

REJECTING OUTER RADIUS BACKGROUNDS IN
SUPERCDMS HIGH VOLTAGE
DARK MATTER SEARCHES

by

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Abstract

SuperCDMS searches for Dark Matter in the form of WIMPs. SuperCDMS is able to reject most common background events by discriminating between electron and nuclear recoils. In the CDMS low ionization threshold experiment mode, electron recoil discrimination is sacrificed when applying a stronger electric potential across the detector. The electric field associated with this potential is not uniform, and the amplification of the phonon signal caused by drifting charges through this potential creates a radial dependence on the reconstructed energy. This thesis explores a new method of identifying and rejecting events at the edge of the detector in order to improve the ratio of signal to background by excluding background events with improperly reconstructed energy.

Acknowledgments

This work takes place under the mentorship and assistance of my supervisor Dr. Wolfgang Rau. Many thanks to him for all of the time he has spent in instructing me and giving feedback on my research. Also thanks to Kedar Page who was instrumental in learning about SuperCDMS and research in general. Colleagues contributed to this work are Adam Anderson at MIT who provided some of the framework for simulations, Muad Ghaith and Xiaohu Zhang who assisted with all lab work at Queen's, and Eleanor Fascione and Amy Warchuk who helped analyze the results of the initial radial simulations I produced. Many thanks to all analyzers in the SuperCDMS analysis and CDMSlite groups, and members of the SuperCDMS collaboration in general who provided feedback and ideas on my research many times throughout the two years I conducted this work.

All of my love to Sofija.

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Chapter 1

Introduction

1.1 Motivation for the Search for a New Kind of Matter

Astronomical evidence for the existence of a non-luminous type of matter has been produced in many contexts [1, 2, 3, 4]. This non-luminous matter comprises more than 25 % of the energy density of the universe and around five times as much of the universe as luminous matter [2]. This matter is non-baryonic and has very weak interactions with other kinds of matter [5]. Strong candidates for dark matter are Weakly Interacting Massive Particles (WIMPs) produced in the big bang [6]. WIMPs may interact, though only extremely infrequently, with ordinary matter in reactions that cause nuclear or electron recoils [1]. The Cryogenic Dark Matter Search (CDMS) attempts to find evidence of WIMPs by looking for heat and charge signals resulting from recoils in cryogenically cooled Germanium crystals [7]. Radial dependent backgrounds created by incorrectly reconstructing energies of events due to a distorted electric field limits how well one can search for WIMPs in one of the operating modes of SuperCDMS [8, 9]. I will demonstrate that a radial parameter built from the phonon pulse-signal shape can be used to select a subset of events which we will

eliminate due to outer radius backgrounds in the detector; a radial cut. I will then show my usage of this radial cut in SuperCDMS high voltage dark matter searches, and how it allows probing of a new parameter space in the search for WIMPs.

1.1.1 Astronomical Evidence for Dark Matter

Early astronomical evidence for dark matter was found by Fritz Zwicky and Jan Oort in the 1930s. Fritz Zwicky made the observation when analyzing the Coma cluster that the average density of matter would have to be about 400 times that of the observed luminous matter to account for the rotational speeds observed with the Doppler effect [10].

Evidence for dark matter is found on smaller scales than clusters as well. Oort measured the tangential velocity distribution of stars in the Milky Way galaxy as a function of radius [11]. The gravitational potential, which is inversely proportional to the distance from the source, exerts a force that should be predictable based on the observed mass of objects within a galaxy. The inward force in turn should provide a mean tangential velocity of stars and dust orbiting the centre of the galaxy that is a function of distance from the center of the galaxy, which for stars in the Milky Way should rapidly drop off after 3 kpc, as that is where the density of visible matter sharply drops off [12]. The velocity should fall off as:

$$v(r) = \sqrt{(G * M/r)}. \quad (1.1)$$

However, what is measured (see Figure 1.2) is that the velocity does not drop off with the visible matter density [12]. Instead, it remains approximately constant

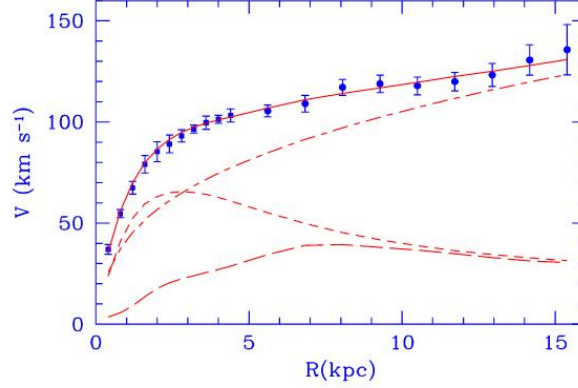


Figure 1.1: The tangential velocity of stars in the Milky Way (1) as observed (data points and fit shown in solid red), (2) as predicted by measuring the visible mass in the stellar disk (short dashes), (3) the contribution from gas (long dashes), and (4) the invisible dark matter halo contribution to the velocity function (mixed long and short dashes) [12].

well into the halo (the approximately spherical component of a galaxy which extends beyond the main (visible) component [12]). This implies that a vast amount of dark matter is located here, as the overall galactic mass distribution does not drop off with the density of visible stars and dust. Vera Rubin confirmed that this is not unique to the Milky Way galaxy by using the Doppler shift of emission lines in the arms of the Andromeda galaxy to calculate the velocity distribution there [13]. Similar to the Milky Way, the velocity of Andromeda does not drop off as $1/\sqrt{r}$.

Sofue and Rubin calculated the velocity distributions of many galaxies. Shown in Figure 1.2, many observed galaxies demonstrate a similar velocity structure. These galaxies also show a distribution of the density of stars and dust that decreases as a function of radius without the velocity distribution falling in parallel, indicating the presence of dark matter [13].

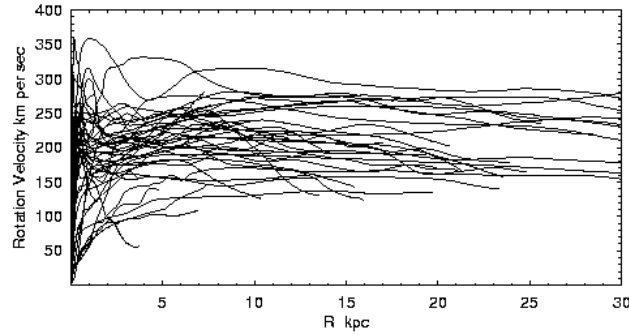


Figure 1.2: The tangential velocity of stars in many galaxies as observed by Sofue and Rubin, generally demonstrating that velocity does not fall as $1/\sqrt{r}$ [13]

1.2 What is Dark Matter?

From the previous section, we see that that galaxies and clusters have more mass than can be accounted for by visible matter. Various proposed solutions to the problem and their flaws, such as different theories of gravity, uncounted normal matter, and undiscovered particles are presented here as an explanation for the observations.

1.2.1 MOND

One hypothesis is that the current theory of gravity is incorrect at long distances or with small accelerations, and so galaxies and clusters not behaving the way solar system scale objects do is not unexpected [14]. This theory, known as MOdified Newtonian Dynamics (MOND) can be fine-tuned to correctly solve almost any individual galaxy's velocity distribution function. Additionally, changes have to be built in to account for the observed Tully-Fisher Law that states the Luminosity of a galaxy is proportional to the average tangential velocity of the halo to the fourth power. The

consequence of this is the velocity function of any point mass must absolutely behave asymptotically, and any evidence of a single galaxy with a velocity function that falls off near $1/r$ would falsify most theories of MOND [14].

Imposing MOND becomes more difficult when one analyzes galaxy clusters. General relativity demonstrates the path photons take are influenced by gravity. If an object is far enough away and has a massive object in front of it, the path of the photons emitted by the more distant object can be such that distorted or multiple images of the further object can be seen around the closer object in a process called gravitational lensing. This can help us differentiate between the theories as it allows us to probe the distribution of the matter in the lensing object[15].

Large objects such as colliding galaxy clusters are ideal test subjects for the MOND versus dark matter theory. By analyzing the stretching and skewing of distant background galaxies into Einstein rings (images of the distant cluster bent around closer lensing objects into a ring or similar shapes) (see Figure 1.3), a mapping of the gravitational potential of the foreground object can be produced.

When galaxy clusters collide, stars and (theoretically) dark matter move through without interaction. The gas and plasma that make up most of the baryonic mass density of the cluster undergo collisions, electromagnetic braking, and create shock waves of slowed matter which clumps towards the center of the collision. The predictions for the distribution of gravitational potential of colliding clusters for MOND and dark matter differ greatly. Figure 1.4 shows how gravitational mapping of the Bullet cluster by Clowe et al. provides evidence that greatly supports the dark matter model over MOND [15].

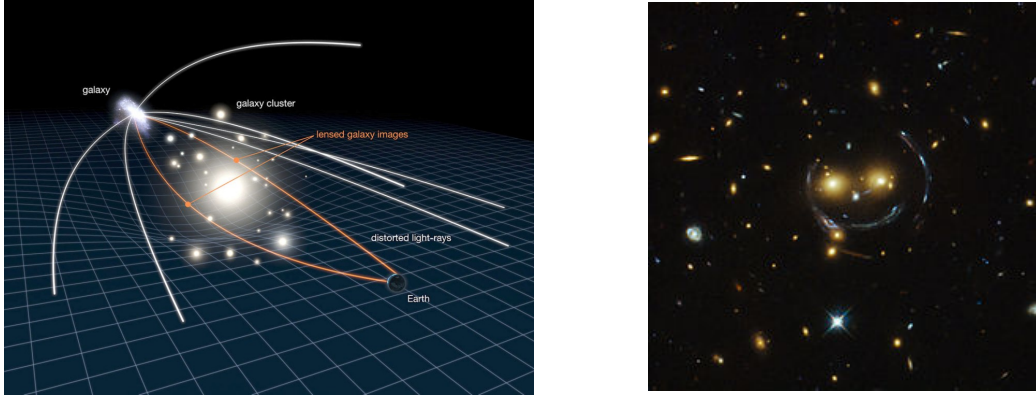


Figure 1.3: The left diagram (from a NASA example) shows ray tracing of light rays around a closer massive object, and how the same object can appear in separate images in the sky [16]. The right image is from NASA's picture of the day archive and shows an example of a distant galaxy's image curved in a near circle around a closer cluster [16].

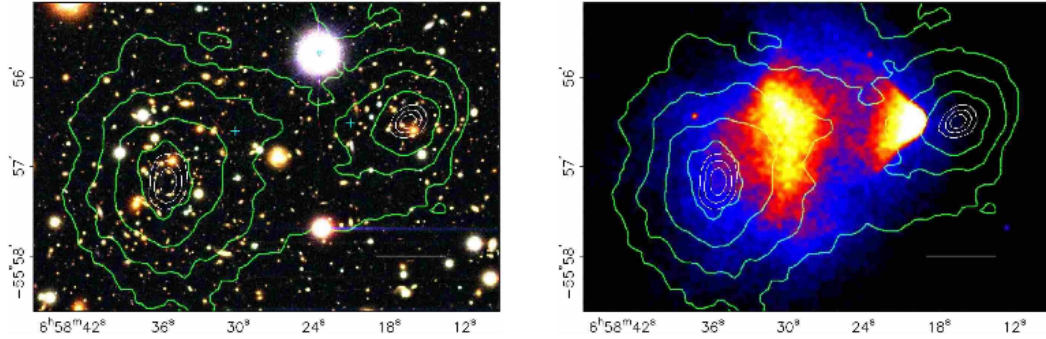


Figure 1.4: The left image is the visual spectrum of the Bullet cluster. Overlaid are mass contour rings showing the center of mass of each cluster. The rings at the center of each separated cluster show high mass regions. On the right, this is compared to the x-ray distribution from hot intergalactic plasma. This represents a majority of the baryonic matter of the distribution. This is located closer to the center of collision. This favours dark matter over MOND because in MOND, the potential should be located around the visible matter. Taken from [15].

1.2.2 MACHOS

By eliminating the possibility of the theory of gravity being incorrect, and accepting there is some additional mass, we consider now whether this missing mass comes in

large or small forms. The theory of Massive Astrophysical Compact Halo Objects (MACHOs) predicts that some or all dark matter is composed of large astronomical bodies, which do not emit much light and thus go unaccounted for in estimates of galactic mass functions (based on luminosity). Isolated black holes, cold white dwarfs, brown dwarfs, planets, and even asteroids could potentially contribute overlooked mass in galaxies' matter components. These objects may emit only small amounts of infrared light that are very difficult to measure directly.

Fortunately, there is another method of detection for these objects. If a MACHO in the galaxy passes in front of a background object, gravitational lensing (the magnification of the background object's light through curving multiple images of the object to the same location), can be used to search for invisible foreground objects. The amplification A of a background object at r_0 has two solutions both images it creates on either side of the lensing MACHO. These solutions are

$$A_{1,2} = abs\left(\frac{r_{1,2}dr_{1,2}}{r_0dr_0}\right) = abs\left(\frac{r_{1,2}^4}{r_{1,2}^4 - R_0^4}\right) \quad (1.2)$$

where $r_{1,2}$ are the two solutions to the positions of the magnified images of the background star [17]. These are represented with equations

$$r_{1,2} = [r_0 \pm (r_0^2 + 4R_0^2)^{1/2}]/2. \quad (1.3)$$

R_0 is the radius of the annular image when the MACHO and the background star are perfectly aligned. The two amplifications are added to become

$$A \equiv A_1 + A_2 = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}} \quad (1.4)$$

where $u \equiv \frac{r_0}{R_0}$ [17]. Whenever an object in the Milky Way passes in front of a distant light source, it causes an amplification of this type, called a microlensing event. The frequency and strength of microlensing events by invisible objects in our galaxy per unit time per unit area of sky gives an approximate number and distribution of MACHOs. This allows a limit to be set on the amount of dark matter MACHOs can explain [17]. The OGLE-III experiment is one of the most recent and most sensitive surveys of microlensing events, and puts limits on the existence of MACHOs as 3 ± 2 % of the Galactic halo mass (see Figure 1.5), which is clearly insufficient to explain most dark matter [18].

1.2.3 WIMPs

Ruling out MOND and MACHOs, dark matter is likely composed of small particles. Molecules and atoms of normal, baryonic matter glow in the infrared, visual, or x-ray. They create absorption or emission lines and are thus relatively easily quantified and accounted for in the calculated masses of galaxies and clusters. Neutral Hydrogen may be the hardest to account for, but the uncertainty on the amount of it is about $\pm 5\%$ [19]. Looking at 21 cm light from the forbidden transition between aligned and unaligned spin of the proton and electron, we can estimate the amount of neutral Hydrogen [19]. Dark matter cannot be made of any charged particles as they would interact with photons and clump in Neutron stars, causing collapse of all neutron stars into black holes on the order of tens of years [20].

The majority of dark matter was produced in the big bang, and given its current

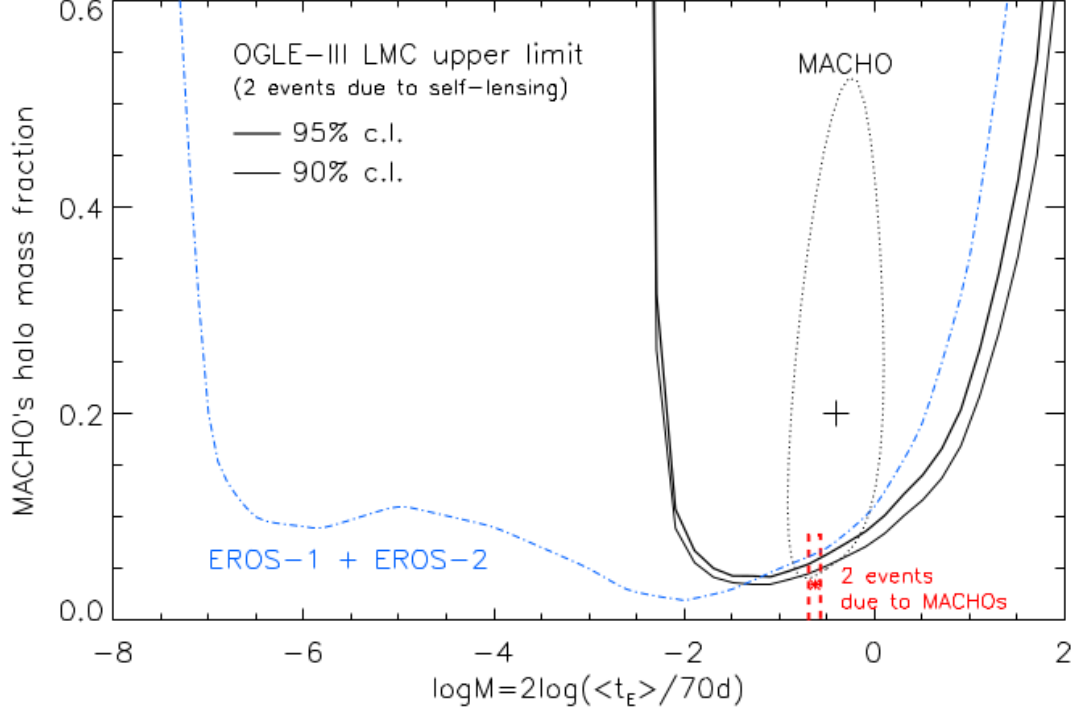


Figure 1.5: Limits on MACHOs as a fraction of the dark matter halo, as a function of MACHO size set by the OGLE-III survey, where M is the mass of the average MACHO, and $\langle t_E \rangle$ is the mean time scale of detections in days. Values above the line are excluded. Two potential MACHO lensing events (red dots) and the phase space they would indicate (red box) are seen at the bottom right. Taken from [18].

density must be very stable [5]. As such, neutrinos are left as the only reasonably stable, neutral, standard model dark matter candidate. However, data from the cosmic microwave background (CMB) suggest that neutrinos' mass and density make them insufficient to explain the majority of dark matter [21]. Additionally, neutrinos are “hot” particles (having a relativistic velocity). Many models of large scale structure formation require a dark matter “seed,” a higher density region which helped the collapse of normal matter into large-scale structures, clusters, and even galaxies [22].

Many simulations of hot dark matter show that it is not capable of being the kind of seed consistent with producing the observed structure. This means dark matter is “cold” (slowly moving, able to clump) [21].

The absence of any known particle, object or force fulfilling the properties of dark matter that we have observed motivates a search for physics beyond the standard model (BSM). Many BSM theories like supersymmetry predict a Weakly Interacting Massive Particle (WIMP) that fits all the properties of dark matter (cold, stable, neutral, weakly interacting) [23]. In simple supersymmetric models, every standard model particle (plus a second Higgs boson) has a partner particle. The partner particles of the B^0 , W^0 and Higgs bosons mix to form four neutral states called neutralinos. The lightest of these particles would be stable and a perfect WIMP dark matter candidate [24].

There are other proposed particles to explain dark matter such as axions [25] (which are proposed as a mechanism to explain why CP violation is so minimal in QCD) and sterile (right handed) neutrinos [26] (which could also explain neutrino oscillations and the baryon-antibaryon asymmetry in the universe). This thesis will focus on the search for WIMPs, which is the dark matter candidate potentially most accessible to the SuperCDMS experiment [8].

1.3 Methods of detection

There are three primary methods of searching for WIMPs.

1.3.1 Production Channel

The production channel involves high energy particle interactions at colliders like the Large Hadron Collider (LHC), where energy from the collision may convert into a WIMP [27]. As there are sophisticated detectors calibrated to look for all kinds of particles coming out, any missing energy from the collision that cannot be accounted for by neutrinos or other neutral standard model particles may be a WIMP [28]. As of 2016, there is no evidence of an above the standard model background in either of the two major experiments at the LHC; A Toroidal LHC ApparatuS (ATLAS) or the Compact Muon Solenoid (CMS) in their 8 TeV dark matter searches [29].

1.3.2 Indirect Detection

The indirect detection channel is a search for evidence of dark matter decay or self-annihilation in unidentified emission lines from areas of high dark matter density like the centers of galaxies [30]. Due to their high dark matter content, and the fact that they lack many astrophysical backgrounds, the Milky Way's dwarf spheroidal galaxies are widely considered to be among the most promising targets for the indirect detection of dark matter via γ ray detection [31]. Ackermann et al. set limits on the order of $10^{-23} - 10^{-26}$ on the dark matter self-annihilation cross section for WIMPs between 1 GeV and 1 TeV [31]. There have been a few claims of unexplained γ ray emission lines but further evidence has cast doubt on many of the claims [30].

1.3.3 Direct Detection

The direct detection channel, which will be explored further, is the search for nuclear recoils caused by dark matter weakly interacting with particles in sensitive detectors.

There are three primary ways to detect recoils: through scintillation, ionization, and heat (phonon) signatures. A graphic showing most experimental methods and corresponding experiments which use these methods is shown in Figure 1.6. Figure 1.7 shows current results in direct dark matter searches. In this thesis I will focus on SuperCDMS and phonon detection.

