters, the 0.1% wt. Gd, the veto was 86 % efficient; it increased to 92 % efficient for 10% wt. Gd.

Since it is difficult to dissolve gadolinium in plastic at the concentrations simulated, the uniformly-doped plastic was compared to configurations where undoped plastic scintillator was interleaved with non-transparent layers of highly-concentrated gadolinium. This can be achieved with over-loading each scintillator layer and orienting the undissolved gadolinium along the bottom surface of each wedge or by coating undoped scintillators with a gadolinium resin. The latter option was modeled in GEANT4, using the following combination of compounds developed by the ZEPLIN-II experiment: 2.76 kg of gadolinium nitrate hexahydrate $[\text{Gd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}]$ combined with 1.92 kg of styrene monomer [186].

8.4.3 *Segmented Neutron Veto*

Azimuthal segmentation was implemented in SuperSim where each of the wedge-shaped segments was coated with the gadolinium resin as shown by the light grey layers in Fig. 8.3, which is an example of a veto design with 40 segments. In order to represent an exact replacement of the passive polyethylene shield layer, the active neutron veto layer thickness remained fixed at 40.64 cm. Thus, the amount of the scintillator must be

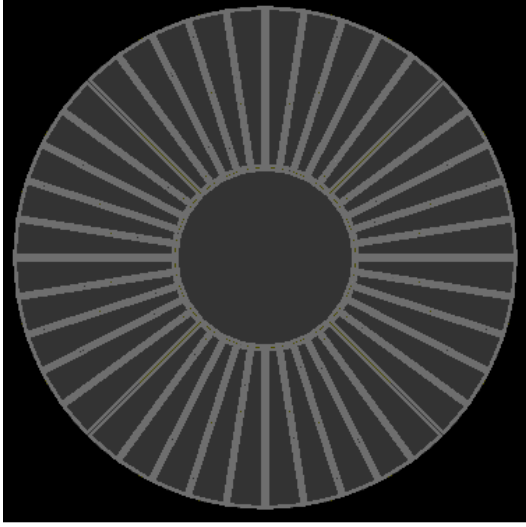


FIGURE 8.3: View from the top of the active neutron veto with 40 segments. The dark gray is scintillator and the light gray is the gadolinium resin.

reduced to accommodate an additional layer of gadolinium resin. The thickness of the resin was set such that the percent weight of gadolinium included in the total mass of the resin remained equivalent to the total amount of gadolinium in the uniformly doped scintillator option. Thus, as more segments were added for a more finely divided cylinder, the thinner the resin layer around each wedge (thickness calculations are presented in Appendix A). Table 8.2 gives the thicknesses of scintillator (outer arch length) and resin for segmentation of 40, 100, and 200 for two considered mass loadings.

The first set of configurations presented had an equivalent mass of gadolinium that was fixed at 1% wt. Gd uniformly doped and resin. Figure 8.4 shows examples of how the veto efficiency for a NR single-scatter event changes as a function of the veto energy threshold and the time window allowed for collecting energy deposited in the scintillator throughout the capture event. The lower the threshold energy, the more likely a NR single scatter is to be tagged by the veto. Four curves are shown on each figure, these correspond to 10 μ s, 30 μ s, 100 μ s, and 300 μ s. The efficiency of the veto increases with collection time. The actual integration time will be determined by practical considerations such as dead time and backgrounds.

Comparing the uniformly doped veto (Fig. 8.4a) with the segmented vetoes for 1% wt. equivalent doped gadolinium (Figs. 8.4b and 8.4c), the shortest timing windows never approach the efficiency of the uniformly doped configuration even with increased segmentation. Choosing the design parameters (integration time of 100 μ s

