

CDMSLITE LIGHTLY IONIZING PARTICLE SEARCH

By

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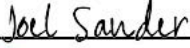
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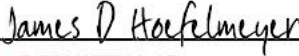
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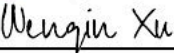
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ABSTRACT

An encouraging avenue of investigation beyond the Standard Model (SM) is the search for particles with fractional electric charge. While the SM does not anticipate the existence of free particles with a fractional electric charge, fractionally charged particles (FCPs) have not been experimentally excluded. Free fractionally charged particles are a feature of viable extensions to the Standard Model with extra U(1) gauge symmetries. This thesis describes a FCP search using CDMSlite Run 2 Period 1 data which results in the first direct detection limits on cosmogenic FCPs with an electric charge as small as $e/10^8$ and the most stringent limit on vertical intensity for FCPs with an electric charge $\leq e/160$. This analysis is also the first to consider cosmogenic FCPs with a wide range of masses ($5 \text{ MeV}/c^2 - 100 \text{ TeV}/c^2$) and velocities ($\beta\gamma = 0.1 - 10^6$). The intensity limit computed for an assumed $\cos^2\theta$ angular distribution is nearly three times weaker than that for an isotropic angular distribution for most assumed values of f .



Dissertation Advisor Approval

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1

Introduction

Although quantization of the electric charge is a principle supported by the Standard Model (SM), numerous experiments are searching for particles that violate this principle. Before the discovery of quarks, all the particles had a charge that was an integer multiple of the electron charge (e). However, now the SM has quarks and antiquarks as fundamental particles with charge $\pm e/3$ and $\pm 2e/3$. These particles are confined within hadrons due to the strong interaction. The fact that the electric charge of all the particles in the SM is an integer multiple of $\pm e/3$ opens a window to the possible existence of Fractionally Charged Particles (FCPs). FCPs are particles with electric charge $q = \pm f e$, where f has a value between 0 and 1.

The mechanism for charge quantization, even though empirically believed, is yet elusive. The magnetic monopole and Grand Unification Theories (GUT) are some of the theories that support the quantization of the charge. Despite significant effort, there has been no confirmed detection of magnetic monopoles. Even following the GUT theories, there is a mechanism for the existence of fractional charge. Holdem [1, 2] showed that in a system with multiple $U(1)$ (electromagnetic) factor, the charged fermions in one $U(1)$ might interact with other, resulting in kinetic mixing, which results in one of the fermions obtaining a fractional

electric charge. Foot [3] showed that the SM with three generations of quark and leptons are not charge quantized unless there is a new physics. Interest in searching for FCPs is growing because of the lack of theoretical and experimental prohibitions on the FCP existence.

FCP particle candidates include unbound quarks, singlet fermions with fractional electromagnetic charge, a paraphoton, or existing particles, like neutron or neutrinos, with a small fractional charge such that they are assumed to be neutral till now. FCPs can be introduced into the SM with an addition of $SU(3) \times SU(2)$, singlet Dirac fermion, with a hypercharge $Y = 2f$. An introduction of unbroken “mirror” $U(1)'$ allows the kinetic mixing of photon and paraphoton (“photon of mirror $U(1)$ ”) causing fermions in $U(1)$ to have fractional charge [1]. Theorists have also proposed theories in which a neutrino flavor or neutrons have a fractional charge [4, 5]. Munoz and Loeb [6] proposed a theory with fractionally charged dark matter. They suggested that up to one percent of the dark matter could be fractionally charged with $f \sim 10^6$ and mass 1 - 60 MeV. Also Foot and Vagnozzi [7, 8] proposed a fractional charge particle to explain the annual modulation signal observed in DAMA/LIBRA [9] and CoGeNT [10] detectors.

Numerous analyses and experiments have searched for and placed constraints on these particles. Cosmological and astrophysical observations exclude some regions of FCP charge-mass parameter space [11]. Three classes of experiments search for FCPs. They are Levimeter-Millikan oil drop-based experiments, accelerator-collider-based experiments, and some direct detection experiments searching for cosmogenic FCPs. Levimeter-Millikan oil drop-based experiments search for FCPs bound to materials [12, 13]. Accelerator-collider-based experiments accelerate a SM particle to achieve high energy and force it to collide with either another highly energetic SM particle or a fixed target material [11, 14]. These collisions can generate conventional particles and possibly exotic species like FCPs. Direct detection experiments wait for the cosmogenic FCPs to interact with their detectors in a low-background environment [15–20].

Highly-energetic free FCPs with a smaller fractional charge can only lightly ionize atoms while passing through a material. Thus, these smaller fractional charges are termed as Lightly

Ionizing Particles (LIPs). LIPs are also referred as milli-charged particles (MCPs) in the literature [14, 21]. The mean energy loss per unit length $\langle dE/dx \rangle$ for LIPs is suppressed by f^2 compared to unit-charged SM particles. In terms of detection physics, a LIP with a small f would deposit a relatively small amount of energy in a detector. Thus, it is necessary to have a detector with a very low energy threshold to search for LIPs with smaller f . This thesis is based on the direct detection search for FCPs with a low-background experiment using a low-threshold germanium detector from the Super Cryogenic Dark Matter Search (SuperCDMS) experiment. The data were collected by the Cryogenic Dark Matter Search low ionization threshold experiment (CDMSlite). CDMSlite is a part of the SuperCDMS experiment focused on lower the energy threshold of a single so-called CDMSlite detector. Data from this detector were used for a LIP search.

Cosmogenic LIPs could be produced in the early universe by a violent astrophysical phenomenon or cosmic-ray interaction with the atmosphere. Astrophysical phenomena like supernova may produce LIPs in the current era. LIPs might even be produced in the atmosphere when a high-energy cosmic ray (CR) interacts with a particle in the atmosphere. A shower of byproducts is created when a CR interacts with the atmosphere. The flux of incoming CRs at a height of 20 km from the Earth's surface is $\sim 2 \text{ cm}^{-2} \text{ s}^{-1}$ [23]. Pions as well as protons and neutrons are produced after the interaction of a CR with the atmosphere [23]. Pions further decay into muons or gamma rays. Figure 1.1 shows secondary particles produced during cosmic activities. LIPs, if they exist, could be created by the same processes. This experiment is sensitive to any cosmogenically-produced LIP regardless of its production mechanism.

This chapter provides a motivation for the FCPs search, provides the current status of the FCPs searches, and introduces the CDMSlite LIPs-search analysis.

1.1 Motivation

The lack of established theories for charge quantization motivates an effort to seek these FCPs. There are multiple ways in which FCPs can exist within the SM, even though the

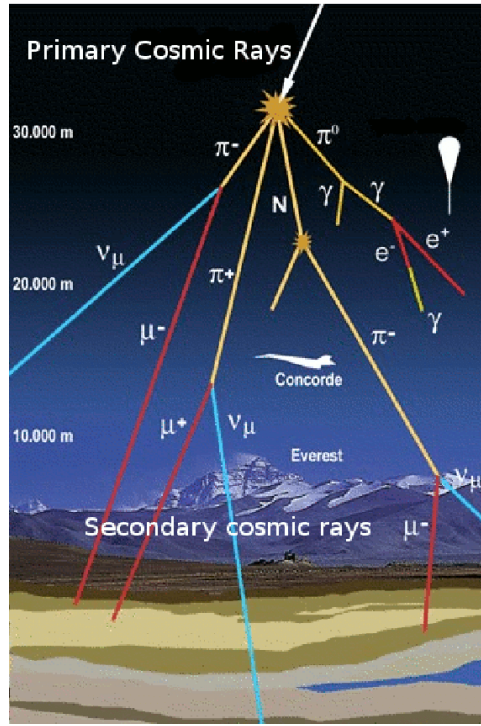


FIGURE 1.1: Secondary particles produced after the interaction of Primary Cosmic rays with atoms of gases in atmosphere. The figure is taken from Ref. [22].

SM empirically supports charge quantization. This section further introduces the theoretical motivations for this FCPs search and introduces theories that accommodate this exotic particle's existence.

1.1.1 Magnetic Monopole, GUT and Charge Quantization

The existence of a magnetic monopole is an appealing theory that would require the quantization of the electric charge. Maxwell did not include isolated magnetic charges in his four equations of the electromagnetic field. In Maxwell's equation, the electric field's divergence is an electric charge, whereas the magnetic fields are divergenceless. The existence of a magnetic monopole would complete the symmetry between electric and magnetic fields. In 1931, Dirac explained that the magnetic monopole's existence implies the charge quantization [24]. According to Dirac, if an isolated magnetic monopole exist, then it has the quantized strength

(μ_o) of

$$\mu_o = \frac{n\hbar c}{2e} \quad (1.1)$$

where, e is electric charge, $\hbar$ is Planks's constant, n is an integer and c is speed of light in vacuum. The theory states that the existence of isolated magnetic poles (monopoles) forces the electric charge to be quantized. However, the absence of experimental confirmation for the existence of monopoles opens the possibility of the existence of FCPs.

Grand Unified Theories (GUT) support the quantization of charge as the existence of magnetic monopole is one of its major predictions. Polyakov [25] and 't Hooft [26] published their famous papers on the existence of magnetic monopole. They argued that monopoles exist naturally in any unified theory. However, some grand unified theories allow the existence of a particle with fractional charge. Holdem [1] proposed that under certain circumstances, charged fermions in an additional $U(1)$ symmetry might interact with ordinary fermions as if they have a non-standard electric charge. Additionally, Witten [27] in 1975 suggested that magnetic monopoles may acquire a fractional electric charge due to CP violation. The CP violation, being a non-quantized parameter, allows the electric charge to have any value. In 1986, Minakata and Hirata [28] also demonstrated that the fractional electric charge induced on GUT monopoles allows natural interpretation as the effect of the chiral anomaly (or Witten effect).

1.1.2 The SM De-Quantization

Foot et al. [3] reviewed whether the criteria defined in the SM are naturally sufficient to require quantization of the electric charge. They were able to conclude the charge quantization for a simple SM model with only generation-one fermions. However, they couldn't prove charge quantization with all three generations of fermions. Figure 1.2 shows quarks and fermions for all three generations of the SM. The authors also reviewed alternate models for possible quantization of the electric charge. This section is based on the conclusions of their review.

Generations

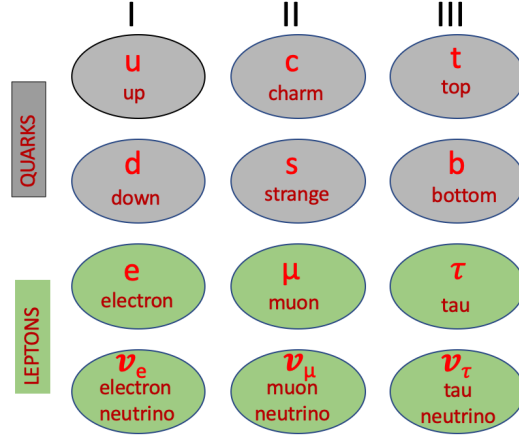


FIGURE 1.2: All three generations of quarks and fermions from Standard Model. The grey-shaded particles are quarks, whereas the green-shaded are leptons.

The One-Generation SM

The one-generation SM contains two quarks: up and down, and two leptons: an electron and an electron neutrino. The authors concluded that the charge is quantized for a simple case of the one-generation minimal SM (i.e., without a neutrino). The calculation was performed by application of the known constrain on the hypercharge of the particles. There are two sources of constraints on the possible hypercharge values of the particles. One constrain comes from a classical Lagrangian, which requires the Lagrangian to be $U(1)$ -symmetric, and another comes from the requirement of gauge anomalies-cancellation [29]. These constraints were enough to determine the hypercharge for all single generation quarks and leptons. The calculation showed the quantization of the charge in a single generation of the SM with an electric charge generator (Q) defined as:

$$Q = I_3 + \frac{Y}{2}, \quad (1.2)$$

where I_3 is a weak isospin and Y is the hypercharge.

Three Generation SM

Even though the single-generation SM showed the charge quantization, the same calculation done for a realistic minimal SM (with all three generations of fermions) could not prove charge quantization. Unlike the simple model with only the first generation of SM, including all three generations makes the calculation complicated. In the absence of a prior requirement for all the generations being perfect copies of each other, the hypercharge for all three generations is expected to be different. The two constraints stated in Section 1.1.2 are insufficient to determine the hypercharges for leptons of all three generations uniquely. The three generations of the SM has four global U(1) symmetries which are generated from: electron-lepton number(L_e), muon-lepton number(L_μ), tau-lepton number(L_τ) and baryon number (B). To check if the combinations of these global symmetries are anomaly free, they are linearly combined such that:

$$L' \equiv \alpha L_e + \beta L_\mu + \gamma L_\tau + \delta B \quad (1.3)$$

. The anomaly constrains are :

$$\begin{aligned} [U(1)_{L'}]^3 &\Rightarrow \alpha^3 + \beta^3 + \gamma^3 = 0, \\ [SU(2)_L]^2 U(1)_{L'} &\Rightarrow 3\delta + \alpha + \beta + \gamma = 0. \end{aligned} \quad (1.4)$$

Using Equation 1.4 with Equation 1.3, yields

$$L' \equiv \alpha L_e + \beta L_\mu + (-\alpha^3 - \beta^3)^{1/3} L_\tau + \frac{1}{3}[-\alpha - \beta - (-\alpha^3 - \beta^3)^{1/3}] B \quad (1.5)$$

.

The actual hypercharge can be represented by a sum of standard hyper charge generator, Y_{SM} and B-L, where B and L are baryon and lepton number U(1) global symmetries. Mathematically,

$$Y = Y_{SM} + \epsilon(B - L) = Y_{SM} + \epsilon L' \quad (1.6)$$

, where ϵ is an arbitrary parameter. So, the electric charge generator, Q, for this model of

all three generations of the SM is

$$Q = I_3 + \frac{Y_{SM} + \epsilon L'}{2} \quad (1.7)$$

. L' depends on two continuous parameters (α and β) and can have any value. This leads to the de-quantization of the electric charge generator. The authors of [3] conclude that the result implies the necessity of new physics to enforce charge quantization. Another possibility is that electric charge is not fully quantized.

1.1.3 Multiple $U(1)$ s and Charge De-Quantization

It is possible to have an apparent fractional charge without violating charge quantization for models with multiple unbroken $U(1)$ symmetries. This scenario provides unique compatibility between magnetic monopoles (GUT) and fractionally charged particles. This section provides an overview of this compatibility based on [1, 2].

Let us start with the assumption that a gauge field defining a universe contains two (or more) $U(1)$ fields, namely $U(1)_A \times U(1)_B$, where each field has its photon and charge of type A and type B. The kinetic term of the Lagrangian of the system is given by [3]:

$$-L_{U(1)}^{kin} = \frac{1}{4}F_A^{\mu\nu}F_{A\mu\nu} + \frac{1}{4}F_B^{\mu\nu}F_{B\mu\nu} + \frac{\epsilon}{4}F_A^{\mu\nu}F_{B\mu\nu} \quad (1.8)$$

where ϵ is a free parameter representing a mixing strength. The first two terms represent the kinetic energy of the $U(1)_A$ and $U(1)_B$ fields, respectively. The last term in the equation represents mixing between two $U(1)$ fields (i.e., two types of photons). The GUT framework disallows this mixing between two $U(1)$ fields at the tree level as each $U(1)$ is itself a free field. However, a radiative correction to higher-order terms in the Lagrangian can induce this mixing. This mixing gives a non-zero coupling between the charged fermions from $U(1)_B$ and photon from $U(1)_A$. This results in an apparent electric charge (q) of type-A for type-B fermions. The induced charge magnitude is $q = \epsilon q_B$ where q_B is B type charge of $U(1)_B$ fermion, and ϵ is the shift in charge.

The kinetic mixing of a photon at loop level is described by Holdom [1]. Let's suppose two fermions f_{AB} and f'_{AB} with both type A and type B charge whose charges are (q_A, q_B) and $(q_A, -q_B)$ respectively. If the mass of f_{AB} and f'_{AB} are different, the mixing between the gauge bosons (photons) corresponding to $U(1)_A$ and $U(1)_B$ has non-zero magnitudes. This gives rise to effective kinetic mixing (third term in equation 1.8) with ϵ given by [2]:

$$\epsilon = \frac{q_A q_B}{6\pi^2} \ln \frac{M'_{AB}}{M_{AB}} \quad (1.9)$$

where M_{AB} and M'_{AB} are masses of f_{AB} and f'_{AB} respectively. The masses have no restriction as long as they are larger than the mass of any known fermions. If M_{AB} and M'_{AB} are of same order ($\frac{M_{AB}}{M'_{AB}} \sim 1.002$) and the coupling constant of both $U(1)$'s are not very different, $\epsilon \approx 10^{-7}$ [2].

1.1.4 Hidden-Sector Models with Fractionally Charged Particles

Theories involving a hidden sector represent a class of models that can generate fractionally charged particles via the method outlined in Section 1.1.3 method. The term “hidden sector” refers to the set of particles whose interactions with known particles are weaker than usual couplings. In this section, we will discuss a few of these hidden sector models with fractional charges. The literature often terms these hidden sector particles as “mirror” particles.

One of these models is based upon CP-symmetric extension of the Minimal Standard Model (MSM) [30]. The model considers a normal and mirror sector with identical coupling constants and also considers a discrete symmetry, A . The Lagrangian of the system after the interchange of normal and mirror sectors is required to be symmetric under CP- A symmetry. According to the authors of [30], this model can only be compatible with experimental data if both normal and mirror sectors cannot be bridged by strong, weak or electromagnetic interactions. Both of these sectors must have their own gauge bosons (photons). The tree-level kinetic mixing between these photons can produce fractional charges via Holdom's effective mixing as discussed above in Section 1.1.3.

Another model, as described in [31, 32] considers a mirror universe which consists of particles and forces isomorphic to the ordinary universe. This consideration is incompatible with Big Bang Nucleosynthesis, as the rate of expansion will be higher if there are a double number of relativistic particles in the early universe. With the higher rate of expansion, the predicted amount of ${}^4\text{He}$ should be more than that observed experimentally now. This problem could be negated if we consider the weak coupling to be $\sim 10\%$ larger during nucleosynthesis than today. We can also consider the possibility that the temperature of the mirror universe is lower than that of our observable universe. The coupling between the observable universe and the mirror universe could bring both the sectors to a thermal equilibrium and produce some fractionally charged particles.

Other models could be imagined containing a mirror sector with a different coupling constant, masses, or particles than the normal sector. All these models anticipate the existence of fractionally charged particles if there is an electromagnetic $U(1)$ field in the hidden sector.

1.1.5 FCPs as Dark Matter

Dark matter particles do not need to carry a quantized charge as long as their electric charge is sufficiently small to evade the observational bounds [33]. Various theories propose FCPs as a possible candidate of dark matter. This section provides an overview of these theories.

Munoz and Loeb [6] proposed a dark matter model with a fractional charge to solve a baryonic temperature problem in the early universe. Recent observations from the EDGES collaboration suggested that during the cosmic dawn, nearly 200 million years after the Big Bang, the baryon temperature was half of the expected value [34]. The authors of [6] proposed that less than one percent of the dark matter has a fractional charge of one-millionth that of the electron charge. They found that for dark matter (a fraction of ($frac_\chi$)), a fractional charge (f) of

$$f = 6 \times 10^{-7} \left(\frac{m_\chi}{MeV} \right) \left(\frac{frac_\chi}{10^{-2}} \right)^{-3/4} \quad (1.10)$$

is sufficient to reduce the baryon temperature by factor of 2. The value of $frac_\chi$ is found to be ≤ 0.1 with m_χ of a few MeV and $f \gtrsim 10^{-6}$.

Foot and Vagnozzi [7, 8] proposed a MeV-scale dark matter which consists of two hidden sector particles charged under unbroken $U(1)'$ symmetry to explain the possible source of the annual modulation seen by DAMA/LIBRA [9] and CoGeNT [10]. The proposed dark matter is a fractionally charged particle with $f \sim 10^{-9}$.

1.1.6 Models without Charge Conservation

Some proposed models [4, 5, 35, 36] lead to the de-quantization of electric charges with broken electromagnetic gauge symmetry. Models predicting non-zero charges of atoms, neutrons and neutrinos are discussed in [4, 5]. According to the authors of [37], any model without charge conservation must include a light scalar particle with “pseudo-electric” charge with $f \lesssim 10^{-2}$. Some models propose a fractionally-charged Higgs-sector particle breaking the electromagnetic symmetry. In [35], the Higgs sector is proposed to contain a minicharged singlet h , which is the only particle to carry a non-quantized charge, in addition to the usual doublet. Another model includes two Higgs doublets and a singlet [36, 38]. The authors propose that there would be a shift in the charge of fermions by a factor of f .

1.2 Current Status

Multiple experiments and analyses have searched for FCPs. The search for FCPs began in the early 1920s as soon as scientists agreed that the electron’s charge is the smallest charge that existed. The Felix Ehrenhaft experiment [39] opposed the charge of an electron as the fundamental charge as they claimed to find particles with a fractional charge of that of e . Their results were never confirmed by other experiments [11]. In the 1960s, with the discovery of quarks as the elementary particle with a charge of $\pm 1/3e$ and $\pm 2/3e$, various experiments started searching for free and isolated quarks. Researchers hypothesized that a quark might become independent during a high-energy interaction. However, according to quantum chromodynamics (QCD), quarks are bound within hadrons by a strong force, which

becomes stronger if the separation increases [40]. After realizing this quark confinement, physicists broadened their search looking for particles with any possible fractional charge. This section will discuss some of the past and present experiments and observations searching for these fractionally charged particles.