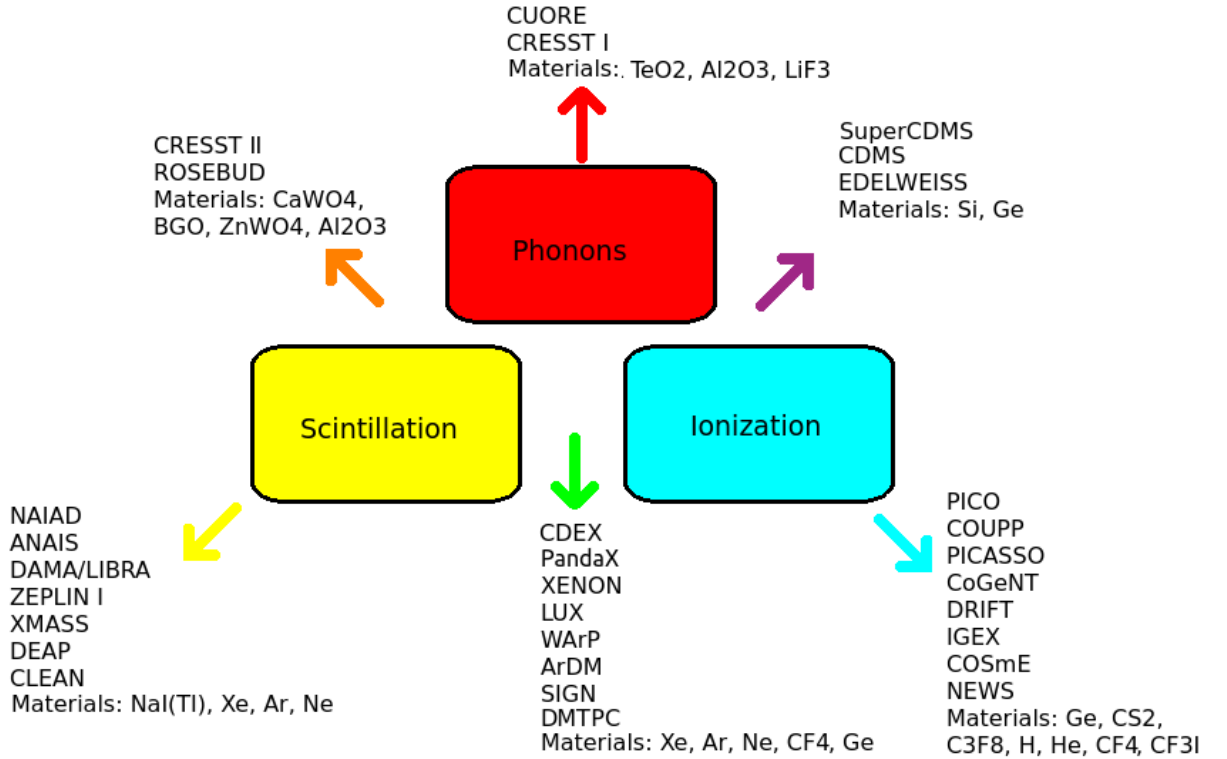


Figure 1.6: Direct searches look in three different channels for dark matter, some of them in multiple channels. Here SuperCDMS is a Ge experiment in the ionization and phonon category. Information compiled from similar graphics in [32, 33].

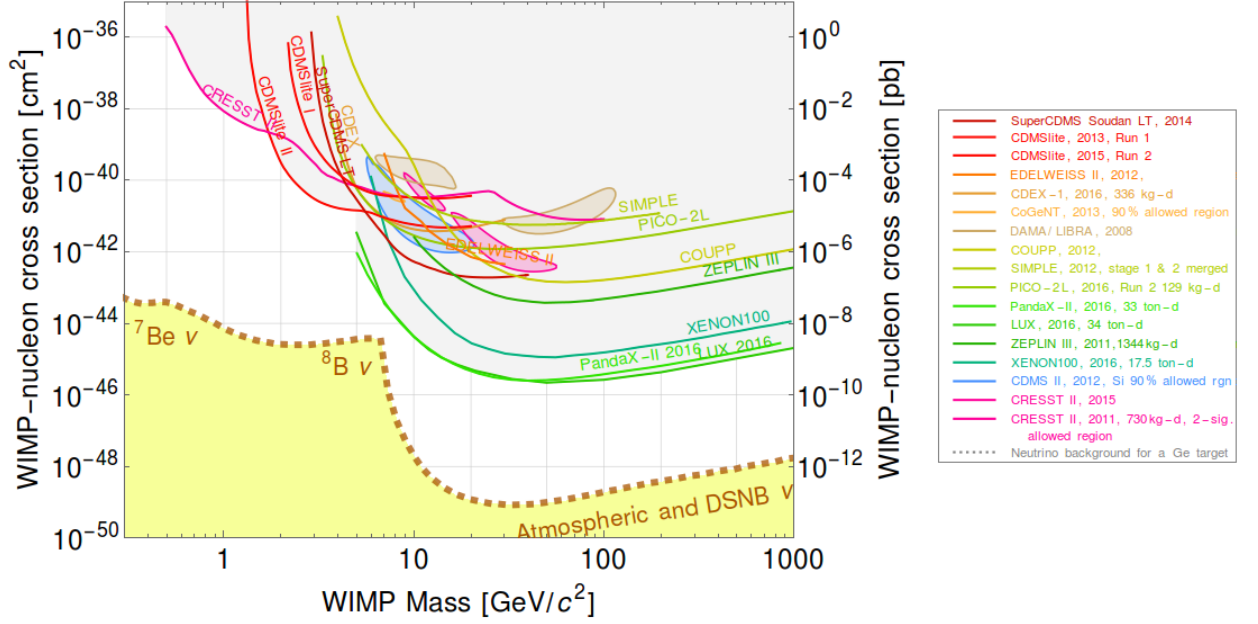


Figure 1.7: Current direct search results in the search for dark matter. Shaded regions are potential signals, lines mark excluded regions in WIMP-nucleon cross section versus WIMP mass. Note low mass detectors (like Ge, Si, CaWO_4 based) dominate the low WIMP mass search, and heavier noble liquid and gas detectors dominate high WIMP mass searches [7, 8, 9, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46]. (References match order of appearance in legend)

1.4 SuperCDMS

The Super Cryogenic Dark Matter Search (SuperCDMS) is an experiment which attempts to discover or place limits on the existence of low mass WIMPs (with a focus below 15 GeV) through ionization and phonon detection [8]. The SuperCDMS Soudan experiment, a successor to the CDMS II experiment, was located at the Soudan Mine in Northern Minnesota from 2012 to late 2015. This experiment consisted of fifteen 620 g Germanium crystal disks, each approximately 3" in diameter and 1" thick [8]. These disks are semiconductor detectors that measure heat and ionization released

from interaction energy deposited in the crystals [8].



Figure 1.8: Layout of SuperCDMS phonon and charge sensors. Each side has three pie wedge shaped phonon sensors and a ring shaped channel around the outside, and two charge sensors. The alignment is rotated by 180 degrees between the sides. [47]

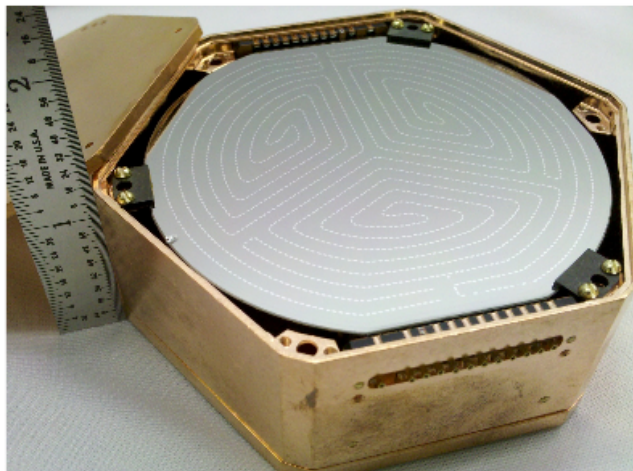


Figure 1.9: SuperCDMS iZIP detector [48].

Germanium is a material of choice for dark matter searches for several reasons. Germanium is a semiconductor, and when cooled to approximately 50 mK, as it is

for the SuperCDMS data taking, has a band-gap between the valence and conduction bands of $E_g = 0.74 \text{ eV}$ [49]. With an electric field applied across the detector, electron-hole pairs liberated by the recoil are drifted apart and collected on the surface. Image charges are induced on the surface and a signal is read out by a coupling capacitor [33]. Particle interactions which cause a recoil in the semiconductor also produce quanta of vibrational energy in the form of athermal phonons.

The SuperCDMS detectors are Germanium crystals with charge and phonon sensitive sensors on the surface [8]. Each side of the detector has four phonon sensors (arranged as in Figure 1.8) and two charge sensors interleaved with the phonon sensors. The detectors are called “interleaved Z-sensitive Ionization and Phonon detectors” (iZIPs). An image of a SuperCDMS iZIP can be seen in Figure 1.9.

1.4.1 Phonons

Phonons are produced in crystals like Germanium when a particle transfers energy to the lattice through interactions such as elastic scattering events. The energy is dispersed in these quasi-particles which are quanta of vibration. High energy phonons produced via a nuclear or electron recoil have high scattering rates ($\tau = 36.7 \times 10^{-42} \nu^4$ for Ge, where ν is the frequency of vibration) [50], which results in a short mean free path and highly diffusive scattering of the phonons. Additionally, phonons constantly decay into two-lower energy phonons until the lattice has come into thermal equilibrium. SuperCDMS measures the phonon signal before the crystal returns to equilibrium [8].

The measurement of phonons in the iZIPs is done with Transition Edge Sensors

(TESs), specifically surface lithographed Quasiparticle-trap-assisted Electrothermal-feedback TESs (QETs) with Aluminum (Al) collector fins held at superconducting temperatures, and the sensor in transition between superconducting and normal.

The QETs are composed of Al collector fins with Tungsten (W) structures. The thinly filmed W has a superconducting temperature adjusted to near 80 mK, and the Al 1.18 K [51]. When scattered phonons in the crystal reach the Al fins, some energy is lost into breaking Cooper-pairs, generating Bogoliubov quasi-particles [52]. These particles diffuse into the Tungsten, and break Cooper-pairs in the Tungsten. The pair-breaking energy for W is lower than Al, so the final quasi-particles are trapped and cannot diffuse back into the Al. As a result, the phonon energy is concentrated in quasi-particles, and their energy brings up the TES from superconducting to normal state. The change in resistance provides a measurement of the phonon energy [51]. An image of the QETs on the surface of a SuperCDMS iZIP is found in Figure 1.10.

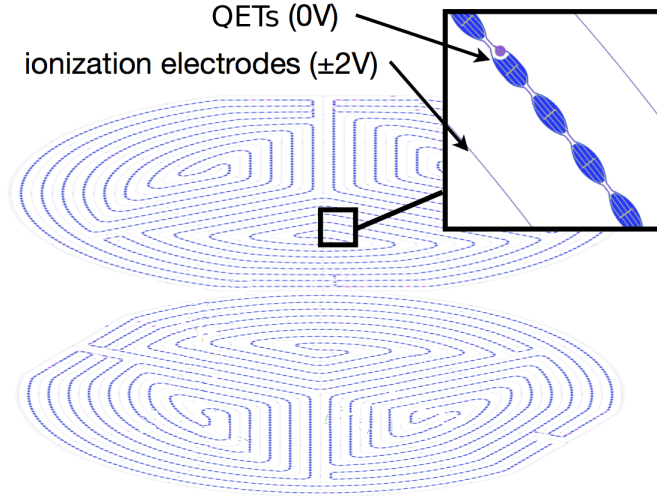


Figure 1.10: The sensors' layout with respect to the iZIP detector, and a closeup of a model of the TES. The Aluminum is blue, and the Tungsten traps are the grey within the blue. Charge sensors are also shown. Modified from an image generated in [53]

Energy information can also be collected based on electric charges. When a recoil occurs, electron-hole pairs are freed at an amount equal to energy of the recoil times the ionization yield function for the type of recoil (which is normalized to 1 for electron recoils), divided by factor ϵ_γ (the average energy to generate one electron-hole pair). For Germanium this is 3 eV for electron recoils [54, p. 376].

The charges are collected by applying a potential difference across the detector and drifting the charges to the surface. Image charges induced on the surface generate a current across a bias resistor that can be read out as a time varying voltage on the coupling capacitor.

When high voltage is applied, the electrons and holes move to the edge of the detector according to the potential. As they move, the charges bounce off the lattice and lose kinetic energy by emitting phonons. This kind of phonon generation is described and quantified by Luke, Neganov and Torfimov, and these phonons are typically called Luke phonons [55] [56]. Thus the phonon signal measured will combine the energy of the initial recoil phonons and the Luke phonons. In Germanium detectors close to 40 mK, electric fields of strength typical to SuperCDMS produce maximum drift velocities for free charges of $10^6 - 10^7$ cm/s, limiting the maximum kinetic energy of the charges to <30 meV [57]. Then the work done by drifting a charge through the detector (> 10 eV), which is much larger than the kinetic energy, is all work done on the crystal by the emission of relaxation phonons [33]. This leads to the result that almost all the work goes into energy from the Luke phonons. This can be expressed as:

$$E_L = N_{e/h} \times eV_b \quad (1.5)$$

where $N_{e/h}$ is the number of electron-hole pairs generated in the initial reaction.

Table 1.1: Energy Labels

Energy	Symbol	Definition
Total Phonon Energy	keV_t	The measured phonon energy that is a combination of the recoil energy (nuclear or electron) and the Luke phonons. It is equal to $E_{recoil} + N_{e/h} \times eV_b$.
Reconstructed Recoil Energy	$\text{keV}_{r(\text{or recoil})}$	The energy reconstructed from the pulse amplitude.
Electron Equivalent Energy	keV_{ee}	The energy assuming that the event was caused by an electron recoil and received full Luke gain. This is the energy used to analyze most data and is scaled such that visible lines in the energy spectrum match with the electron recoil energy of known sources.
Nuclear Recoil Energy	keV_{nr}	The reconstructed energy assuming the event was from a nuclear recoil and received full Luke gain.

1.4.2 Energy

SuperCDMS uses several different subscripts when referring to the energy of an event. Since the total energy is deposited in both charge and phonons, and it is difficult to know the true energy of an event in the data. The Luke gain, and thus the measured energy, depend on the radius (explained in Chapter 2). Because of this, there are several ways to describe an energy. The four main energies needed for this paper are the electron equivalent energy, nuclear recoil energy, the reconstructed recoil energy, and total phonon energy. Table 1.1 explains the various parameters.

1.4.3 Experiments

SuperCDMS performed three main experiments, all three of which used the same crystals, but were operated (and the resulting data analyzed) in slightly different manners. The standard low and high threshold analyses at SuperCDMS have an impressive ability to reject background [7]. Recall, the method SuperCDMS uses to hunt dark matter is searching for recoils of particles in the Germanium lattice through an interaction with another particle. Dark matter is not the only kind of matter which can interact with the crystal. α s, β s, and γ s can all interact with the crystal, producing a background of primarily electron recoils. The SuperCDMS detectors have the ability to collect both charges and heat. Due to the inertia of the heavier mass of a nucleus, less ionization is produced as it recoils than for a lighter electron recoiling. Nuclear and electron recoil events produce a different ratio of phonon to charge signal measured that allows for a rejection power better than one in 10^6 for electron recoils [7]. Figure 1.11 shows charge vs. phonon energy for data generated with two different radioactive sources; grey for $^{133}\text{Barium}$ data, events from which exclusively produce an electron recoil via a gamma, and dark blue for $^{252}\text{Californium}$ data, events from which fall within a 3σ nuclear recoil band, which primarily produces a nuclear recoil via neutron-neutron scattering.

The CDMS low ionization threshold experiment (CDMSlite) aims to achieve a lower threshold, and thus allows us to search for WIMPs of lower masses than most other dark matter searches. It achieves this by sacrificing electron recoil background rejection for amplification of phonon signals by drifting charges at high voltage (-70 V for the run which the majority of this thesis is based on) through the detector. The high voltage mode primarily searches for recoils from WIMPs around 2-6 GeV/c^2 ,

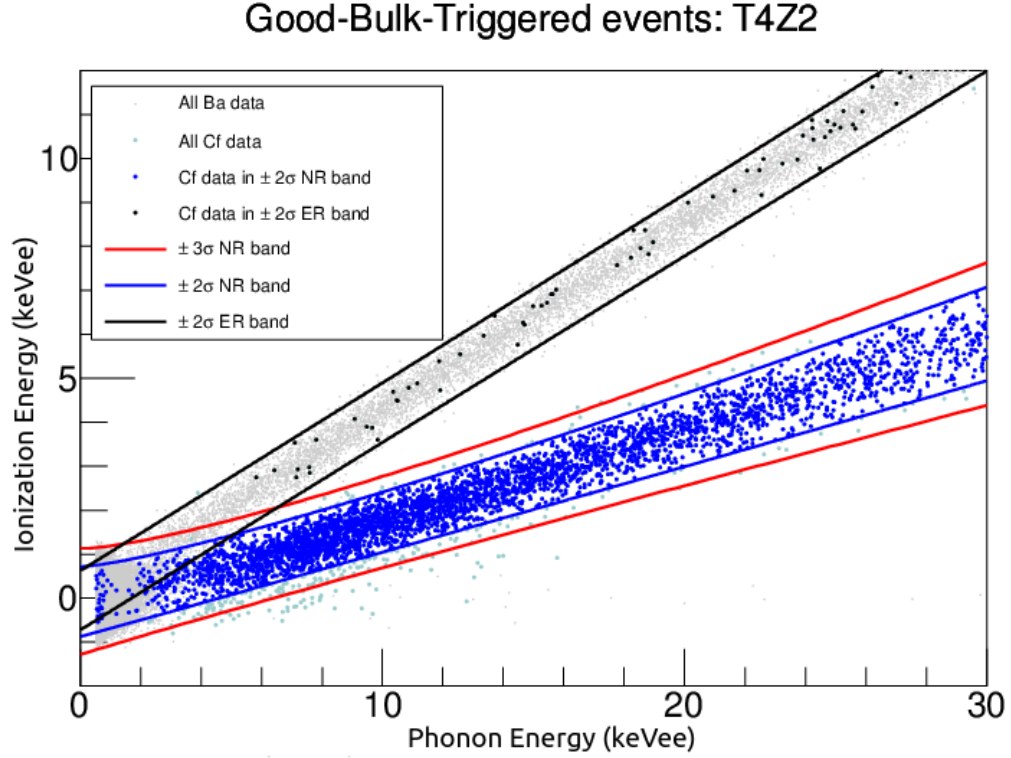


Figure 1.11: Charge vs. phonon signal for ^{133}Ba and ^{252}Cf from one of the fifteen SuperCDMS detectors. There are two structures, an upper grey band of electron recoils from the Barium gamma and a lower blue band of nuclear recoils from the Californium source. Some ^{252}Cf events are caused through electron recoil and are seen as the black events. Cf events falling outside both nuclear and electron recoil bands are light blue. From [58]

which deposit about 1 keV_{nr} . Charge sensors in SuperCDMS are typically sensitive to $\mathcal{O}(5 \text{ keV}_{nr})$, below which Johnson noise from the resistor makes the pulse amplitude indistinguishable from noise, making the ionization energy an ineffective tool in searching for nuclear recoils from 2-6 GeV/c^2 WIMPs [33, 9].

1.5 Motivation for this Thesis

CDMSlite sacrifices electron-recoil-identification background rejection in exchange for a lower threshold and the ability to search for lower mass WIMPs. Loss of rejection power leads to the data becoming background limited, to the point where after taking just a few months of data, the primary factor on improving the sensitivity depends not on more statistics but on reducing the background. Several sources contribute to this background. A large one which can be addressed is the events measured from charges from recoils at the edge of the detector which produce electron-hole pairs that do not experience the full electric potential. These events are then reconstructed at an incorrect energy lower than the true energy.

1.6 Objective

The objective of this thesis is to reduce this and some other backgrounds found in the second major run of the CDMSlite detector.

1.6.1 Hypothesis

The electric field configuration of the detector is such that it is the events at the edge of the detector which do not receive proper amplification. By developing an improved radial parameter and excluding events on the edge of the detector, we hypothesize many of the events which have their energy improperly reconstructed can be removed while retaining a large fraction of the signal. Using a selection of events that are

known to uniformly span the volume of the detectors allows us to calculate the efficiency of excluding events at certain radial thresholds as a function of energy.

1.7 Organization of Thesis

After the introduction of dark matter and SuperCDMS in this first chapter, I go on to discuss in Chapters 2 and 3 the CDMS low ionization threshold experiment, and my work on excluding outer radius background events. Analysis of post-experiment high voltage tests at Queen's and comparison of the tests to other facilities is presented in Chapter 4. Chapter 5 concludes and outlines future work.

Chapter 2

CDMSlite

2.1 CDMS low ionization threshold experiment

CDMSlite had three main data taking periods (“runs”). Here I will focus primarily on the second data period (“Run 2”), with data collected from February through November 2014.