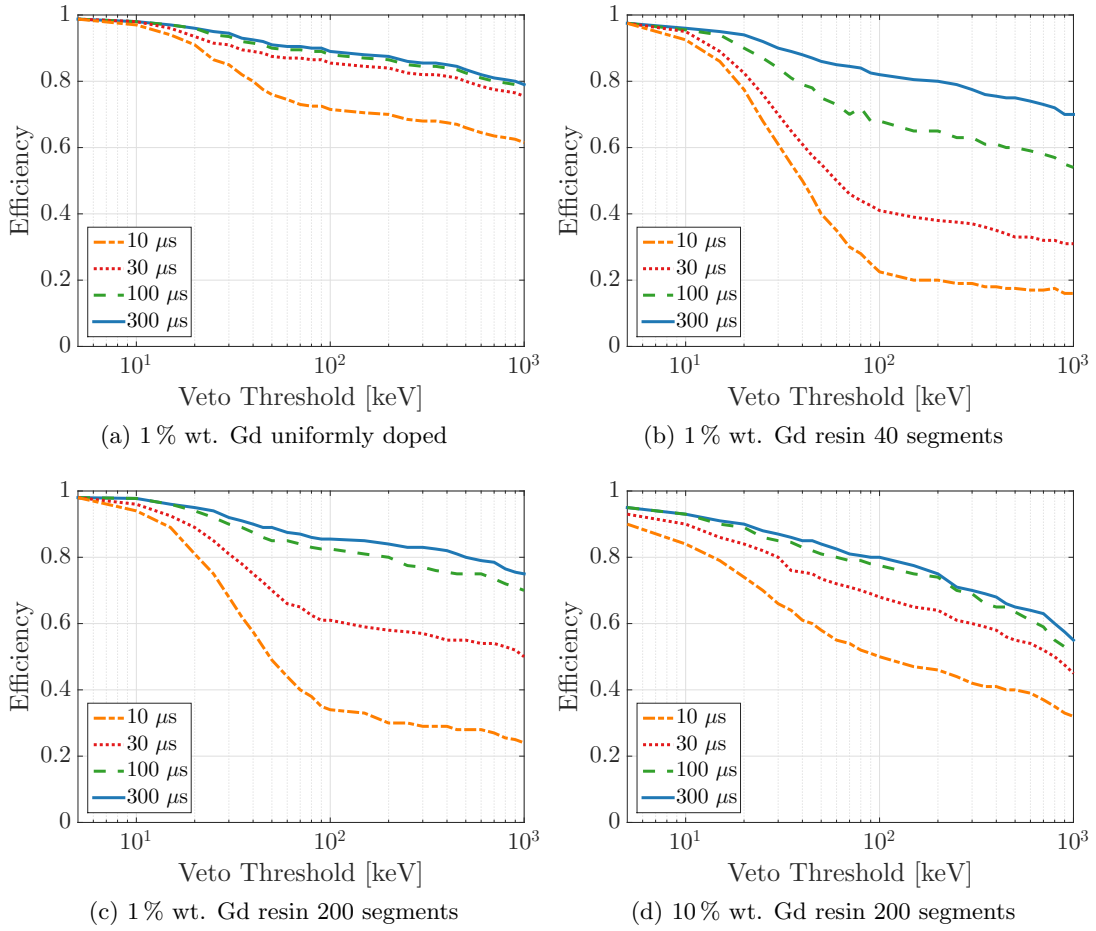


FIGURE 8.4: Efficiency of the active neutron veto for ^{232}Th neutrons from the innermost copper cryostat can as a function of threshold energy and integration times for various loadings and segmentations. (a) 1 % wt. Gd uniformly doped into the scintillator. 1 % wt. Gd equivalent mass applied as resin with 40 (b) and 200 (c) segments. (d) 10 % wt. Gd equivalent mass as resin for 200 segments. The integration times shown are $10\ \mu\text{s}$ (orange dash-dot), $30\ \mu\text{s}$ (red dotted), $100\ \mu\text{s}$ (green dashed), and $300\ \mu\text{s}$ (blue solid). Each plot has an equivalent number of initial primary neutrons simulated.

		Number of Azimuthal Segments		
		40	100	200
1% wt. Gd	Scintillator [cm]	10.57	4.17	2.07
	Gd Resin [cm]	0.17	0.097	0.056
10% wt. Gd	Scintillator [cm]	6.62	2.07	0.91
	Gd Resin [cm]	2.07	1.13	0.63

TABLE 8.2: Thicknesses of scintillator and resin for 40, 100, and 200 segments with 1 % and 10 % mass equivalent gadolinium.

and a 50 keV_{ee} threshold), the uniformly doped veto has an efficiency of 90 %. The segmented vetoes are only 15 %, 8 %, and 5 % less efficient for 40, 100, and 200 segments, respectively. This set of simulations suggest that, with a scintillator to resin ratio of 35:1 (calculated from Table 8.2), it is possible to come within 5% of the veto efficiency of a uniformly doped veto of mass equivalent 1 % with the same mass fraction in resin.

Another way to reach the veto efficiency of the uniformly doped configuration is to increase the thickness of the resin. Table 8.2 also gives the thicknesses of resin and scintillator for a 10 % mass equivalent gadolinium. The thickness of the resin increases in proportion to the increase in mass fraction; the resin for 40 segments was ~ 0.2 cm for 1 % and 2 cm for 10 %.

Figure 8.4d shows the efficiency for the veto with 200 segments at 10 % wt. Gd from ^{252}Th -like neutrons originating from the bulk of the inner cryostat can. The efficiency curves for the longest timing windows, 100 μs and 300 μs , are lower than for 1 % wt. Gd over all possible threshold values. This was characteristic of all segmentations and 10 % wt. Gd, though the largest decrease in efficiency was in the veto with 40 segments. For 40 segments, the required thickness of the resin comes to 2 cm (scintillator:resin ratio of 3:2), making it impossible to consider actually fabricating a 40 segment, 10 % mass equivalent gadolinium resin layer.