One of the techniques looking for these particles uses an experimental setup based on levitation, which is similar to the classical Millikan oil drop method [12, 13]. In these experiments, a small drop of liquid or solid grains is isolated and levitated in an electric field. The charge contained in them is measured from their speed as they are allowed to fall. In 1981 LaRue *et al.* [41], reported an observation of fractional charge of $1/3e$ in niobium using the superconduction levitometer method. Nevertheless, no such observations were found by Smith *et al.* [42], when they used a ferromagnetic levitometer with five times larger niobium samples. Similar experiments have searched for fractional charge particles in sea water [43], meteorites [44] and various other materials [11]. These experiments searched for fractionally charged particles bounded to ordinary matter [45]. These experiments are sensitive to deviations from the integer units of fundamental charge but are generally insensitive to smaller deviations ($f \lesssim 10^{-1}$). However, recently in 2014, David C. Moore et al. [46] were able to set limits for ordinary-matter bound fractional charge particles with $f \lesssim 10^{-5}$ using optically levitated microspheres of dielectric materials in high vacuum.

Accelerator-based experiments are another type of experiment searching for terrestrially-produced lightly ionizing particles (LIPs). In an accelerator based experiment, a particle is accelerated to achieve high energy to finally collide with a fixed target nucleon, which may produce LIPs or other unknown particles along with some known particles. Figure 1.3 shows the constraints on LIP mass-charge parameter space from accelerator-based experiments (AC) taken from [11]. The figure includes constraints from other accelerator-based experiments: the SLAC millicharged particle search (SLAC) [50], OPAL [47], ArgoNeut [14], the search for the invisible decay of ortho-positronium (OP) [49] and the Lamb shift experiment (L) [51]. These experiments can probe deeply (put strong constraint) for LIPs provided that the LIP mass is not too large and the electric charge is not too small. Their search for smaller

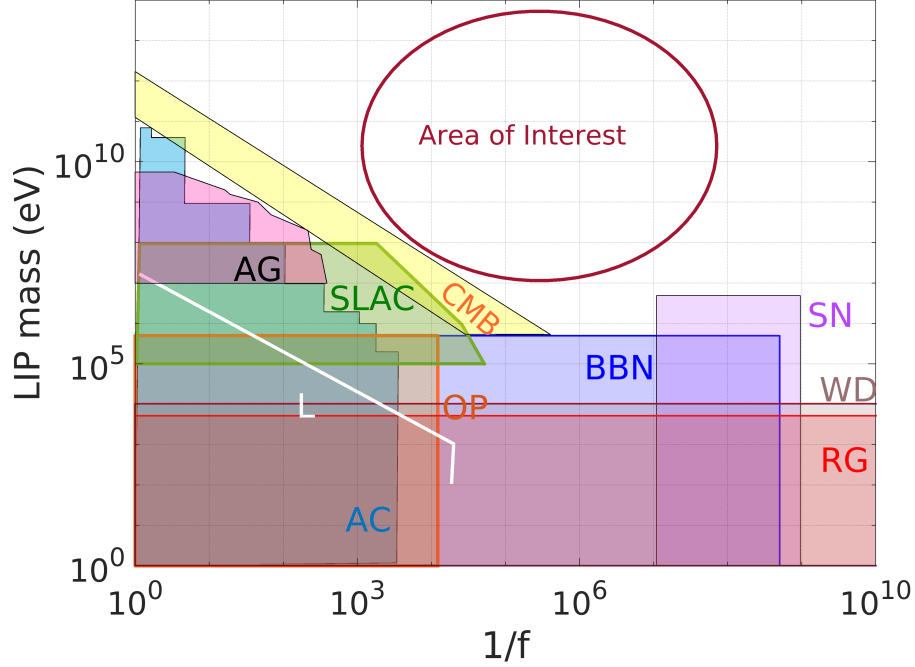


FIGURE 1.3: Constraints on LIP mass-charge parameter space from cosmological observations and laboratory experiments. Un-searched parameter space exist for smaller f with mass $\gtrsim 5 \text{ MeV}/c^2$. This analysis is interested in the parameter space shown by the red circle. The figure is adopted from Refs. [14, 21] and include those from accelerator-based experiments (AC) [47, 48], ArgoNeut (AG) [14], the search for the invisible decay of ortho-positronium (OP) [49], the SLAC millicharged particle search (SLAC) [50], the Lamb shift (L) [51], Big Bang nucleosynthesis (BBN) [21], plasmon decay in red giants (RG) [52], plasmon decay in white dwarfs (WD) [52], the cosmic microwave background (CMB) [53] and Supernova 1987A (SN) [54].

fractional charge and the larger mass range is restricted by the energy of the accelerated particles [11]. The maximum mass reach of this search is given by

$$m_{LIP,max} \approx (2m_N E)^{1/2} \quad (1.11)$$

where E is the beam energy and m_N is the mass of nucleon. So, this technique cannot search for heavier LIPs with very smaller fractional charges.

A strong constraint on lighter LIPs with smaller f comes from cosmological and astrophysical calculations as shown in Figure 1.3. The cosmological constraints are based on the

framework of Big Bang nucleosynthesis (BBN) [21], and models of the cosmic microwave background (CMB) [53]. The astrophysical constraints arise from the observation of plasmon decay in red giants (RG) [52], plasmon decay in white dwarfs (WD) [52], and Supernova 1987A (SN) [54].

In this dissertation, we will discuss another method, which is the direct detection of the cosmological LIPs in a low-radioactivity environment. In this detection technique, a detector is kept in a low-radioactivity environment (usually underground) and waits for evidence of the LIPs interactions in the detector. All the prior direct cosmogenic LIPs search experiments: MACRO [20], CDMS II [15], MAJORANA [16] and TEXONO [17] constrain the intensity of incident cosmogenic FCPs (see Chapter 2 for more details). In the 1990's, Kamiokande [18] and LSD [19] reported intensity limits on $f = 1/3$ and $f = 2/3$. In 2006, MACRO reported sensitivity to LIPs with $f > 1/6$ and sensitivity to vertical intensity as low as $6.1 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [20]. In 2015, CDMS II reported sensitivity to LIPs with f as small as $1/200$ and vertical intensity as low as $7 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [15]. In 2018, MAJORANA reported sensitivity to LIPs with f as small as 10^{-3} with the greatest sensitivity of $2 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for f between $1/6$ and $1/30$. In 2020, TEXONO [17] reported sensitivity to f as small as $e/(3 \times 10^5)$. All these prior experiments assume minimum-ionizing LIPs and considered only electromagnetic interaction. Therefore these experiments do not constrain the LIP mass as the ionization process is independent of LIP mass.

This thesis is based on the direct detection of cosmological LIPs using the Cryogenic Dark Matter Search low ionization threshold experiment (CDMSlite) detector. This is the first direct detection experiment searching for LIPs in mass-charge parameter space. This search is fascinating as it is sensitive to heavier LIPs with smaller f (area shown by a red circle in Figure 1.3), which may be produced during high-energy cosmic activity in the upper atmosphere. The LIP sensitivity is limited by exposure and difficulty in distinguishing LIP-induced events from radioactive backgrounds. This analysis is also the first direct detection search to consider a range of LIP momenta. Chapter 2 describes the direction detection approach of the CDMSlite LIPs search analysis. Section 1.3 introduces the LIPs search

analysis and parameter space of this search.

1.3 SuperCDMS CDMSlite LIPs Search

The Super Cryogenic Dark Matter Search (SuperCDMS) experiment is a low-background, underground experiment operating with solid semiconductor detectors kept at cryogenic temperature. SuperCDMS was located in the Soudan Underground Laboratory (SUL) in Minnesota. The experiment operated at 714 m underground, providing shielding from the cosmic muons. Along with the natural shielding from rock overburden, SuperCDMS also employed several layers of shielding around its detectors to minimize the background from surrounding radioactive materials. The experiment consisted of approximately-cylindrical 15 Ge detectors each with a mass of around 0.6 kg with a height of 25 mm and a diameter of 76 mm. These detectors were cryogenically cooled to (~ 40 mK) temperature. These detectors are sensitive to the energy deposited in the form of heat and ionization by particles during their interaction.

SuperCDMS operated a single detector with an ultra-low ionization threshold. The operation of this detector is termed the CDMS low ionization threshold experiment (CDMSlite), and data from it was used to search for low-mass dark matter. The LIPs search analysis described in the dissertation is based on data collected by the CDMSlite Run 2 Period 1 (February through July 2014) [55]. The details of the experiment are described in Chapter 3.

This analysis is a direct search for cosmologically produced LIPs and is independent of the production mechanism. If the cosmogenic LIPs are energetic such that they can reach and interact with a detector underground, they may deposit energy in the form of heat and charge. Energy depositions in the CDMSlite detector result in phonons that are detected and used to calculate the total recoil energy deposited. This distribution of recoil energy is compared with expected energy distributions to search for these hypothetical LIPs. Chapter 2 describes the direct-detection search for LIPs using the CDMSlite data.

Using the CDMSlite detector gives an advantage over the previous LIPs analysis performed by the CDMS II group and prior cosmogenic LIPs searches. The low-energy threshold

of the detector significantly improves the LIPs search parameter and the limits. LIPs with smaller fractional charges deposit a smaller amount of energy in the detector (see Section 2.1). The lower energy threshold, $\sim 100 \text{ eV}_{ee}$ (more information on Section 4.2), of the CDMSlite detector allows searching for fractional charged LIPs with smaller fractional charge. This is the first analysis that searched for LIPs with f as small as 10^{-8} .

All prior cosmogenic LIPs searches assumed minimum ionizing LIPs, which are only capable of interaction via the ionization process. This analysis considers a signal model where LIPs can interact via ionization and through bremsstrahlung and pair production. The amount of energy lost due to bremsstrahlung depends on the mass of LIPs. Thus, the impact of mass is considered in the signal model generated for this analysis, making this first cosmogenic LIPs search to constrain LIPs mass from $5 \text{ MeV}/c^2$ to $100 \text{ TeV}/c^2$. LIPs signal model was defined for a particle with a mass much larger than an electron. So, the model was only validated for LIPs with mass as small as $\sim 5 \text{ MeV}/c^2$.

The signal model for various initial LIP momenta is also generated for this analysis. This is also the first cosmogenic LIPs search to vary LIP $\beta\gamma$ value from 0.1 to 10^6 , where $\beta = v/c$, $\gamma = 1/\sqrt{1 - \beta^2}$, and v is the LIP velocity. All prior direct detection analysis assumed minimum-ionizing LIPs with $\beta\gamma = \sim 3.1$. This is the first cosmogenic LIPs analysis to set limits on non-relativistic LIPs.

The LIPs flux distribution when it reaches the underground detector is uncertain. This LIPs search analysis takes a conservative approach by calculating the intensity limit for two extreme angular distributions possible for LIPs as in Ref. [16]. The angular distributions considered are the isotropic angular distribution and muon-like cosine-squared angular distribution. The isotropic distribution resembles the distribution for LIPs with very small f , which do not often interact, whereas cosine-squared distribution is another extreme for LIPs with larger fractional charge. Section 2.1.2 has more information about the angular distribution. [Note: Muons are treated as the LIPs with the largest f and mass of 100 MeV .]

2

LIPs direct detection

Cosmogenically produced lightly ionizing particles (LIPs) might be detected via their electromagnetic interactions with a detector, kept at a low-background environment. LIPs entering the earth's surface are assumed to be highly energetic such that they can easily reach an underground detector. The data collected by a detector is then compared to the expected LIPs signal in the detector. A potential discovery requires a strong exclusion ($> 5\sigma$) of the null hypothesis of LIPs existence. Otherwise, an experiment sets a limit on the incoming intensity (flux) of LIPs.

In the early 1960s, scientists started searching cosmogenic fractionally charged particles using cloud chambers [56, 57]. A LIP while passing through the chamber was expected to make a track of lesser density than particles with electronic charge. Most of the searches reported negative results but McCusker & Cairns [58, 59] reported finding a lesser density track corresponding to $2/3e$. No other experiments were able to confirm the result, including an experiment from Napolitano et al. [60] which was able to reach the intensity sensitivity of $\sim 10^{-10} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ (better by a factor of $\sim 10^3$ than McCusker & Cairns result).

Modern day low-background experiments with larger exposure are searching for LIPs [11] as shown in Figure 2.1. These experiments are situated underground, which reduces the back-

ground due to muon activity. The Large Scintillation Detector (LSD) experiment [19] in the early 1990s searched for free fractionally charged particles with a charge of $\pm e/3$ and $\pm 2e/3$. They conducted the experiment for a live time of 2097 days using 90 tons of liquid scintillators. They did not find any evidence of a fractionally charged particle but reported a limit of $10^{-13} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ for those particles. The Kamiokande II experiment [18] improved the sensitivity for these fractionally charged particles by two orders of magnitude using 2400 tons of water as a detector for 1009 days. MACRO experiment [20] later searched for LIPs with $f \geq 1/5$ and was able to set a very strong limit on the order of $10^{-16} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$. Their detector was composed of steamer tubes that can track the particle trajectories and a scintillator system with an improved capacity to reject radioactive or cosmogenic backgrounds. In early 2010, the CDMS-II [15] experiment published limits for $f < 1/6$ for the first time using five stacks (six detectors in each stack) of semiconductor (silicon and germanium) detectors. MAJORANA [16] later improved the existing limits and also published limits for LIPs with f as small as 10^{-3} using 58 germanium detectors with a combined weight of 44.1 kg. Recently in 2019, TEXONO [17] published limits for LIPs with f smaller than 10^{-3} using a germanium detector. This analysis reported here extends the direct search for LIPs with f as small as 10^{-8} using a germanium detector. Chapter 3 has detailed information on the detector and experimental setup.

LIPs interact and deposit energy in a medium as they pass through it. This analysis defines a simple LIP model assuming it to be a stable particle that does not undergo decay. All prior direct search experiments assumed only minimum-ionizing LIPs. The CDMSlite LIP-search analysis is the first direct search analysis to consider a range of LIP $\beta\gamma$ and mass values. This is also the first analysis to consider the radiative energy loss process (bremsstrahlung or pair production) for LIPs in addition to the ionization process. LIPs signal models for a variety of LIP charges, $\beta\gamma$, and mass are generated via Monte Carlo simulation. After generating the signal model, the model is used to set 90% confidence level limits on the vertical intensity of incoming LIPs.

This chapter describes the generation of the LIPs signal model in Section 2.1, and the

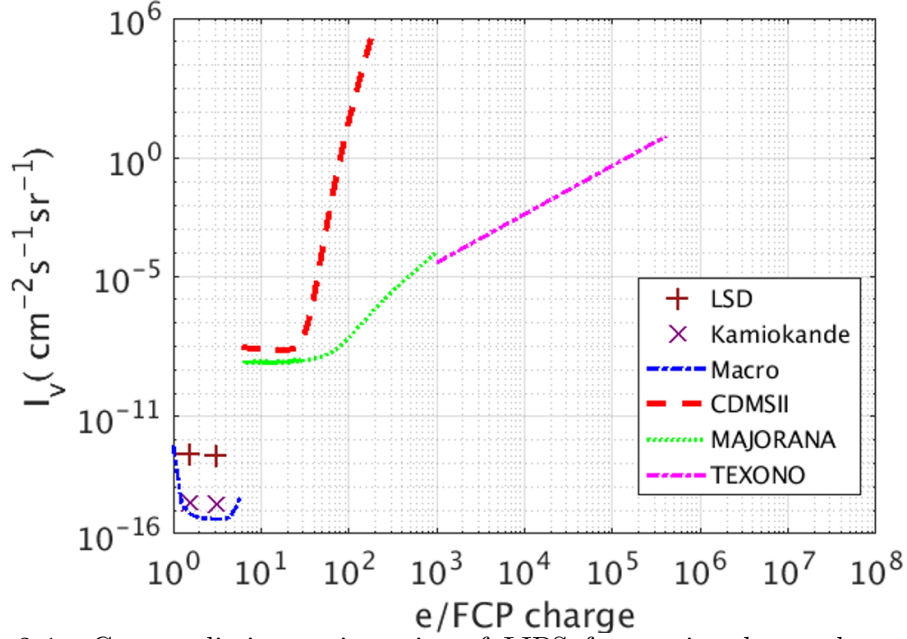


FIGURE 2.1: Current limits on intensity of LIPs from prior detect detection searches; LSD [19] (brown +), Kamiokande [18] (purple $\times$), MACRO [20] (blue dot-dashed), CDMS-II [15] (red dashed), MAJORANA [16] (green dotted), and TEXONO [17] (magenta dot-dashed).

procedure for setting 90% C.L upper limit on LIPs intensity in Section 2.2.

2.1 LIPs Signal Model

LIPs, while traveling through a detector, might interact with atoms in a detector and lose some of their kinetic energy. An expected energy-deposition distribution is computed via Monte Carlo simulation, which models the signature of LIPs in the detector. These LIPs signal models are generated using GEANT4.

A new LIP particle-class is defined in GEANT4. It is a non-decaying muon-like particle with a positive or negative fractional charge and mass. LIPs are capable of interacting in the detector via ionization, bremsstrahlung, and pair production processes. This analysis generates signal models for LIPs with a variety of $\beta\gamma$ and two extreme angular distribution, i.e., muon-like $\cos^2\theta$ (where θ is the angle of incident LIP relative to zenith) distribution as an extreme for larger f , and an isotropic angular distribution another extreme for smaller

f. The initial kinetic energy of the incident LIPs can be varied, which allows us to vary the $\beta\gamma$ values for LIPs. This section describes the physics processes for LIPs, choice of angular distribution, and thus obtained LIPs signal model.

2.1.1 Physics Processes

An energetic LIP traveling through medium loses energy via ionization and radiative processes. The ionization process is the dominant process for most LIPs. But, LIPs with smaller mass or higher $\beta\gamma$ might lose significant energy via bremsstrahlung or pair production. Figure 2.2 shows Feynman diagrams for different LIPs interactions with an electron in the medium. Figure 2.2 (a) shows the Feynman diagram for the ionization process where a LIP loses energy due to interaction with an electron. Along with ionization, a fast LIP can interact with an electron or an atom and loses its energy kinetic energy in the form of photons via the bremsstrahlung process shown in Figure 2.2 (b) or produces an electron-positron pair via the pair-production process shown in Figure 2.2 (c) & (d).

The simulation models incorporated in GEANT4 for different physics processes are shown in Table 2.1. Some of the processes were already defined, which we used without any alteration. The simulation model for bremsstrahlung was modified to respect the fractional charge. All these models were individually validated for LIPs within the analysis window. The validation, as described in each sub-sections below, is performed by cross-checking the stoppage power $\langle dE/dx \rangle$ of LIPs with that for muons. LIPs don't lose an appreciable amount of energy due to Coulomb scattering and multiple scattering. So, this section only describes the impact and the validation of the ionization, bremsstrahlung, and pair production GEANT4 processes for LIPs.

Ionization

A LIP loses its energy when it ionizes electrons as it pass through the detector. Ionization is the dominant process by which LIPs lose their energy. Assuming an electron is free, its interaction with a LIP of fractional charge of fe is described by the Rutherford differential

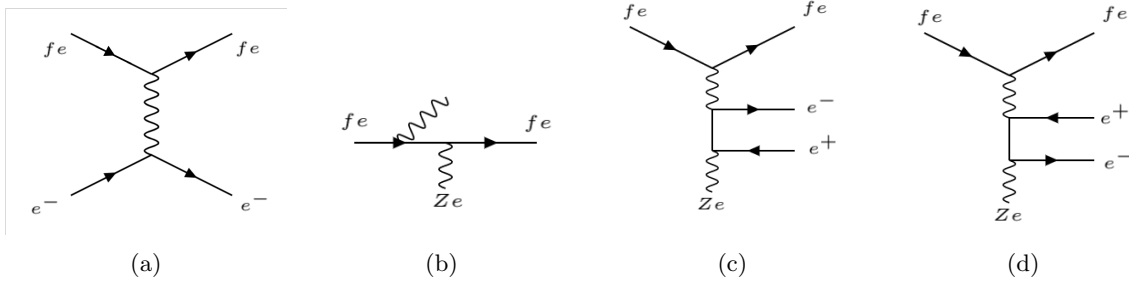


FIGURE 2.2: Feynman diagrams of LIPs interaction (symbolized by fe) for various physics process: (a) Ionization (b) Bremsstrahlung (c) & (d) pair production

Physics Process	Simulation Models	Energy range	Remarks
Ionization	G4PAIModel	0-100 TeV	Used without change
Bremsstrahlung	G4MuBremsstrahlungModel	0-100 TeV	Modified to respect fractional charge
Pair production	G4MuPairProductionModel	0-100 TeV	Modified to respect fractional charge
Coulomb scattering	G4eCoulombScatteringModel	0-100 TeV	Used without change
Multiple scattering	G4WentzelVIUniModel	0-100 TeV	Used without change

Table 2.1: All the physics process and models used for defining and simulating LIPs. G4MuBremsstrahlungModel written for muons was modified to respect LIP fractional charge. All other models were used without alteration.

cross-section [61]

$$\frac{d\sigma_R(E; \beta, f)}{dE} = \frac{2\pi r_e^2 m_e c^2 f^2}{\beta^2} \frac{(1 - \beta^2 E/E_{max})}{E^2} \quad (2.1)$$

where r_e is the classical radius, m_e mass of electron, c is speed of light, and $E_{max} \sim 2m_e(\beta\gamma)^2 c^2$ is the maximum energy possible to transfer in a single collision. However, electrons in the detector are bounded inside atoms. When a LIP interacts with bounded electron, there is an additional loss of energy due to the exchange of virtual photons between LIP and atom [62]. An energy-dependent inelastic form factor is calculated to account for these bound electrons. There are different studies [63–65], conducted for understanding this form factor. In the analysis described here, the Photo Absorption Ionization (PAI) model is used to obtain the inelastic form factor [62]. The PAI model assumes that the momentum of the virtual

photon is given by $p = E\epsilon^{1/2}/c$ where $\epsilon = \epsilon_1 + i\epsilon_2$ is dielectric constant of the material. ϵ_1 and ϵ_2 describe the polarization and absorption properties, respectively. According to Ref [62] the cross-section for photo absorption ionization depends directly on dielectric values by

$$\sigma_y = \frac{Z\omega}{Nc} \frac{\epsilon_2}{(\epsilon_1)^{1/2}} \quad (2.2)$$

where Z is the atomic number, N is the electron density, and $\omega = E/\hbar$. The differential cross-section for energy loss ($d\sigma(E)/dE$) by a fractional charged particles when it interacts with a bounded electron using PAI model as given in [66] is:

$$\begin{aligned} \frac{d\sigma(E)}{dE} = & \frac{\alpha}{\beta^2\pi} \frac{\alpha_y(E)}{EZ} \ln[(1 - \beta^2\epsilon_1)^2 + \beta^4\epsilon_2^2]^{-1/2} + \frac{\alpha}{\beta^2\pi} \frac{1}{N\hbar c} (\beta^2 - \frac{\epsilon_1}{|\epsilon|^2}) \Theta \\ & + \frac{\alpha}{\beta^2\pi} \frac{\alpha_y(E)}{EZ} \ln(\frac{2mc^2\beta^2}{E}) + \frac{\alpha}{\beta^2\pi} \frac{1}{E^2} \int_0^E \frac{\sigma_y(E)}{Z} dE \end{aligned} \quad (2.3)$$

where α is fine structure constant and $\Theta = \arg(1 - \epsilon_1\beta^2 + i\epsilon_2\beta^2)$.