2.2 Electric Field Configuration

To understand the effect of the Luke gain, the electric field throughout the detector needs to be understood. The electric field resulting from the voltage applied to the detector is dependent on the geometry of the housing. For CDMSlite Run 2, a bias of -70 V is applied to one side of the detector with the other held at ground. Ideally CDMSlite would operate with symmetric potential and flat field lines. However the copper sidewalls of the housing are also at ground. This creates an asymmetric electrical field, seen in Figure 2.1.

Events which happen in the green region in Figure 2.1 will release electron-hole

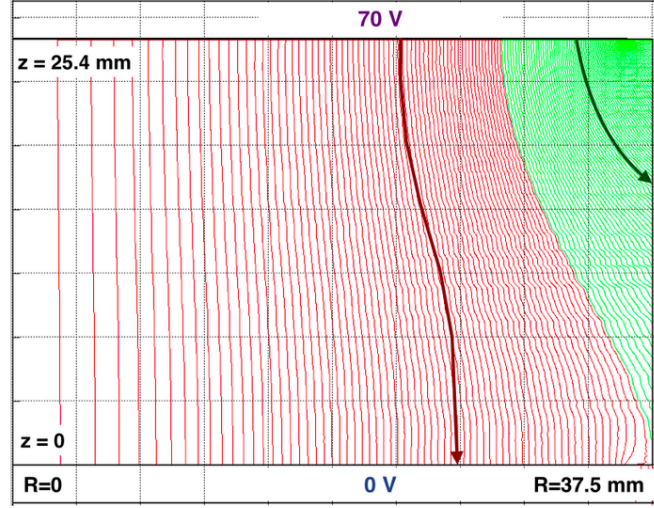


Figure 2.1: A simulation of the electric field configuration of the CDMSlite experiment. The top of the figure represents the top of the crystal which is at -70 V. The bottom of the detector is at 0 V and the housing (right side) are also at 0 V. As the housing is outside the detector, there are potential lines passing through the sidewall, and events with charges that terminate in these (green in the figure) regions experience less potential difference. From [9]

pairs where one of the charges is drifted to the side of the detector instead of the full distance to the bottom of the crystal. Thus, the charged particle experiences a lower potential drop and creates fewer Luke phonons. When the phonon signal from one of these events is processed, the energy is reconstructed as lower than the true energy of the recoil because the reconstructed energy assumes every event receives full Luke gain. This issue presents a major background to low energy WIMP searches [9].

2.3 Pulse Shape of CDMSlite Events

The readout from the QETs is an electrical pulse. The pulses, which are an electric signal converted from a heat signal measured in the phonon sensors, have distinct shapes that allow radial and energy information to be extracted. Pulses have a fast rise (the steepness of which is partially determined by how close to the sensor the event occurred), level off briefly and then fall in a manner homogeneous between all pulses. The total integral of the pulses gives the total phonon energy collected by the sensors. The amplitude of the pulses is approximately proportional to the energy. Example pulse shapes are seen in Figure 2.2 and demonstrate that the greatest variance between normalized pulses lies at the start of the pulse. The average of these normalized pulses can be used as a template representing the shape of the pulse and capturing a majority of the energy information the pulse contains. As the falling tails on the end of these pulses take on the same shape, this is called the “slow” template.

An interesting feature of the pulses can be seen in the residuals of the normalized

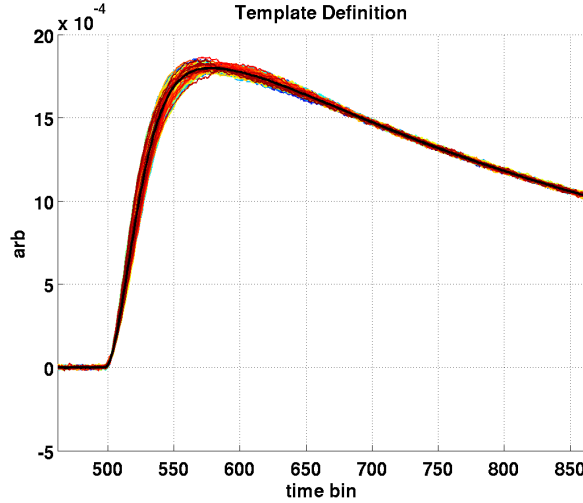


Figure 2.2: A collection of good pulses, zoomed into the peak region. The black line defines the average. [59]

pulses. Seen in Figure 2.3, the amplitudes of the residuals differ in magnitude and sign, but the shapes are similar. By orientating all the pulses so the peak is positive, and averaging these residual pulses, one obtains a second pulse-template shape, called the “fast” or residual template.

The magnitude of the total pulse height containing energy information, and

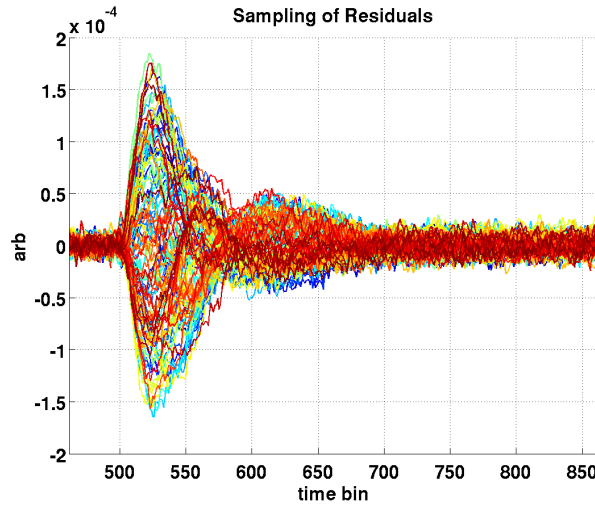


Figure 2.3: The residual of each of the pulses from the average. [59]

proximity to a particular sensor determining the steepness of the rise of the pulse, the components of the shape of the pulse contain both energy and position information. To collect this information, fits are done to the pulse shape to extract the start time, rise, and size of the event. The fits are done with optimal filter algorithms, procedures which fit templates to pulses in Fourier space to reduce the influence of noise (See Appendix A and [33] for more information on Optimal Filters). Three parameters are fit. The first two are the slow and fast templates, to capture the pulse shape. The third parameter is the difference between the hardware trigger time and the start time of the pulse as determined by the fit.

A set of example fits is seen in Figure 2.4. These fits are important because

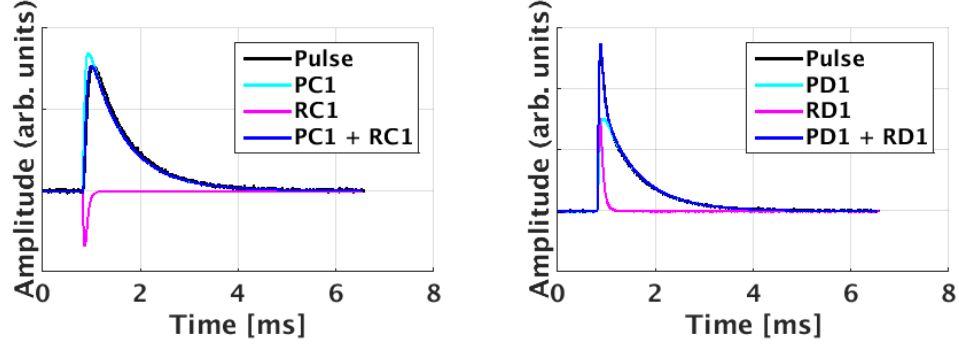


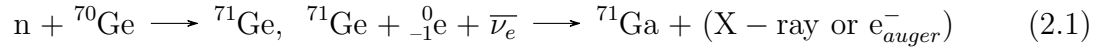
Figure 2.4: Two sample events with two-template fits. The data is black, the slow template is shown in light blue, the fast template is pink, and the total fit is dark blue. One “peaky” pulse (large positive fast template amplitude) is shown on the right, and one smooth rise (small or negative fast template amplitude) is shown on the left.

the “peakiness” of the pulse (how large the fast template amplitude is) gives radial information about the event, the energy of our event, and because we can get a measure of the performance of how well our templates represent the fit from a χ^2 value. Events occurring very near a sensor quickly deposit a large number of primary phonons to the sensor, resulting in a peaky pulse with large positive fast amplitude. An event far from the sensor would rise more slowly, and have a negative fast amplitude. While any net negative part of the pulse does not have physical meaning, the homogeneous part of the pulse is defined on the average pulse, so a fit to an event furthest from the sensor which should have the least fast phonons must compensate for the lack of fast phonons relative to average by adding a negative fast amplitude. To see how we use this information to build an estimator of where in the detector an event occurred, see Chapter 3

2.4 Californium Activation Periods

An important part of any experiment is calibration of the readout. In the case of CDMSlite, the pulse readout needs to be converted into an energy. Energy is approximately linear with the amplitude of measured pulses, so if there exists a known energy feature in the measured spectrum of energies, then the energy of most pulses can be quantified.

For the energy calibration, we use the electron capture lines of ^{71}Ge which we produce by irradiating our detectors with a neutron source. ^{252}Cf produces neutrons which are captured on the ^{70}Ge atoms in the detector, which become ^{71}Ge . Then an electron is captured from the K, L or M-shell into the nucleus, converting a proton into a neutron, and then an x-ray or auger e^- is released. The full process is seen in equation (2.1).



The electron capture process has a 11.43 day half life, and produces narrow energy peaks. A K-shell capture produces an x-ray that is approximately 10.37 keV [49], and will define the primary energy feature used to calibrate the second run of CDMSlite. The L-shell capture has an energy of about 1.30 keV [49]. The M-shell has an energy of 158 eV [49]. Throughout the rest of this thesis, these energy features will be primarily referred to as the 10.4 keV, 1.3 keV, and 160 eV peaks, respectively. The branching ratio is such that the majority of events (88.03 %) are K-shell captures [60]. L-shell captures make up much of the remainder at 10.30 %, and M-shell captures are the rarest at about 1.67 % [60].

There were three Californium activation periods throughout the second run of CDMSlite. The first starting in February 2014, then a second in May 2014. Finally, after a period of hardware upgrades, a third Cf activation was performed in late September 2014. Our data were taken immediately after these activation periods, and when they are discussed separately, they will be referred to as the February, May, and October data sets, respectively (despite the fact that the data collection period may span more than the one month). The periods after the February and May Cf activation periods will collectively be referred to as CDMSlite Run 2a, and the October dataset, which occurred after the hardware upgrades, and which has a different noise signature and calibrations, is referred to as CDMSlite Run 2b.

2.4.1 Reduced Energy Events

The Cf activation peaks provide valuable calibration data. However, without electron recoil discrimination they also create a background indistinguishable in pulse shape and properties from WIMPs. If energy was reconstructed perfectly, one could just avoid using events which fall within a certain energy range of the peaks for a WIMP search. However, the events with reduced Luke gain fall outside of the lines when energy is reconstructed. The data analysis from the first CDMSlite run did not consider this effect. Here we explore how the background and the loss in efficiency are handled in the second CDMSlite run.

Figure 2.5 shows radius (explanation of radial parameter found in Section 3.2.3) vs. reconstructed energy for the dataset. The K-shell capture line is clearly seen as the vertical structure on the right of the figure. Trailing off the top of this line

across the plot to lower energy are 10.4 keV events in the outer radius that had their energy improperly reconstructed. Unfortunately, referring back to the electric field in Figure 2.1, we see that the reconstructed energy will not only be a function of r but of z , as the events at the top at outer radius will receive much less Luke gain than events at the bottom at the same radius, and more, the true radius of these events cannot be reconstructed. So no correction as a function of radius can be applied to fix the reconstructed energy. Instead, eliminating all events which could be at a radius where they do not receive full Luke gain will be our tactic to reduce the background.

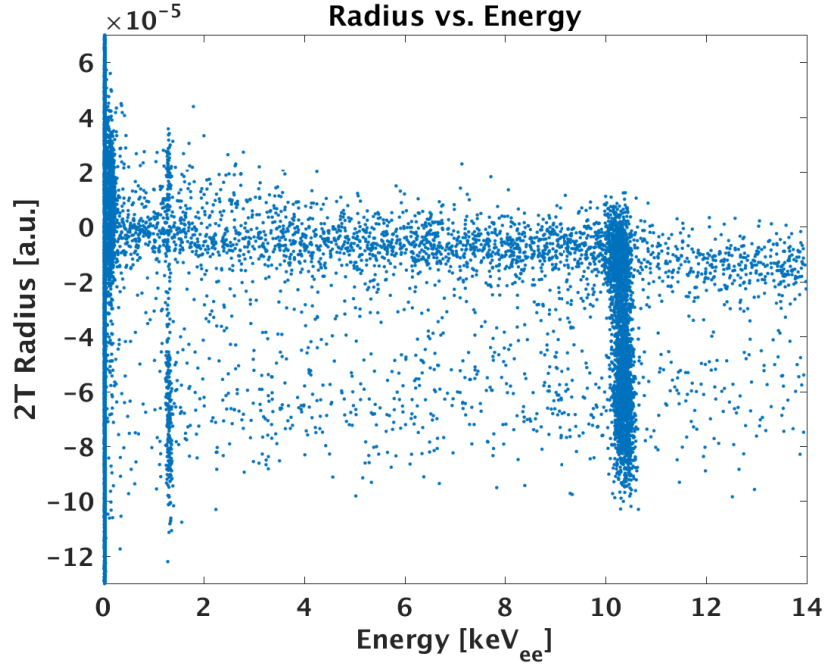


Figure 2.5: Radius vs. Energy for the full CDMSlite Run 2 data period, with all quality cuts (defined in the next chapter) applied.

Chapter 3

Analysis of CDMSlite Data

3.1 Goals

The primary goal of this section is to set a radial cut, and determine its efficiency as a function of energy. To do this we find a sample of events which should be uniform in volume; our ^{71}Ge activation lines serve this purpose. Then we must create a technique that allows us to find the reconstructed radial distribution of a uniform distribution for lower energy events. The technique; a simulation using pulse shapes constructed by the two-template optimal filter algorithm, rescaled to lower energy, and added to real noise traces, allows for the calculation of the efficiency of the radial cut at lower energies.

3.2 Data, Parameters, and Quality Cuts.

3.2.1 Data

Recall, the data used come from the second run of the CDMSlite experiment. There were two periods of data in this run separated from by hardware upgrades; primarily repairing the cryo-cooler which had been degrading over time and increasing the noise.

Run 2a occurred from February 7 to July 14, 2014 with two Californium activation periods interspersed. Run 2b occurred after the hardware upgrades and WIMP search data came from September 23 to October 17, 2014. The detector used was the middle detector in the 5th tower, denoted T5Z2 or iZIP 14, and the detector was biased so that one side was at -70 V, with the other side held at ground, and the housing of the detector also at ground.

3.2.2 Parameters

The main radial cut analysis relied on several parameters. The most important parameters mostly have to do with the amplitudes of pulse fitting algorithms:

- The two amplitudes of the two-template optimal filter algorithm (see Appendix A) from the two-template optimal filter algorithm were used in multiple ways throughout the analysis. Specifically, they are used in creating a radial parameter.
- The difference between the hardware trigger and the beginning of a pulse as determined by the two-template optimal filter algorithm is called the delay, and the difference in the measured delays in different channels of the same event contains some radial information.
- A non-stationary optimal filter amplitude used on the sum of the four phonon channels (PT) is used as the starting point for the energy. This algorithm takes into account the fluctuations in the first 100 μs of the pulse shape arising from the position dependence. Using the residuals from the average fitting as time

dependent noise allows the fit to de-weight the rise in the χ^2 and make the fit focus on the falling part of the pulse (which contains the energy information). The amplitude from this fit is corrected to an energy in keV_{ee} by centering the observed K-shell capture ^{71}Ge line at the proper energy of 10.37 keV. Noting time dependence in the location of the peak, subtracting the correlation between the amplitude and the base temperature of the cryostat, and the correlation with leakage currents (leakage currents imply some of the voltage does not reach the detector and the amplification is affected) corrects this energy parameter. The energy is further corrected by subtracting out the correlation with the fast amplitude, as some of the energy information is captured in the rise of the pulse. The final electron equivalent energy estimator ptnf_{ee} is obtained after all of these corrections. The slow amplitude of the two-template optimal filter algorithms also contains energy information, however, the corrected non-stationary optimal filter energy presents a marginally better energy resolution when looking at the width of the 10.4 keV peak.

- The radial parameter (“2T Radius”; see Section 3.2.3) is built from two-template optimal filter parameters.
- The EventTime was looked at to determine how long after a Californium calibration an event occurred.

3.2.3 Radial Parameter

The radial parameter for CDMSlite was primarily designed and calibrated by Wolfgang Rau. This parameter is not a radius in a classical sense, as it is not linear and does not represent a true position in the detector. What it does is approximately sort

events by those closest to the center by comparing facets of the pulse shape. This gives the ability to apply a cut on all events who have a radial value larger than a certain threshold.

The radial parameter is largely based on the two-template optimal filter algorithm that is, recall, described qualitatively in Chapter 2 and quantitatively in Appendix A. When an event occurs close to a given sensor, primary phonons are immediately absorbed, leading the detected phonon pulse shape to acquire a sharp rise and "peaky" structure at the beginning of the pulse shape. The rest of the phonons scatter homogeneously and the pulse shape falls off in the same way regardless of where the initial event occurred in the crystal.

Recalling the sensor layout (see Figure 3.1), knowledge of the properties of phonon pulse shape based on location can be used to define a radial parameter. The red x in Figure 3.1 occurs in sensor D. As this sensor is the closest, it will receive the largest amount of fast phonons that are immediately absorbed, making it the most peaky channel. Channel A, which is in the outer circle will have a much less peaky signal.

For the other event, marked with a green x, which occurs in channel A, channel A will have the most peakiness in its pulse shape. The event occurs much closer to channel C than B or D, so sensor C will detect more fast phonons than the other two inner channels.

Building off of this, constructing the radial parameter becomes a matter of identifying which inner channel the event occurs closest to by examining the peakiness of the three inner channels, and then comparing this channel with the outer channel A. The difference in the peakiness, or in this case the difference in the fast amplitudes

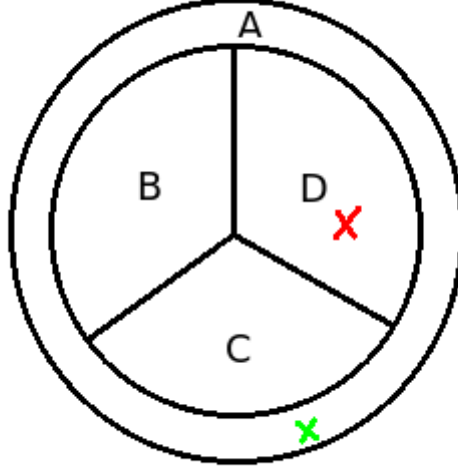


Figure 3.1: The sensor layout of the four phonons sensors called A, B, C, and D is shown here. Red and green marks are used to denote places where events could occur, as references for describing example template shapes.

produced by the two-template optimal filter algorithm will define the primary component of the radial parameter.

There are some secondary corrections to make. Besides amplitudes for the fast and slow templates, The two template algorithm also returns a delay; a factor which quantifies a shift in time between the detector triggering and the real rise of the pulse. Each individual channel is triggered at the same time, but the delay for each sensor is not always the same in each fit. The delay the fast template amplitude contain some degenerate information in the rising part of the fit and so individual channels have some of the radial information captured in the delay quantity. The radial parameter attempts to quantify this by adding in the difference in delay between the channel A fit and the fit of inner channel closest to the event. The initial channel parameter then looks something like this:

```

pa2t = PA0F1X2delay - PAfastAmp/PT*scalefactors
pb2t = PB0F1X2delay - PBfastAmp/PT*scalefactors
pc2t = PC0F1X2delay - PCfastAmp/PT*scalefactors
pd2t = PD0F1X2delay - PDfastAmp/PT*scalefactors

```

The channel parameters can be changed into x, y, and phi components based on the geometry of the detector.

```

px2t = (pb2t - pd2t)*cos(30/180 * pi)
py2t = pc2t - (pb2t + pd2t)/2
pphi2t = (sign(px2t)+1)/2 * pi +atan(py2t./px2t)-pi/2

```

The radial parameter is produced as a simple

```

pr2t = min([pb2t, pc2t, pd2t])-pa2t

```

. But this produces a correlation in phi, seen in Figure 3.2. This can be corrected out, and this correction is applied as seen in Figure 3.3

```

pr2t_c = pr2t + 3.5e-5*exp(-abs(phi2t/0.3)) ...
+ abs(abs(1-abs(pphi2t/pi)-1/3)-1/3)*8e-5

```

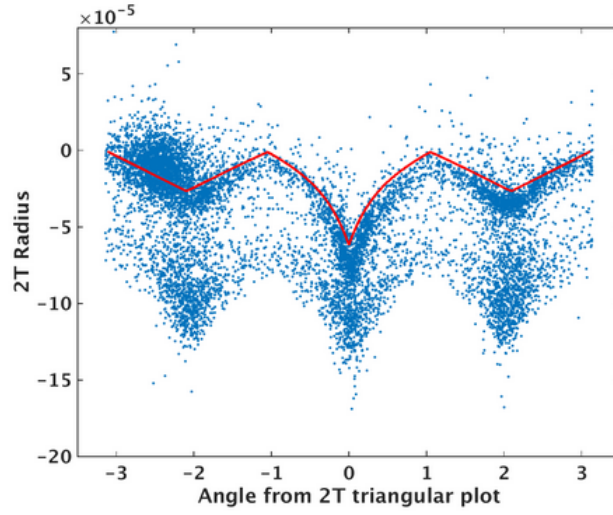


Figure 3.2: A clear dependence on ϕ is observed for the initial radial parameter, which can be corrected out.