With 200 segments at the design parameters, the 10 % mass equivalent veto had an efficiency of 80 %, which is 10 % less efficient than the design goal. As with the 40 segmented veto, this is due to the decrease in the amount of scintillator. Since the resin is not an active part of the veto, there is effectively less energy in the veto which makes

it less efficient. However, there is an increase in the veto efficiency for all thresholds above 30 keV_{ee} for the shortest two timing windows (10 μ s and 30 μ s). Thus, if a short time window is necessary to identify NR single-scatter events, the ratio of scintillator to resin would be 13:9. This gives, for a threshold of 50 keV_{ee} and a timing window of 30 μ s, a decrease in veto efficiency of 13 %, where the 1 % uniformly doped veto is 87 % efficient.

Alternative Material

Gadolinium boride, GdB₆ was also considered as a possible dopant/resin material since it includes two elements with high neutron cross sections. It was discovered that when uniformly doped with 0.1 % equivalent concentrations of gadolinium, GdB₆ performed the same as pure gadolinium. When applied as resin on the surface of six segments in any level of thickness, the GdB₆ had worse performance. This is due to the fact that the α emitted by the boron does not reach the scintillator, but is trapped within in the resin. This option was not pursued since favorable results were achieved using a resin of gadolinium nitrate hexahydrate.

8.4.4 Summary

Based on the simulations presented here for an active neutron veto of the type studied for SuperCDMS SNOLAB, it is possible to approach the same level of veto efficiency as a uniformly doped gadolinium plastic scintillator by applying a gadolinium resin to the outside of small segments of scintillator. This study suggests that a ratio of approximately 35:1 of scintillator to resin will give efficiencies within 5% of the uniformly doped veto of the same gadolinium mass fraction. This is close to the design goal of 90%, but there is room for further optimization to narrow the difference. However, it is likely not possible to achieve the same sensitivity to neutron capture with a scintillator and resin mix as with a uniformly doped scintillator. The thickness of the resin should not exceed 1 mm.

CDMSlite Likelihood Limit and Future Outlook

A complete understanding of the backgrounds is necessary in order to implement likelihood techniques in the framework which set limits on the interactions between WIMPs and target nuclei. These likelihood analyses fold in information about the background when searching for a potential dark matter signal. Because of the developments in the understanding of the CDMSlite backgrounds through the work in this thesis, likelihood techniques were applied to the Run 3 analysis. There are also many future applications for these models and a variety of physics that can be extracted from further analysis of the CDMSlite data sets.

9.1 Applications of Current Background Models

9.1.1 *Profile Likelihood Ratio Method*

There are many benefits to using a profile likelihood ratio (PLR) method in searching for dark matter: it gives additional sensitivity beyond the optimum interval limit setting method [105] which can only produce upper limits; second, PLR can potentially be used for WIMP discovery; finally, the systematics are folded into the PLR technique and expressed in the final limit.

For a given WIMP mass m_χ , the hypothesis is tested that N_s signal events are present in the data, with the number of events proportional to the WIMP-nucleon cross

section σ . The probability of observing N_s signal events is calculated assuming the hypothesis is true.

The p -value of a hypothesis is computed in a number of steps [187]. First, the q statistic is calculated as

$$q_{N_s} = \begin{cases} -2\ln\lambda(N_s) & \hat{N}_s < N_s \\ 0 & \hat{N}_s > N_s \end{cases}, \quad (9.1)$$

where $\lambda(N_s)$ is a ratio of likelihoods for a given fit of a background and signal component to the data:

$$\lambda(N_s) = \frac{\mathcal{L}(N_s, \hat{\theta})}{\mathcal{L}(\hat{N}_s, \hat{\theta})}. \quad (9.2)$$

Here, $\mathcal{L}(N_s, \hat{\theta})$ is a likelihood fit with the signal constrained to the test hypothesis value N_s and $\hat{\theta}$ are nuisance parameters that maximize the likelihood with the constraint. The denominator of $\lambda(N_s)$ is the likelihood with no constraints applied; both the number of events N_s and the nuisance parameters θ are fit freely, and the values that maximize the likelihood are labeled $\hat{N}_s$ and $\hat{\theta}$, respectively. The ratio of likelihoods $\lambda(N_s)$ ranges from 0 to 1, with $\lambda(N_s) = 1$ ($q_{N_s} = 0$) corresponding to the most signal-like result (i.e. the best fit $\hat{N}_s$ equals the hypothesis value N_s).

The simple expression of the likelihood for a data set with N events of energy E_i is

$$\ln\mathcal{L} = -(N_s + N_b) - \ln(N!) + \sum_i^N \ln[N_s \times f_s(E_i) + N_b \times f_b(E_i)], \quad (9.3)$$

where N_b is the number of background events such that $N = N_s + N_b$, $f_s(E_i)$ is the probability distribution function (PDF) of the signal, and $f_b(E_i)$ is the PDF of the background.

The observed q statistic $q_{N_s, \text{obs.}}$ is calculated for a data set. Then, the probability of obtaining that value is given by

$$p_{N_s} = \int_{q_{N_s, \text{obs.}}}^{\infty} f(q_{N_s} | N_s) dq_{N_s}, \quad (9.4)$$

where $f(q_{N_s}|N_s)$ is the probability distribution function of q_{N_s} assuming the text hypothesis is true. This process is repeated in a scan over the number of signal events N_s to determine the probability of hypotheses and evaluate a cross section for WIMP interaction.