Also, for f , the cross section changes as:

$$\frac{d\sigma(E, f)}{dE} = f^2 \left(\frac{d\sigma(E)}{dE} \right) \quad (2.4)$$

. The PAI differential cross-section depends on $\beta\gamma$ and f but doesn't depend on LIP mass. For more information on the PAI model and cross-section calculation, see Ref. [66, 67].

This analysis uses an already existing G4PAIModel, based on the PAI model, to define the ionization process for LIPs in GEANT4. For validation purposes, we compared the stopping power ($\langle dE/dX \rangle$) of simulated LIPs with that for muons traveling through germanium. For each chosen value of $\beta\gamma$ and f , 10^8 LIPs are simulated towards a germanium detector; the average energy lost per unit distance, from all 10^8 events, is the stopping power for simulated LIPs. The stopping power for muon is obtained from the particle data group (PDG) [68]. From the definition of LIPs in GEANT4, LIPs with $f=1$ and mass $\sim 100 \text{ MeV}/c^2$ must behave like non-decaying muons. For each considered $\beta\gamma$ values, $(1/f)^2 \langle dE/dX \rangle$ due to ionization

for LIPs with charge f must be equivalent to the stopping power of muons due to ionization; this must be true for all LIP mass considered as ionization is independent of mass. Figure 2.3 (a) shows the $(1/f)^2$ times $\langle dE/dX \rangle$ value for LIPs with $f=1/1000$ for mass of $1 \text{ GeV}/c^2$ (blue squares) and $100 \text{ MeV}/c^2$ (red circle). The $(1/f)^2 \langle dE/dX \rangle$ value for both of these LIPs is expected to overlap with the stopping power of muons (green dotted curve). The figure shows $(1/f)^2 \langle dE/dX \rangle$ values for both LIPs are consistent with that expected for muon's stopping power for $\beta\gamma \lesssim 10^3$. A sudden spike in stopping power for both LIPs is observed for $\beta\gamma \gtrsim 10^3$. This jump in $\langle dE/dX \rangle$ value is due to few events with high energy deposition on the order of a few GeV. The reason for the existence of these events is unknown. These high-energy events will not be observed in the detector with an upper threshold $< 1 \text{ GeV}$. The CDMSlite detector with an upper limit on energy range of 2 keV , doesn't detect these events. If we calculate the $\langle dE/dX \rangle$ after removing these higher energy events with an energy deposition of $\geq 1 \text{ GeV}$, the $(1/f)^2 \langle dE/dX \rangle$ values for considered LIPs match the stopping power of muons.

Figure 2.3 (b) compares the $(1/f)^2 \langle dE/dX \rangle$, for LIPs with $f=1000$, calculated before (red circle) and after (blue triangles) the rejection of events $\geq 1 \text{ GeV}$. The $(1/f)^2 \langle dE/dX \rangle$ values calculated only using events with energy less than 1 GeV matches the stopping power for muons (green-dashed).

Bremsstrahlung

LIPs when passing through a detector decelerate due to the Coulomb field of the atoms and lose a fraction of their energy in form of photons. This is the only physics process used to define LIPs in this analysis whose interaction cross-section changes with LIP mass. The cross-section for Bremsstrahlung is given by Ref. [69]:

$$\begin{aligned} \frac{d\sigma(E, \epsilon, Z, A)}{d\epsilon} &= \frac{16}{3} \alpha N_A \left(\frac{m_e}{m} r_e \right)^2 \frac{1}{\epsilon A} Z(Z\Phi_n + \Phi_e) \left(1 - v + \frac{3}{4}v^2 \right) \\ &= 0 \text{ IF } \epsilon \leq \epsilon_{max} = E - m \end{aligned} \quad (2.5)$$

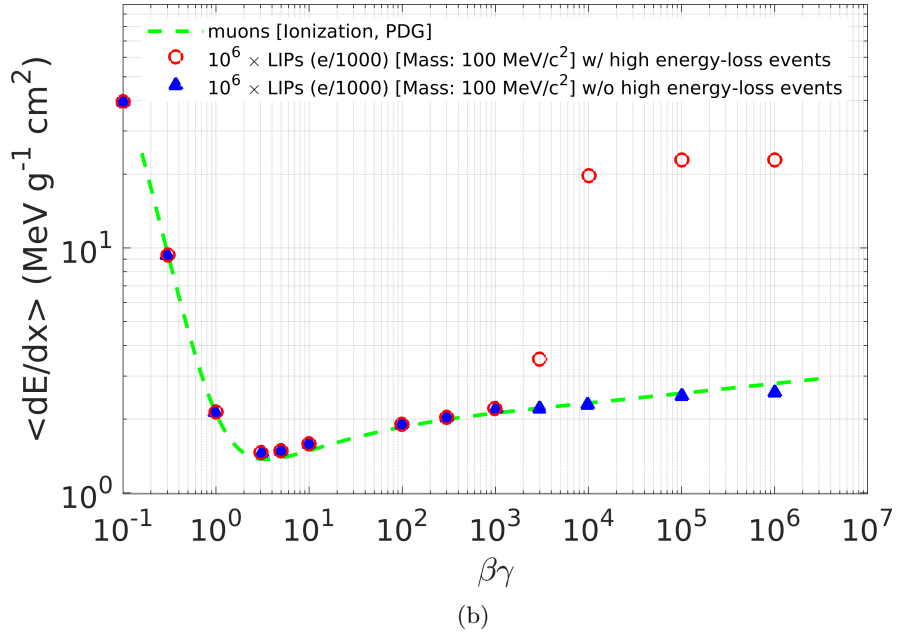
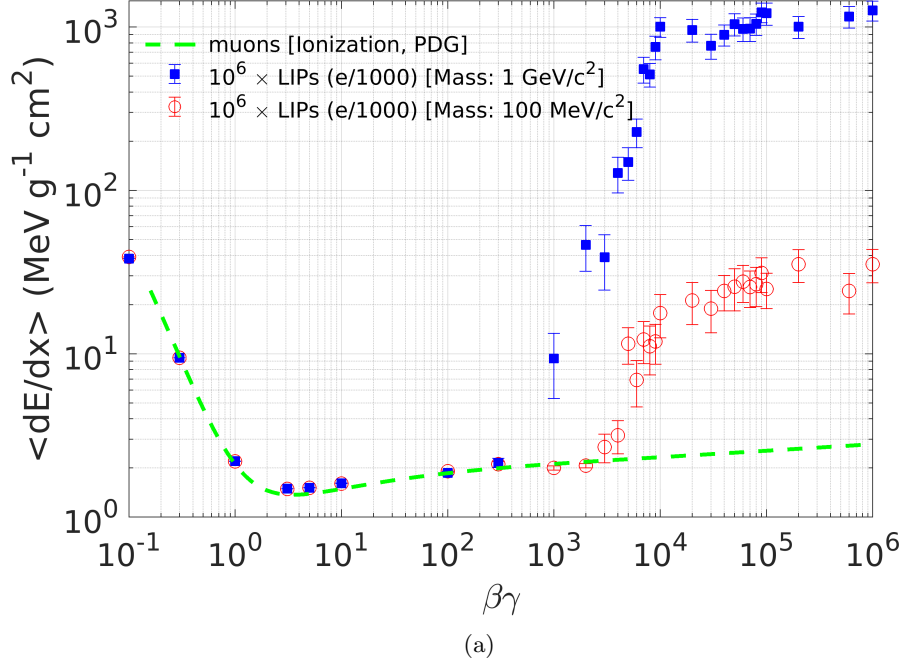


FIGURE 2.3: (a) Simulated $(1/f)^2 \langle dE/dX \rangle$ values for LIPs with charge $e/1000$ assuming mass $1 \text{ GeV}/c^2$ (blue squares) and $100 \text{ MeV}/c^2$ (red circles) for the ionization process. The green-dashed curve is the stopping power for muon. (b) Comparison of $(1/f)^2 \langle dE/dX \rangle$, for LIPs with $f=1000$, calculated before (red circles) and after (blue triangles) the rejection of events $\geq 1 \text{ GeV}$. The $(1/f)^2 \langle dE/dX \rangle$ calculated only using events with energy depositions less than 1 GeV matches the stopping power for muons (green-dashed curve).

where, m and m_e are the LIP mass and electron mass, Z and A are atomic number and atomic weight of the material, N_A is Avogadro's number, E is initial total kinetic energy of LIP and ϵ is the energy of emitted photon. Φ_n and Φ_e represents contribution due to nucleus and electron respectively as explained in [69]. We modified G4MuBremsstrahlungModel (defined for muon) such that it respect the fractional charge to define a bremsstrahlung process for LIPs in GEANT4.

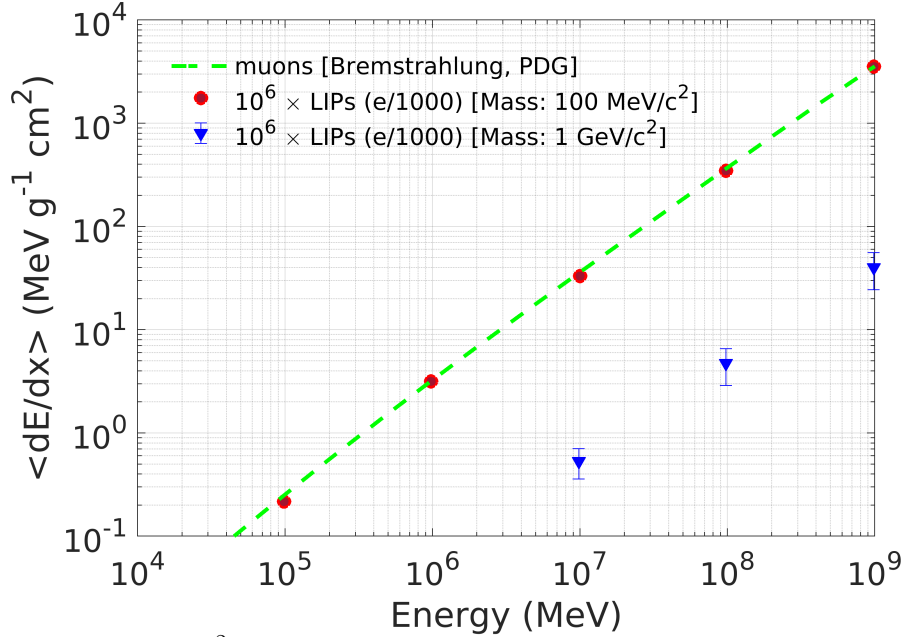


FIGURE 2.4: The $(1/f)^2 \langle dE/dX \rangle$ values for the $f=1/1000$ and mass $100 \text{ MeV}/c^2$ (red circle) with only bremsstrahlung process is consistent with stopping power of muons (green dashed) for bremsstrahlung process. The $(1/f)^2 \langle dE/dX \rangle$ values for LIP of mass $1 \text{ GeV}/c^2$ falls lower than the muon curve as expected.

To validate the implementation of the LIP-specific bremsstrahlung process within GEANT4, we compared $(1/f)^2 \langle dE/dX \rangle$ values obtained for bremsstrahlung process of LIPs with $f=1/1000$ and mass $100 \text{ MeV}/c^2$ to the stopping power of muons for bremsstrahlung process. As shown in Figure 2.4, the $(1/f)^2 \langle dE/dX \rangle$ for the $f=1/1000$ and mass $100 \text{ MeV}/c^2$ is consistent with stopping power of muons. As expected the $(1/f)^2 \langle dE/dX \rangle$ values for LIPs with $f=1/1000$ and mass $1 \text{ GeV}/c^2$ (blue triangle) is smaller than stopping power of muons as shown in Figure 2.4 by the predicted factor of the square of mass.

Pair Production

LIPs, like muons, with larger energy, can directly produce electron-hole pairs. LIPs will lose energy while producing electron-hole pairs. The average energy loss due to pair production increases with LIPs energy, and it becomes the dominant process of energy loss for highly energetic (TeV-scale) LIPs. The cross-section for the pair-production is given by [70]:

$$\sigma(E, \nu, \rho) d\nu d\rho = \frac{2}{3\pi} (Z\alpha r_o)^2 \frac{1-\nu}{\nu} \left(\Phi_e + \frac{m^2}{\mu^2} \Phi_\mu \right)^2 d\nu d\rho; \quad (2.6)$$

$$\Phi_{e,\mu} = L_{e,\mu} B_{e,\mu} + \frac{1}{2} \Delta_{e,\mu},$$

where E is energy of the primary LIPs (muons), ν is the energy fraction transferred to the pair, ρ is the coefficient of energy distribution of the pair, Z is atomic number, $\alpha = 1/137$, r_o is the classical electron radius, μ is mass of LIPs (muons) and m is mass of the electron. The values of $B_{e,\mu}$, $L_{e,\mu}$ and $\Delta_{e,\mu}$ depend on the model used for the cross-section calculation. Their values are summarized in Ref. [70].

For LIPs simulation, the G4MuPair production file written for muons is modified to respect the fractional charge. More information about the process can be found at [69].

To validate the implementation of the LIP-specific pair-production process within GEANT4, we compared $(1/f)^2 \langle dE/dX \rangle$ values of LIPs with $f=1/1000$ of mass $100 \text{ MeV}/c^2$, $1 \text{ GeV}/c^2$ and $10 \text{ GeV}/c^2$ to the stopping power of muons. As shown in Figure 2.5, the $(1/f)^2 \langle dE/dX \rangle$ values for all these LIPs is consistent with the stopping power of muons as expected.

2.1.2 LIPs Angular Distribution

This LIPs search analysis is a direct-detection search for cosmogenic LIPs independent of its production mechanism. Even if we assume that they are produced isotropically outside the Earth's atmosphere, the angular distribution might differ due to their interaction with the Earth's atmosphere and rock overburden before reaching the underground detector. Since we do not know the actual angular distribution, we can use two extreme angular distribution

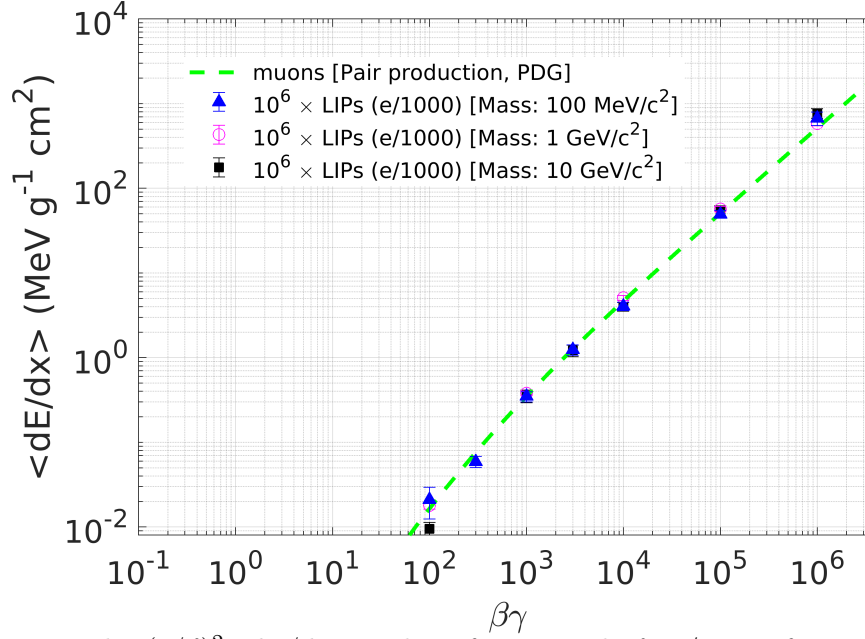


FIGURE 2.5: The $(1/f)^2 \langle dE/dX \rangle$ value of LIPs with $f=1/1000$ of mass $100 \text{ MeV}/c^2$, $1 \text{ GeV}/c^2$ and $10 \text{ GeV}/c^2$ with only pair-production process compared to the stopping power of muons for pair production processes. $(1/f)^2 \langle dE/dX \rangle$ values for all these LIPs is consistent with the stopping power of muons as expected for pair production processes.

cases to cover the range of plausible distributions: (1) an isotropic angular distribution and (2) a $\cos^2\theta$ distribution.

1. Isotropic angular distribution: LIPs with smaller f have a probability of interaction that decreases with f^2 . That means LIPs with very small f rarely interact with the Earth's atmosphere and rock overburden above the detector. One extreme case would be to assume that LIPs do not interact before reaching the detector. If LIPs have no interaction along the path, they will have an isotropic angular distribution on the detector.
2. Muon-like $\cos^2\theta$ angular distribution: Muons have charge of an electron with a mass similar to LIPs mass range considered here in the analysis. One can think of the muon as simply the most ionizing LIP, and the attenuation would be maximum for muon compared to a LIP. This is the other extreme case where LIPs are highly interactive.

The angular distribution of muons at the Earth’s surface is $\cos^2\theta$. The largest fractional charge considered in this analysis is $f=1/100$. LIPs with $f = 1/100$ are 10^4 times less ionizing than muons. The depth of the Soudan Underground Laboratory is ~ 0.5 km. It is conservative to assume the angular distribution for strongly ionizing LIPs have a similar distribution to that of a muon on the Earth’s surface.

2.1.3 LIPs Signal Model

After the validation of the physics processes, LIPs defined in GEANT4 are simulated to obtain the probable energy-deposition distribution, $\frac{dP}{dE}$, or simply LIP signal model. The processes followed for the generation of $\frac{dP}{dE}$ can be described as:

1. LIPs were simulated towards the sensitive volume in GEANT4 mimicking the CDMSlite detector. 10^9 events were simulated either in an isotropic angular distribution or $\cos^2\theta$ angular distribution from a cylindrical surface just bigger than the size of the detector to compute $\frac{dP}{dE}$ for a LIP with assumed f , $\beta\gamma$ and mass. A histogram of the energy deposition distribution from all those events gives a raw $\frac{dP}{dE}$.
2. The raw $\frac{dP}{dE}$ is smeared with the energy resolution (see Section 3.8) of the CDMSlite detector. All the energy deposited in the detector needs to be smeared by the detector’s resolution to resemble the reconstructed deposition in the detector. An expected $\frac{dP}{dE}$ is obtained after the smearing process.
3. The expected $\frac{dP}{dE}$ is normalized by dividing it by a total number of simulated events incident on the detector and is then smoothed before utilization as a LIP signal model¹. All the following figures in this section show the smeared-normalized-smoothed $\frac{dP}{dE}$.

$\frac{dP}{dE}$ is found to be independent of LIP mass for a mass-range considered in this analysis. While the bremsstrahlung process is affected by LIP mass, the number of events due to bremsstrahlung interactions is very rare. The energy deposition due to these events are

¹ A Matlab function “smoothdata” is used with “rloess” as smoothing method.

in the MeV-scale, which is significantly higher than the upper threshold of the CDMSlite detector. So, the LIPs signal models are effectively independent of LIP mass and are a function of $\beta\gamma$ and f .

Signal Models for Isotropic Angular Distribution

Signal models for an assumed isotropic angular distribution is computed for LIPs with various f and $\beta\gamma$ values. LIPs were simulated with an isotropic angular distribution towards a GEANT4 detector resembling the CDMSlite detector. The $\frac{dP}{dE}$ distribution for minimum ionizing ($\beta\gamma = 3.1$) and assumed most ionizing ($\beta\gamma = 0.1$) for various f values are described in detail in this section.

Figure 2.6 (a) shows $\frac{dP}{dE}$ distribution for a variety of LIP charges with $\beta\gamma$ value of 3.1 for an isotropic angular distribution. The characteristics atomic shell peaks are visible for LIPs with $f < 1/200$. A minimum ionizing LIP with $f = 1/100$ has a 67% probability of depositing energy within the analysis energy window. Its probability to deposit energy less than 0.1 keV_{ee} is ~4.3% and its probability to deposit more than 2 keV_{ee} energy is ~26%. About ~2.6% of these LIPs with $f = 1/100$ pass through the detector without interaction. As seen in Figure 2.6 (a) the probability of energy deposition for these LIPs, shown in the red curve, is larger towards the higher end of the analysis energy window. LIPs with smaller fractional charges are expected to deposit a smaller amount of energy than that for LIPs with $f = 1/100$ as they have a smaller interaction cross-section. As expected, LIPs with $f = 1/200$ have smaller probability (~3%) to deposit energy greater than 2 keV_{ee} in the detector. They have ~65% probability of depositing energy within the analysis window. The probability of these LIPs passing through the detector without interaction increases to ~11%. The blue curve in Figure 2.6 for $f = 1/200$ shows that the peak of the probability distribution shifts towards the lower energy end of the analysis window. For LIPs with even smaller fractional charges, the probability of them traveling through the detector without energy deposition increases, resulting in a decreased probability of energy deposition within the analysis window. The probabilities of LIP energy depositions below, within, or above the

analysis window are summarized in Table 2.2.