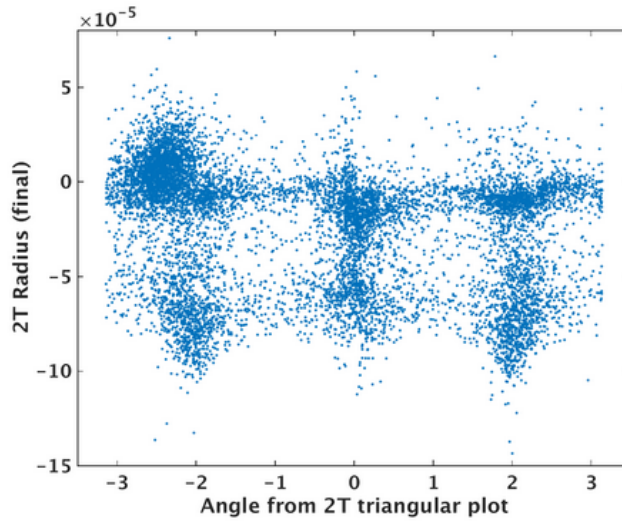


Figure 3.3: The dependence on ϕ is corrected for the final radial parameter.

After the ϕ corrections we have a final radial parameter.

3.3 Quality Cuts

Before examining the radial distribution and cut, we remove as many bad events as possible from the data by applying quality cuts. Those cuts are:

- χ^2 cut: Removes events which are badly fit by the templates
- Randoms Cut: Removes events which are determined to be noise traces
- HV Cut: Removes events from periods where the voltage was not being applied properly
- Low Frequency Noise Cut: Removes events affected by low frequency noise by fitting a low frequency noise template and examining the difference between the chi-square values of fits between the phonon template fit and a low frequency noise template fit
- Glitch Cut: Removes events caused by trigger glitches and events which are above a certain threshold when examining the difference between chi-square fits of glitch templates and pulse templates
- Bad Noise-Series Cut: Identifies series in Run 2b that did not have proper pre-biasing of the voltage and eliminates them from the data
- Multiples Cut: Removes Pileup events where a new event started during the previous event's pulse signal
- PTNF Fit Cut: Removes events which have unphysical negative non-stationary optimal filter algorithm fit amplitudes

- Baseline Cut: Removes events without a flat baseline
- Muon Veto: Removes events with triggers on many detectors, or that have an energy depositions above a certain threshold in a muon veto panel

These cuts are all applied before the designing of the radial parameter and the setting of the radial cut and determination of the efficiency.

3.4 Radial Cut

A radial cut for CDMSlite was chosen to achieve two purposes. The first was to address the backgrounds of reduced Luke gain events present at all energies. This is necessary in both the Run 2a and Run 2b time periods. However, in the second time period, there is an additional background. Figure 3.4 shows the different backgrounds that can be addressed by a radial cut. A large spot around 200 eV_{ee} visible in Run 2b is localized to the outer radius. Figure 3.5 shows this spot is localized in one region of the detector and is time dependent, and therefore is some sort of hardware background [9].

The radial cut is placed separately for Run 2a and Run 2b. This is partly due to the spot in Run 2b, but also due to the slight change in the distribution of the radial parameter due to the difference in operational parameters and changes in the noise environment between runs. This can be seen in the bottom of Figure 3.4 where the red points in the 1.3 keV line spread a wider range below where the black Run 2a points stop. Here, fixed radial values for the cut are chosen mostly by eye, where the reduced Luke gain events and spot are mostly above the line. For Run 2a, the value chosen is $-4\text{e-}5$, and for Run 2b, the value chosen for the cut is $-5\text{e-}5$. Recall, these values are arbitrary and not so much a true radius as an effective tool for sorting the

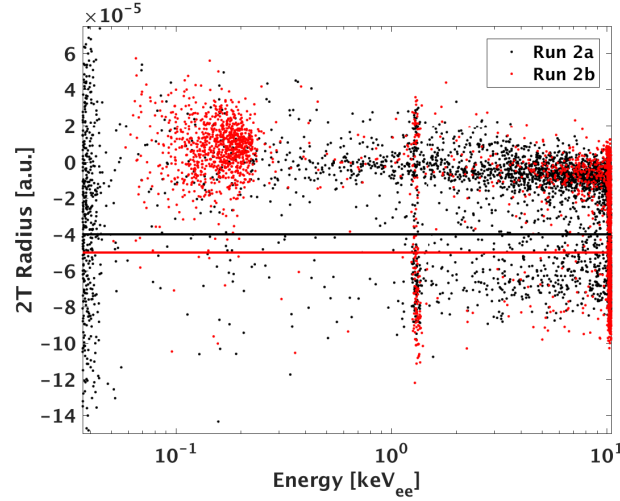


Figure 3.4: Run 2a (black) shows evidence of the reduced Luke gain events across the top center, while Run 2b (red) shows an additional background around 200 eV_{ee}. The black and red lines show the locations of the radial cuts for the respective runs.

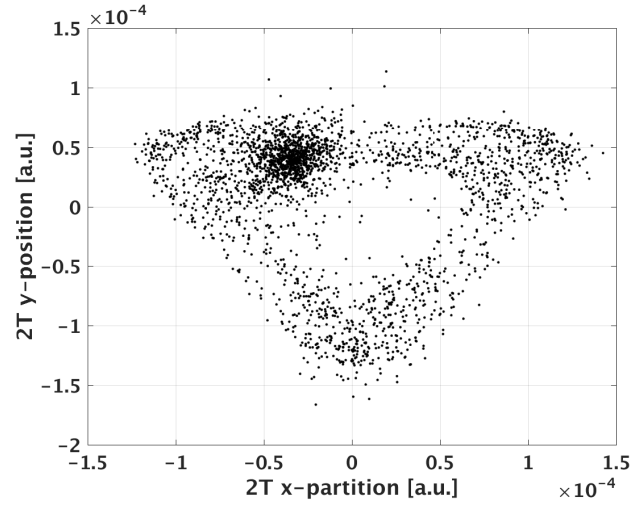


Figure 3.5: The x-y partitioning of the data shows that the “spot” seen in Run 2b is localized to one area of the detector.

events into inner radius events (below the radial cut) and outer radius events (greater than the radial cut).

3.5 Simulations

Given a radial cut, it is important to be able to determine the efficiency of the cut at any given energy. There is no easy answer for this, as the low energy data are extremely statistics limited, and it is impossible to determine which events are reconstructed at the correct energy. The solution then is to take a collection of events from which the radial and energy properties are well known and transform them to look like lower energy events.

First, a radial parameter distribution that is uniform throughout the full radial range (which a true dark matter signal would be) must be modeled. As the two-template algorithm can very closely match the shape of almost any good data event, and the radial parameter is built from the two-template algorithm, if a selection of real data can be found that fills the full radial range, those events' two-template fits could be used as the base of a simulation of lower energy events. By taking real pulse shapes, rescaling them to a lower energy by lowering the amplitudes of the templates, and adding back in real noise traces, one can create events which should behave very similarly to real low energy events.

The first simulation base candidate to consider would be the 10.4 keV line, as this collection of events has great statistics. However, the 10.4 keV peak fails to accurately portray the same radial distribution as lower energies. This may be because the outer channel A begins saturating above a few keV. Saturated pulses have the peak of the pulse reduced, so events which are “peaky” (those with large positive fast amplitudes) will be most affected by this. Figure 3.6 shows the effect of the saturation on the fast template. The positive amplitude fast templates above 2 keV_{ee} do not scale with energy, which they should. Figure 3.7 demonstrates that this is not an issue for the

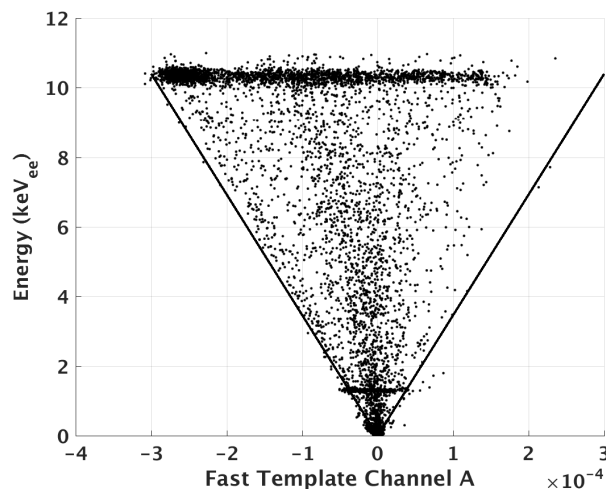


Figure 3.6: The fast amplitude in channel A ceases spanning the full range above a few keV_{ee}

inner channels by showing that the fast amplitude distribution for channel B scales with energy.

The next candidate for the simulation base is the 1.3 keV line. This line is much

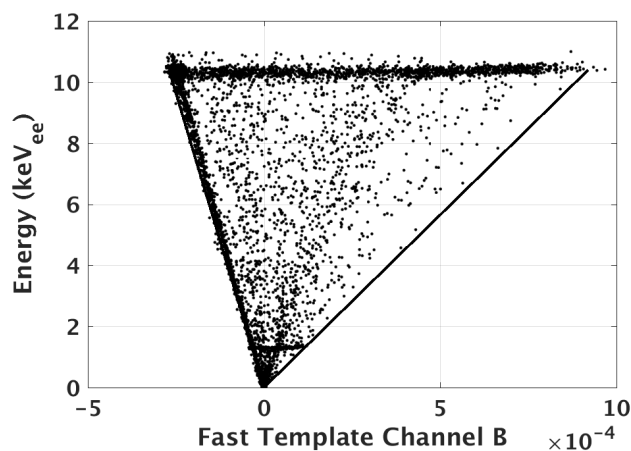


Figure 3.7: Channel B (and the other inner channels) has a fast amplitude which scales with energy.

lower in statistics than the 10.4 keV line, having only 216 events for Run 2a and 275

events for Run 2b, which is a factor of 10 lower than the 10.4 keV line. However, this line does not suffer from the saturation in Channel A that distorts the radial distribution of 10.4 keV line. As seen in Figure 3.6, the 1.3 keV line is much more representative of the radial distribution for lower energy events.

3.5.1 Simulation Mechanics

The simulations were done separately for Run 2a and Run 2b, as the noise was quite different and the corrections for the energy were different in both of these runs. Figure 3.8 shows the 1.3 keV line separately for the two runs. Only events which pass all quality cuts are shown. As input for the simulation, events with an energy (ptnf_{ee}) between 1.22 and 1.45 keV_{ee} (216 events for Run 2a and 276 events for Run 2b) were used.

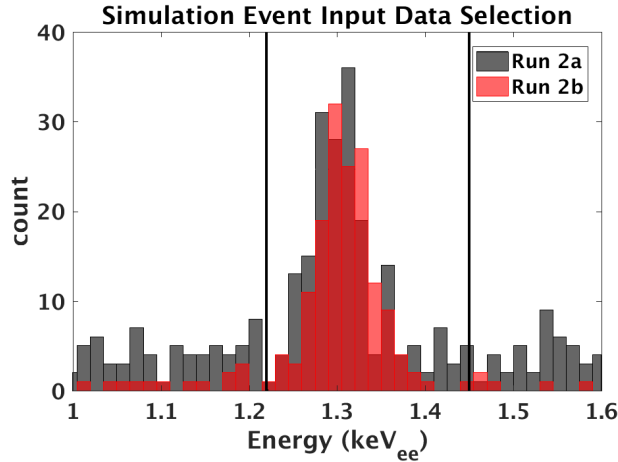


Figure 3.8: The 1.3 keV line spans from about 1.22 to 1.45 keV and is the event selection used to choose events for simulation. The lines denote the bounds where events fall inside or outside of selection criteria.

We develop a simulation that takes the template amplitudes from the fits to our input, rescales the templates to lower energies and adds noise. We can justify the rescaling by assuming that ratio of the amplitudes of the two parts of the pulse is energy independent (the fact that the density and maximum range of the fast template are linear in energy for channel A below 3 keV_{ee} in Figure 3.6, coupled with Figure 3.9 showing that the slow amplitude is linear in energy).

The optimal filter fit values from a data processing of our 1.3 keV line can be

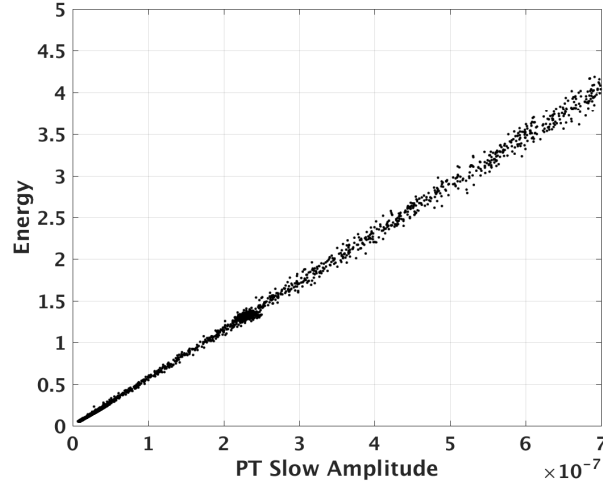


Figure 3.9: Slow amplitude vs. Energy, showing slow amplitude is nearly proportional to energy.

saved and then reused to create a new set of “simulated” data.

During data taking, at the beginning of every data series of three hours, the first 500 events are forced triggers on whatever is being recorded. By selecting good randoms from these forced triggers (those traces which are pure noise with no detected pulses and which have passed certain cuts on low frequency noise), we build a collection of noise traces.

The simulation takes the amplitudes of the two template fits from real pulse data,

rescales them to a desired energy and then adds a good noise trace from a randomly selected data series close in time, so that the amplitudes would have similar corrections to them (recall, there are time dependent differences in the base temperature and leakage current which affect the pulse amplitude) done to them in both original data and simulated data. In the original simulation, there are two methods of rescaling the templates to a desired energy. First, multiplying all templates by the same ratio, which scales the center of the line (1.3 keV_{ee}) to a desired output energy. This means that events which fall in the 1.3 keV line but have measured energies closer to the 1.22 or 1.45 keV bounds keep their status as being near the outskirts of the line, and the simulation preserves the relative width of the 1.3 keV line (plus a factor depending on the energy resolution due to the noise at the simulated energy). This method is called “wide” simulations.

The second method involves dividing the amplitudes by their energy, in this case the uncorrected non-stationary optimal filter amplitude and then scaling to the desired energy. This takes away most of the energy variation of the simulation input and makes the output a much narrower line; the resulting energy resolution in this case is dominated by the effect of the noise that is added to the pulses. This simulation mode is called “narrow” simulations.

When determining the efficiency of the radial cut, both kinds of simulation were used. Narrow simulations for $40, 60, 80, 100, 120, 140, 160, 180, 200, 250$, and $1,300 \text{ eV}$ were performed. Wide simulations, which span a greater band of energies were done at $80, 150, 300, 650$, and 1300 eV . For the final analysis, the lower energy ranges were filled out by the narrow simulations from 40 - 250 , and $1,300 \text{ eV}$ were used, but with larger spacings to fill out the upper energies, the wide simulations of 300

and 650 eV were used in the calculation of the efficiency.

3.5.2 Simulation Results

In order to understand the output of the results, we can plot the new radius versus energy and colour them by the original data. If the energy and radius were perfectly reconstructed, then the efficiency of the radial cut at every energy would be the same. However, as seen in Figure 3.10, some events which were inner in the the original data switch to being outer, and vice versa, with the effect being much more pronounced at lower energies. As a test for the method, we did one simulation where the output energy was not scaled; Figure 3.11 shows the result of this simulation.

One would expect the output to be the same as the input with only small variations generated by the changes in the actual noise. In the figure, we see two events moved from the outer to the inner region, denoted by x's. It is tricky to estimate the exact number of events that are expected to switch from inner to outer or vice-versa, but looking at the observed radial distribution of the events (see Figure 3.12) and the density of events near the cut line, this appears to be a reasonable number.

3.6 Calculation of the Efficiency

A first estimate of the efficiency of the radial cut can come from observing the number of events which pass and fail the radial cut at any energy in a line, the “Peak Efficiency”. For example, all events below the line in the simulation in Figure 3.11 pass, and all above fail. This gives an estimate of $53 \pm 9 \%$ efficiency, and cuts $47 \pm 9 \%$ of the line.

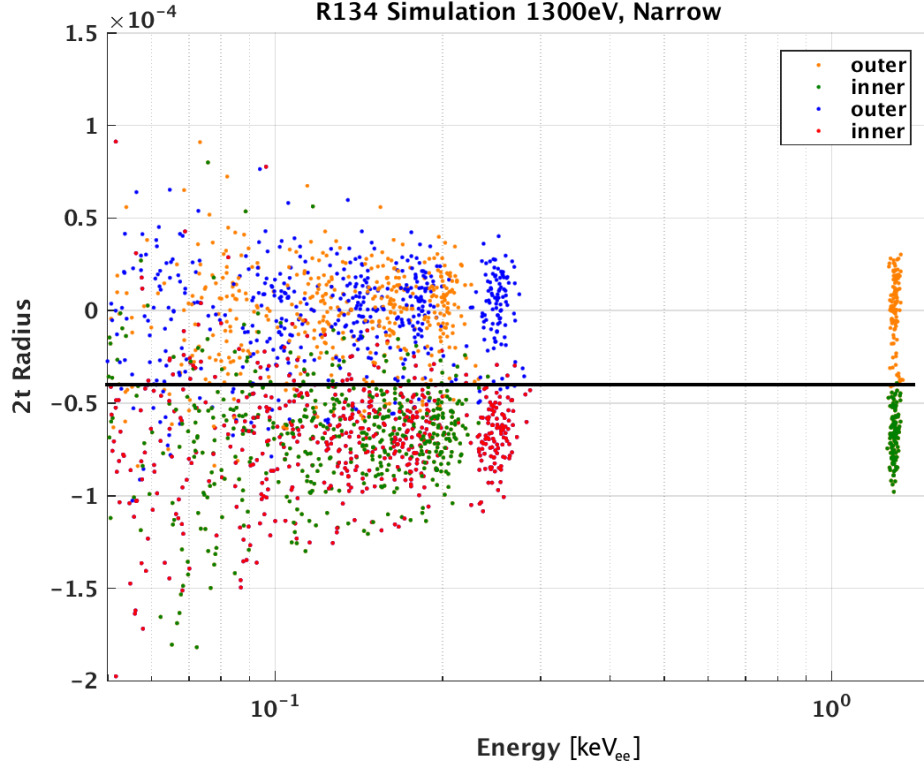


Figure 3.10: All narrow simulations are shown, with output energies alternating in colours with inner events from data being coloured red/green and outer events in data being coloured blue/orange. Events which cross over the cut line are the ones of interest here, as they are the ones that change the efficiency of the radial cut at various energies.