9.1.2 Results from CDMSlite Run 3

The likelihood given in Eq. 9.3 was expanded for the CDMSlite Run 3 analysis to include background contributions from tritium, Compton scattering, four activation peaks (^{71}Ge , ^{68}Ga , ^{65}Zn , and ^{55}Fe), and the three components of the surface events (TopLid (T), Housing (H), and Germanium (G)). Of these background components, only the surface events had constraints which were determined by the α study. Additional terms were added to the likelihood to allow the Lindhard yield model [160], signal efficiency, and resolution of the backgrounds to deviate from their central values given a Gaussian constraint [141].

Prior to unblinding the Run 3 data, a threshold p -value of 0.05 was chosen as the point of comparison for the observed p -value. A p -value below 0.05 indicates an incomplete, or inaccurate, background model, and the profile likelihood limit would be discarded. Once unblind, the observed p -value was 0.988, which indicated the developed background models describe the Run 3 data well. The background only fit that maximizes the likelihood is shown in Fig. 9.1.

The visualization of backgrounds in Fig. 9.1 cannot represent the various correlations between the components. For example, due to the voltage map systematics (see Sec. 7.3), the surface backgrounds were highly correlated. Additionally, there was covariance between the tritium and Compton backgrounds; in the Run 3 energy region of interest, 0.07–2 keV_{ee}, there were no features in the spectra to break the degeneracy between the tritium and Compton components.

The final 90 % confidence level (CL) PLR limit for spin-independent WIMP-nucleon cross section for WIMP masses below 10 GeV/ c^2 is given in Fig. 9.2. There is a factor of 2–3 improvement over the Run 2 optimum interval limit in the WIMP mass range of 2.5–10 GeV/ c^2 despite the reduced exposure (36 kg-days for Run 3 vs. 70 kg-days for Run 2) and increased background rate. Below 2.5 GeV/ c^2 no additional parameter space was excluded since the Run 3 threshold of 0.07 keV_{ee} was comparable to Run 2.

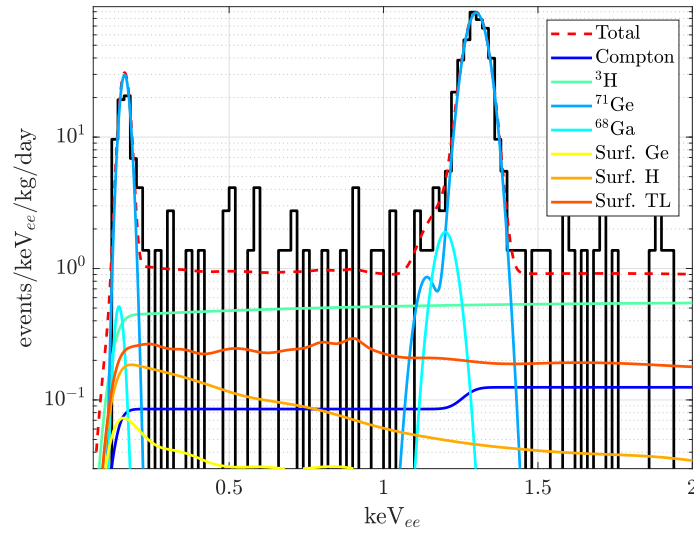


FIGURE 9.1: CDMSlite Run 3 final energy spectrum with the best-fit background components overlaid. The energy spectrum is given as the black histogram with the background spectra in color. These are Compton (dark blue), tritium (green), ^{71}Ge (blue), ^{68}Ga (light blue), germanium surface events (yellow), housing surface events (orange), and top lid surface events (red). The sum of the backgrounds is given as the red dotted line. The best-fit values for ^{65}Zn and ^{55}Fe are below the scale of the plot. This visualization suppresses the covariances between backgrounds. Figure from Ref. [141].

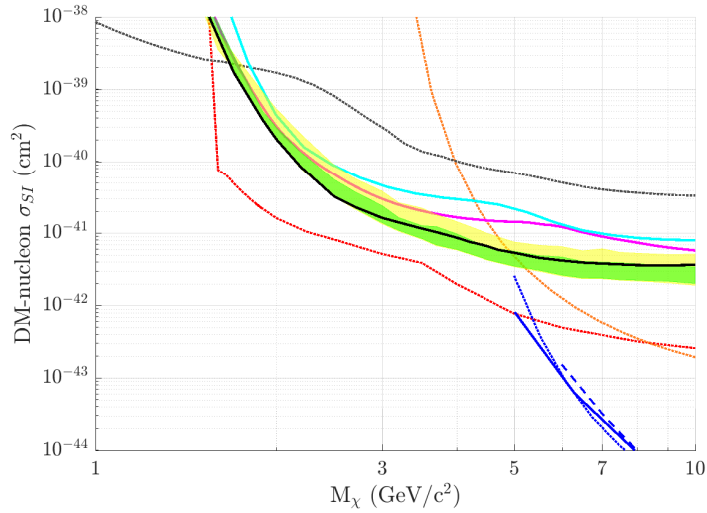


FIGURE 9.2: CDMSlite Run 3 90% CL PLR limit (solid black) compared with other current direct detection limits in the WIMP mass range of 1–10 GeV/c^2 . Also shown are the $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) sensitivity bands estimated before unblinding. The Run 3 PLR limit is compared with the CDMSlite Run 3 (cyan) and Run 2 (magenta) [106] optimum interval limits; and recent results from DarkSide-50 (red) [74], LUX (blue dotted) [60], XENON1T (blue dashed) [62], PandaX-II (blue solid) [61], PICO-60 (brown) [78], and CRESST-II (grey) [79]. Figure from Ref. [141].