$\beta\gamma$	f^{-1}	Edep = 0	$0 < \text{Edep} < 0.1$ keV	$0.1 \leq \text{Edep} \leq 2$ keV	Edep > 2 keV
3.1	100	0.026	0.043	0.67	0.26
3.1	200	0.11	0.21	0.65	0.031
3.1	500	0.57	0.3	0.13	0.0036
3.1	1000	0.86	0.11	0.03	0.00087
3.1	5000	0.994	0.0051	0.0012	0.000035
3.1	10000	0.998	0.0013	0.00029	0.0000085

Table 2.2: Integrated probabilities for various ranges of energy depositions in the detector for various LIPs of charge f with a $\beta\gamma$ value of 3.1 for an assumed isotropic angular distribution. Energy deposition equal to zero corresponds to the case when LIP passes through the detector without interacting with the detector material.

Figure 2.6 (b) shows $\frac{dP}{dE}$ for a variety of LIP charges with a $\beta\gamma$ value of 0.1 for an isotropic angular distribution. LIPs with $f = 1/100$ and $1/200$ have a larger probability to deposit energy greater than the upper analysis threshold than within the analysis window. As f decreases, the probability of depositing a smaller amount of energy into the detector increases, as seen in Table 2.3.

$\beta\gamma$	f^{-1}	Edep = 0	$0 < \text{Edep} < 0.1$ keV	$0.1 \leq \text{Edep} \leq 2$ keV	Edep > 2 keV
0.1	100	0.00063	0.0011	0.0152	0.98
0.1	200	0.0027	0.0045	0.061	0.93
0.1	500	0.0172	0.0283	0.50	0.45
0.1	1000	0.07	0.13	0.75	0.05
0.1	5000	0.80	0.15	0.045	0.0013
0.1	10000	0.94	0.04	0.00108	0.00032

Table 2.3: Integrated probabilities for various ranges of energy depositions in the detector for various LIPs of charge f with an $\beta\gamma$ value of 0.1 for an assumed isotropic angular distribution. Energy deposition equal to zero corresponds to the case when LIP passes through the detector without interacting with the detector material.

Signal Models for $\cos^2\theta$ Angular Distribution

LIPs were simulated with a $\cos^2\theta$ angular distribution towards a GEANT4 detector resembling the CDMSlite detector. Similar to isotropic angular distribution, the $\frac{dP}{dE}$ is generated for LIPs

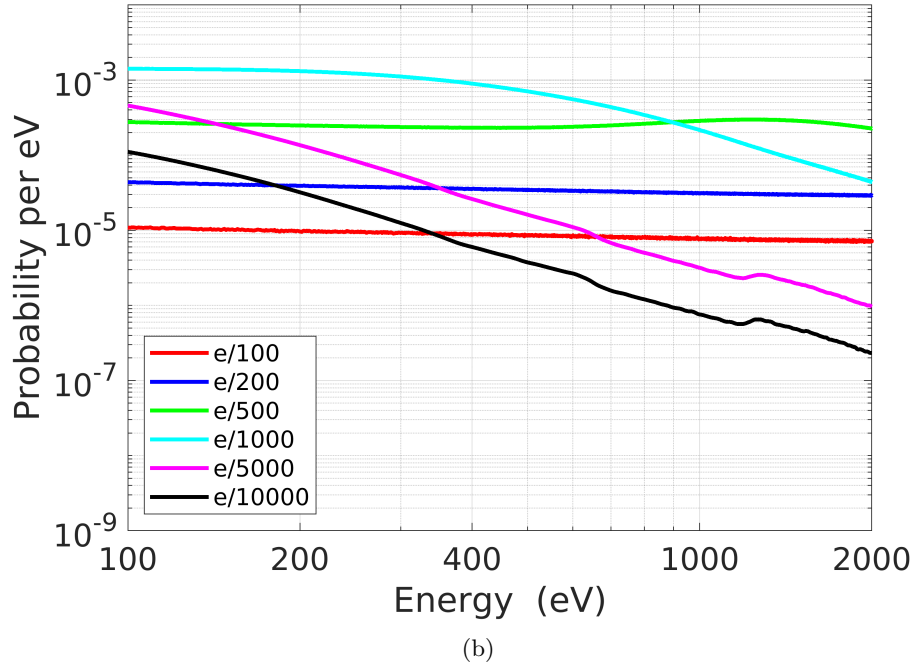
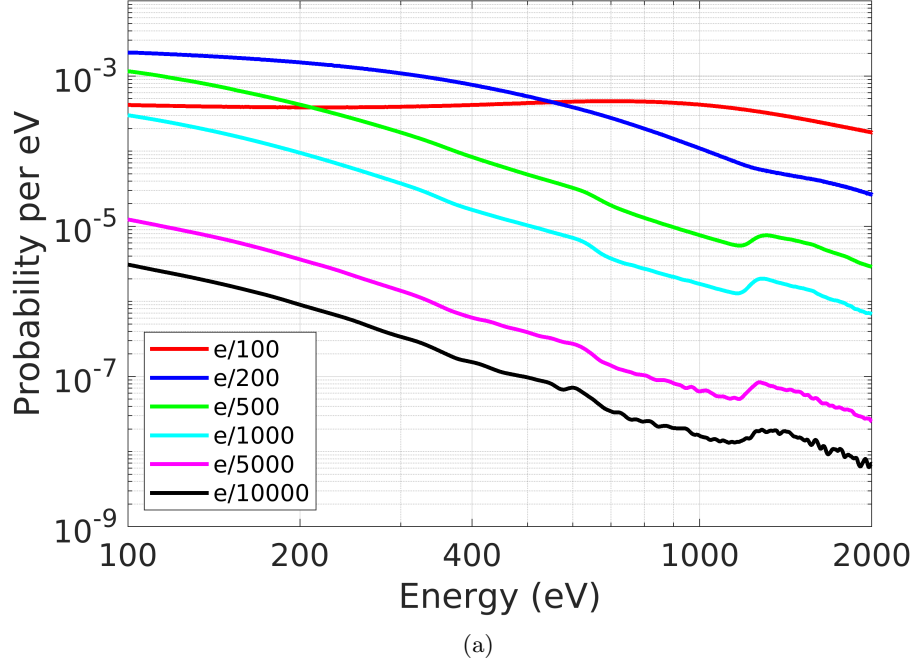


FIGURE 2.6: (a) Smeared-normalized-smoothed $\frac{dP}{dE}$ for a variety of LIP charges with a $\beta\gamma$ value of 3.1 for an isotropic angular distribution. LIPs with charge $e/200$ have a maximum probability of depositing energy within the analysis energy thresholds. (b) This is similar to Figure (a) except it is for a $\beta\gamma$ value of 0.1. LIPs with charge $e/1000$ have a maximum probability of depositing energy within the analysis energy thresholds.

with a variety of f and $\beta\gamma$.

Figure 2.7 (a) and (b) shows the $\frac{dP}{dE}$ for a variety of LIP charges with $\beta\gamma$ value of 3.1 and 0.1 respectively with a $\cos^2\theta$ angular distribution. Similar to an isotropic angular distribution for $\beta\gamma$ of 3.1, minimum ionizing LIPs with $f \sim 1/200$ have the greatest probability of depositing energy within the analysis energy thresholds for all values of f considered. For $\beta\gamma$ of 0.1, LIPs with $f \sim 1/1000$ have the greatest probability of depositing energy within the analysis energy window. Table 2.4 shows the probability of energy deposition for LIPs with $\beta\gamma$ values of 0.1 and 3.1 with a $\cos^2\theta$ angular distribution.

$\beta\gamma$	f^{-1}	Edep = 0	$0 < \text{Edep} < 0.1$ keV	$0.1 \leq \text{Edep} \leq 2$ keV	Edep > 2 keV
0.1	100	0.00068	0.0011	0.015	0.98
0.1	200	0.0027	0.0045	0.061	0.93
0.1	500	0.0172	0.028	0.59	0.36
0.1	1000	0.07	0.15	0.75	0.05
0.1	5000	0.82	0.14	0.037	0.0011
0.1	10000	0.95	0.039	0.0089	0.00027
3.1	100	0.025	0.042	0.747	0.184
3.1	200	0.125	0.25	0.616	0.0114
3.1	500	0.62	0.27	0.107	0.0013
3.1	1000	0.88	0.094	0.025	0.00031
3.1	5000	0.995	0.0042	0.00098	0.000012
3.1	10000	0.998	0.0011	0.00025	0.0000030

Table 2.4: Integrated probabilities for various ranges of energy depositions in the detector for various LIPs of charge f with an $\beta\gamma$ values of 0.1 and 3.1 for an assumed $\cos^2\theta$ angular distribution. Energy deposition equal to zero corresponds to the case when LIP passes through the detector without interacting with the detector material.

Isotropic vs $\cos^2\theta$ Angular Distribution

The section compares $\frac{dP}{dE}$ for LIPs with an isotropic vs a $\cos^2\theta$ angular distribution. LIPs with $\beta\gamma = 3.1$ are chosen as the representative for all other $\beta\gamma$ values. All other $\beta\gamma$ values also show similar differences between two angular distributions.

The primary reason for the difference in $\frac{dP}{dE}$ for these angular distributions is the average path length traveled by LIPs within the detector. The isotropic distribution allows LIPs to

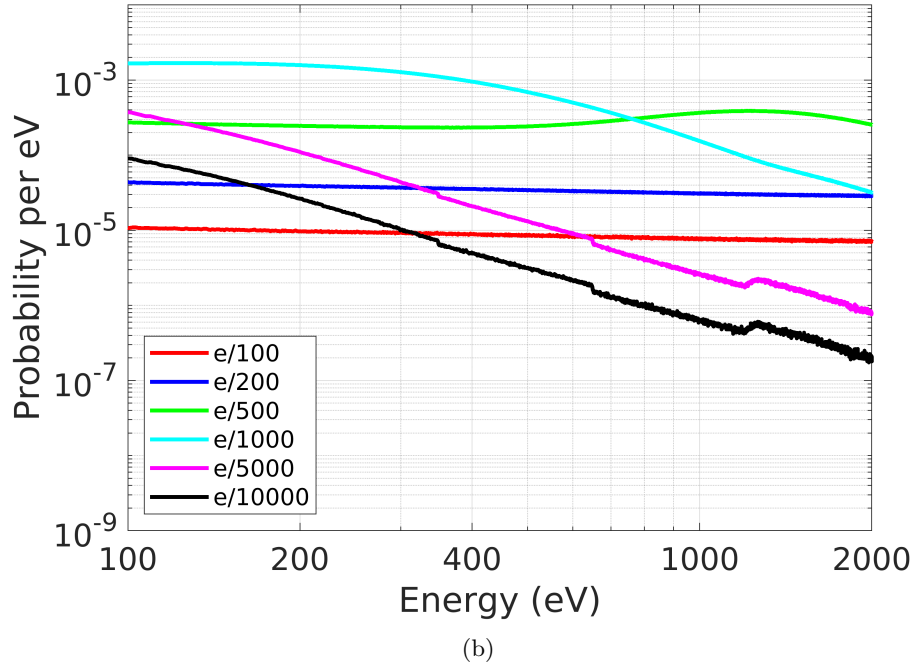
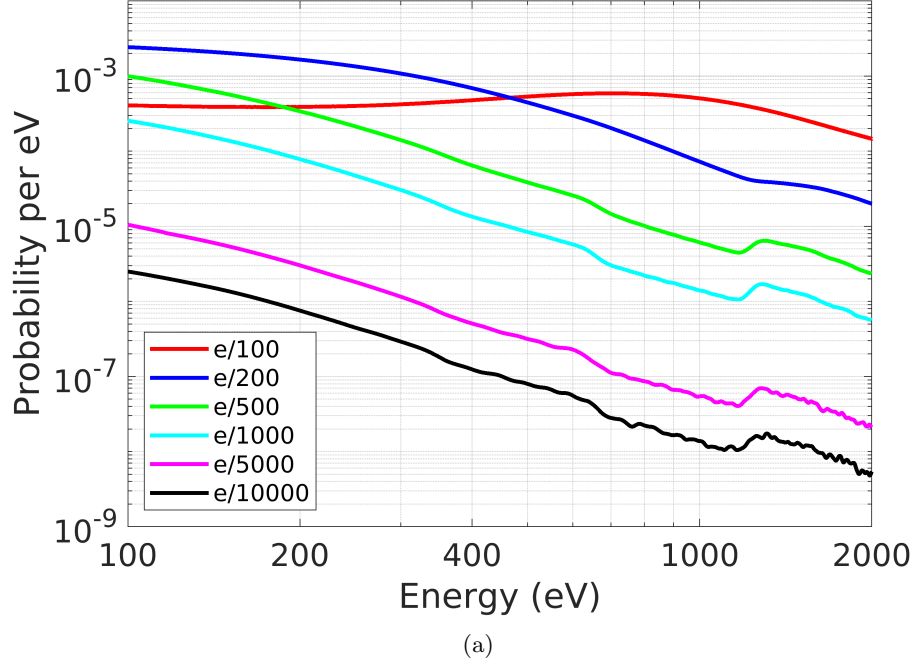


FIGURE 2.7: (a) Smeared-normalized-smoothed $\frac{dP}{dE}$ for a variety of LIP charges with $\beta\gamma$ value of 3.1 for an $\cos^2\theta$ angular distribution. LIPs with charge $e/200$ have greatest probability of depositing energy within the analysis energy range. (b) This is similar to Figure (a) except it is for $\beta\gamma$ of 0.1. LIPs with charge $e/1000$ have greatest probability of depositing energy within the analysis energy range.

travel with a larger path length within the detector (larger probability than $\cos^2\theta$), thereby increasing the probability of the interaction with the detector. So, the isotropic angular distribution is expected to include more events with a greater number of interactions and hence greater energy deposited in the detector than compared to $\cos^2\theta$ angular distribution.

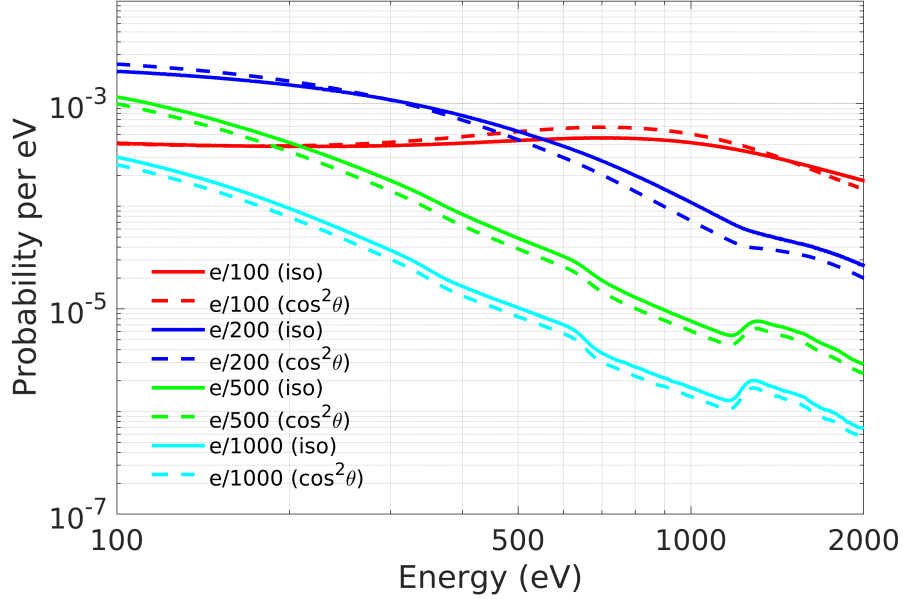


FIGURE 2.8: The comparison between $\frac{dP}{dE}$ for LIPs with $\beta\gamma$ of 3.1 and 0.1 for isotropic (iso) angular distribution and $\cos^2\theta$ angular distribution. LIPs with an isotropic angular distribution deposit more energy on average than LIPs with a $\cos^2\theta$ distribution because the average LIP path length is greater under the assumption of an isotropic distribution.

Figure 2.8 shows a comparison on $\frac{dP}{dE}$ for an isotropic angular distribution and $\cos^2\theta$ angular distribution. For all four LIP charges considered in the figure, the probability of larger energy deposition is higher for isotropic angular distribution.

Signal Model Scaling for LIPs with Very Small f

A LIP with a very small interaction cross-section often does not interact as it passes through the detector. Table 2.2 shows that more than 99% of LIPs with $\beta\gamma=3.1$ for isotropic angular distribution and $f > 1/5000$ just pass through the detector without interaction. Similarly, Table 2.3 shows that 94% of LIPs with $\beta\gamma=0.1$ for isotropic angular distribution and $f > 1/5000$

doesn't interact with the detector. The probability of these less-ionizing LIPs interacting multiple times while passing through the detector is small. The probability distribution obtained for these LIPs is approximately the same as the "single interaction PDF". For LIPs with "single interaction PDF", the shape of the deposition distribution remains the same for all these LIP charges. But, the probability of any interaction changes by a factor of f^2 ; hence the amplitude of the $\frac{dP}{dE}$ changes with f^2 . Mathematically for LIPs with a single interaction PDFs for smaller fractional charge (f'),

$$\frac{dP}{dE}(f', \beta\gamma) = \left(\frac{f}{f'}\right)^2 \frac{dP}{dE}(f, \beta\gamma). \quad (2.7)$$

Figure 2.9 shows $\frac{dP}{dE}$ for $f=1/5000$ and $f=1/10000$ for $\beta\gamma$ values of 3.1 and 0.1. The figure also shows that scaling $\frac{dP}{dE}$ for $f=1/10000$ by a factor of $(10/5)^2$ resulted in the deposition-distribution consistent with that for $f=1/5000$ for both $\beta\gamma$ values.

The simulation of LIPs to generate $\frac{dP}{dE}$ for very small fractional charge ($f < 1/10^4$) is computationally expensive. Instead, a simple scaling of the single interaction PDF (PDF for $f = 1/10^4$ for all $\beta\gamma$ values) by a ratio of f^2 can be used to generate the $\frac{dP}{dE}$ for these LIP charges.

2.2 Intensity Limit Calculation

The primary goal for LIP-search analysis is to set a 90% confidence-level upper limit on the vertical intensity, I_v^{90} , of cosmogenic LIPs. The intensity limit for LIPs with f and $\beta\gamma$ can be represented by the following basic equation:

$$I_v^{90}(f, \beta\gamma) = \frac{N^{90}(f, \beta\gamma)}{\tau \times \sigma(f, \beta\gamma)} \quad (2.8)$$

where N^{90} is 90% confidence upper limit on the number of events observed due to possible LIP interaction, τ is the CDMSlite detector livetime and σ is product of the effective cross-sectional area of the detector and the total probability of LIP detection.

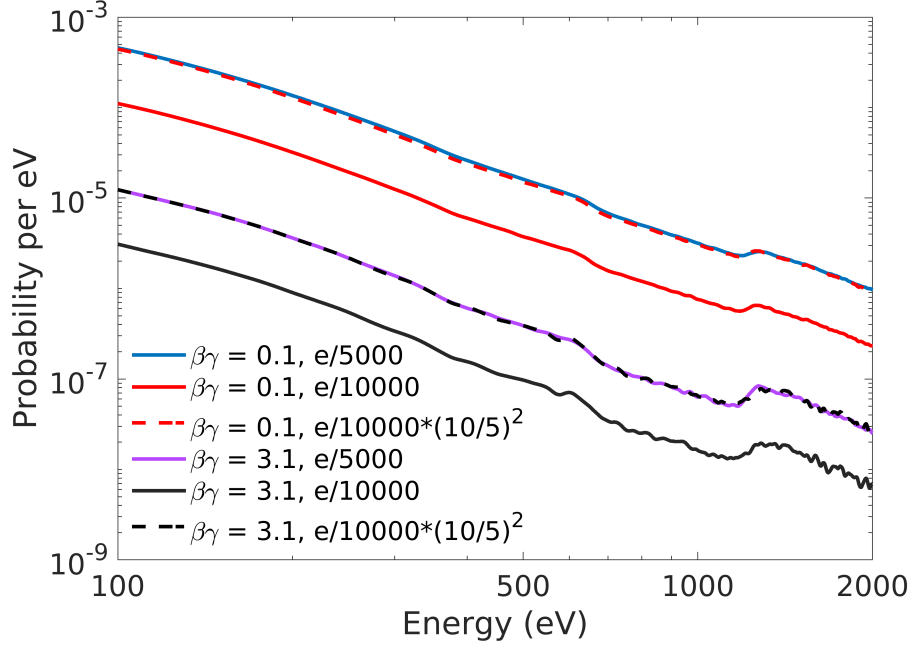


FIGURE 2.9: The $\frac{dP}{dE}$ for $f=1/5000$ and $f=1/10000$ for $\beta\gamma$ values of 3.1 and 0.1. The figure also shows that scaling $\frac{dP}{dE}$ for $f=1/10000$ by a factor of $(10/5)^2$ resulted in the deposition-distribution consistent with that for $f=1/5000$ for both $\beta\gamma$ values.

N^{90} is calculated using the optimum interval (OI) method. Section 2.2.1 has more information on the OI and N^{90} calculation. σ is the product of the effective cross-sectional area of the detector, $A(\theta)$, and the total probability of a LIP-interaction to be detectable (depositing energy within analysis energy thresholds of 0.1 keV and 2 keV) in the detector. The total probability of a LIP-interaction is simply the product of LIPs signal model, $\frac{dP}{dE}$, and the analysis efficiency, ϵ to identify a LIP interaction. The $\frac{dP}{dE}(f, \beta\gamma, \theta)$ calculated via GEANT4 simulation in this analysis is already integrated for θ . Equation 2.8 for the CDMSlite LIP-search analysis can be now written as:

$$I_v^{90}(f, \beta\gamma) = \frac{N^{90}(f, \beta\gamma)}{\tau \int_{0.1 \text{ keV}}^{2 \text{ keV}} \underbrace{\epsilon(f, \beta\gamma, E) \frac{dP}{dE}(f, \beta\gamma) dE}_{\text{detection efficiency}} \underbrace{\int A(\theta) d\Omega}_{\text{geometric factor}}}. \quad (2.9)$$

where Ω is a solid angle, E is the deposited energy within the threshold of 0.1 keV to 2

keV, and θ is the angle between incident a LIP and the zenith.