This comes with several caveats. For our simulation input, we wanted a distribution that is uniform throughout the volume. If our list of events that go into the simulation included all L-shell capture events, and only L-shell capture events, then we have a good sample. However, some of our desired input events are lost to lower energies since they do not receive full Luke gain. Additionally, there are some events which are not truly 1.3 keV_{ee} but are reconstructed at that energy. Additionally there are some backgrounds in the form of other lines close in energy to the 1.3 keV line that are partially included in our input sample, and a background from Compton

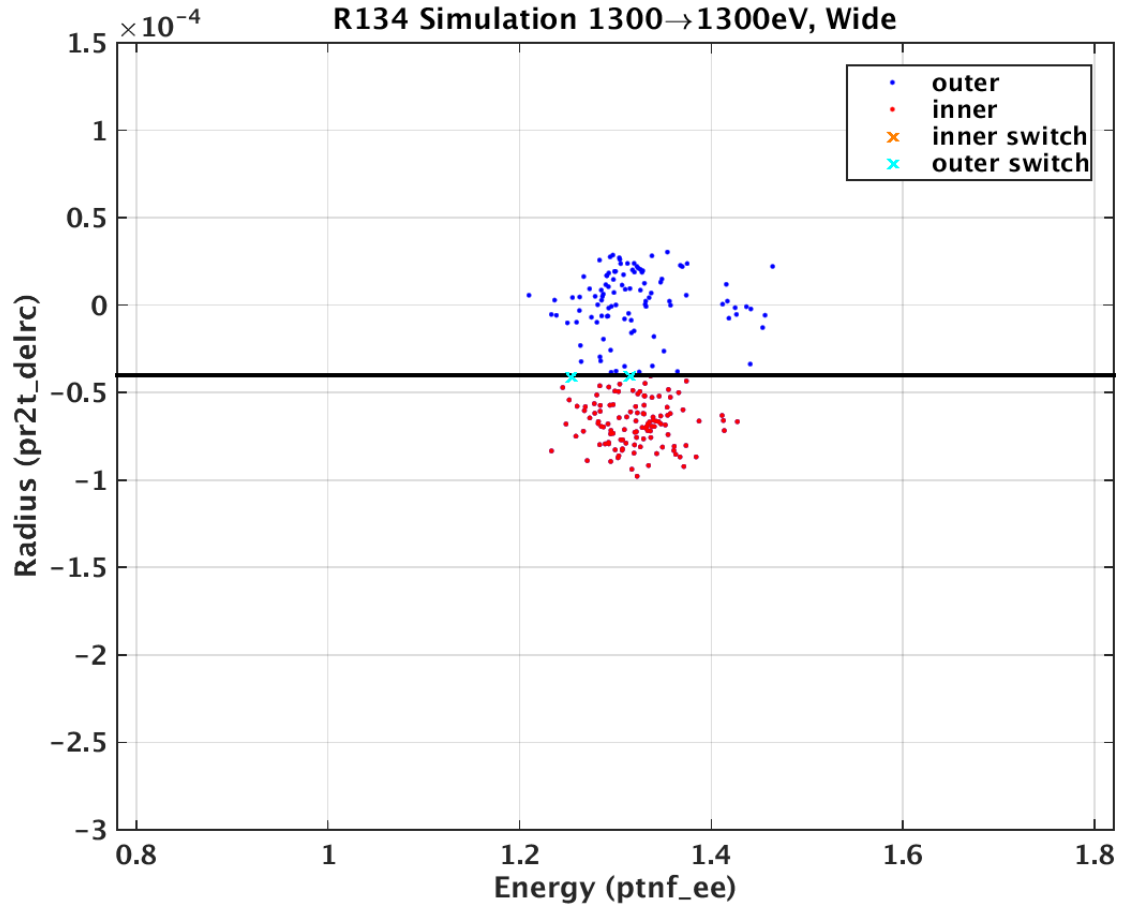


Figure 3.11: The wide simulation for 1.3 keV_{ee} . Two events which were measured as outer events in the data switch over the boundary and become inner are marked by the two blue x's. In this simulation, no events which should be inner become outer (Seen in the lack of orange x's).

scattering of γ s which may not be uniform in radius. Corrections to the calculation must be made to get a better estimate of the efficiency and its uncertainty.

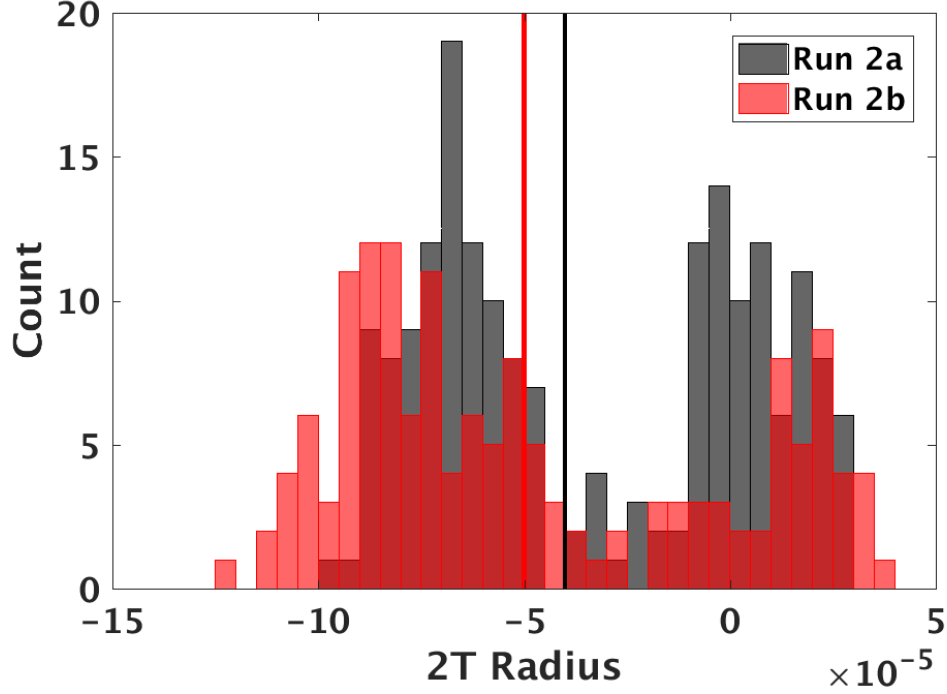


Figure 3.12: The radial distributions of Run 2a (black) and Run 2b (red), with lines of the same colours to denote the location of the cut. Given how close some events are to cut threshold, it is not unexpected even slightly different noise could flip a few events over the line.

3.7 Corrections to the Efficiency

The first correction is figuring out what happens to true 1.3 keV events that are lost and not included in the input due to reduced Luke gain. Here we use the fact that essentially all reduced energy events are outer events. We can additionally draw information from the 10.4 keV line. Since we have no reason to expect that the fraction of events receiving reduced Luke gain at any given energy is different (as this is purely a geometry effect of where they occur in the detector) and we see that all events with reduced Luke gain are outer when we count the number of ^{71}Ge events in inner radial bins (see the upcoming Section 3.7.1), we can use the fraction of 10.4 keV

events that receive less Luke gain as an estimate for the number of 1.3 keV events which also receive reduced Luke gain.

To determine which events outside (and inside) the line are true ^{71}Ge events, and therefore find what fraction falls outside the line, we identify how many events there are in different regions in the plane spanned by our radial parameter and the reconstructed energy by looking at the rate of events in these parameter spaces over time.

3.7.1 Alignment of Data Periods by Activation Strength

Since the ^{71}Ge events we are looking for have a known half-life of 11.43 days [61], we can sort the data by the relative activation strength in each time period. We use events that have a measured energy between 9.7 and 11.2 keV_{ee} to define the 10.4 keV line. Recalling that there were three activation periods, these activation periods are sorted by relative strength by fitting decaying exponentials with an 11.43 day half-life to the the event rate. Assuming that other backgrounds at this energy are uniform in time, the fit includes a flat background. The fit also acknowledges that the data-taking had periods where for various reasons no data was collected (represented by a step-function; SF), and accounts for the downtime in each day by multiplying the daily event count by the inverse of the fraction of the downtime to get the expected true daily rate. The fit is a log likelihood of the ratio of the exponential and flat components;

$$\text{exp : flat} = \min_r \left(- \sum_i \log \left(\frac{r * e^{-i/\tau} \cdot SF(i) + (1-r) \cdot SF(i)}{r * \sum_k (e^{-k/\tau} \cdot SF(k)) + (1-r) * \sum_k SF(k)} \right) \right) \quad (3.1)$$

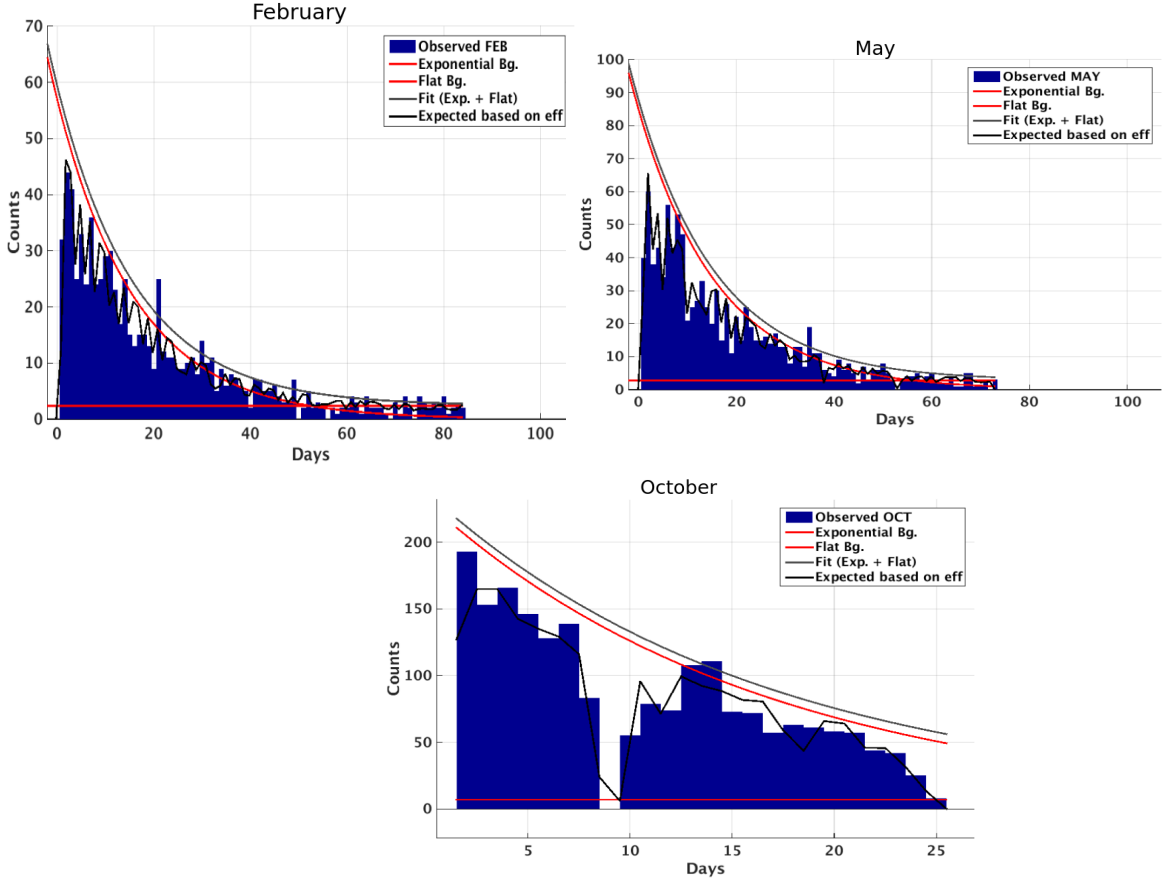


Figure 3.13: From Clockwise from top left: February, May, and October event rates as a function of time. The fits were done as log likelihood fits of the ratio (see equation 3.1) of exponential signal to flat background with a condition to force the combined signal to flat background to exactly equal the total number of events. The red curves give the exponential and flat components of the fit. The jumpy gray curve gives the expected daily amount factoring in daily efficiency. The smooth grey curve gives the expected rate of events with perfect efficiency.

where τ is the lifetime/ $\sqrt{2}$, r is the ratio of signal to background, and i and k are indices of time to be summed over. Figures representing the fits to the post-February, May and October calibrations are presented in Figure 3.13.

The October dataset clearly has the highest rate, while the February dataset has

the weakest activation but lasts the longest. Taking these factors into account, a weighted average of the flat background between each of the three datasets proves consistent with all three individual periods at a rate of about 3/day. The three time periods then can be combined as one dataset by sorting them and aligning them by activation strength. The start (post-activation) of the May data (being the second strongest activation) would be equivalent to happening $15.6 \pm .3$ days after the start of the (strongest) October activation. The start after the February activation is equivalent in strength to observing $21.8 \pm .1$ days after the October activation. If you plot these together on the same figure by adding the aligned data (and efficiency functions) together, then you can improve the total statistics and by fixing the flat background get the best fit of the exponential, which by integrating gives the total expected number of ^{71}Ge events. Figure 3.14 shows the combined fit.

3.7.2 Energy Efficiency Calculation

The combined number of signal events in this region gives one part of our needed estimation of what fraction of events that are ^{71}Ge K-shell captures are reconstructed at the correct energy; our “Energy Efficiency”. Next, the number of ^{71}Ge K-shell capture events outside of the 10.4 keV line need to be counted. This can be achieved by doing similar fits to correctly time-aligned data in other energy and radial regions. Figure 3.15 shows how the regions are divided. The regions are divided visually by the estimated 10.4 keV contamination. Notice the lowest energies are not included in these counts. This is because we know that even if there is no Luke gain, there is a minimum amount of primary recoil energy from a ^{71}Ge event. Recall, $E_t = E_r + E_L$,

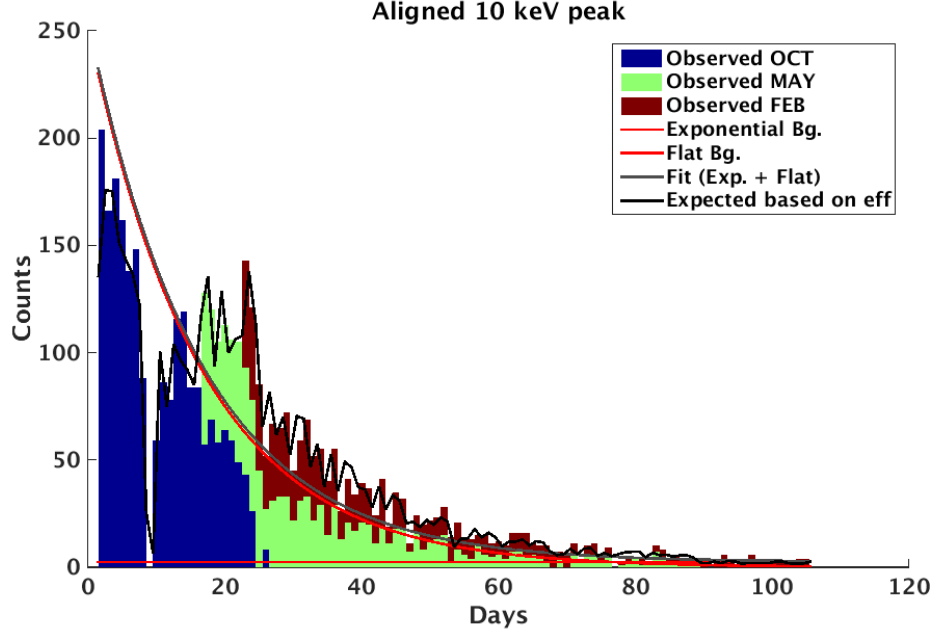


Figure 3.14: All 3 datasets aligned by activation strength with background fixed and exponential fit.

and $E_L = E_R/3 \times 70$ for electron recoils. Rearranging these equations gives a lower bound on 10.4 keV contribution of $.426 \text{ keV}_{ee}$.

Descriptions of regions and the fit values associated with them are seen in table 3.1.

The true efficiency of a cut on the line is the 10.4 keV Ge contributions in the line divided by the total from every bin. We call this the “Energy Efficiency”; it can be expressed as:

$$\text{Energy Efficiency} = \frac{Ki_{10} + Ko_{10}}{Ki_{10} + Ko_{10} + Ko_{110} + Ki_{110} + Lo_{10} + Lo_{210}} \quad (3.2)$$

where the subscript 10 implies events from the energy bin that come from ^{71}Ge K-shell electron captures, as found by the log-likelihood ratio fits. Some of these aren’t

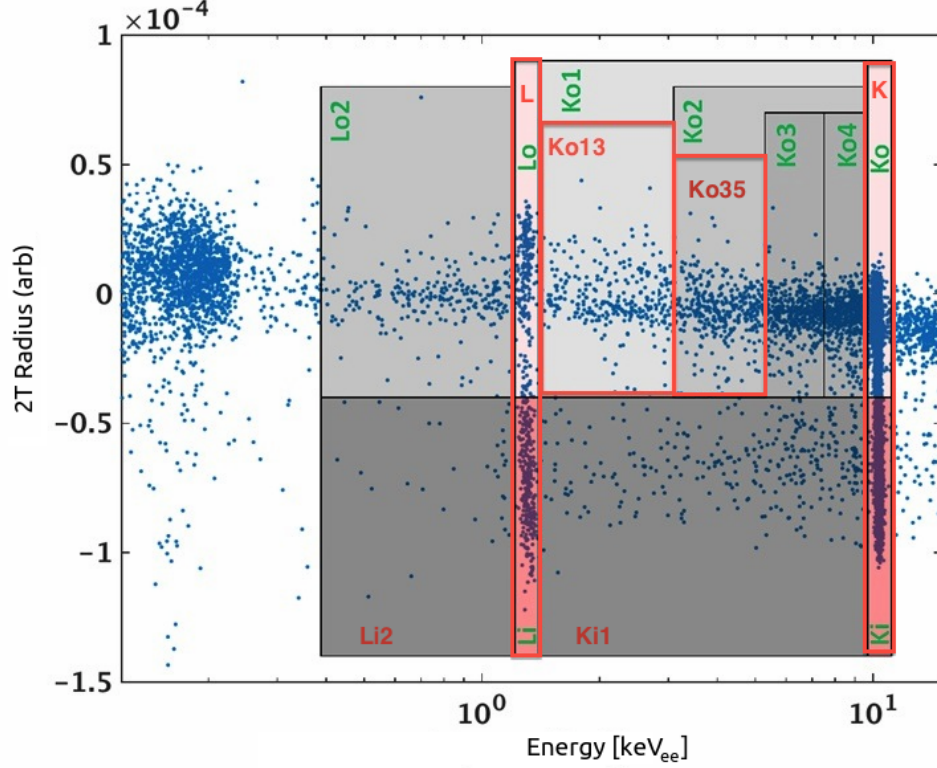


Figure 3.15: The various regions in Energy-Radius space and their assigned names.

quite so simple. We should not simply take the exponential component from Lo and Lo2, because the L-shell capture also has an 11.43 day half-life (see Figure 3.16). We can estimate the true number of 1.3 keV events the line should have based on the theoretical ratio of K to L shell captures and the total number of K shell captures found in the 10.4 keV line. The ratio of K to L shell captures is 0.12:1 [61]. By finding the expected number of 1.3 keV events in Lo and Lo2 based on Ko and Ko1, and subtracting that from the total exponential events in those bins we are left with the 10.4 keV contribution.

An uncertainty is found on the Energy Efficiency by finding the error on the fit count estimates in each bin and doing a Monte Carlo simulation selecting a count

Table 3.1: Energy-Radius spaces sorted by varying ^{71}Ge and flat background contributions

Region	Description of Region	Number of ^{71}Ge Events	Number of Bg Events
Ki	10.4 keV line events passing radial cut	2143	100
Ko	10.4 keV line events failing radial cut	1737	214
Ko1	All outer events between 1.3 and 10.4 keV lines	534	1023
Ko2	All out events above 3.1 keV and below the 10.4 keV line	498	780
Ko3	Outer events from 5.3 to 7.5 keV	173	251
Ko4	Outer events from 5.7 to 9.7 keV	248	256
Ko13	Outer events from 1.45 to 3.1 keV	33	247
Ko35	Outer events from 3.1 to 5.3 keV	72	279
Ki1	All inner events between 1.3 and 10.4 keV lines	59	248
Li	1.3 keV line events passing radial cut	274	10
Lo	1.3 keV line events failing radial cut	171	36
Li2	Inner events from .39 to 1.22 keV	2	29
Lo2	Outer events from .39 to 1.22 keV	75	169

for signal and background, and propagating that forward to get the efficiency 10,000 times. Kedar Page was primarily responsible for calculating this uncertainty. Fitting a Gaussian to the distribution gives an Energy Efficiency of $86.37 \pm .86 \%$. The true efficiency of the radial cut would be the Peak Efficiency multiplied by the Energy Efficiency.