9.1.3 *Additional Applications in CDMSlite*

A partial background model was used in two analyses of the CDMSlite Run 2 data. The first analysis used the Compton background and the analytical forms of the activation peaks and tritium to extract production rates of tritium and the other cosmogenic isotopes using a maximum likelihood technique [115]. A dark matter effective field theory analysis of the Run 2 data utilized the Compton and tritium background to set limits on the interaction of WIMPs through many additional interaction mechanisms that can include the spin and/or momentum of the WIMP and/or nucleus [188].

In the future, these background models can be used with CDMSlite data to do additional likelihood analyses on the Run 2, Run 3, or combined Run 2/3 data. Instead of searching for nuclear recoil signatures, dark matter candidates that produce electron recoils can also be considered. Some interesting models originate from dark sector theories which introduce a supplementary force mediated by a long-range gauge field, dark electromagnetism, which couples only to dark matter [189–192]. This force carrier is called the dark photon $\tilde{\gamma}$ and has a creation and annihilation interaction of $\chi\bar{\chi} \longleftrightarrow \tilde{\gamma}\tilde{\gamma}$. The interaction with the Standard Model would be provided by kinetic mixing between dark photons and ordinary photons, where the cross section of elastic scattering is related to the degree of kinetic mixing and the dark photon mass [191]. Many of these theories predict low-mass dark matter candidates for which low ionization threshold experiments, like CDMSlite, are ideal.

Another collection of these theories, called asymmetric dark matter (ADM), postulate an asymmetry between dark matter and its antiparticle linked to the baryon/anti-baryon asymmetry. Based in the observation that $\Omega_\chi \approx 5\Omega_B$, ADM models theorize this relationship is not coincidental, but a manifestation of the associated asymmetries [193–196]. Using the proton mass for m_B and the relation of relic densities gives a dark matter mass of $m_\chi \sim 5\text{--}15 \text{ GeV}/c^2$ [197, 198]; this mass range is optimal for low threshold experiments. ADM models are frequently broad and overarching, paring with other models to give numerous potential dark matter candidates [199, 200].

9.2 Future Outlook and Improvements

The models developed in this thesis are a significant first step toward understanding the backgrounds in SuperCDMS detectors. Though the spectral forms of Compton scattering and the ^{210}Pb surface events may not be directly transferable to SNOLAB detectors, the methodology of their development can be immediately applied. Moreover, in the transition period before the G4DMC is completely integrated into SuperSim, the detector response function has been shown to adequately model the CDMSlite data and, with alternative voltage maps, can help predict complex background spectra in the SNOLAB HV detectors.

New SuperCDMS Soudan data is also available to give further validation of the Compton spectrum and the yield model implemented in the detector response function. These come from a set of photo-neutron calibration data. For this data, γ radiation from ^{88}Y and ^{124}Sb sources interacted with a beryllium wafer creating photo-neutrons with a narrow range of energy; the small differences in energy are related to the outgoing angles of the neutrons. For ^{88}Y , the 1.84 MeV γ 's create neutrons with energy 148–156 keV, and the 1.69 MeV γ 's from ^{124}Sb produce neutrons of 21–25 keV. These low-energy nuclear recoils can be used to calibrate the nuclear-recoil equivalent energy scale, particular for CDMSlite- or HV-type detectors. This information on the yield model will help give more accurate background spectra for future analyses.

Additionally, data taken with the ^{88}Y or ^{124}Sb sources and no beryllium wafer give high statistics γ -only data in CDMSlite mode that can be analyzed for the lower-energy Compton steps, such as the L - and M -shell steps at 1.26 and 0.13 keV, respectively. This data can be used for further validation and improve the Compton model developed from GEANT4.

As data taking with SuperCDMS SNOLAB commences, it is likely that unexpected backgrounds will appear. Thus, there will be opportunities to further explore the variety of signals in germanium and silicon detectors and the way they respond to low-energy particle interactions.

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A

Calculations for the Active Neutron Veto Simulations

In order to accurately simulate the passage of particles through matter, GEANT4 requires the density of the material and its molecular makeup [121]. Thus, to construct the SuperCDMS SNOLAB active neutron veto from a plastic scintillator doped with gadolinium (Gd), both the percentage of the atoms in the compound and the resulting change in density of the plastic were necessary.