Section 2.1.3 describes the computation of $\frac{dP}{dE}$, Section 2.2.2 describes A and Section 4.7 describes the calculation of ϵ .

2.2.1 The Optimum Interval Method

An upper limit is calculated if an expected signal does not exist in the spectrum or if the signal exists below the sensitivity of the experiment. If the experiment has an accurate understanding of the background, it can subtract the background from their spectrum and calculate strong upper limits. However, in our case, due to lack of complete understanding of background sources, a conservative method, known as the optimum interval (OI)[71] method, is used for N^{90} calculation where all the events in the data spectrum are treated as signal events.

The OI method is used only to calculate the upper limit on the signal. It cannot be used for the discovery of a signal in the data. The method searches for an “optimum gap” in the data spectrum; an optimum gap is the interval in the data spectrum with few numbers of observed events but has a higher probability of observing the signal. The method finds the optimum interval (an interval that gives the best limit) and also corrects for the possible bias in using the best gap.

2.2.2 The Effective Cross-Section Area

The effective cross-section area, $A(\theta)$, is the surface area that allows incoming LIPs, at an angle of θ with respect to the zenith, to enter the detector. Since the analysis only considers downward going LIPs, only LIPs entering the detector via the top surface or the curved surface are considered. This analysis assumes the CDMSlite detector to be perfectly cylindrical for simplicity.

1. Top surface: For a detector of radius r , the total effective cross-section for LIPs to enter into the detector is:

$$A_{top\ surface}(\theta) = \int dA \cos\theta = \pi r^2 \cos\theta \quad (2.10)$$

2. Side surface: For a detector of radius r and height h , the total effective cross-section for LIPs to enter into the detector is:

$$A_{side\ surface}(\theta) = \int dA \sin\theta = 2rh \sin\theta \quad (2.11)$$

Therefore, the total effective cross-section, $A(\theta)$, is

$$A(\theta) = A_{top\ surface} + A_{side\ surface} = \pi r^2 \cos\theta + 2rh \sin\theta \quad (2.12)$$

Similarly, for the $\cos^2\theta$ distribution, the total effective cross-section is weighted by a factor of $\cos^2\theta$. For the $\cos^2\theta$ distribution,

$$A(\theta) = (\pi r^2 \cos\theta + 2rh \sin\theta) \cos^2\theta \quad (2.13)$$

A study using a Monte Carlo simulation was also performed to verify the above analytical calculation. LIPs were incident from a spherical surface on a cylinder with the same dimensions as the CDMSlite detector with an isotropic angular distribution. A normalized probability distribution of LIPs passing through the detector as a factor of incident θ is calculated. The analytical method predicts the distribution of events for an given angle θ would have following geometrical factor (G.M.):

$$G.M. = \int A(\theta) d\Omega = \int \int A(\theta) \sin\theta d\theta d\phi = 2\pi \int (2rh \sin\theta + \pi r^2 \cos\theta) \sin\theta d\theta \quad (2.14)$$

So, the analytical calculation predicts the GM factor, obtained after integrating $A(\theta)$ over solid angle $d\Omega$, should have a functional form of

$$\text{isotropic distribution : } 2\pi \int (2rh \sin\theta + \pi r^2 \cos\theta) \sin\theta d\theta$$

and

$$\cos^2\theta \text{ distribution: } 2\pi \int (2rh\sin\theta + \pi r^2\cos\theta)\sin\theta\cos^2\theta d\theta.$$

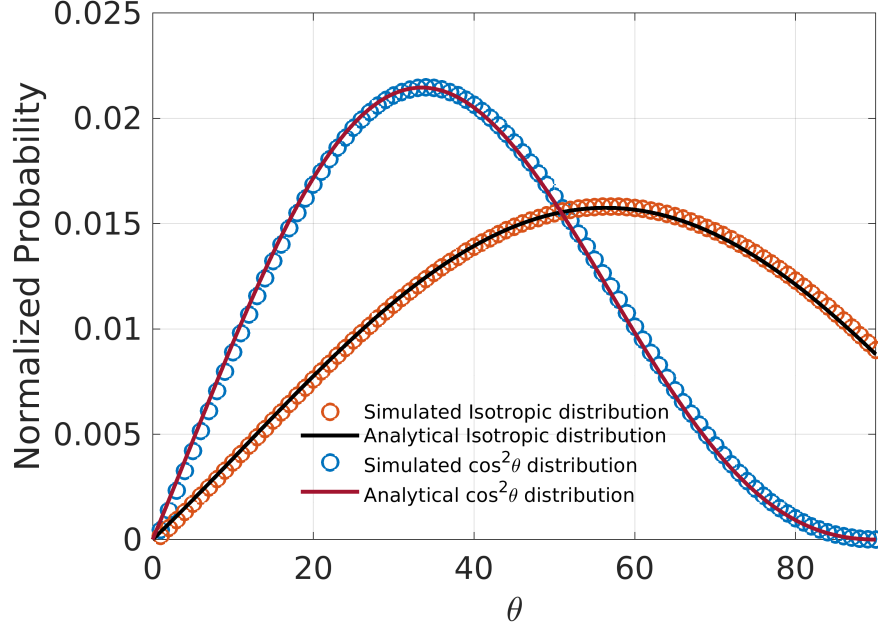


FIGURE 2.10: The geometric factor from simulation for isotropic (orange) and $\cos^2\theta$ (blue) is statistically consistent with analytical calculation shown in black and red respectively. θ cuts off at 90° as the analysis only considers downward going LIPs.

The results from the simulation are consistent with the analytical prediction as seen in Figure 2.10. The normalized distribution obtained from simulation for isotropic distribution (orange) and $\cos^2\theta$ (blue) is consistent with the analytical calculation in black and red, respectively.

3

CDMS low ionization threshold experiment

The Super Cryogenic Dark Matter Experiment (SuperCDMS) was a low background experiment at the Soudan underground laboratory in Minnesota to search for the dark matter. The experiment was designed to search for Weakly Interacting Massive Particles (WIMPs), aiming to detect events where a WIMP interacts via elastic scattering with a nucleus of the cryogenically cooled (~ 40 mK) Ge detectors. The CDMS low ionization threshold experiment (CDMSlite) [55], a part of the SuperCDMS experiment, was specially designed to achieve a low threshold to search for low mass WIMPs. The CDMSlite detector has four phonon sensors that collect the phonons produced by a particle interaction. The total energy of the collected phonons is used to reconstruct the recoil energy. The low-energy-threshold data collected by the CDMSlite detector can be used for a LIPs search. A LIP with smaller f deposits a small amount of energy when it interacts with the detector. The lower threshold (compared to prior direct detection experiments) of the CDMSlite detector improves the sensitivity for LIPs with small fractional charge.

This chapter describes the experimental shielding, the CDMSlite detector, phonon sensors, measurement of phonon energy and details of experimental data used for analysis.

3.1 Shielding

The SuperCDMS Soudan experiment operated at a facility located at 714 m below the surface level. The rock overburden above provides shielding from the cosmic muons that can produce background secondary particles, including neutrons or photons. A reduction in neutron flux is essential for a WIMP-search experiment as neutrons, like WIMPs, also interact with the nucleus of the detector's atoms. For an experiment like CDMSlite, which cannot differentiate between a nuclear recoil or an electron recoil, gamma and beta particles are also concerning backgrounds. The rock overburden above the mine reduces the muon flux by a factor of 5×10^4 with respect to the surface [55], thereby reducing the probability of neutron or gamma production in the underground laboratory. All these neutron, gamma and beta particles are also backgrounds for the LIP search and removal of these backgrounds is essential.

Along with natural shielding due to rock overburden, SuperCDMS also employed several layers of both active and passive shielding around its detectors. The active shielding is the muon veto panels made up of a plastic scintillator. The passive shielding includes inner and outer layers of polyethylene and a lead layer as shown in Figure 3.1 which attenuate incident neutrons and gammas. The outermost 40 cm thick polyethylene layer is followed by a layer of 22.5 cm thick of lead. The inner 4.5 cm thick layer of lead was ancient lead, obtained from a sunken Roman ship, with a depleted amount of dominant radioactive ^{210}Pb isotopes. A 10 cm thick inner layer of polyethylene was employed inside the lead. The copper cans housing the detectors resided inside the inner polyethylene.

Muons with high energy can still penetrate through the Earth's surface and reach the underground laboratory. These muons may interact with the passive shielding and produce secondary background particles. The information from the muon veto panels can be used to identify these neutrons or other secondary particles induced from the muons.

Another source of background is the presence of airborne ^{222}Rn which are a daughter product of the Uranium chain. The air volume near the detectors was purged with ~ 3 -4 week old air. The time period of ~ 3 -4 weeks was enough for ^{222}Rn and its immediate

daughters to decay.

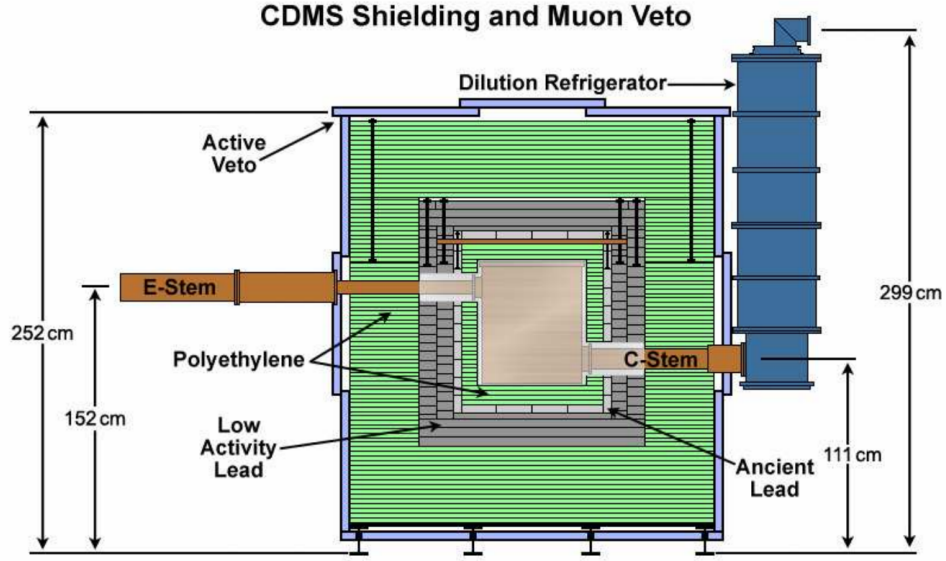


FIGURE 3.1: Schematic view of active muon and passive shielding for the SuperCDMS, Soudan experiment. The blue layer outside is the scintillator, the green layers are polyethylene, the dark grey layers are lead, and the light grey layer is low-radioactive lead. The figure is taken from Joel Sander's thesis [72].

3.2 Detectors

There were 15 Ge approximately cylindrical detectors deployed in the experiment weighed around 0.6 kg with a height of 25 mm and a diameter of 76 mm. These detectors were enclosed in a copper housing, as shown in Figure 3.2. Each of these interleaved Z-sensitive Ionization Phonon (iZIP) detectors was stacked in 5 columns known as towers, where each tower had 3 detectors. The iZIP detector is sensitive to the z-position (depth) in addition to the x-y location of an event in the detector. This sensitivity of the detector to z-position allows it to reject the surface events, which are primarily due to electromagnetic interactions due to backgrounds. The top and bottom surfaces of each iZIP detector have two charge sensors (inner and outer charge channels) and four phonon sensors (A-D phonon channels). The ionization channels were biased with +2 V on the top surface and -2 V on bottom surface. The outer ionization channels were co-located with the phonon channel A. The inner ionization

channel covers the other three phonon channels (B, C and D). The partitioning of these channels provides x- and y-position of the event in the detector. The detector is sensitive to energy deposition in the form of both ionization and phonon, so these detectors can distinguish between electron recoil and nuclear recoil [55]. The arrangement of these detectors in five stacks is illustrated in Figure 3.3.

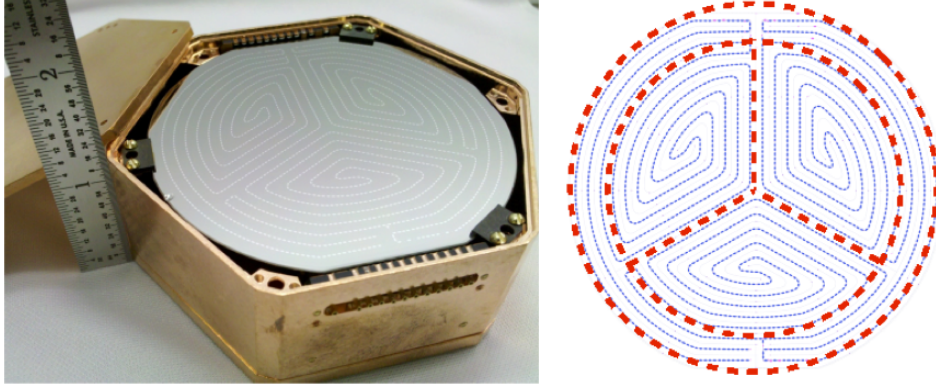


FIGURE 3.2: Left: a photo of an iZIP detector inside its copper housing. Right: the layout of the sensor on the top surface of the detector. The iZIP detector was kept within a copper case where charge and phonon sensors are laid on both sides of the detector. The red dotted lines in the left figure show the layout of four phonon sensors.

In order to achieve a lower-energy threshold, one of the iZIP detectors was biased with higher voltage to utilize the Neganov-Trofimov-Luke (NTL) effect. The detector biased with a higher voltage for the CDMSlite Run 2, the second detector of the fifth tower (see Figure 3.3), is termed as the High Voltage detector (HV detector) or the CDMSlite detector. The biasing of the detector with a relatively high voltage (~ 70 V) lowered the energy threshold to 56 eV_{ee} [55] (nearly ~ 20 times smaller compared to iZIP detectors), but at the cost of the charge sensors, which meant the detector could no longer distinguish between electron recoils and nuclear recoils.

Only phonon sensors are described in the thesis as the reconstructed energy deposition in the CDMSlite detector only uses phonon sensors. Section 3.3 describes the detector phonon sensors, and Section 3.4 describes the production and measurement of energy deposited in

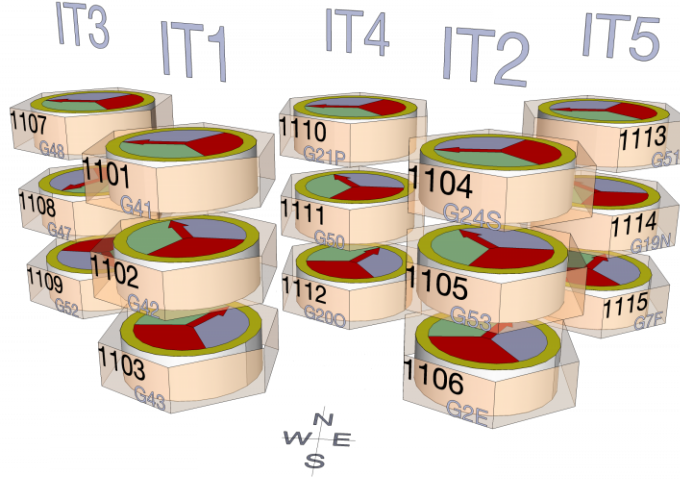


FIGURE 3.3: Stacking visualization of the detector with their naming convention. The first detector in the first tower was named as “T1Z1” or 1101. The second detector of the fifth tower was named “T5Z2” or 1114. T5Z2 was converted into the CDMSlite HV detector during the time period when LIP-search data was obtained.

the form of phonons.

3.3 Phonon Sensors

Quasi-particle-trap-assisted Electrothermal-feedback Transition-edge-sensors (QETs) are used as phonon sensors for SuperCDMS detectors. QETs consist of aluminum fins which work as a trap for quasi-particles [73], along with a thin tungsten filament. QETs are photolithographically placed on the top/bottom (horizontal) detector surfaces. The detectors are cooled to a cryogenic temperature such that both aluminum and tungsten are cooled beyond their critical temperature (T_C) and are superconducting.

When a particle interacts with an electron or a nucleus of the detector, it produces primary phonons and electron-hole pairs. The voltage bias in the detector causes the electron-hole pairs to drift towards opposite surfaces of the detectors. This drifting of these charged particles produces more phonons called NTL phonons. Section 3.4 describes the physics related to the production and energy of phonons. The QETs are sensitive to both types of

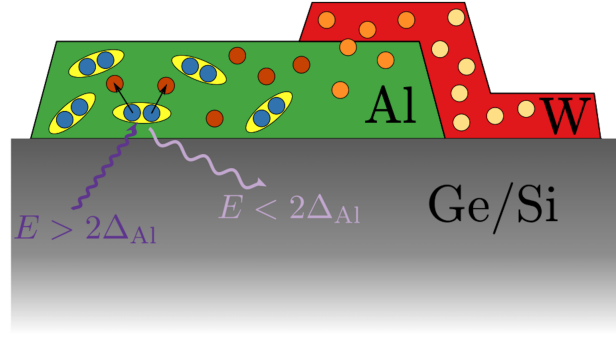
phonons.

The phonons that reach the detectors' surfaces undergo reflections from the surfaces until the aluminum fins of QETs absorb them. An absorbed phonon can break a Cooper Pair contained in the superconducting Al, if its energy is greater than two times the gap-energy of Al ($2\Delta_{Al} = 340 \mu\text{eV}$) [74]. Quasi-particles are produced after the breaking of a Cooper Pair. The resulting quasi-particles diffuse in all directions, and they may again produce lower energy phonon. If phonon's energy is lower than $2\Delta_{Al}$, it cannot create more quasi-particle. The sensors do not collect the energy of these phonons.

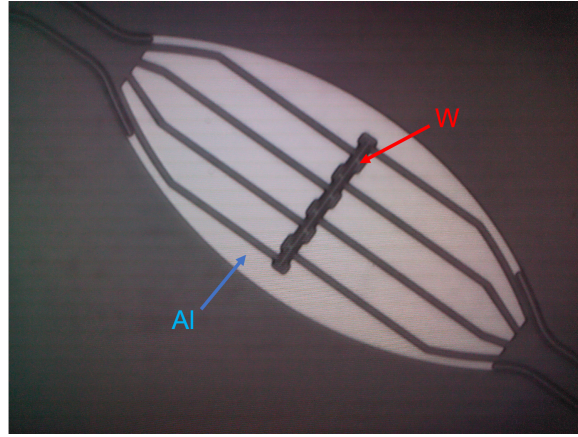
Some of the quasi-particles created in an Al fin diffuse towards the tungsten (W) strip with a gap-energy of $2\Delta_W = 20 \mu\text{eV}$ [74]. They reach the bi-layer (overlap between Al and W) in $1\text{-}2 \mu\text{s}$. The bi-layer has an intermediate gap energy between that of Al and W ($2\Delta_{Al} < 2\Delta_{bi} < 2\Delta_W$). Once a quasi-particle reaches the bi-layer, all the energy lost by the particle will be trapped as phonons produced during its interaction cannot break a Cooper Pair in Al. These trapped quasi-particles diffuse and some head towards the W layer. Phonons produced from these quasi-particles can break a Cooper Pair in the W. All the energy lost by these trapped particles will remain in the W and can be read out using electronics. Figure 3.4 is a diagram demonstrating the physics behind the QETs.

The energy collected in the array of tungsten transition-edge sensors (TESs) can be converted into an electric signal. The tungsten layer is voltage-biased to Joule heat it up to its transition temperature (temperature between superconducting and normal conducting). When phonons created in the crystal reach the biased W layer of the TES, its temperature increases. This increase in temperature sharply increases TES's resistance, which is used to estimate the total energy deposited in the crystal. Also, an increase in the resistance decreases the Joule's power which was heating the TES. This decrease in Joules power leads to decreased TES temperature and returns the TES to its prior temperature. This method of stably maintaining the TES temperature at transition temperature is known as electrothermal feedback (ETF).