3.7.3 Peak Efficiency Corrections

The first estimate we used for the peak efficiency assumed that all events in the input simulation were L-shell capture events, because this one set of events should give us a distribution that is uniform in volume. We know this is not the case. We have already mentioned that some events are reduced Luke gain K-shell capture events, and there

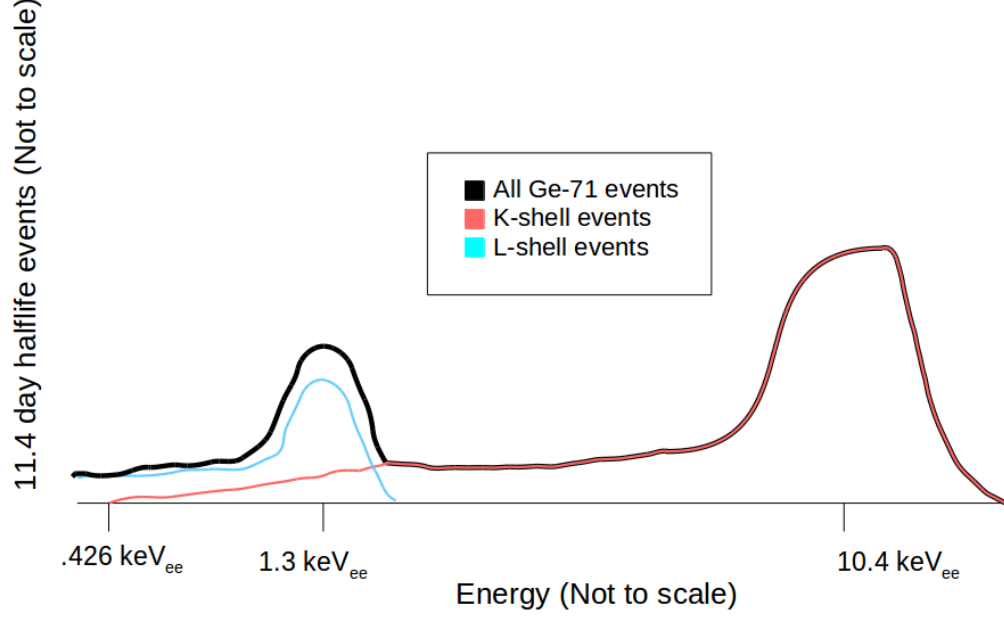


Figure 3.16: A cartoon representing ^{71}Ge contributions as a function of energy. Red signifies contributions from the K-shell line, with reduced Luke gain events spanning down to 426 eV_{ee} . Contributions from the L-shell capture line are blue. The combined signal, which is observed, is seen in black. Notice at 1.3 keV_{ee} there are 11.4 day half-life contributions from both K and L-shell captures.

are other backgrounds under the line as well. It is impossible to tell which events are which type, but we can plot the radial distribution of the line ($1.22 - 1.45 \text{ keV}_{ee}$) compared to the radial distribution of events just outside the line and compare the distributions. We see this in Figure 3.17. In the distributions, it is seen that most of the background falls into a certain radial range corresponding to reduced Luke gain outer events. If we calculate the peak efficiency as

$$\epsilon_{\text{peak,data}} \equiv \epsilon_{\text{p,d}} = \frac{N_i}{N_i + N_o - N_b} \quad (3.3)$$

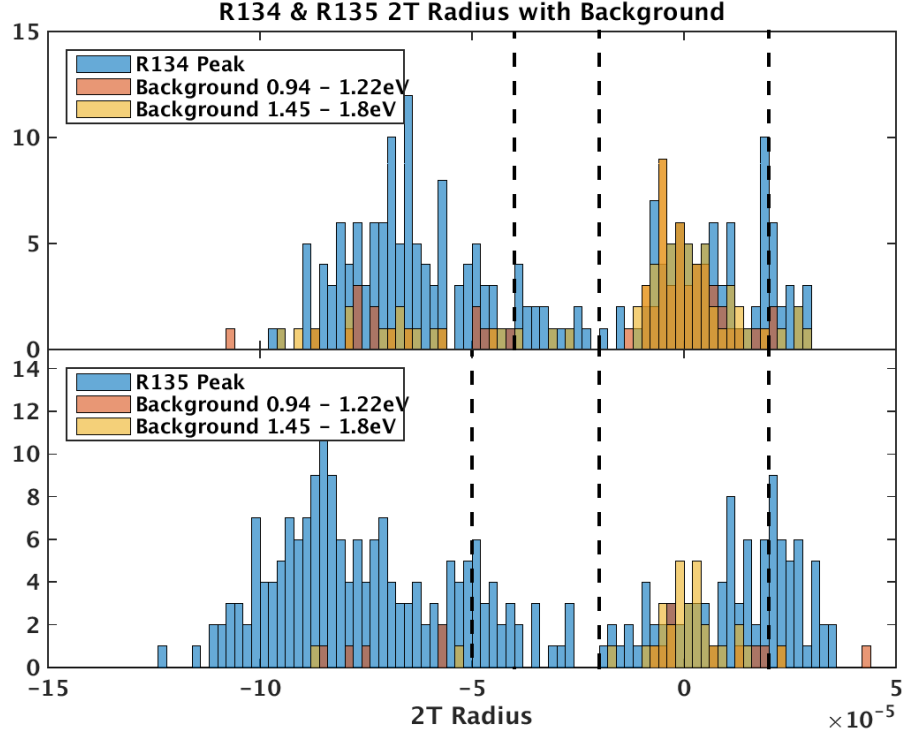


Figure 3.17: The radial distribution of the 1.3 keV line of Run 2a (top) and Run 2b (bottom) compared with the radial distribution below (red) and above (orange) the line in energy.

where $i \equiv$ inner, $o \equiv$ outer, $b \equiv$ background, then we must determine how many events are good inner events, how many are good outer events, and how many are background events. If we divide the radial distribution in Figure 3.17 into 4 bins; inner ($r < -4 \times 10^{-5}$), outer-1 ($-4 \times 10^{-5} < r < -2 \times 10^{-5}$), outer-2 ($-2 \times 10^{-5} < r < +2 \times 10^{-5}$), and outer-3 ($+2 \times 10^{-5} < r$), then we see most background of the data is in radial bin outer-2. To a first approximation, we can ignore the background in the inner, outer-1, and outer-3 bins. We can define outer signal events as $N_{o13} \equiv N_{o1} + N_{o3}$. N_{o2} has both signal and background components denoted N_{so2} and N_{bo2} respectively. If we look at the efficiency for any simulation, regardless of where an event type $\mathcal{A}$

falls in data, if it passes in the simulation we denote it $N_{\mathcal{X} \rightarrow i}$ and any event of a type $\mathcal{X}$ that fails the cut in the simulation is denoted as $N_{\mathcal{X} \rightarrow o}$. We can extract the efficiency for any given energy from a simulation as follows:

$$\epsilon_{p,\text{sim}} = \frac{N_{i \rightarrow i} + N_{(o13) \rightarrow i} + N_{(o2) \rightarrow i} \times (N_{so2})}{N_i + N_{o13} + N_{o2} - N_{bo2}}, \quad (3.4)$$

where we get the fraction of signal outer-2 events to outer-2 events from $N_{so2}/N_{o2} = (1 - N_{bo2}/N_{o2})$. Now we find these values and their uncertainties. We can count the events from data used as input which are in each radial bin. The uncertainties on these events are unrelated to the simulation and are $\sqrt{N}$. This gives us $N_i, N_{o1}, N_{o2}, N_{o3}, N_{o13}$ and their respective uncertainties. $N_{i \rightarrow i}, N_{o13 \rightarrow i}$, and $N_{o2 \rightarrow i}$ come from independent simulations and are statistically independent. The uncertainties, as they are drawn from finite populations can be approximated

$$\Delta N_{\mathcal{X} \rightarrow i} = \sqrt{\frac{N_{\mathcal{X} \rightarrow i}(N_{\mathcal{X}} - N_{\mathcal{X} \rightarrow i})}{N_*}} \quad (3.5)$$

where $\mathcal{X} = i, o13, o2$.

Now we must calculate N_{bo2} , N_{so2} and their uncertainties. We see in Figure 3.18 the distribution of the outer-2 radial bin from 300 eV_{ee} up to 3.5 keV_{ee} . The Compton background is mostly flat above and below the line. A simple approximation could just take the average number of events/energy above and below the line. However, there is visual evidence of small satellite peaks at 1.5 keV_{ee} and perhaps 1.1 keV_{ee} (which is more visible in the middle bin of Run 2b data).

We also have L-shell events with reduced Luke gain below 1.22 keV_{ee} . If we take new bins corresponding to Ko3 and Ko4 but scaled by 1.3/10.37, we end up with

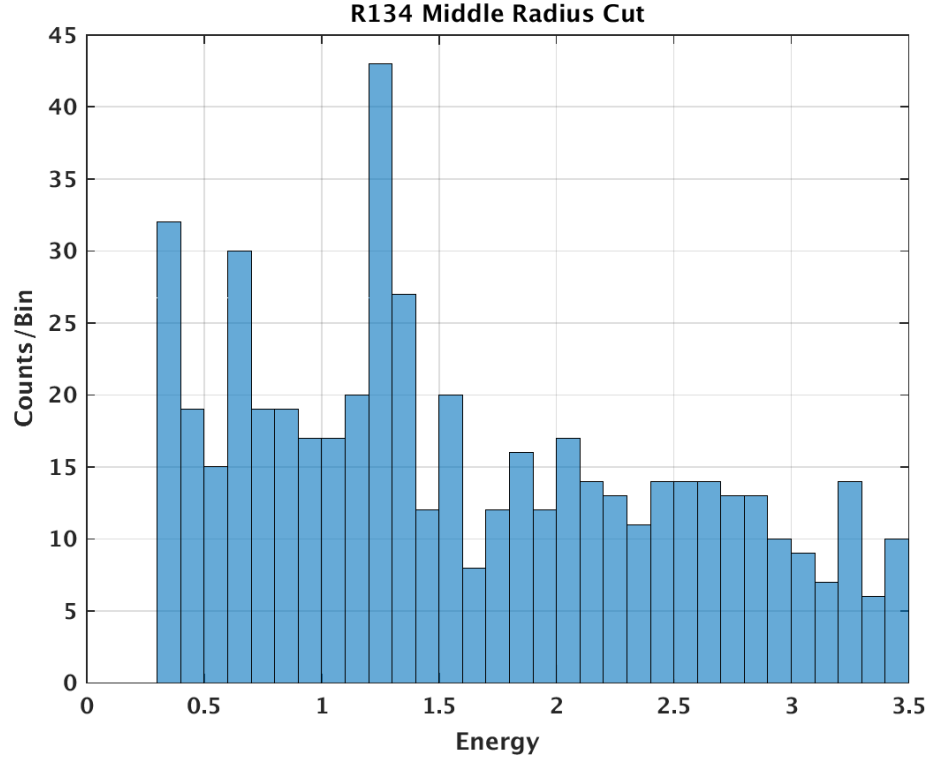


Figure 3.18: Outer bin 2 energy histogram for Run 2a. We see evidence that there are more events lower in energy than higher from L-shell captures with reduced Luke gain.

Lo3 bounded by $[0.665, .94]$ keV_{ee} and Lo4 bounded by $(0.94, 1.22)$ keV_{ee} . We have already calculated the K-shell leakage into Ko3 and Ko4 earlier, and if we multiply by the theoretical branching ratio for L:K of 0.12:1, we get an estimate of the number of L-shell events we need to subtract from these bins to obtain the flat Compton background.

To avoid the small lines being included into the Compton estimate, we investigate different choices of bins (see Figure 3.19). First we examine a bin from 1.45 to 1.8 keV_{ee} which includes the 1.5 keV_{ee} satellite peak. A second binning that spans from 1.6-3.1 keV_{ee} is also considered. For the first bin we calculate the background both

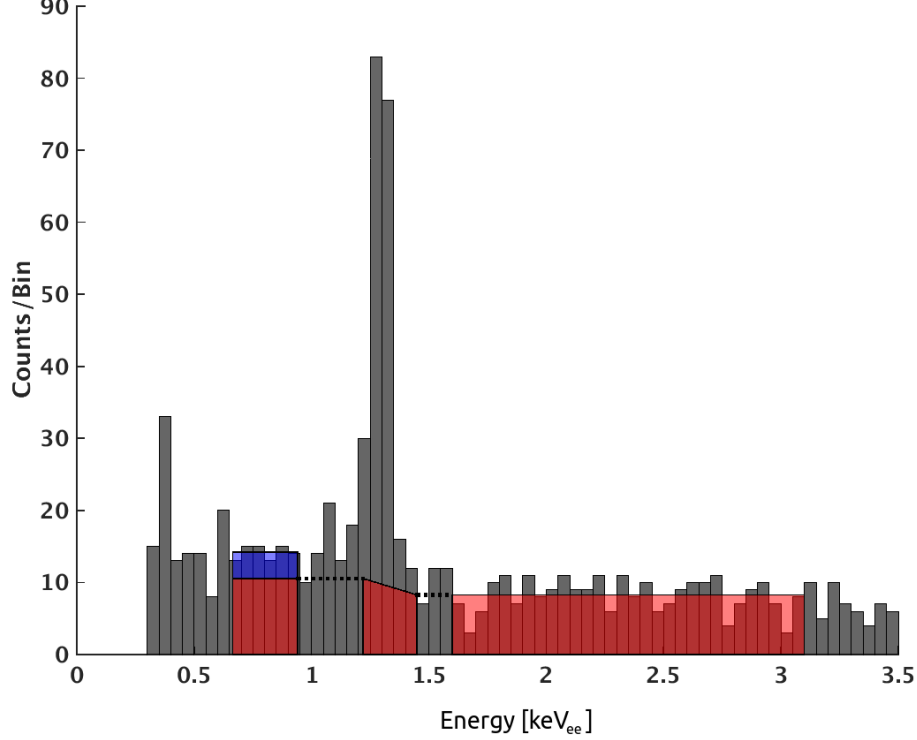


Figure 3.19: We see an estimate of background contributions from Reduced Luke gain events (blue) and flat backgrounds (red) overlaid on data and spaced to avoid potential satellite peaks.

with and without subtracting the peak contribution. We determine the satellite peak contribution by counting the potential peak events that pass the radial cut and use the same peak efficiency as we calculate for the L-peak to estimate the number of peak events that fail the radial cut. But we need the peak subtraction to calculate the true peak efficiency. Thus it is necessary to do this step in iterations. Since the dependence of the peak efficiency on this correction is very small, a one-step iteration is sufficient. The other bins provide a range which helps determine the uncertainty on this background.

From this method we obtain a background of 28^{+9}_{-4} from the 71 total o2 events

Table 3.2: Efficiencies from the pulse sim. Final efficiencies are the product of the Peak Efficiency and the Energy Efficiency ($86.4 \pm 0.9 \%$)

Sim. Energy Run 2a	Peak Efficiency	Final Efficiency
40 eV	$57.5 \pm 5.7\%$	$49.7 \pm 5.0\%$
60 eV	$57.0 \pm 5.6\%$	$49.2 \pm 4.9\%$
80 eV	$55.5 \pm 5.4\%$	$48.0 \pm 4.7\%$
100 eV	$54.9 \pm 5.3\%$	$47.4 \pm 4.6\%$
120 eV	$54.8 \pm 5.3\%$	$47.3 \pm 4.6\%$
140 eV	$57.4 \pm 5.4\%$	$49.6 \pm 4.7\%$
160 eV	$59.0 \pm 5.5\%$	$51.0 \pm 4.8\%$
180 eV	$59.6 \pm 5.5\%$	$51.9 \pm 4.8\%$
200 eV	$60.6 \pm 5.6\%$	$52.4 \pm 4.8\%$
250 eV	$61.7 \pm 5.6\%$	$53.3 \pm 4.9\%$
300 eV*	$60.6 \pm 5.6\%$	$52.4 \pm 4.8\%$
650 eV*	$60.1 \pm 5.6\%$	$51.9 \pm 4.8\%$
1300 eV	$60.6 \pm 5.6\%$	$52.4 \pm 4.8\%$
Sim. Energy Run 2b	Peak Efficiency	Final Efficiency
40 eV	$54.9 \pm 4.5\%$	$44.3 \pm 3.7\%$
60 eV	$51.3 \pm 4.3\%$	$44.3 \pm 3.8\%$
80 eV	$50.9 \pm 4.3\%$	$44.0 \pm 3.7\%$
100 eV	$52.5 \pm 4.3\%$	$45.4 \pm 3.7\%$
120 eV	$53.0 \pm 4.2\%$	$45.8 \pm 3.7\%$
140 eV	$53.7 \pm 4.3\%$	$46.4 \pm 3.7\%$
160 eV	$54.1 \pm 4.3\%$	$46.7 \pm 3.7\%$
180 eV	$53.7 \pm 4.3\%$	$46.4 \pm 3.7\%$
200 eV	$54.5 \pm 4.3\%$	$47.0 \pm 3.7\%$
250 eV	$55.6 \pm 4.3\%$	$48.0 \pm 3.8\%$
300 eV*	$56.4 \pm 4.4\%$	$48.7 \pm 3.8\%$
650 eV*	$56.0 \pm 4.4\%$	$48.3 \pm 3.8\%$
1300 eV	$56.7 \pm 4.4\%$	$49.0 \pm 3.8\%$

for Run 2a and 9 ± 2 background events of the 59 o2 events in Run 2b. With this we now have all the information needed to calculate the efficiency for all energies for which we have generated simulations. Table 3.2 summarizes the efficiencies for the simulations.

3.8 CDMSlite Run 2 WIMP search

The SuperCDMS collaboration produced a publication in January 2016 using these efficiency results in a WIMP search [9]. The second run of CDMSlite drastically improved the sensitivity to low mass WIMPs from 2-5 GeV/c^2 over previous results. No WIMPs were found. Figure 3.20 shows the exclusion limits (a plot which shows the limit for how large the interaction cross section between WIMPs and the detector material can be as a function of WIMP mass, based on how sensitive the search was and the total number of events seen in the search region) for CDMSlite Run 2 compared to other similar WIMP searches at the time of publishing. To calculate the limit, a combination of the efficiencies is taken on events in the signal region; below 2 keV_{ee} and above the hardware trigger threshold. The trigger threshold is the 50% level for when the readout properly triggered on an event. With strict cut to remove events that could cause triggers due to noise or cross talk between the detectors, a 50% trigger threshold for Run 2a was calculated to be $75^{+4}_{-5} \text{ eV}_{ee}$. With the better noise in Run 2b, the trigger threshold was lowered to $56^{+6}_{-4} \text{ eV}_{ee}$ [9]. Other cuts on low-frequency noise based on pulse shape goodness of fits were used with varying strictness throughout the Run, as the cryo-cooler began to degrade throughout Run 2a creating a noise with a period of about 830 ms, before the issue was resolved prior to Run 2b [9]. The final combination of the cuts has an efficiency near 50% for the higher portion of the search range in energy. With a radial cut efficiency of around 55%, this means all other cuts have a very high efficiency in this range. The other cuts, however quickly fall off in efficiency below 100 eV_{ee} . This is seen in Figure 3.21.

A Monte Carlo method was used to determine the final energy-dependent efficiency and corresponding uncertainties [9]. Using an optimum interval method with

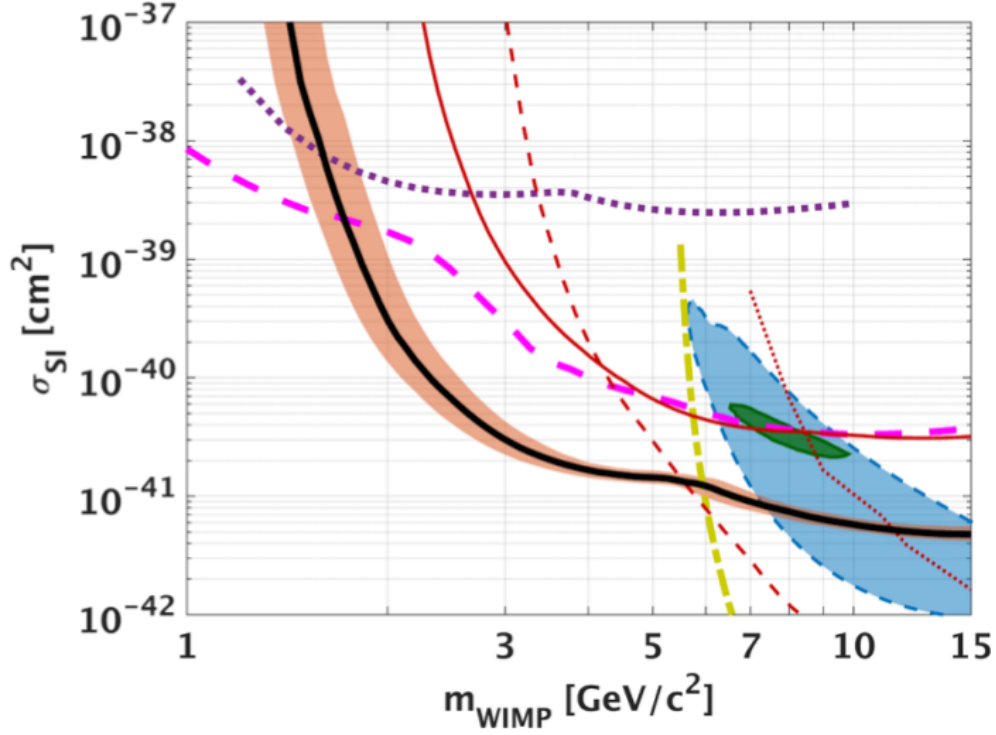


Figure 3.20: The CDMSlite Run 2 WIMP median 90% confidence limit exclusion curve (black) with 95% confidence bands (salmon shaded bands). CDMSlite Run 1 is the thin red solid curve [8]. Other selected results are SuperCDMS (red thin dashes) [7], LUX (dark-yellow dashes) [42], CRESST (magenta dashes) [46], DAMIC (purple dots) [62] and EDELWEISS-II (red thin dots) [36]. Previous results with potential WIMP signals which are at least partially excluded by this result are CDMS II Si (blue shaded region) [45] and CoGeNT (dark-green shaded region) [34]. Figure from [9].

no background subtraction [63] and taking into account the efficiencies, using standard galactic dark matter distributions of $0.3 \text{ GeV}/\text{cm}^3$ local density, 220 km/s mean Galactic WIMP velocity, 232 km/s mean orbital velocity of Earth around the galactic center, and galactic escape velocity of 544 km/s [64, 9] and using a Helm form factor, the WIMP limit seen in Figure 3.20 is calculated.