The segmented neutron veto had layers of gadolinium resin applied to the outer surfaces of each wedge-shaped piece. For comparison to the uniformly doped veto, an equivalent mass percentage of gadolinium was needed in the resin as uniformly doped. The details and assumptions of the calculation for the thickness of gadolinium resin are presented in this appendix.

A.1 Simple Chemistry

A.1.1 *Density of a Composite Material*

The density for materials of the same state (solid, liquid, etc.) is calculated equivalently to composite materials:

$$\rho_{\text{new}} = \frac{M_1 + M_2 + \dots}{\frac{M_1}{\rho_1} + \frac{M_2}{\rho_2} + \dots}, \quad (\text{A.1})$$

where ρ_{new} is the density of the new, mixed material; M_1 , ρ_1 are the mass and density of the first material, respectively; and likewise for the second material and third, etc.

Alternatively, if only two materials are integrated, the density of the new material is determined based on the fraction by mass of one of the materials. For the gadolinium doped polyethylene (poly), if x is the mass fraction of gadolinium, then the mass of the gadolinium is $M_{\text{Gd}} = x \cdot M_{\text{tot}}$, and the mass of the polyethylene $M_{\text{poly}} = (1 - x) \cdot M_{\text{tot}}$ where $M_{\text{tot}} = M_{\text{Gd}} + M_{\text{poly}}$. Thus,

$$\rho_{\text{doped}} = \frac{1}{\frac{x}{\rho_{\text{Gd}}} + \frac{1-x}{\rho_{\text{poly}}}}. \quad (\text{A.2})$$

An example of 1% wt. Gd, or $x = 0.01$, is used throughout this appendix; it is constructive for some of the more complicated calculations in Sec. A.2. With the fraction $x = 0.01$, $\rho_{\text{doped}} = 0.948 \text{ g/cm}^3$.

A.1.2 *Conversion to Volume of Gadolinium Resin*

The gadolinium resin consists of 2.76 kg of gadolinium nitrate hexahydrate $\text{Gd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (abbreviated GdNH), mixed with 1.92 kg of styrene monomer $\text{C}_{10}\text{H}_8\text{O}_4$ (abbreviated SM), and a small amount of catalyst [186]. For a direct comparison to the uniformly doped neutron veto, it is important to calculate an amount of resin that corresponds to the same mass fraction of gadolinium. The uniformly doped neutron veto has the following properties:

- radii: inner $R_i = 98.4234 \text{ cm}$, outer $R_o = 139.063 \text{ cm}$
- heights: inner $H_i = 159.39 \text{ cm}$, outer $H_o = 240.67 \text{ cm}$
- volume of the neutron veto: $V_{\text{NV}} = 9.771 \times 10^6 \text{ cm}^3$

The total volume of the veto must remain constant; as resin is added around the segments, the amount of polyethylene is reduced.

The densities of the required materials are:

- $\rho_{\text{GdNH}} = 2.332 \text{ g/cm}^3$
- $\rho_{\text{SM}} = 1.27 \text{ g/cm}^3$
- $\rho_{\text{resin}} = 1.736 \text{ g/cm}^3$ (using Eq. A.1)

- $\rho_{\text{poly}} = 0.94 \text{ g/cm}^3$
- $\rho_{\text{Gd}} = 7.9 \text{ g/cm}^3$

Extracting Mass of Gd

Since the loading of gadolinium occurs by mass fraction, it is necessary to determine the total mass of gadolinium in the polyethylene. This is the total veto volume multiplied by the mass fraction and the density of the doped polyethylene. For 1 % wt. Gd, the total mass is $M_{\text{Gd}} = x \cdot V_{\text{NV}} \cdot \rho_{\text{doped}} = 92664 \text{ g}$.

Converting to GdNH

The molar mass of GdNH is calculated using the molar mass of the atoms which form the compound and the chemical formula, $\text{Gd}(\text{NO}_3)_3 6 \text{H}_2\text{O}$:

$$\text{molar mass} = (\text{Gd}) + (3 \cdot \text{N}) + (3 \cdot 3 \cdot \text{O}) + (6 \cdot 2 \cdot \text{H}) + (6 \cdot \text{O}) = 451.52 \text{ g/mol.} \quad (\text{A.3})$$

Then, the percent by mass of gadolinium in GdNH is,

$$\text{Gd frac} = \frac{\text{Gd}}{\text{Gd}(\text{NO}_3)_3 6 \text{H}_2\text{O}} = 35 \%. \quad (\text{A.4})$$

Finally, the amount of GdNH necessary to achieve the same equivalent mass as in the doped polyethylene is given by

$$M_{\text{GdNH}} = \frac{M_{\text{Gd}}}{\text{Gd frac}}. \quad (\text{A.5})$$

Again, considering 1 % wt. Gd, the weight calculated was 93 kg, which gives a total mass of GdNH as $M_{\text{GdNH}} = \frac{92664 \text{ g}}{0.35} = 265614 \text{ g}$.