Figure 3.5 shows the electric circuit used to read out the change in resistance of a TES



(a)



(b)

FIGURE 3.4: (a) A diagram demonstrating the physics behind QETs. A phonon created in the detector can break a Cooper Pair (two blue pairs inside yellow oval) into two quasi-particles (red circles) if the phonon has energy greater than $2\Delta_{Al}$. The phonons produced in the aluminum layer will dissipate back to the detector and are lost energy if its energy is less than $2\Delta_{Al}$ (light purple). These quasi-particles lose energy, and some diffuse into the tungsten layer. (b) A photo of a single QET.

array. As the resistance of TES (R_{TES}) increases, the current through the TES (I_s) as well as the current through the input inductor (L_i) of Superconducting Quantum Interference Device (SQUID) also decreases. A change of current in L_i changes the magnetic flux at L_i . This results in a change of voltage in the feedback inductor, L_{fb} which has ~ 10 times more turns than L_i . This resulting current through L_{fb} is read out as an output voltage of V_o . So,

$$V_o = 10I_s R_{fb} \quad (3.1)$$

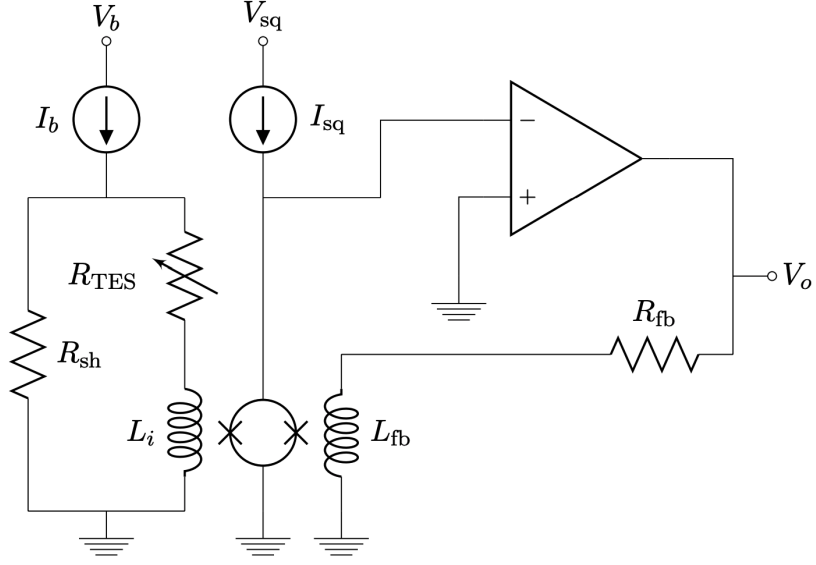


FIGURE 3.5: A simplified single phonon sensor read-out circuit. The resistances $R_{TES} \approx 100 - 200 \text{ m}\Omega$ and $R_{sh} \approx 25 \text{ m}\Omega$ draws current I_b . In a case of an event, the current I_b through, $L_i = 250 \text{ nH}$, changes and induces current through L_{fb} . The current through L_{fb} is read out as V_o through feedback resistor ($R_{fb} = 1 \text{ k}\Omega$).

The output voltage readout varies with I_s ; I_s changes due to the energy deposited by quasi particles in the TESs. The energy deposited by quasi-particles is dependent on the amount of energy deposited by the particle in the detector. Thus, the readout of V_o is proportional to the energy deposited in the detector.

3.4 Phonon Measurement in CDMSlite

Athermal phonons (quantized crystal lattice vibration) are generated when a particle scatters off an electron or nucleus of the detector. More than $\sim 70\%$ of the energy deposited during the scattering of the particle is converted into phonons [74]. An incident particle when interacting with atoms of the detector, produces primary phonons and electron-hole pairs. The drifting of charged particles generates Neganov-Trofimov-Luke (NTL) phonons [75]. Furthermore, relaxation phonons are produced at the end of a charge carrier's trajectory. This section describes different types of athermal phonons and total energy deposited in the form of phonon energy. Figure 3.6 shows the production stages of primary phonons and Neganov-

Trofimov-Luke (NTL) phonons.

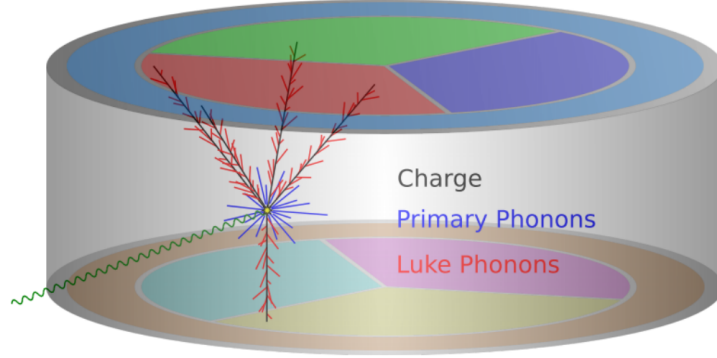


FIGURE 3.6: A schematic view of a particle interaction with the CDMSlite detector. An incident particle (green curved line) interacts with the detector producing primary phonons (blue lines near the interaction vertex) and charged particles (long black lines). The bias in detector caused the particle to drift, and during the drifting it produces NTL phonons (red short red lines departing from the charged particle tracks).

3.4.1 Primary Phonons

Primary phonons are created during the time of the initial scattering with the Debye energy (frequency $\mathcal{O}10$ THz in Ge). Each primary phonon immediately undergoes quasi-diffusion where it decays into two phonons, each with reduced energy. When the frequency (ν) of the phonon drops to $\lesssim 1$ THz due to quasi-diffusion, the mean free path of phonon becomes comparable to the detector dimension [76]. These phonons, referred as ballistic phonons, can now travel freely towards the surfaces of the crystal where they would either be absorbed by the phonon sensor or reflected by surfaces and continue scattering. The energy of the primary phonons (E_P) produced by a particle interaction is given by

$$E_P = E_r - N_{e/h} E_{gap} \quad (3.2)$$

where E_r is total recoil energy, $N_{e/h}$ is total number of electron/hole pairs produced and E_{gap} is the band gap energy.

3.4.2 Neganov-Trofimov-Luke Phonons

Neganov-Trofimov-Luke (NTL) [75] phonons are created when free electron-hole pairs (produced along with primary phonons) drift across the biased detector. The charged carriers are accelerated by the electric field but lose energy as they travel due to interactions with the detector medium. So, a charge carrier obtains a terminal drift velocity, comparable to the speed of sound, in $\lesssim 1$ ns. The drift velocity depends on the magnitude of the electric field. If a electric field of 1-100 V is applied to germanium crystal at ~ 40 mK temperature, the drift velocity is $\sim (10-100)$ km/s [77]. The work done by the electric field on accelerating drifting charge carriers is transferred to the crystal lattice and thus NTL phonons are produced. Thus, the amount of work done on the charge carriers equals the energy of the NTL phonons produced and depends on the voltage applied across the crystal. The energy of the NTL phonons is given by (E_{NTL}):

$$E_{NTL} = eN_{e/h}V_b - E_{KE}, \quad (3.3)$$

where $N_{e/h}$ is the number of electron/hole pair produced, V_b is the voltage applied across the detector, and E_{KE} is the kinetic energy of the drifting charge carrier. In the CDMSlite detector, NTL phonons are of particular interest because the higher voltage applied to the detector helped improve the detector's energy threshold. The ~ 70 V electric field applied across the CDMSlite detector (compared to 4 V across the other iZIPs) resulted in an amplification of the charge signal in the form of NTL phonon, allowing it to achieve a < 100 eV energy threshold.

3.4.3 Relaxation Phonons

Relaxation phonons are produced at the end of the charge carrier's trajectory when they reach the surface of the detector. As a charge carrier reaches the electrode, it down-scatters and relaxes to the Fermi level. Thus releasing the energy required to free charge carrier $N_{e/h}E_{gap}$ and the kinetic energy of the carrier as relaxation phonons. The total energy for

relaxation phonons (E_{rel}) is:

$$E_{rel} = N_{e/h}E_{gap} + E_{KE} \quad (3.4)$$

3.4.4 Total Phonon Energy

The total phonon energy (E_T) is the sum of the phonon energy from primary, NTL and relaxation phonons.

$$\begin{aligned} E_T &= E_P + E_{NTL} + E_{rel} \\ &= E_r - N_{e/h}E_{gap} + eN_{e/h}V_b - E_{KE} + N_{e/h}E_{gap} + E_{KE} \\ &= E_r + eN_{e/h}V_b \end{aligned} \quad (3.5)$$

The number of electron/hole pairs produced in the detector depends on whether the interaction causes an electron to recoil (ER) or a nucleus to recoil (NR). The number of charge pairs produced in an ER is greater than that for a NR. The general equation for the total number of charge carrier e/h pair produced is

$$N_{e/h} = Y(E_r)E_r/\epsilon(r), \quad (3.6)$$

where $Y(E_r) = E_q/E_r$ is the ionization yield and is defined to be the ratio of energy deposited in the electron-hole pairs to total recoil energy. $\epsilon(r)$ is the amount of energy on average required to produce one electron-hole pair in germanium which is 3 eV [55]. The value of $Y(E_r) = 1$ for ER when all the deposited energy is collected, and it is less than 1 for a NR. Using Equations 3.4 and 3.5, the E_T can be written as

$$E_T = E_r(1 + Y(E_r)eV_b/\epsilon(r)). \quad (3.7)$$

If we assume an ER then

$$E_T = E_{r,ee}(1 + eV_b/\epsilon(r)), \quad (3.8)$$

$$E_{r,ee} = E_T/(1 + eV_b/\epsilon(r)), \quad (3.9)$$

where $E_{r,ee}$ is the electron equivalent recoil energy, with $Y(E_r)=1$, which has units of electron

volt electron equivalent (eV_{ee}). Similarly, If a NR is assumed,

$$E_{r,nr} = E_T / (1 + Y(E_r) eV_b / \epsilon(r)), \quad (3.10)$$

where $E_{r,nr}$ is nuclear-recoil equivalent energy with units of eV_{nr} .

3.5 Data Division

A period of data taken throughout a stable cryogenics setup is called a “run”. A run would end once the detectors are warmed back up again. A run consisted of many small segments of continuous data-taking periods termed as data series. The length of the data series is determined by the length of time in which the detector is expected to lose neutralization; a detector loses neutralization when it traps sufficient charge carriers. The loss of neutralization causes a significant reduction in the charge signal. For the CDMSlite detector, the time period for loss of neutralization was about ~ 3 hours for a low background environment. Before the start and end of the data series, a set of random (non-physical) triggered events were recorded to understand and characterize the detector noise environment. Even during a data series, detectors were randomly triggered to understand the noise performance throughout the series. All these random triggered events are generally termed as “randoms”.

There are three primary types of data taken by the experiment. They are

1. Low-Background: Low-Background data series taken in a low-radioactivity environment and are used to search a rarely interacting particles, including LIPs and WIMPs.
2. ^{252}Cf Calibration: These are the data series taken when detectors are exposed to a radioactive ^{252}Cf . ^{252}Cf decays with the emission of neutrons and the data collected during the period is used for NR calibration for iZIP detectors [74]. These data series are also used for the efficiency calculation of some selection criteria. The activation lines observed in subsequent low-background series due to exposure of the detector to the ^{252}Cf are used for energy-scale calibration of the CDMSlite data.
3. ^{133}Ba Calibration: These are the data series taken when detectors are exposed to a

radioactive ^{133}Ba . ^{133}Ba decays with emission of β and γ source, which is used for energy-scale calibration and ER band calibrations for iZIPs [74].

3.6 Data Period

The second run in the CDMSlite mode took place from February 4, 2014, to November 10, 2014. The Run 2 period was basically divided into two portions: Run 2 Period 1 (SuperCDMS run 134) and Run 2 Period 2 (SuperCDMS run 135). As a reminder, only data taken during Run 2 Period 1 is considered in the LIP-search analysis. Table 3.1 shows the operational period and the live time for the data taken during two periods of the CDMSlite Run 2.

During the data-taking period, five ^{252}Cf calibrations periods were interspersed throughout. The half-life of electron capture decay of the activated ^{70}Ge during ^{252}Cf calibrations is 11.47 days which means the ^{70}Ge decays are also be observed during subsequent data-taking periods. M-shell events typically deposit relatively little energy (160 eV). As a result, they are of particular interest as it is a region of optimal sensitivity for a LIP event also because it is near the low-energy threshold and so helps to understand the energy calibration for the lowest energy recoils considered. During Run 2 Period 1, there were two periods of calibration; one at the beginning of the Run 2 Period 1 and the other on May 2nd, 2014.

Label	Time span	Raw Live Time (days)
Run 2 Period 1	4 Feb 2014 - July 14 2014	110.28
Run 2 Period 2	23 Sep 2014 - 10 Nov 2014	21.95

Table 3.1: A table showing the data taking period of the CDMSlite Run 2. The live time shown in the table are raw live time before application of data selection criteria described in Chapter 4.

The cryo-cooler used for the experiment was run for about 10 years, which was longer than the recommended period. The cryo-cooler condition became worse as the run progressed, which increased the production rate of low-frequency noise observed in the detectors. The higher rate of the low-frequency noises induced higher trigger rates. Figure 3.7 shows that the trigger rate increased as time progressed through the data-taking period. After observing

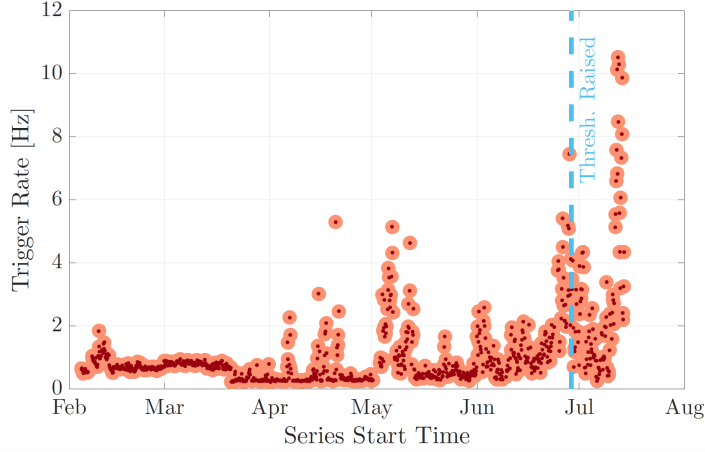


FIGURE 3.7: The trigger rate for Run 2 Period 1 as a function of time. The trigger rate was stable at the beginning of the run, but a spike in rate was observed after 3 months of operation. Due to this increase in the rate, the trigger threshold was increased at the end of June, which is marked by the blue dashed line. After raising the threshold, the trigger rate was stable for ~ 15 days but then increased by enough to force cryocooler maintenance and end data taking.

an increase in the trigger rate at the end of June, the trigger threshold value was increased to lower the trigger rate. This change decreased the rate of noise triggers for awhile, but a huge spike in the trigger rate was observed again at the end of June. At this point, the data taking was stopped for maintenance of the cryo-cooler. This was the end of Run 2 Period 1 (SuperCDMS Run 134), and Run 2 Period 2 (SuperCDMS Run 135) began after the maintenance of the cryo-cooler.

3.7 Data Processing and Calibration

The data taken in each data series consists of raw traces of phonon and charge channels of each data event, veto and trigger data, along with all other experimental conditions. All the information about the events is extracted, including total recoil energy, from these raw traces. The recoil energy computed is calibrated using a known gamma source. The CDMSlite uses the recoil energy computed from phonon traces. This section describes the process of energy reconstruction from phonon traces and calibration of thus obtained energy scale.

3.7.1 Phonon Energy Reconstruction

The data for analysis can be obtained by fitting the raw phonon traces with signal templates using the optimal-filter (OF) algorithm [74]. Generally, OF fits a signal trace ($S(t)$) as a combination of the signal template ($A(t)$), which can be shifted in time (t_o is the time delay to fit template with signal trace), and a noise template ($n(t)$) as:

$$S(t) = aA(t - t_o) + n(t) \quad (3.11)$$

where a is the amplitude value for scaling the template which also provides information about the deposited energy. The signal templates ($A(t)$) are created from averaging of raw traces for physics events, whereas noise templates are created from averaging random events.

A non-stationary optimal filter (NSOF) algorithm is used to estimate an event's energy deposition. The NSOF algorithm uses the same signal template and noise template as the standard OF fit. The difference between the raw traces and the OF template is treated as non-stationary noise by this method. This process is found to have slightly better resolution than the standard OF [74]. So, this algorithm was used for energy estimation. However, this algorithm cannot give information about the position of the event as the initial portion of each phonon pulse, which has the position information, is treated as non-stationary noise. So, a two-template OF-fitting (2T-fitting)) is used in the analysis to obtain information about the event location.

Two-template OF-fittings fit a raw phonon trace with a fast template whose amplitude provides event location information and a slow template whose amplitude gives an estimate of energy deposited. The OF algorithm now fits the signal trace ($s(t)$) to two templates and noise template as

$$S(t) = \sum_{i=s,f} a_i A_i(t - t_o) + n(t). \quad (3.12)$$

A_s is commonly known as a slow template due to its slow fall time, and it is the standard signal template created by averaging the raw traces. The amplitude a_s obtained when the

signal trace is fitted with this template provides an estimate of the energy deposited. A_f on the other hand is known as a fast template as it has a fast fall time. This template is created by averaging the residual traces [74]. Residual traces are the traces obtained after subtracting the slow template from the actual signal trace. The amplitude a_f obtained from the fittings gives information about the position of the event. Figure 3.8 shows a 2T fitting used by the OF algorithm to extract position and energy information.

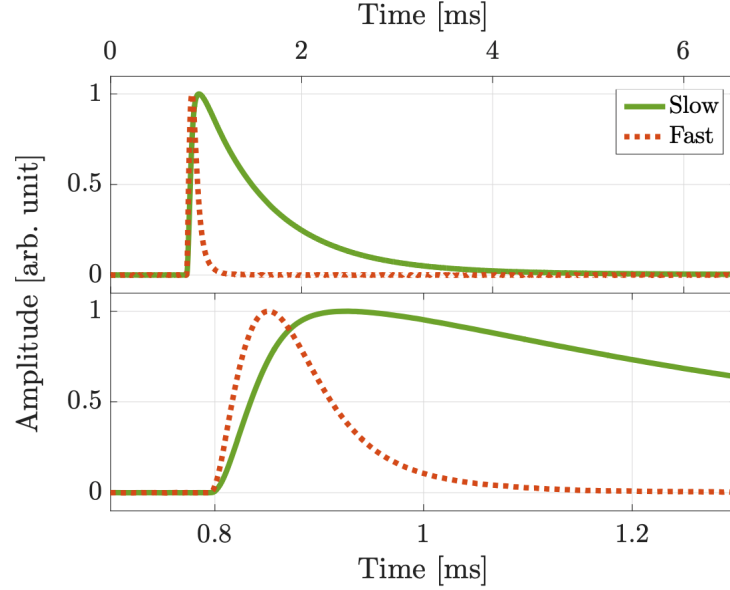


FIGURE 3.8: The templates used for two template fittings for the CDMSlite data processing. The top panel shows the templates for the full-time length, whereas the bottom one is zoomed around the rising time. The slow template (green) is a simple OF template used for gaining energy information from the traces calculated, averaging all the phonon traces. The template is also equivalent to the template used for NSOF calculation. The fast template (red) is only used to extract position information from the OF algorithm. It is created by averaging of the difference between traces and slow templates.

The traces obtained from each phonon channel were fitted with these two templates assuming the same time delay for both templates. Application of the fitting resulted in four important output parameters: the amplitude for a fast template (position information), the amplitude for the slow template (energy information), the time delay and χ^2 value of fitting. Figure 3.9 shows the 2T fitting to an event for all four phonon channels of the CDMSlite

detector.

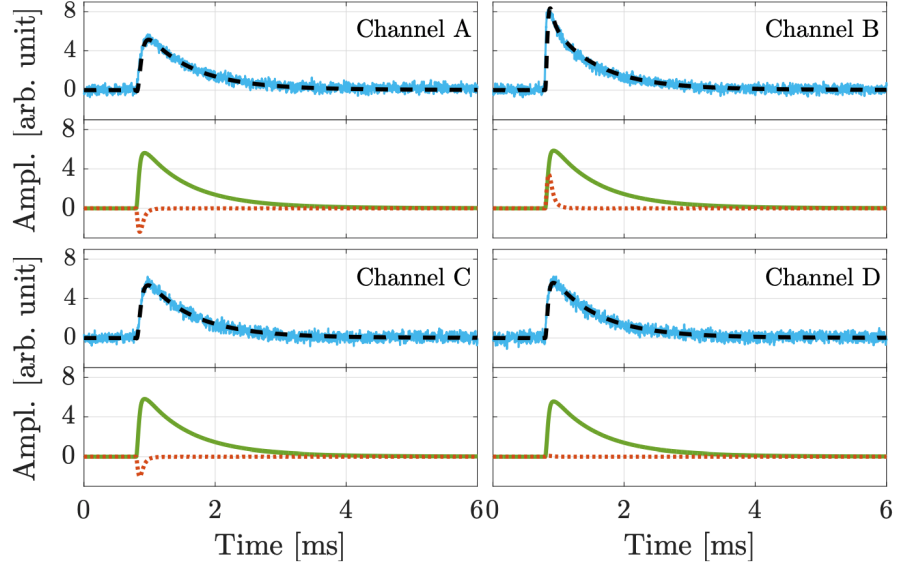
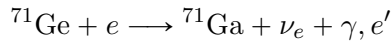
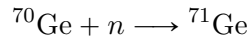


FIGURE 3.9: An example of 2T fitting with an example event for all four channels (A-D) for the CDMSlite detector. A raw trace (blue) is fitted with 2T fitting to obtain the black dashed curve, which is the linear sum of the fast template (red dotted) and the slow template (green). The amplitude of the slow template gives the total energy deposited in the channel, whereas the amplitude of the fast template gives the proximity of the position of an actual event. The amplitude of the red template being higher for channel B gives information that the event took place near channel B, whereas negative amplitude for A and D suggests that it happened far from them.

3.7.2 Calibration

The energy calibration of the CDMSlite detector for electron recoils was performed by using data resulting from a ^{252}Cf neutron source [55]. It is used for obtaining the energy calibration in keV_{ee} scale (keV electron recoil equivalent), which can be converted into keV_{nr} using the median value of the assumed ionization yield ($Y(E_r)$). Upon the capture of a neutron, ^{70}Ge turns into unstable ^{71}Ge with a half-life of 11.43 days, which decays by electron capture.



X-rays (γ) and Auger electrons(e') are also released during the decay process. The total energy of the released X-rays and Auger electrons depends on the shell of the electron captured. Table 3.2 shows the corresponding energy levels of ^{71}Ge with their branching fractions for the decay. Two clear peaks were observed in the energy spectrum for K- and L-shell electron captures and were used for energy calibration. The M-shell peak became visible was also visible just above the threshold after some data refining as described in Section 4.7.

Capture Shell	Branching fraction (%)	Energy (keV)
K-Shell	87.57	10.37
L-Shell	10.43	1.30
M-Shell	1.78	0.160

Table 3.2: This table shows the energy and branching fraction of the activation peaks due to the ^{252}Cf calibration [55].

The final energy scale in keV_{ee} was used assuming all the events to be an ER (with $Y(E_r) = 1$). The scale of reconstructed energy was calibrated using K-shell peak such that the position of K-shell was at 10.43 keV_{ee} . This energy scale of keV_{ee} still required further correction for environmental and detector conditions.