The total new parameter space excluded by CDMSlite Run 2 ranged from 1.6 to

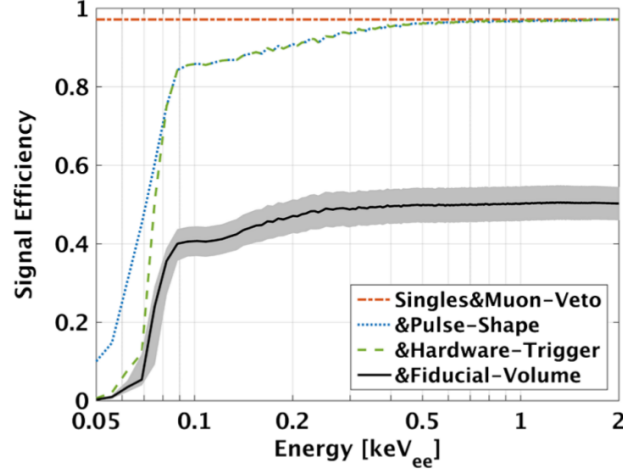


Figure 3.21: Efficiencies of the layers of cuts, with single event and muon veto in red, adding in pulse shape and data quality cuts in blue, the further effect of the hardware trigger threshold cut in green, and finally the radial cut applied in black, with a grey 95% confidence band. From [9]

5.5 GeV/c².

3.9 Post Publication Radial Work

Since the publication of the analysis, several ideas to improve the radial parameter and simulations have been explored.

3.9.1 Adding Delay Into Simulation

After the publication, on further consideration it was noticed that when doing the simulation, the measured delay from data was not incorporated into the pulse simulation. The fact that the simulations seemed to perform as well as they did for the paper result seems to stem from the fact that the delay and fast template are so correlated, and that the true shape of the pulse is not at all determined by the delay. Realigning the pulse just causes the fast template fit to compensate in terms of contribution to

the radial parameter. Nonetheless, the simulation mechanism was changed to allow the data delay to be included. Additionally, the method of the scaling of the pulses was changed, so that instead of first scaling down by PTNF (narrow) or normalizing both amplitudes to a slow pulse amplitude of 1 (wide) and then multiplying by the desired energy in a separate step, both pulse heights were just changed by a fixed ratio, which should produce a result the same in energy resolution to the wide simulation.

The results of this simulation are encouraging in that the final efficiencies do not change drastically. Table 3.3 compares the peak efficiency of the new simulation with the delay added in, compared to the simulation without it.

All of the results are consistent with the old simulation in terms of peak efficiency. The values are well within one sigma uncertainty. The biggest change in efficiency is at 60 eV_{ee} for Run 2b, where the efficiency changes in an unfavourable way by about 3.4 percentage points, or about 7 %. This is still well within the statistical uncertainty. The fact that all of the values are so close probably reflects the correlations in the input between the different simulations, as every simulation used the same noise traces for the same inputs. A plot of all of the simulations matching what is seen in Figure 3.10 is produced for the new simulations in Figure 3.22.

3.9.2 Attempted Two-Template Optimal Filter Usage Improvement

The three parameters that come out of the two-template optimal filter are important in calculating the radial parameter. With some redundancy in the “peakiness” information captured between the delay and the fast-template amplitudes, it may be possible to refine the radial parameter by using the phonon total (PT) trace (the

Table 3.3: Efficiency comparison between the new and old pulse simulations. * marks wide simulations in the old method.

Run 2a Sim Energy	New PE	Old PE	Δ PE
40 eV	$55.1 \pm 5.1\%$	$57.7 \pm 5.7\%$	$-2.6 \pm 10.8\%$
60 eV	$54.2 \pm 4.7\%$	$57.0 \pm 5.6\%$	$-2.8 \pm 10.3\%$
80 eV	$56.2 \pm 4.6\%$	$55.5 \pm 5.4\%$	$+0.7 \pm 10.0\%$
100 eV	$56.3 \pm 4.5\%$	$54.9 \pm 5.3\%$	$+1.4 \pm 9.8\%$
120 eV	$56.4 \pm 4.4\%$	$54.8 \pm 5.3\%$	$+1.6 \pm 9.7\%$
140 eV	$58.5 \pm 4.5\%$	$57.4 \pm 5.4\%$	$+1.1 \pm 9.9\%$
160 eV	$60.1 \pm 4.5\%$	$59.0 \pm 5.5\%$	$+1.1 \pm 10.0\%$
180 eV	$60.6 \pm 4.5\%$	$59.6 \pm 5.5\%$	$+1.0 \pm 10.0\%$
200 eV	$60.6 \pm 4.5\%$	$60.6 \pm 5.6\%$	$0 \pm 10.1\%$
250 eV	$62.2 \pm 4.6\%$	$61.7 \pm 5.6\%$	$+0.5 \pm 10.2\%$
300 eV*	$61.7 \pm 4.6\%$	$60.6 \pm 5.6\%$	$+1.1 \pm 10.2\%$
650 eV*	$61.7 \pm 4.6\%$	$60.1 \pm 5.6\%$	$+1.6 \pm 10.2\%$
1300 eV	$60.6 \pm 4.5\%$	$60.6 \pm 5.6\%$	$0 \pm 10.1\%$
10370 eV	$60.1 \pm 4.5\%$	NA	NA
Run 2b Sim Energy	New PE	Old PE	Δ PE
40 eV	$51.9 \pm 4.4\%$	$54.9 \pm 3.7\%$	$-3.0 \pm 8.1\%$
60 eV	$47.9 \pm 4.1\%$	$51.3 \pm 3.8\%$	$-3.4 \pm 7.9\%$
80 eV	$49.8 \pm 4.0\%$	$50.9 \pm 3.7\%$	$-1.1 \pm 7.7\%$
100 eV	$52.5 \pm 4.1\%$	$52.5 \pm 3.7\%$	$0 \pm 7.8\%$
120 eV	$53.3 \pm 4.1\%$	$53.0 \pm 3.7\%$	$+0.3 \pm 7.8\%$
140 eV	$54.1 \pm 4.1\%$	$53.7 \pm 3.7\%$	$+0.4 \pm 7.8\%$
160 eV	$54.8 \pm 4.2\%$	$54.1 \pm 3.7\%$	$+0.7 \pm 7.9\%$
180 eV	$55.6 \pm 4.2\%$	$53.7 \pm 3.7\%$	$+1.9 \pm 7.9\%$
200 eV	$55.6 \pm 4.2\%$	$54.5 \pm 3.7\%$	$+1.1 \pm 7.9\%$
250 eV	$56.0 \pm 4.2\%$	$55.6 \pm 3.8\%$	$+0.4 \pm 8.0\%$
300 eV*	$55.6 \pm 4.2\%$	$56.4 \pm 3.8\%$	$-0.8 \pm 8.0\%$
650 eV*	$55.6 \pm 4.2\%$	$56.0 \pm 3.8\%$	$-0.4 \pm 8.0\%$
1300 eV	$57.9 \pm 4.3\%$	$56.7 \pm 3.8\%$	$+1.2 \pm 8.1\%$
10370 eV	$56.0 \pm 4.2\%$	NA	NA

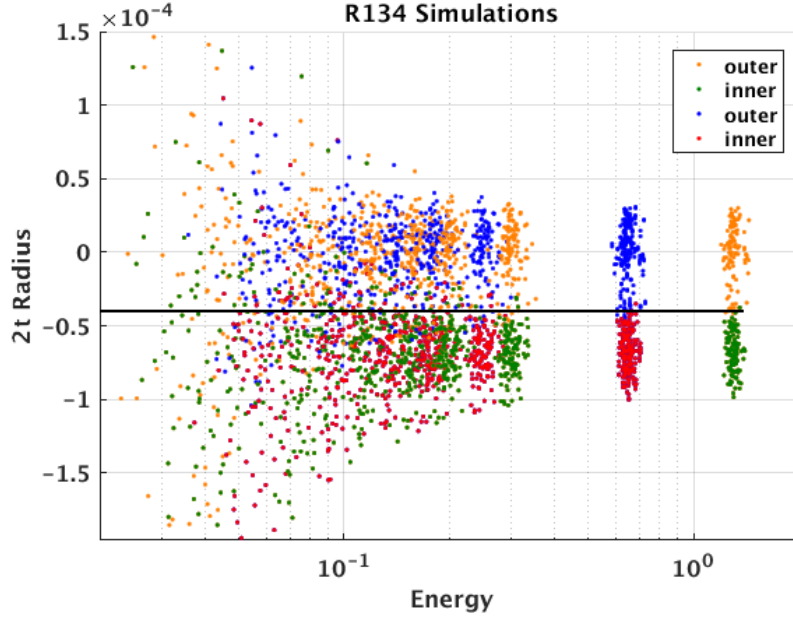


Figure 3.22: Radius vs. Energy for all Run 2a Simulations. Blue/orange events were inner in data, and red/green events were outer in data.

weighted sum of all four phonon channels) to get information about the individual channels. Because radial information is extracted from individual channels, which are noisier than the combined PT trace (since it is an average), any parameters associated with PT should be closer to the true values. It is expected (see Chapter 2) that the late part of the pulse captured by the slow-template amplitude should be the same in all channels, as that is the result of phonons scattering throughout the detector in a way that has reached equilibrium. Since the PT trace should have the best signal to noise, if the slow amplitude for the four individual channels is fixed to the slow amplitude of the PT (multiplied by appropriate relative amplitude calibration factors), then the fit for the individual channels should have one less parameter to account for when fitting and be able to best extract information about the peakiness from the remainder.

Since the same event is being measured in all channels, the real start time of the event should be the same. A pulse that is very peaky will rise above the noise quicker than a non-peaky pulse, so there should be some degeneracy between the delay and fast template. If we fix the delay to PT, then hopefully all the relevant information for the position should be found in the fast amplitude.

So we proceed by fixing the slow amplitude and the delay to PT in the two-template Optimal Filter fit. So the difference in delay between channels that was used in calculating the radial parameter goes to 0, but channels that have the templates shifted backward due to removal of a positive delay in time now may overestimate the rise in the early part of the pulse if the fast template was kept the same. But the fast template, left as the only free parameter for the individual channel compensates by having an amplitude that is more negative than it would have been with a free delay parameter. The newly introduced difference in the fast amplitude compensates for the delay's previous contribution to the radial parameter.

Work in this area is ongoing. It was temporarily put on hold to pursue other efforts when it was determined a full analysis would not be complete in time to confirm success of and implement the new method before the processing of the CDMSlite Run 3 data.

Chapter 4

Queen's Facility HV Tests

4.1 High Voltage Breakdown

When high voltage is applied across a Germanium detector, there is a possibility that eventually there will be a breakdown associated with a current across the detector, resulting in a rapidly rising temperature, a loss of pulses, and an instability of the noise. In the first Run of CDMSlite at Soudan, a bias voltage of $V_b = -69$ V was chosen for the detector (though with leakage currents later considered, probably ran at a much lower bias across the detector). During calibration runs, increases of the noise were observed to start around -60 V, and then went up significantly above -85 V [8]. The bias is picked to maximize the signal to noise ratio, and for Run 1 it was -69 V. CDMSlite Run 2 used a bias of -70 V, and CDMSlite Run 3 used a different detector, T2Z1 (iZIP 4) and the detector was biased to -75 V.

While high voltage is applied, charges build up on the surface of the detector and get trapped in defects in the crystal. This creates a field which opposes the one created by the applied voltage. To fix this issue, a flash of an LED is applied to neutralize these charges between runs. Typically, this is enough to reset the detector

to a neutral state, and after cooling down from an LED flash, data taking can be resumed. After the CDMSlite Run 3 WIMP search ended, the voltage was turned off. Later, when the voltage was resumed, despite flashing the detector, a stable run of -75 V was never achieved again, and only up to -25 V was achieved for a stable run.

4.2 Queen's G16K Detector

The Queen's Test facility has done most of its testing on the G16K detector. This is a HiZIP (Half iZIP) detector [32], which has a slightly different configuration from the iZIPs used at Soudan. As mentioned earlier, iZIPs have four phonon sensors and two charge sensors on each side of the crystal. The charge sensors in an iZIP are usually labeled QIS1, QOS1, QIS2, and QOS2 (see Figure 4.1), for charge inner and outer on each side. In order to gain sensitivity to surface charges, we change on the HiZIP the phonon sensors on one side by wire bonding them together and attaching them to a charge readout. This modified sensor is called Qp. As the readout electronics are only capable of reading four charge channels, instead of overhauling that system, QIS2 and QOS2 are connected together, and read out as one channel called Q2. A diagram of the layout of the HiZIP is seen in Figure 4.2.

4.3 High Voltage Tests at Queen's Test Facility

Unlike other test facilities, Queen's has had some success with running detectors at positive high voltage. In a run performed by Muad Ghaith, the G16K successfully

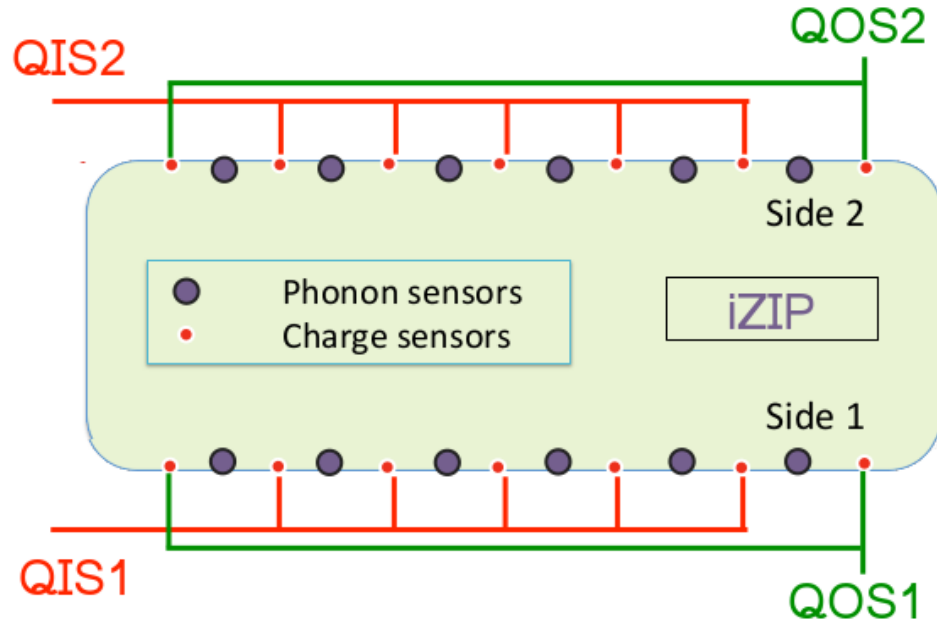


Figure 4.1: The iZIP detector has four charge channels labeled QIS1, QOS1, QIS2, and QOS2 interleaved with phonon sensors. Modified from a figure in [32]

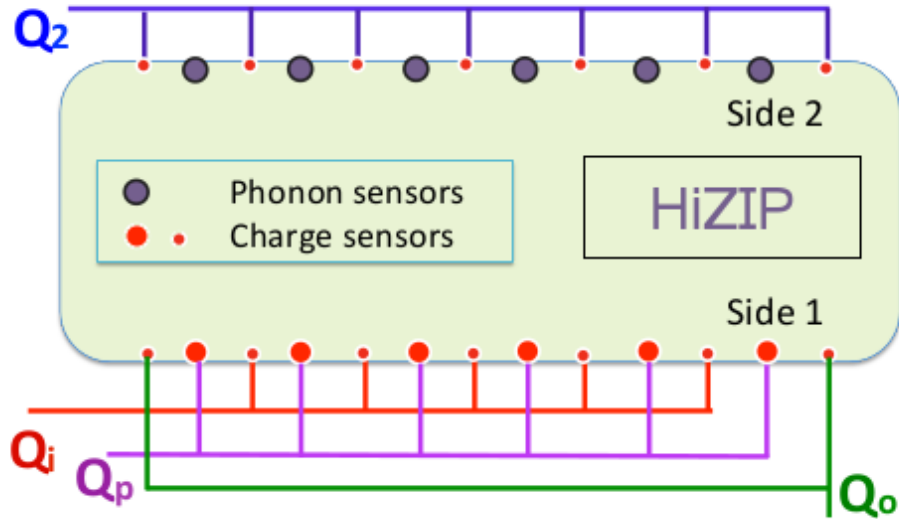


Figure 4.2: The HiZIP detector has Q_i , Q_o , and Q_p on side 1 and phonon sensors and Q_2 on side 2. Modified from a figure in [32]

took positive high voltage to +120 V [65], which is impressive considering the typical breakdown that occurs around +25 to +40 V at other facilities.

Another high voltage test for the G16K was planned so that all four phonon channels could be operated (there were issues with at least two channels during Muad’s first run). This run (Run 68 at the Queen’s Test Facility) took place in April-May, 2016. There was a special hardware configuration for this run. An optical fiber was installed to be able to expose the detector to short bursts of IR photons of different wavelengths [65]. This optical fiber may have played a role in the results of the high voltage tests.

To recreate a similar electric field configuration to CDMSlite, a voltage was applied to one side of the detector through the charge readouts Q_i , Q_o , and Q_p . With the full side biased, and Q_2 on the other side held at ground, there is a field that should be the same as in CDMSlite.

4.3.1 Summary of Run 68 Tests

A range of data series and tests were performed for Run 68. Data were taken at a range of voltages from -90 to +60 V. Before each data period, the detector is placed at about 10 V higher than the intended voltage for about 2 minutes in order to “pre-bias” the detector; to free all the trapped charges that would be freed at the operating voltage and stabilize the noise. Between every run a 15 second LED flash was used to reset the detector.

Data Quality

There were some issues with data quality in this run. Superconducting Quantum Interference Devices (SQUIDs) need to be properly tuned by adjusting a bias across it. If the SQUIDs are not properly tuned, then the pulses' read out will not be of the

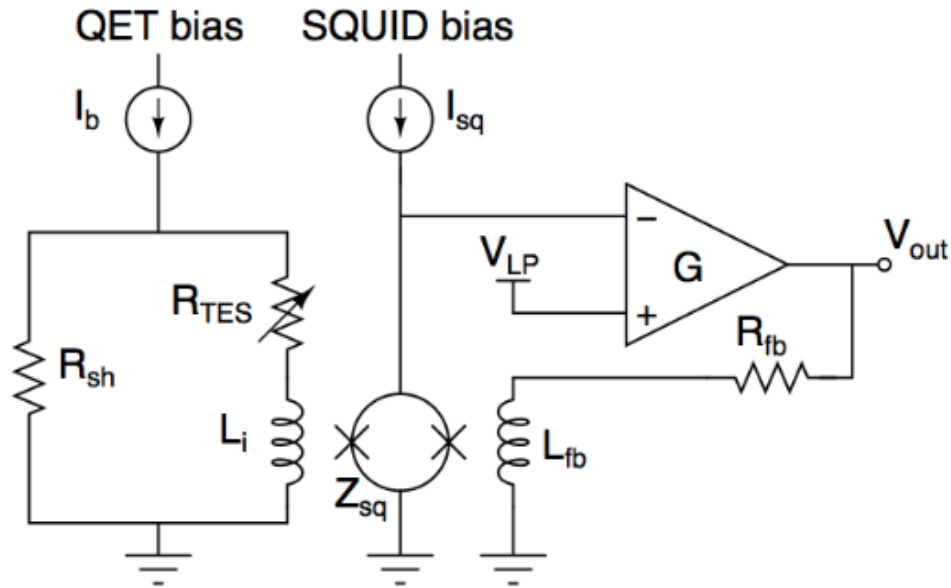


Figure 4.3: The SQUID array (From [33])

best quality, as the noise performance and stability of the detector is dependent on the proper SQUID tuning.

Throughout Run 68, the QET bias and other operating conditions had to be re-tuned many times, resulting in varying relative calibrations. This makes it difficult to compare events between series, as an absolute magnitude of a pulse amplitude does not mean much if a similar energy event would not produce the same amplitude with different relative calibration factors. Problems with Run 68 were multiple. The detector could be turned up to high voltages for short periods of time, and seem to

perform stably, then quickly degrade and get a large leakage current. A theory to account for this is that the optical fiber lets in a multitude of infrared photons which would free enough charges that with all of the Luke amplification, are enough to heat the detector.

In the end for Run 68, it is tough to say much other than that the detector was mostly stable to to -100 V, and +60 V (events showing successful pulses at -75 and + 60 V voltages are shown in Figures 4.4 and 4.5. The unstable operating conditions prevented confirmation of the earlier measurement.