Calculating Amount of Resin

To calculate the corresponding amount of resin, the mass of SM is needed. This is accomplished using the ratio of the two masses from the recipe:

$$M_{\text{SM}} = M_{\text{GdNH}} \cdot \frac{1.92 \text{ kg} \cdot \text{SM}}{2.76 \text{ kg} \cdot \text{GdNH}}. \quad (\text{A.6})$$

Thus, the total mass of resin is $M_{\text{resin}} = M_{\text{GdNH}} + M_{\text{SM}}$, and the volume of resin

$$V_{\text{resin}} = \frac{M_{\text{resin}}}{\rho_{\text{resin}}}. \quad (\text{A.7})$$

Continuing, with the demonstrative example of 1% wt. Gd, the mass of SM is

$$M_{\text{SM}} = 265614 \text{ g} \cdot \frac{1.92 \text{ kg} \cdot \text{SM}}{2.76 \text{ kg} \cdot \text{GdNH}} = 184775 \text{ g}, \quad (\text{A.8})$$

giving a total mass of $M_{\text{resin}} = 450389 \text{ g}$ for the resin. The necessary volume of resin is then

$$V_{\text{resin}} = \frac{450389 \text{ g}}{1.736 \text{ g/cm}^3} = 259441 \text{ cm}^3. \quad (\text{A.9})$$

A.2 Thicknesses of Resin for Neutron Veto

There were two configurations of the neutron veto simulated for which resin was applied. The continuous veto was the geometry with the resin on the outer and inner surfaces of the polyethylene, or scintillator. The segmented veto had the polyethylene separated like staves of a barrel with resin on the outside of each piece.

A.2.1 *Continuous Veto*

A cartoon of the continuous veto showing the locations of the resin on the inner and outer surfaces of the scintillator is given in Fig. A.1.

It is imperative that the total volume of the veto remain constant. To include layers of resin, the volume of the scintillator must decrease, thus

$$V_{\text{NV}} - V_{\text{resin}} = V_{\text{poly}}. \quad (\text{A.10})$$

This volume can be calculated by subtracting the inner cylinder volume from the total volume

$$V_{\text{poly}} = \pi \left[(R_o - t)^2 \cdot (H_o - 2t) - (R_i + t)^2 \cdot (H_i + 2t) \right], \quad (\text{A.11})$$

which is solved for the thickness t of the resin.

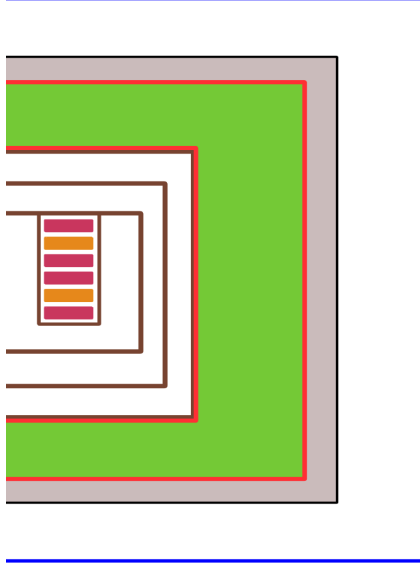


FIGURE A.1: Cartoon of the SuperCDMS SNO-LAB active neutron veto showing the locations of scintillator and resin for the continuous veto configuration. The cryostat cans and tower are in brown containing the germanium (pink) and silicon (orange) detectors; surrounded the cryostat are the active neutron veto (green), lead (gray), and water (white with blue edges) shielding layers. A layer of resin is applied to the inner and outer surfaces of the scintillator (salmon).

A.2.2 Segmented Veto

It is more feasible that the neutron veto will be constructed from many extruded pieces of scintillator, like the staves of a barrel, making it possible to coat the outside of each piece with resin. A sketch of this idea with the resin and scintillator identified is shown in Fig. A.2. It is likely that the veto will be stacked, with a cap of thickness $(H_o - H_i)/2$ on the top and bottom, and segments of height H_i around the detector cavity.

Keeping the volume of the veto constant, an equation is written for the volume of polyethylene as a function of the thickness of the resin. However, there will be a new parameter, the number of staves to the barrel. The resulting expression can be evaluated with a numerical solver.

All sections, except the center two circles of the caps on the top and bottom, have the same general shape, which is shown in Fig. A.3. This gives an exaggerated view of the polyethylene with a uniform thickness of resin around the edges. The inner and outer radii are the same as the previous geometry.