The energy scale was corrected for a fluctuating current from the High-Voltage Power-Supply (HVPS), fluctuation in base temperature, discrete shifts in energy scale, and position dependence. The fluctuation in the current (usually resulting in a potential difference less than 70 V) from the HVPS led to a reduced NTL gain. A correction factor was calculated for each event to rectify this reduction in the NTL gain [74]. For each event, the correction factor was the ratio of the total expected NTL amplification to the total observed amplification. The correction was about $\sim 2\%$. The deposited energy was found to be linearly dependent on the experimental base temperature [74]. The slope of the energy vs. temperature distribution was used to remove the temperature dependence. The correction was about $\sim 3\%$. The energy estimation obtained from the NSOF seems to have some position dependence and has a strong correlation with an amplitude of the 2T fast templates. The position dependence was removed using the slope of the energy vs. position distribution. The correction was

between 0 - 330 eV_{ee} [74].

3.8 Detector Resolution

Along with the low-energy threshold for the CDMSlite detector which is essential for searching LIPs with smaller fractional charge, the detector also requires to have better resolution so that it can resolve low energy recoils. The resolution of the detector is also used to smear the signal model (see Section 2.1) to generate the expected LIPs distribution in the detector. This section describes the energy resolution of the CDMSlite detector.

The LIPs-search analysis only uses the resolution for Period 1, this section only describes the detector resolution for Run 2 Period 1. The detector's energy resolution was calculated using the width of all three activation peaks and the noise distribution [55]. The noise distribution was generated using random triggered events and is used to calculate the baseline resolution (energy independent noise resolution). The resolution calculated for the Run 2 Period 1 is shown in Table 3.3.

Peak	Location (keV _{ee})	Resolution (eV _{ee})
Baseline	0	9.7 ± 0.1
K-Shell	0.16	18.6 ± 4.2
L-Shell	1.30	31 ± 2
M-Shell	10.37	101 ± 1

Table 3.3: A table showing the energy resolution for different peaks observed in the CDMSlite Run 2 Period 1 energy spectrum.

Using these numbers, an energy resolution model was developed for CDMSlite Run 2. The total energy resolution for the detector is:

$$\sigma_T = \sqrt{\sigma_E^2 + \sigma_F^2(E_{r,ee}) + \sigma_{PD}^2(E_{r,ee})}, \quad (3.13)$$

where σ_E^2 is baseline resolution, $\sigma_F^2(E_{r,ee})$ is the energy resolution due to Fano statistics and $\sigma_{PD}^2(E_{r,ee})$ is the resolution due to the position dependence. U. Fano [63] computed that the variance for N number of electron-hole pairs produced in an interaction is $\sigma^2 N = FN$ where

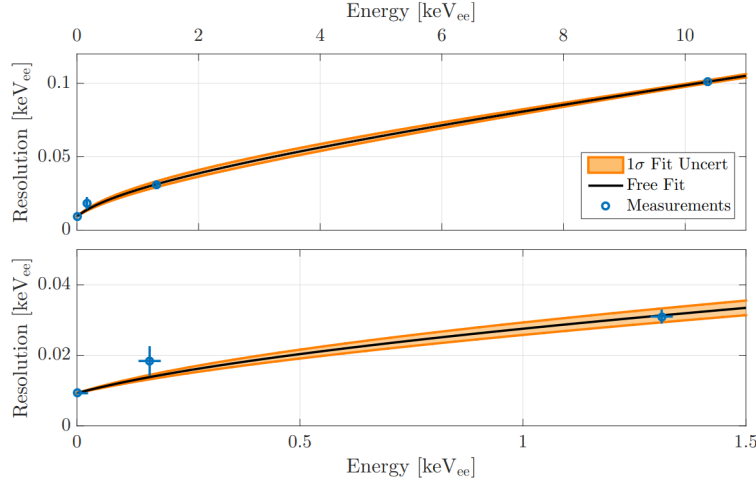


FIGURE 3.10: The measured resolution values (blue) for the CDMSlite Run 2 Period 1 are fitted with the resolution model in Equation 4.10. The black curve is the fitted line with orange uncertainties. The top figure shows the fitting for all four peaks, whereas the bottom figure shows the fitting for the lowest energies.

F is Fano factor. For ER, the variance is $\sigma_F^2(E_{r,ee}) = \sigma_N^2 \epsilon(r)^2$ for $N = E_{r,ee}/\epsilon(r)$. So,

$$\sigma_F^2(E_{r,ee}) = \sigma_N^2 \epsilon(r)^2 = FN \epsilon(r)^2 = FE_{r,ee} \epsilon(r) \equiv BE_{r,ee}. \quad (3.14)$$

The Fano factor for Ge is measured to be 0.13 [78], which means the expected value for B is 0.39 eV_{ee}. Also, the effect for the position is assumed to be quadratic [55], so $\sigma_{PD}^2(E_{r,ee}) = (AE_{r,ee})^2$. Hence, the final resolution function in terms of B and A is given as:

$$\sigma_T = \sqrt{\sigma_E^2 + BE_{r,ee} + (AE_{r,ee})^2}. \quad (3.15)$$

Figure 3.10 shows the fitting of the detector resolution model with the observed events from the CDMSlite Run 2 Period 1 calculated by the CDMSlite WIMP search [55]. The fitting was performed with no restrictions on all three parameters. The fitting resulted are $B = 0.67 \pm 0.11 \text{ eV}_{ee}$ and $A = (5.68 \pm 0.94) \times 10^{-3}$. The values of A and B have strong anti-correlation ($\rho_{AB} = -0.984$). If the value of B was fixed to the expected value, the value of $A = (7.73 \pm 0.13) \times 10^{-3}$ which gave slightly worse fitting. This analysis uses $\sigma_E^2 = 9.26 \pm 0.11 \text{ eV}_{ee}$, $B = 0.67 \pm 0.11 \text{ eV}_{ee}$ and $A = (5.68 \pm 0.94) \times 10^{-3}$ for the calculation

of the energy resolution.

4

LIP-search Analysis

The CDMSlite LIP-search analysis uses the data collected by the CDMSlite detector (described in Chapter 3) from February through July 2014 to set a limit on the LIP vertical intensity for LIPs with various values of electric charge and $\beta\gamma$.

4.1 Analysis Overview

The analysis is performed in the following manner:

1. An analysis window is defined such that it would give us substantial sensitivity to LIPs with a smaller electric charge. That window was 100 eV_{ee} to 2 keV_{ee}. The analysis is primarily focused on the search for LIPs with smaller fractional charges. LIPs signal model showed that LIPs with smaller f are most likely to deposit energy in the lower energy region of the analysis window. The low energy threshold of the CDMSlite detector allows to search for LIPs with smaller f than have ever been searched before. Section 4.2 has more discussion on these analysis thresholds.
2. LIP event selection criteria are defined to select probable LIP events without any experimental anomaly from all data series. These criteria are defined to reject both non-physical events and physical events due to the interaction of the SM particles

(background events).

The application of the selection criteria decreases the exposure of the experiment. The exposure is a product of the detector’s mass, the length of observation time (live time), and the recoil-energy-dependent accuracy of LIP identification (efficiency). Suppose a selection criterion rejects an event due to the failure of the experimental setup. In that case, the live time of that event is not included in the total live time of the experiment. For all other criteria, the probability for them to reject the true LIPs event is calculated. Section 4.3 provides an overview of the selection criteria and their effect on the exposure.

3. A limit-setting framework is developed using an expected background distribution obtained from a simulation of the background model defined for the CDMSlite Run 2 [79]. While a similar dataset (the full Run 2) is published, the analysis is “effectively blind” as the analyzers did not use data for limits calculation until the expected intensity limits are calculated.

The optimum interval [80] (OI) method is used to calculate a 90% upper confidence limit on the expected number of observed LIP events. The OI method conservatively assumes all the observed events could be due to LIPs interaction.

Chapter 5 discusses the background model, the calculation of expected sensitivity, and uncertainties on expected sensitivity.

4. After calculating the expected sensitivity, the selection criteria were applied to the data for the first time. The final vertical intensity is calculated, using data, for LIPs with various f and $\beta\gamma$. Chapter 6 provides a description on computing the final limit results.

4.2 Energy Thresholds

The lower energy threshold of 100 eV_{ee} and upper energy limit of 2 keV_{ee} is chosen for this LIP-search analysis. These thresholds are chosen based on the observations made by the CDMSlite WIMP-search analysis and are explained in the next paragraph.

The CDMSlite WIMP-search chose an analysis threshold at a reconstructed energy bin where the triggering efficiency of the experimental setup was 50% (see Section 4.7.2 for more information on trigger efficiency) [55]. To be conservative and for simplicity, we chose an energy threshold of 100 eV_{ee} where the trigger efficiency reaches $\sim 100\%$. The low energy threshold of the CDMSlite detector is key to obtaining sensitivity to LIPS with a smaller f possible.

The upper limit on energy range analyzed is chosen to be at 2 keV_{ee} , like that for the CDMSlite WIMP-search [55], based on the limitation observed on 2T-fast template fitting. An event with energy deposition greater than 2 keV_{ee} observed saturation on the amplitude of 2T-fast template fitting. These events were not applicable for the fiducial volume selection criteria (Section 4.14). Hence, due to an incomplete understanding of this saturation, an upper energy threshold of 2 keV_{ee} was chosen. This limit on upper energy range wouldn't impact much on the sensitivity of the smaller fractional charged LIP as these charges has a larger probability to deposit energy less than 2 keV_{ee} .

4.3 LIPs Event Selection

The motive for using selection criteria is to select only events caused by the interaction of a LIP in the detector. The selection criteria must be applied to the data set to maximize the LIP sensitivity. A selection parameter defined for each criterion requires balancing between the rejection of non-LIP interaction and retaining LIP selection efficiency. The total exposure (E_{expo}) for a detector with mass (M), the length of observation time, live time, (τ) is given by

$$E_{expo} = M \times \tau \times \epsilon, \quad (4.1)$$

where ϵ is the energy-dependent efficiency of the selection criteria to identify a true LIPs interaction. The selection criteria can reduce two of these aspects of exposure: live time (τ) and efficiency (ϵ). Based on their effect on the exposure, selection criteria are broadly divided into two categories:

1. Live Time: This category of the selection criteria rejects an event observed during a period with a suspect experimental performance. The live time for this event is not included in the total experimental live time as the experimental setup was not entirely prepared to observe a LIP interaction.
2. Signal Efficiency: Some of the selection criteria are defined to remove background events, either due to reduced detector performance or interaction of non-LIP particles. The application of these selection criteria might reject an event due to a LIP interaction when it tries to remove the background events. For each of these criteria, a signal efficiency is calculated. The signal efficiency for a particular criterion is its probability of retaining a LIP interaction.

This LIP-search analysis uses all the selection criteria defined by the CDMSlite WIMP-search analysis [55]. The CDMSlite WIMP-search analysis used combined data from the CDMSlite Run 2 Period 1 and Period 2 to set a limit on WIMP mass and cross-section. The rate of interaction for LIPs with smaller f is minimal (see Chapter 2) and comparable to WIMPs. This means the selection criteria defined for the WIMP search are applicable for the LIP search as well.

All these selection criteria (i.e. cuts) can be divided into three broad categories:

1. General quality cuts: General quality cuts are the cuts defined to remove events during a known period of poor or suspect detector performance. So, they are also called “bad event cuts”. The potential signal collected during the susceptible performance of the detector cannot be treated as a signal event. All of these cuts are live time cuts. Section 4.4 provides an overview of some of the significant general quality cuts and their effect on the total live time.
2. Phonon pulse-shape cuts: Phonon pulse-shape cuts are defined for selecting events with proper phonon-pulses. Those events that pass both the general quality cuts and phonon pulse shape cuts are commonly known as “good” events. Section 4.5 provides

an overview on these types of cuts and Section 4.7 discusses the signal efficiency for them.

3. Physics cuts: Physics cuts are defined to reject an event observed due to the interaction of background particles with the detector. Section 4.6 provides an overview on these types of cuts and Section 4.7 discusses the signal efficiency for them.

4.4 General Quality Cuts and Live Time

General quality cuts are defined to reject the event caused by poor or susceptible detector performance. These cuts are designed to remove events that are electronic glitches, non-physics phenomenons, and events collected during an anomaly in the experiment. All of these cuts reduce the experimental live time. Mark Pepin's thesis [74] has more information on these cuts. Some of the significant general quality cuts used for the analysis are:

- Bad Base Temperature, HVPS Current, or 2T-Fit: The base temperature of the experiment, the output current from the high voltage power supply (HVPS), and 2T-fit are essential for energy scale calculation as discussed in Chapter 3. An event collected during the period when the base temperature and HVPS current are missing, or suspect cannot be accurately calibrated. This cut also rejects an event with high base temperature and high HVPS current. This cut also removes an event for which the 2T-fit algorithm failed to work. The energy reconstructed for these events is not trustworthy. This cut removes about 0.23% of the total CDMSlite Run 2 Period 1 live time.
- Asymmetric Multiply-Triggered and Ionization Glitches: Glitches are event whose recorded pulses (ionization or phonon) have fast rise or fall time. This cut is designed to reject these glitches. The glitches primarily arise from voltage spikes in the TES-biasing lines. If the voltage spike is large enough, these glitches may trigger phonon or charge channels. Usually, for a physics event, the number of charge-triggered and phonon-triggered channels are roughly equal. If a significant difference is observed between the number of charge-triggered and phonon-triggered channels, these events are possibly

due to glitches. This cut keeps an event which has a nearly equal number (difference less than 6 and greater than 1) of charge-triggered and phonon-triggered channels while rejecting all other events. This cut removes about 0.60% of the total live time.

- **Non-triggered Ionization Glitches:** A different type of ionization glitch was observed in the outer charge channel of the CDMSlite detector. These glitches fit poorly with the physical charge template. An event whose ionization pulse fits poorly with physics charge template (large χ^2 value) is rejected. This cut removes about 0.98% of the total live time.
- **Good Phonon Baseline Noise:** The phonon pulse baseline before a triggered event is expected to be nearly flat with some noise. Sometimes, an odd baseline is observed due to an unexpected noise or the tail of a previously occurred event. This baseline noise will be an issue while fitting the observed pulse with the flat-based phonon template for an energy reconstruction. The cut rejects an event with a pre-pulse width greater than 4σ from the mean value calculated using randomly triggered events. This cut removes about 1.97% of live time.
- **Bad Data Series:** There were few series within Period 1 data that were identified as problematic while development of ionization glitches and phonon baseline noise cuts. These series were entirely removed from the analysis with a big loss in live time. This cut removes about 7.63% of the total live time. The criteria for series to be removed as a “bad series” are:
 1. If a series loses more than 4% of live time due to application of ionization glitch cut; 72 series are removed.
 2. if a series has phonon pulses with long tail on randomly triggered events; 3 series are removed.
 3. if a series was taken without pre-biasing the detector; 5 series were removed.

The total live time of the data collection was reduced by $\sim 11.3\%$ after the application of general quality cuts. The greatest reduction in the live time is from the bad series cut, which removed about 7.63% of the total live time. The total live time of the CDMSlite Run 2 Period 1 is divided into 8 time blocks based upon the cryocooler behavior (see Chapter 3). Figure 4.1 shows the reduction of the live time after application of these cuts on different time blocks.

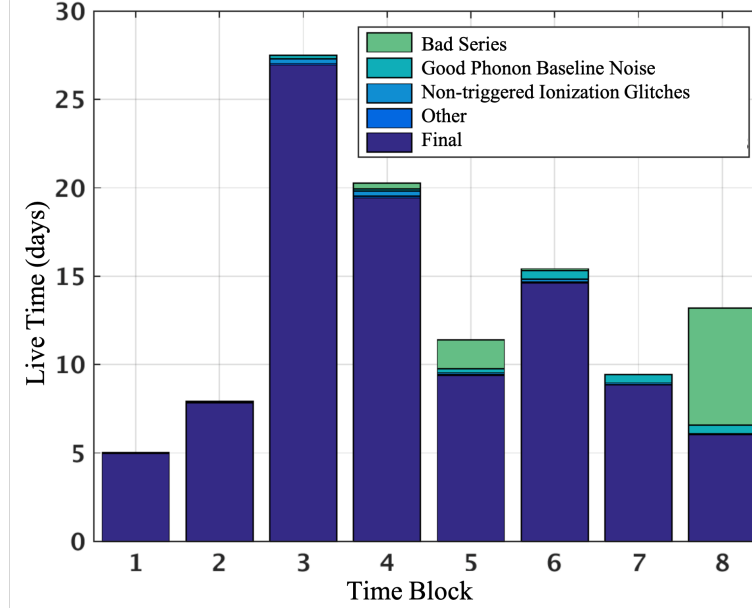


FIGURE 4.1: Live time remaining after application of live time cuts on the total CDMSlite Run 2 Period 1 data set. The bad series cut reduces the live time significantly compared to other cuts.

The raw live time of 110.28 days is reduced to 97.81 days after applying the cuts mentioned in Section 4.4. Table 4.1 shows that $\sim 11.3\%$ of total live time of the data period is lost due to the application of general quality cuts.

4.5 Phonon Pulse-Shape Cuts

Phonon pulse-shape cuts are defined based on the shape of the event's phonon pulse. The phonon pulse for an event is fitted using three different templates, i.e., a template for standard physics events, a template for low-frequency noise and a template for electronic glitches. The

Category	live time (days)	Exposure (kg-days)
Raw live time	110.28	66.88
Final live time	97.81	59.32

Table 4.1: A table showing the data taking period of the CDMSlite Run 2 Period 1. The live time shown in the first row of table are raw live times before the application of general quality cuts. The live time decreases by $\sim 11.3\%$ after the application of cuts.

application of these cuts primarily removes an event with a bad phonon pulse, but may also remove some true signal event. A signal efficiencies for these cuts are calculated and combined with efficiency from other cuts to obtain final analysis efficiency. This section provides a brief introduction about these cuts, and Section 4.7.5 provides an overview of the efficiency calculation for these cuts.

The phonon pulse-shape is divided into three subcategories:

- (a) Phonon Pulse Quality: The energy for a phonon pulse is estimated using NSOF fit (discussed in Chapter 3.7.1) for this analysis. The goodness-of-fit χ_{NSOF}^2 value is calculated while fitting the phonon-pulse of each event with NSOF template. This cut removes pulses with likely low quality fits by rejecting events with large χ_{NSOF}^2 values. Pulses with multiple peaks, saturated peaks, are examples of the pulse with large χ_{NSOF}^2 values.
- (b) Low-Frequency (LF) Noise: Some registered events were observed due to the low-frequency noise. The trace due to this low-frequency noise has a slower rise and fall time compared to those observed from a physics event. The noise from the cryocooler was recognized as the primary source of low-frequency noise [55].

A LF noise template was developed averaging over a large set of LF noise events. These noise events were selected from a pool of all observed events where an event took more than 1 ms to reach their peak value and was observed to have reconstructed energy deposition characteristics of low-frequency noise. This new template is used to fit all the traces, and the goodness-of-fit (χ_{LF}^2) parameter was calculated. The traces with

smaller χ_{LF}^2 (a better fit by LF noise hypothesis) are rejected by this cut. Figure 4.2 shows the template created for the LF noise.

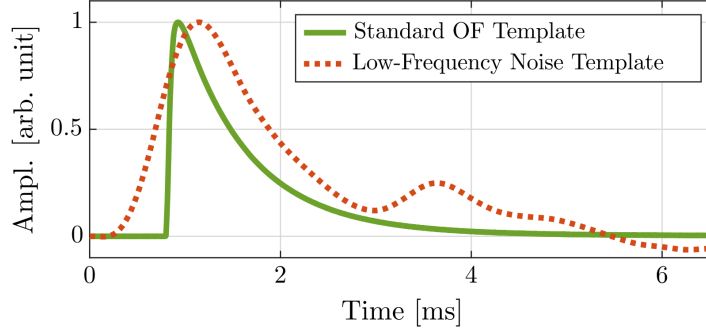


FIGURE 4.2: A low-frequency noise template (red-dotted) developed to identify noise events from the cryocooler and the standard OF template. The LF noise templates are created from events with a longer rise time (> 1 ms) compared to the standard OF template (green solid). The low-frequency noise also has multiple peaks and slower fall time.

- (c) **Pulse-Shape Glitches:** This cut is defined to reject the low-energy phonon glitches which are not rejected by the glitch cut discussed earlier. The glitch templates were developed averaging over the probable glitch event from an earlier SuperCDMS data taking Run [81]. Figure 4.3 shows the glitch template compared with the physics pulse. The glitch template has a sharper rise and fall as expected. Similar to LF noise, all traces are fitted with the glitch template, and a glitch template goodness of fit (χ_{GL}^2) are calculated. The traces with better χ_{GL}^2 are rejected by this cut.