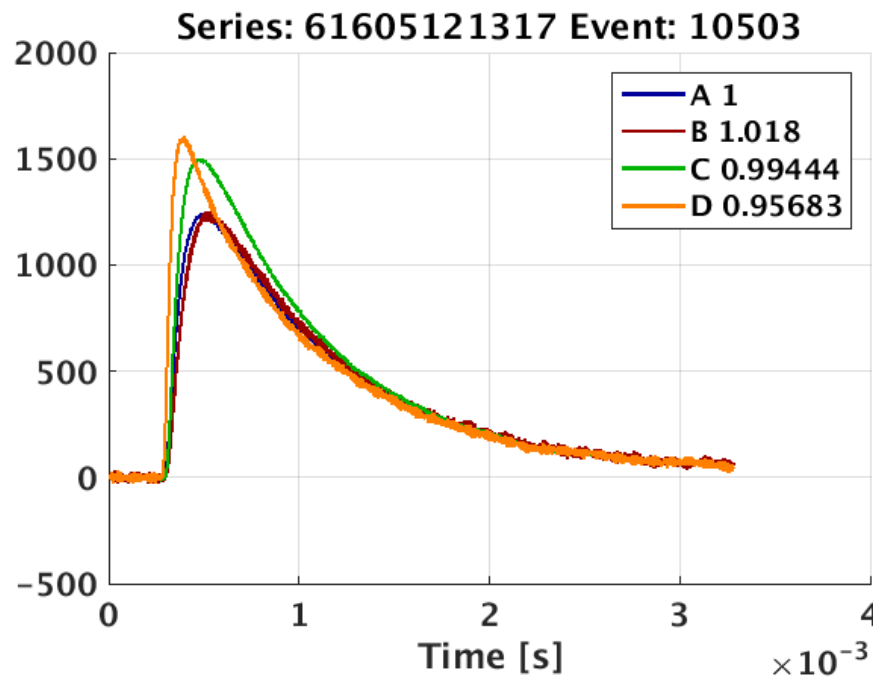


Figure 4.4: The shape of the pulses for Run 68 is demonstrated to be good at -75 V

4.3.2 Run 69

Queen's Test Facility Run 69 was very similar to Run 68, with the G16K set in the high voltage mode. The major difference between runs was that the optical fiber was

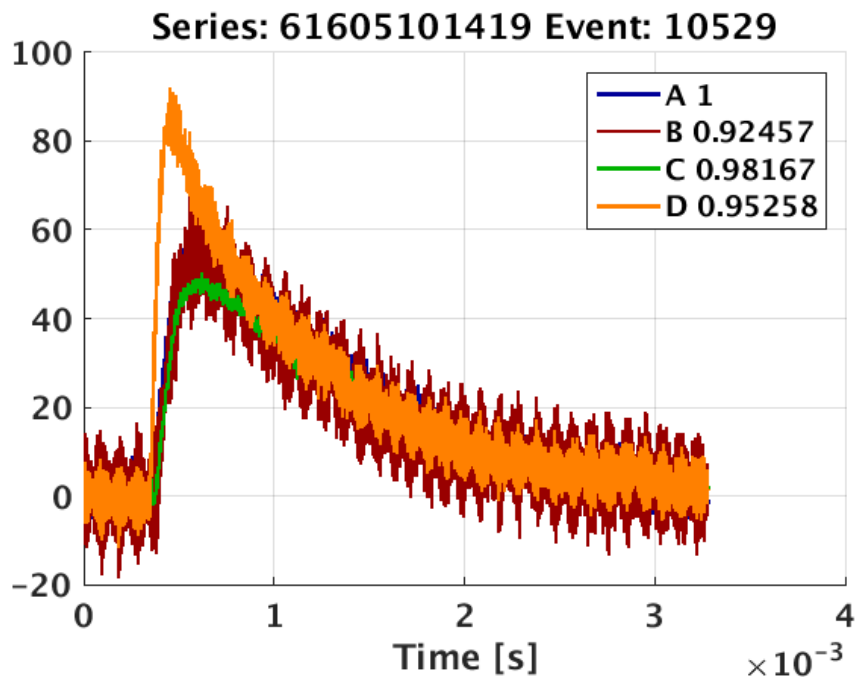


Figure 4.5: The pulse shape for Run 68 is mostly good (with the exception of noise) at +60V

removed, subtracting a source of background infrared photons. In this run, similar difficulties were encountered to Run 68 with SQUID tuning, in a way that pulses were distorted at high voltage. While the pulses are not very useful, the noise can be observed and compared for various voltages.

Figure 4.6 shows the PSD of the noise for Run 69 with increasing negative voltages, and Figure 4.7 shows the same for the set of positive voltages.

4.3.3 Run 70

After the decommissioning of SuperCDMS Soudan, the five towers from the experiment were shipped to different test facilities for inspection. Queen's received tower 2 (T2). T2Z1 is a particularly important iZIP, as it ran at -75 V for CDMSlite Run 3.

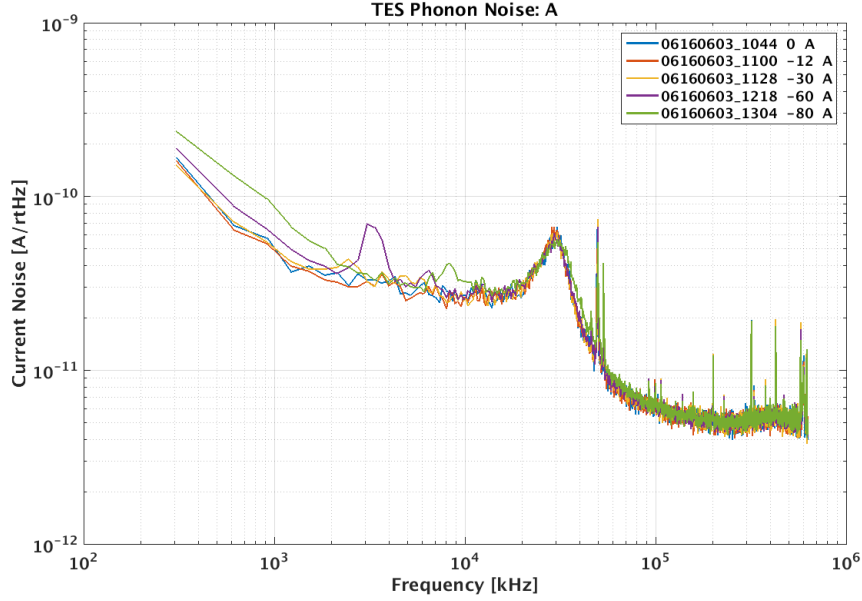


Figure 4.6: Current Noise vs. Frequency in channel A for 5 negative voltage datasets from Run 69. The pattern is mostly as expected, except we see limited amplification of the low frequency noise for the -12 and -30 V data sets.

Recall, when later tests at Soudan attempted to bring it back up to high voltage, the detector could not go above -40 V in tests (set to -25 V for operation) without a breakdown. This inconsistent behavior is troubling, and we attempted to explore the high voltage capabilities of this detector at Queen's. The same readout electronics were all used where possible to mimic the Soudan environment.

A selection of data was taken with a barium source, though no lines from the source were visible. Data sets in a range from -60 to $+100$ V were taken in the standard CDMSlite configuration. Additionally, the end the bias was placed on was reversed, moving the bias from the top to the bottom and the detector was observed operating stably at both $+120$ and -120 V in this reverse CDMSlite mode, though

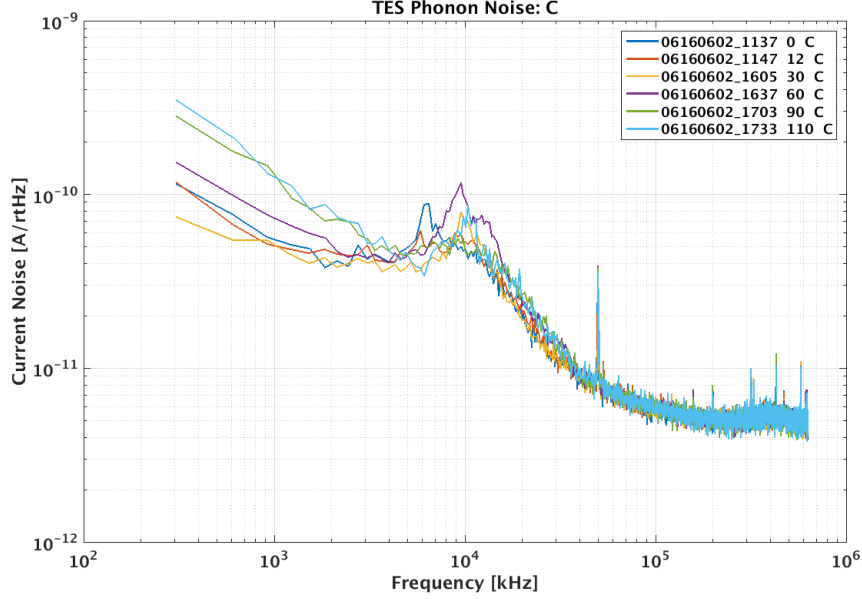


Figure 4.7: Current Noise vs. Frequency in channel C for 6 positive voltage datasets from Run 69. The pattern is mostly as expected, except the low frequency noise from the 0 and 12 V run is higher than the 30 V run. This is not unexpected as the operating parameters were tweaked between these data-taking periods.

data sets were not taken. The only breakdown seen was in standard CDMSlite negative voltage configuration, above -95 V. Data up to the -75 V range used in the experiment worked fine, and there was no evidence of the issue that arose for the photo-neutron calibration. Figure 4.8 shows the noise PSDs for a collection of negative voltage datasets.

4.4 Conclusions

While the data obtained is limited in quality and there are many limits to what can be done with it, we showed that the breakdown at the Queen's test facility generally occurs at much higher voltages than were observed at Soudan and other test facilities.

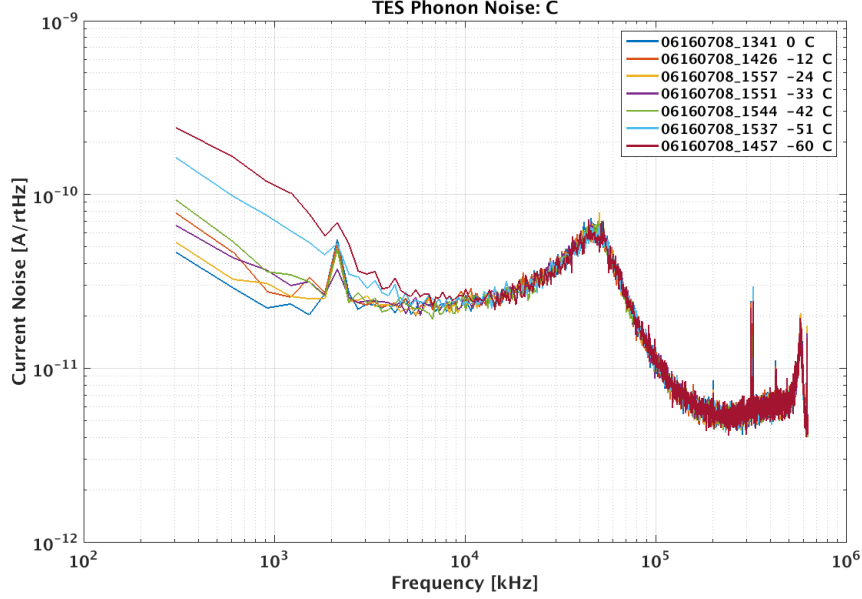


Figure 4.8: Current Noise vs. Frequency in channel C for seven negative voltage datasets from Run 70. The pattern is mostly as expected, except the low frequency noise from the -12 and -33 V runs are switched. This behaviour is unexpected here. There may be pulses in what should be pure noise traces. Statistics were too limited to further tighten cuts rejecting more pulse like traces.

Other test facilities rarely achieve greater than +40 V. It is currently unknown why the performance at Queen's is so much superior to the other facilities, even with the same detector and hardware. If not all of the voltage was being applied across the detector, this could be a solution, but measurements throughout of the leakage current indicate this is not the case. We are planning another data run, this time with a source that will allow us to observe a gamma absorption line. This in turn will allow us to directly measure the Luke gain as confirmation that the voltage is correctly applied and held by the detector.

Assuming that this is not the problem, there is some confusion as to why Queen's has better high voltage performance. The only hardware difference that could possibly

contribute seems to be the difference between the cryostats. The Queen's test facility has so far been the only one that is based on a dry dilution refrigerator, whereas all of the others are wet fridges, and have the possibility of getting trace amounts of Helium on the surface of the detectors. It is unknown how this would cause a breakdown, and the only evidence for this theory is the lack of any other noticeable difference between setups. Plans to test this theory by introducing a bit of Helium to the detector level at Queen's are under careful consideration, and enacting these plans will certainly constitute future work beyond this thesis.

Chapter 5

Summary and Conclusions

5.1 Summary

The astronomical evidence for dark matter is overwhelming. The distribution of mass seen in observational astronomy differs significantly from the mass distribution known from the dynamics of stars in the halos of galaxies. Evidence from larger scales indicates this discrepancy is not unique to galaxies, and it is not entirely explainable by altering the laws of gravity for large scales and masses. A strong to explain the difference is the presence of dark matter in the form of weakly interacting massive particles. These particles are favourable candidates due to the natural production of particles with WIMP properties if supersymmetry (a hypothesis favoured by theoretical particle physics for reasons other than just explaining dark matter) is a correct model of the universe.

SuperCDMS searches for WIMP dark matter by observing recoils in Germanium crystals. Recoils create phonon and charge signals which can be measured in sensors on the surface of the crystals. In CDMSlite, a voltage across the detector is used to create a phonon amplification of the charge signal, while the actual charges are no

longer read out. An effect from the asymmetric electrical field leads to events at large radius having improperly reconstructed energies, because the charges do not receive full Luke gain. This creates a radial-dependent background.

Phonon signal pulses are fit using a two-template optimal filter algorithm, and a radial parameter based on pulse shape is created. This radial parameter is developed by noting that position information can be captured from events which occur in close proximity to a sensor. These events deposit more fast phonons, creating a pulse shape with a quickly rising peak, which is captured in the magnitude of the residual template fit from the two-template optimal filter algorithm. The layout of the four sensors on the surface of the detector allows a comparison of how many fast phonons are seen in the outer phonon channel compared to any of the inner phonon channels, which leads to a quantitative estimation of whether an event should be classified as an inner or outer event. Outer events are excluded to reduce the background from low Luke gain events and a hardware background seen at outer radius in one of the data taking periods.

A simulation models the energy dependent efficiency of a radial cut by taking the fits of high energy pulse shapes, rescaling the amplitudes to lower energy, adding real noise traces and reprocessing these simulated pulses to model the effects of the noise on energy and position resolution. A calculation of the fraction of events reconstructed at the correct energy is also assessed.

CDMSlite published a WIMP search which utilized a radial cut based on the two-template radial parameter, and efficiencies calculated by my radial simulations. This WIMP search saw no WIMPs but excluded WIMPs around a factor of seven better at 3-6 GeV compared to the previous CDMSlite run, which did not include a radial

cut. This result is currently the most sensitive WIMP search in this mass range. The radial cut was the primary improvement in lowering the WIMP-nucleon cross-section exclusion in this range.

5.2 Future Work

There is much future work that can build on the results in this thesis. The simulation and the two-template optimal filter dependent radial parameter continue to be investigated in an effort to understand the radial parameter at a deeper level and to be prepared for CDMSlite Run 3 and SuperCDMS SNOLAB. The third CDMSlite dataset is almost ready for analysis, and a radial cut study similar to the one done for Run 2 needs to be implemented. Further studies on fixing delay and slow template amplitude parameters to the PT fit will be explored. An addition to that study might be to add another free parameter in the form of separate delays for the fast and slow amplitudes, with the slow delay fixed to the PT, but the fast template free floating. The framework of the two-template simulations I built are being used in a salting scheme for CDMSlite Run 3. By creating artificial pulses with the simulation and injecting them into the raw data, analyzers will not be able to tune cuts to remove everything from the signal region, because analyzers will know some signal should be there.

Further studies of T2Z1 will take place at Queen's. This time, a source with strong lines will be used for a study of the Luke gain, and more careful tuning and monitoring of the SQUIDs will take place. Configurations of the Queen's cryostat will be considered that might allow us to test the theory that trace amounts of Helium

on the surface of the detector are what cause the noise breakdown at high voltage for other facilities.

High voltage is a big part of the future of SuperCDMS. When the next generation experiment is ready for operation at SuperCDMS SNOLAB, this work will be important. Many of the new detectors will be operated at around 100 V in order to focus on finding low mass WIMPs. The new fridge will not have an exchange gas, and if we can confirm that breakdown is related to Helium traces on the detector, then efforts to change the sensors to prevent breakdown at high voltage will be less urgent.

5.3 Conclusion

The work done in this thesis demonstrates the effectiveness of a radial cut on reducing backgrounds in CDMSlite style experiments. I have demonstrated that simulations using a pulse shape reconstructed from a two-template optimal filter algorithm combined with a real noise trace can accurately recreate realistic energy and radial distributions. This allows an estimation of the efficiency of a radial cut. The future of SuperCDMS high voltage WIMP searches involves using these techniques to eliminate much of the background that limits the search, and estimate the efficiency of a radial cut on a WIMP signal.

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Appendix A

Two Template Optimal Filter Algorithm

A.1 Optimal Filter Algorithms

Optimal Filter Algorithms are designed to take a set template and fit data points to templates in Fourier space to create the best fit while accounting for the noise. Given a real event which should match a template nearly exactly except for noise, Optimal Filtering attempts to estimate the signal amplitude in a way maximally robust to the measurement noise. It can be shown that optimal filtering gives the optimal resolution possible in the case of a known pulse shape and a known spectrum of stationary noise [33].

When considering using an Optimal Filter Algorithm, the signal and noise must be right for this process. The algorithm is only optimal when you have a fixed signal shape that varies only in amplitude and stationary noise. One begins by assuming there is a template for our fixed signal shape. The signal shape will have an amplitude which will be the primary focus of the fitting algorithm. If one measures a signal shape

in the detector $S(t)$, then one can deconstruct this signal into

$$S(t) = a \times A(t) + n(t) \quad (\text{A.1})$$

where $A(t)$ is the template, a is the amplitude of the template and $n(t)$ is the stationary noise.

In the case of Gaussian stationary noise, one can use a simple time domain fitting process which minimizes the χ^2 between the multiplied template and the real trace. Time-domain fitting has significant drawbacks in the case of non-Gaussian (though stationary) noise, however. Non-Gaussian noise introduces correlations in the noise at different times and so χ^2 is no longer an optimal fit in the time domain. So in order to create a proper optimal fit one must change to the frequency domain with the Fourier transform

$$\tilde{\psi}(\nu) = \int_{-\infty}^{\infty} \psi(t) e^{i2\pi\nu t} dt. \quad (\text{A.2})$$

The different frequency components of stationary noise are uncorrelated, so a frequency-domain χ^2 minimization removes the issue of correlation in the time domain. One can account for the variation in noise with frequency by treating the noise spectrum as a set of error bars for the corresponding frequencies of the trace's Fourier transform. This is exactly what standard optimal filtering is; a one-parameter fit in the frequency domain, accounting for the dependence of noise variance with frequency.

The χ^2 is defined as

$$\chi^2(a) \equiv \sum_x \frac{\|Data(x) - Fit(x, a)\|^2}{N}, \quad (\text{A.3})$$

which in this case goes to

$$\chi^2(a) \equiv \sum_{\nu} \frac{|\tilde{S}(\nu) - a\tilde{A}(\nu)|^2}{\tilde{J}(\nu)} \quad (\text{A.4})$$

where $\tilde{J}(\nu)$ is the spectral noise density $\langle \tilde{n}^2(\nu) \rangle$. Minimizing the χ^2 returns the amplitude which provides the best fit. Following the derivation in [33] that amplitude is found to be

$$a = \frac{\sum_{\nu} \tilde{S}(\nu)\tilde{A}(\nu)/\tilde{J}(\nu)}{\sum_{\nu} \tilde{A}(\nu)\tilde{A}^*(\nu)/\tilde{J}(\nu)}. \quad (\text{A.5})$$

This solves for the amplitude assuming the template is fixed in time to the triggered pulse. However, a delay parameter can be added in to improve the fit, as the triggering is imperfect. Converting back to the time domain with a shift we obtain

$$\psi(t) = \int_{-\infty}^{\infty} \tilde{\psi}(\nu) e^{-i2\pi\nu(t-t_0)} d\nu \quad (\text{A.6})$$

which gives

$$\chi^2(a, t_0) = \sum_{\nu} \frac{|\tilde{S}(\nu) - ae^{-i2\pi\nu t_0}\tilde{A}(\nu)|^2}{\tilde{J}(\nu)}. \quad (\text{A.7})$$

This can be expanded to fitting multiple templates at the same time. The two-template optimal filter takes in two separate templates and fits the amplitudes simultaneously in Fourier space. The final result for the χ^2 following derivations in [33] is

$$\chi^2(t_0) = \sum_{\nu} \frac{1}{\tilde{J}(\nu)} (\tilde{S}^*(\nu)\tilde{S}(\nu) + a^j \tilde{A}_j^*(\nu)\tilde{A}_k(\nu)a^k - 2e^{i2\pi\nu t_0} a^l \tilde{A}_l^*(\nu)\tilde{S}(\nu)) \quad (\text{A.8})$$

where

$$a^j \equiv \left(\sum_{\nu} \frac{\tilde{A}_k^*(\nu) \tilde{A}_j(\nu)}{\tilde{J}(\nu)} \right)^{-1} \cdot \sum_{\nu} \frac{\tilde{A}_k^*(\nu) \tilde{S}(\nu) e^{2i\pi\nu t_0}}{\tilde{J}(\nu)}. \quad (\text{A.9})$$

Minimizing the χ^2 with respect to t_0 is done computationally over a bounded range determined by the trigger window settings, and the values of the amplitudes a^j are explicitly dependent on this t_0 .