If the lines of uniform thickness are continued until they cross the radial lines (red dotted lines), the angular spread of the consecutive pieces is equivalent. Shifting the polyethylene down by the amount of the thick blue line (see Fig. A.3) covers a distance $x = t / \sin(\theta/2)$, where the blue line bisects the angle of the segment. The number of

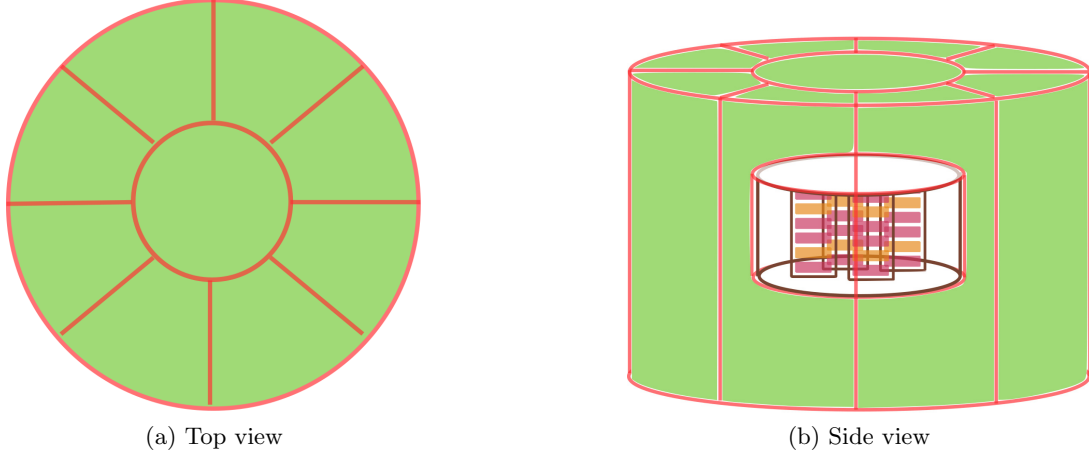


FIGURE A.2: Cartoon of the SuperCDMS SNOLAB active neutron veto showing the locations of scintillator and resin from the top (a) and side (b) for the segmented veto configuration. The cryostat cans and tower are in brown containing the germanium (pink) and silicon (orange) detectors; surrounded the cryostat is the active neutron veto (green) with a layer of resin is applied to the inner and outer surfaces of each scintillator segment (salmon). The veto caps are not accurately depicted.

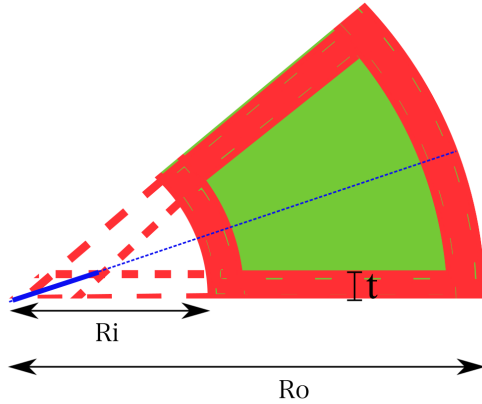


FIGURE A.3: An exaggerated view of one of the sections of the veto for parameter definition. The resin (salmon) of thickness t is applied to the scintillator (green). The inner radius of the veto is R_i and the outer radius R_o . The angle of the segment is given by θ .

segments n determines θ as $\theta = 2\pi/n$. This effectively removes the resin on the sides of the section and creates a simple circle of pure polyethylene. The radii are reduced by the amount x , and the cross-sectional area of the adjusted segment is

$$A_{\text{poly}} = \pi (r_o^2 - r_i^2) \quad (\text{A.12})$$

where $r_o = R_o - t - x$ and $r_i = R_i + t - x$.

Using this adjusted segment, the volume of the various components to the veto are calculated

I. Segments around cryostat cavity

The cryostat cavity has a height of H_i , but the layer of resin added must reduce the height of the polyethylene by $2t$. Thus, the volume of the polyethylene just around the cryostat cavity is

$$V_{\text{seg,cavity}} = A_{\text{poly}} (H_i - 2t). \quad (\text{A.13})$$

II. Segments of veto caps

The height of the two caps on the veto, assuming just polyethylene, is given by $\frac{H_o - H_i}{2}$. Adding the resin layers requires the subtraction of $2t$ giving

$$V_{\text{seg,caps}} = A_{\text{poly}} \left(\frac{H_o - H_i}{2} - 2t \right). \quad (\text{A.14})$$

III. Inner circles of caps

The radius of the inner circle of the caps will only be reduced by t with a height the same as for the segments of caps, $\frac{H_o - H_i}{2}$, so

$$V_{\text{circle,caps}} = \pi (R_i - t)^2 \left(\frac{H_o - H_i}{2} - 2t \right). \quad (\text{A.15})$$

Each of these pieces are added together to determine the total volume of polyethylene. There are two caps, therefore II. and III. must be multiplied by two:

$$V_{\text{poly}} = V_{\text{seg,cavity}} + 2 \cdot V_{\text{seg,caps}} + 2 \cdot V_{\text{circle,caps}} \quad (\text{A.16})$$

$$= \pi \left[(R_i - t)^2 (H_o - H_i - 4t) + (r_o^2 - r_i^2) (H_o - H_i - 4t) + (r_o^2 - r_i^2) (H_i - 2t) \right]. \quad (\text{A.17})$$

The number of segments gives the value of θ used in calculating x , r_i , and r_o . With a known volume of resin and Eq. A.10, the thickness t of the gadolinium resin is determined for the segmented neutron veto given a particular gadolinium concentration of the uniformly doped veto.