4.6 Physics Cuts

Physics cuts reject an observed event due to an interaction of a background particle with the detector. The LIP-search uses the same physics cuts as the CDMSlite WIMP search. The physics cuts defined for the CDMSlite WIMP search are designed to remove non-WIMP events. WIMPs are expected to scatter no more than a single time in the experimental apparatus. LIPs, however, can scatter more than once, necessitating the calculation of LIP-specific efficiency correction factors described in Section 4.8. Despite the additional inefficiency, the

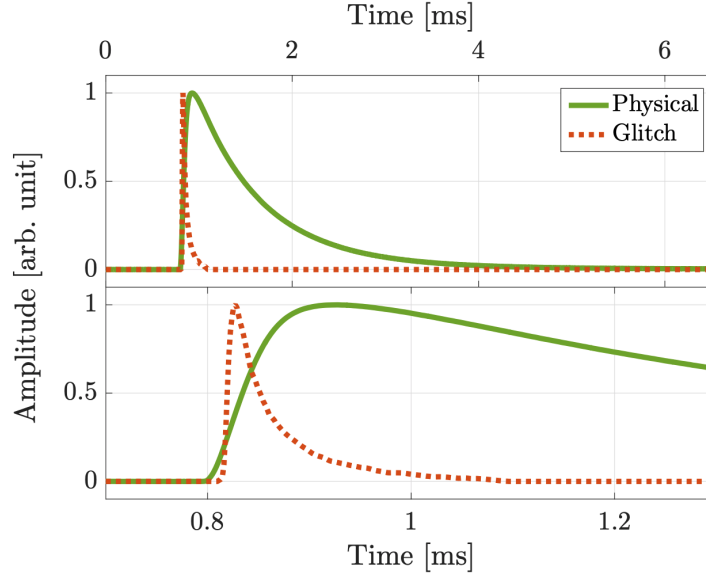


FIGURE 4.3: A glitch template (red-dotted) developed for low-energy phonon glitches and a standard OF template (green solid). The top figure shows the full glitch and pulse template, whereas the bottom one is a zoomed-in version around the peak. The low-frequency noise also has a sharp rise and fall time in comparison to OF pulse template.

LIPs analysis still benefits from using these physics cuts as they remove common backgrounds, including surface and bulk β s, γ s, etc.

All the physics cuts used for WIMP-search analysis and this analysis are described in this section. This section describes why it is appropriate to retain each cut for the LIP search. Section 4.7.5 describes the CDMSlite WIMP-search efficiency for these cuts. Section 4.8 describes the calculation of additional LIP-specific efficiency correction factors.

4.6.1 Veto Cut

The veto cut used by the CDMSlite WIMPs-search analysis is designed to reject cosmogenically-induced events. Muons with high energy can still penetrate through the rock overburden and reach the underground laboratory. These muons are capable of producing background particles, including neutrons and γ s.

SuperCDMS surrounded the detector volume with 5cm-thick organic scintillator paddles. Energy depositions in the paddles were used to tag muons as they entered or exited the

detector volume. Muons, while passing through these scintillator paddles, generally deposit about 10 MeV into the paddles. The energy threshold for muon detection is set to be about 1-2 MeV [55]. All events within 50 μ s after observing more than ~ 1 MeV deposition in veto paddles are deemed to be veto-coincident events. Some of the veto-coincident events are probably due to the interaction of secondary neutrons or γ s produced from muons, which are backgrounds for a dark matter search and are therefore rejected by the veto cut. Section 4.7.1 describes the signal acceptance efficiency for this cut.

Muon-induced electron recoil events, from γ , are a background for the LIP-search analysis. A nuclear recoil event observed due to a muon-induced neutron is also the background for this analysis as the CDMSlite detector cannot distinguish a nuclear recoil and an electron recoil event. So, this LIP-search analysis also applies the same muon veto cut to remove veto-coincident events.

When applied to the LIP search, the efficiency of the veto cut is expected to be the same as that measured for the WIMP search because no additional LIPs event is suspect of removal from this cut. Energy deposited by a LIP passing through a veto paddle relative to that of a muon can be estimated using the charge inverse-square law. LIP with electric charge $e/100$, the largest charge considered for LIP-search analysis, is likely to deposit energy 100^2 times smaller than that of a muon following the same path through a paddle, which is about 1 keV energy. LIPs with smaller electric charges are expected to deposit less energy. This means LIPs considered by this analysis are very unlikely to deposit energy greater than the muon detection energy threshold of ~ 1 MeV, into veto paddles. Therefore, the application of this cut will not result in an appreciable loss of LIP events. Hence, there is no additional inefficiency due to the muon veto cut for the LIP-search analysis.

4.6.2 *Singles Cut*

A singles cut is defined to reject an event that deposits appreciable energy in more than one detector. For a particle with a small interaction cross-section (including a WIMP or a LIP with a small electric charge), its probability of interacting with more than one detector

is minimal. The singles cut removes all events in which multiple detectors have energy deposition more than their single cut's energy threshold. Suppose a particle deposits energy greater than the threshold in the CDMSlite detector and greater than a single's cut energy threshold in any other detector. In this case, the event is deemed as a multiple-detector-scatter event and is rejected by the singles cut. For the singles cut, the non-CDMSlite detectors are used as a veto, and are hereafter referred to as veto detectors. B. Welliver [82] developed this selection criterion for SuperCDMS analyses.

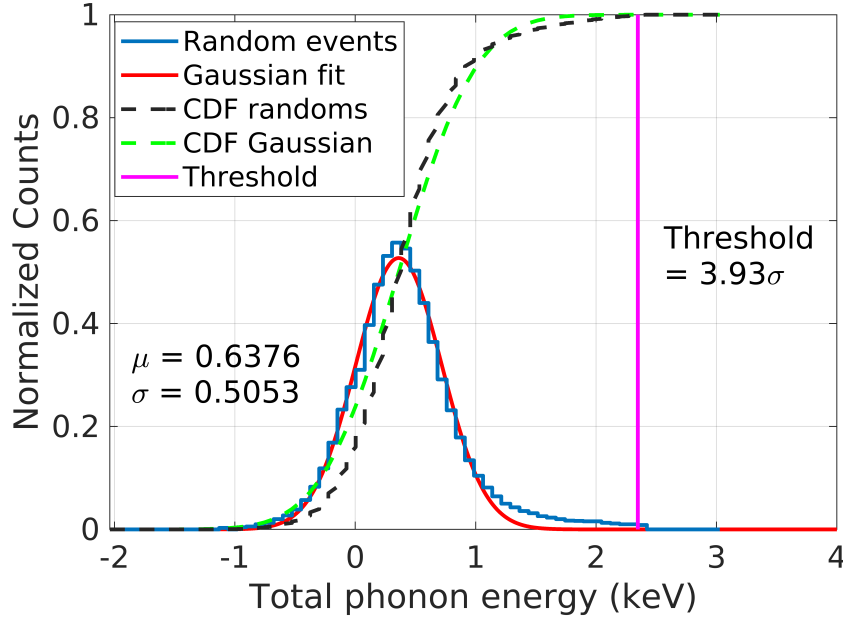


FIGURE 4.4: An energy deposition distribution of randomly triggered events (noise) in a data series for one of the iZIP detector (T3Z2) in blue and the Gaussian fit to the noise distribution in red. The blue histogram is not Gaussian with an excess of events on the high energy tail. The black is the cumulative distribution function (CDF) for the random events, and the green line is the Gaussian fit to that. The threshold shown in magenta is chosen, using the CDF of randoms (black-dashed), such that 99.87% of randoms are below this threshold. The threshold for this series is calculated to be 2.34 keV which corresponds to about 3.93σ above the mean of the Gaussian fit (red).

The single cut's energy threshold for a detector is defined such that it is greater than 99.87%, 3σ equivalent for the Gaussian distribution, of the noise events. The energy distributions of randoms are non-Gaussian with a greater tail on the positive end, as shown in Figure 4.4. The threshold was conservatively chosen using the cumulative distribution

function (CDF) of the random events' energy distribution. The threshold is chosen such that 99.87% of the observed random events are below this threshold.

Along with being non-Gaussian, the distribution is also not time-invariant. The noise distribution for the same detector varies between data series. So, time blocks were created for each detector combining data series with similar noise performance. Each detector will have one threshold value for each time block. Elias Lopez created the following criteria for dividing time blocks [83].

1. For each series, the energy thresholds were calculated for each detector using the CDF of randoms.
2. A cluster of 20 consecutive series is formed to allow sufficient statistics.
3. A time block is formed by adding consecutive clusters.
4. The energy thresholds for each series with in a cluster are analyzed. A cluster should only contain those series whose thresholds are within 20% of the time block's minimum threshold.
5. A series that doesn't follow above criteria is chosen as the boundary for the time block.

After determining the time blocks, an energy threshold for each of those time blocks is computed using the same method described for the series. The number of time blocks for each detector could be different depending on their performance. The data series is divided into more than 100 time blocks for each detector where T3Z1 has a maximum of 115 time blocks. Appendix A has a threshold and live time tabulated for each time block for all detectors.

With singles cut thresholds determined for all time periods and all detectors, the singles cut criterion can now be defined. The flow chart shown in Figure 4.5 describes the algorithm for determining single-scatter events. The algorithm for working of singles cut can be summarized as:

1. Select events that deposits energy greater than threshold in the CDMSlite detector.

2. For all those selected events, check all the veto detectors to see
 - (a) if energy deposition in the detector is greater than the threshold.
 - (b) if those events are due to LF noise or electronic glitches
3. if a selected event has energy deposition over the threshold on veto detectors and is not a LF noise or a glitch, then these events are deemed as multiple and are removed by singles cut.

The singles cut is one of the best way to remove background events caused by electron recoils, including high energy β s and γ s, which can easily interact with more than one detector. It becomes even more useful for the CDMSlite detector, which cannot distinguish between an electron recoil and a nuclear recoil. This ability to reject multiple detector deposition events is essential for the LIP-search analysis too. A LIP with smaller f has a small interaction cross-section, which means it has a low probability of interacting with multiple detectors. The relatively higher energy threshold (> 10 times) of the veto detectors relative to the CDMSlite detector also makes it highly unlikely for these LIPs to deposit above-threshold energy in a veto detector. Since the analysis is more interested in searching for LIPs with smaller f , the singles cut is appropriate without change for the LIP-search analysis.

LIPs with larger f have a larger interaction cross-section and have a non-negligible chance of depositing above-threshold energy in a veto detector. This means the singles cut can reject some true LIPs event which results in the need to estimate the LIP-specific singles cut inefficiency for singles cut when used for LIP-search. A correction factor is calculated to incorporate this additional source of inefficiency. Section 4.7.1 describes the estimate of the singles cut efficiency and Section 4.8.1 describes more about the calculation of the LIPs-specific inefficiency.

4.6.3 Radial Cut

The radial cut is defined to select the event within the fiducial volume of the detector. The non-uniform electric field within the CDMSlite detector at higher radii may cause an incorrect

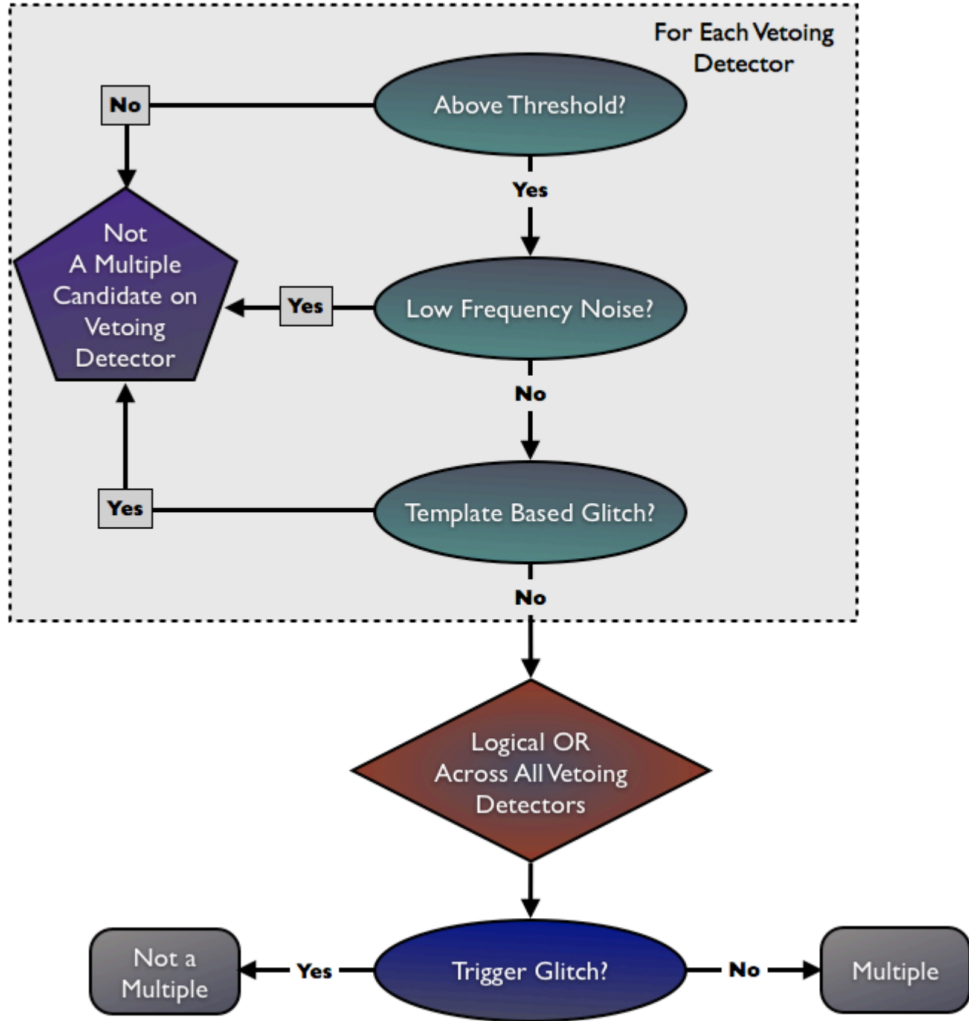


FIGURE 4.5: A flow chart explaining the working algorithm of the singles cut. The grey dashed block at the top shows the processes that are looped over each of the vetoing detectors. First of all, each event depositing energy above threshold in the CDMSlite detector is checked to determine if any detector has an above-threshold energy deposition. Then the pulses of those events are checked to see if they are noise or electronic glitches. An event will be tagged “multiple” only if it deposits energy larger than the threshold on any one of the veto detectors and passes the LF noise and glitch cut. These multiple events are then rejected by singles cut.

energy reconstruction, so to achieve accurate energy-deposition necessitates the removal of high-radius events [55]. The total recoil energy as defined in Equation 3.9 ($E_{r,ee} = E_T/(1 + eV_b/\epsilon(r))$) is dependent on bias voltage between the two faces of the detector. The drop in potential at the higher radius, as shown in Figure 4.6, decreases the NTL amplification on events occurring at a higher radius. Reduced NTL amplification results in an underestimate of the energy deposition. Ideally, one would correct the energy deposition estimate to account for regions of reduced NTL amplification. In practice, one attempts to remove events occurring in regions of the detector suffering from reduced amplification. The radial cut is defined to remove these events.

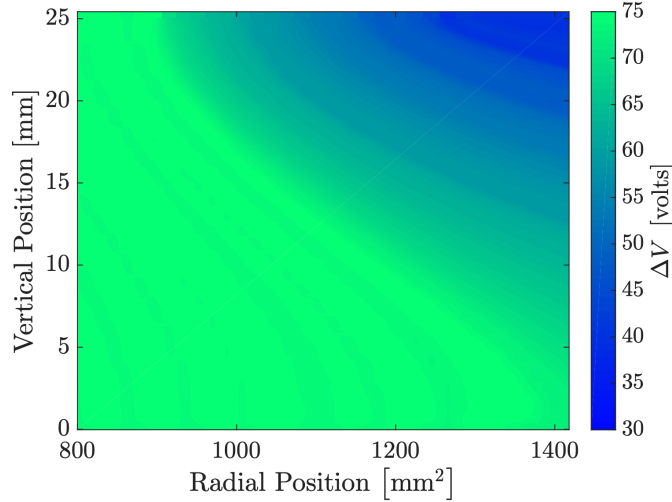


FIGURE 4.6: The potential difference calculated between a top face and a bottom face of the cylinder kept at a bias voltage of $\sim 70V$ (from Ref. [84]). The potential difference decreases at the higher radius of the detector, as shown by the blue gradient of the plot. Events occurring at higher radius experience incomplete NTL-amplification and their reconstructed energy is correspondingly underestimated.

The radial cut is instrumental in clearing up the low energy region ($100 - 2000 \text{ eV}_{ee}$), which is the range of energy depositions considered by this LIP search. The position information obtained from the 2T-fitting of a fast pulse is used to compute the radial parameter for all the recorded events. The cut removes an event with a larger radial parameter. This cut is developed by Wolfgang Rau and his team. It is described in detail in [74].

The procedure to calculate the radial parameter can be summarized in following steps:

1. The amplitude of the slow template is corrected using the correction factor as discussed in Section 3. The corrected amplitude for fast template (N_f^{corr}) is also calculated following the same procedure. [N = A, B, C or D channel]
2. Construct a corrected delay parameter ($\Delta_{N;2T}^{Corr}$) for each channel using the following equation:

$$\Delta_{N;2T}^{Corr} = \delta_{N;2T} - \delta_{total;2T} - \xi_{N;2T} \cdot N_f^{Corr} / E_{r,ee} \quad (4.2)$$

where $\delta_{N;2T}$ is 2T-delay for channel N , $\delta_{total;2T}$ is 2T-delay for phonon pulse, $\xi_{N;2T}$ is relative calibration factor for the slow-template and $E_{r,ee}$ is the total reconstructed energy of the event. The 2T-delay parameter uses the time for pulse to reach the peak.

3. The cartesian position parameters (X_{2T} and Y_{2T}) are computed using the following equation :

$$\begin{aligned} X_{2T} &= \cos(30^\circ)D_{N;2T}^{Corr} + \cos(150^\circ)B_{N;2T}^{Corr} + \cos(270^\circ)C_{N;2T}^{Corr} \\ Y_{2T} &= \sin(30^\circ)D_{N;2T}^{Corr} + \sin(150^\circ)B_{N;2T}^{Corr} + \sin(270^\circ)C_{N;2T}^{Corr} \end{aligned} \quad (4.3)$$

The center of Channel D is at 30° from the center of the detector. All the channels are rotated by 120° from each other as seen in Figure 3.2.

4. The preliminary radial parameter $R_{0;2T}$ is calculated using the corrected delay parameter as:

$$R_{0;2T} = \min(D_{N;2T}^{Corr}, B_{N;2T}^{Corr}, C_{N;2T}^{Corr}) - A_{N;2T}^{Corr} \quad (4.4)$$

5. The final radial parameter R_{2T} is calculated by angular correction of $R_{0;2T}$ using angle (ϕ_{2T}). ϕ_{2T} is calculated using X_{2T} and Y_{2T} .

Figure 4.7 shows the plot of the final radial parameter as a function of deposited energy. The blobs of events at the higher radius near the M-, and L-shell peaks are visible. An energy-independent threshold is chosen on radial parameter guided by the separation in the

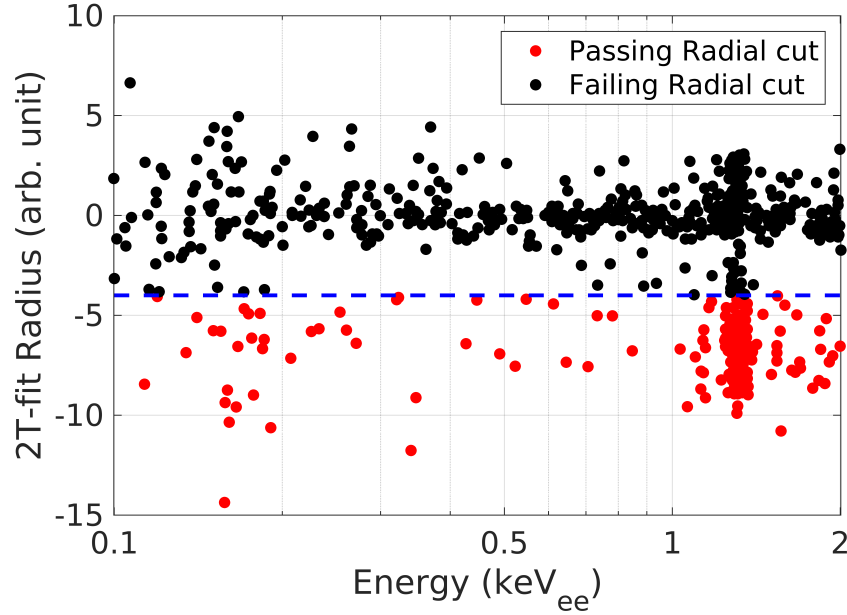


FIGURE 4.7: The distribution of 2T-fit based radius parameter as a function of deposited energy for the CDMSlite Run 2 Period 1 data. The blue line is the threshold chosen on the radial parameter. The radial cut rejects all events with a reconstructed high radius (above the blue line). The rejected events are shown in black and accepted events in red.

K-shell’s inner and outer peak [55]. The radial cut rejects all events above the threshold as high-radius events. The application of the cut removes reduced NTL events and some surface events due to background.

The radial cut has a considerable significance for LIP-search analysis as it removes the undesirable events with misreconstructed energy especially at the low energy region. Most of the LIPs considered in this analysis has the greatest sensitivity at low energy region. The M-shell peak at 160 eV becomes visible after application of this cut which also helped greatly with confidence in our energy calibration. However, an additional LIPs-specific inefficiency arises while using this cut. LIPs with larger f may interact multiple times within the CDMSlite detector. The event reconstruction algorithm is not optimized for events with multiple interaction points within a single detector. This may cause to reject some true LIPs events. A correction factor is calculated to incorporate this additional source of inefficiency. Section 4.7.4 describes the estimation of the radial cut efficiency for particles that singly-scatter

like WIMP and Section 4.8.2 describes the calculation of radial cut correction factor while using the cut for the LIPs.

4.7 CDMSlite Efficiency

The analysis efficiency for a cut is the probability of retaining a signal event after its application. This section provides an overview on the calculation of efficiencies for analysis cuts, defined in Section 4.5 and 4.6, for CDMSlite WIMP-search and LIP-search analyses.

4.7.1 *Singles Cut and Muon Veto Cut Efficiency*

Both the singles cut and the veto cut have an energy-independent analysis efficiency. The efficiency for singles cut is calculated using random events. Random events generally do not contain energy depositions, so events with reconstructed energy that is above the threshold for one detector are not generally expected to have above-threshold reconstructed energy in another detector. Therefore, one can use random events to estimate the fraction of the time that the energy reconstruction of a non-physics event in any other detector is above its singles cut threshold as an estimate of the singles cut efficiency. The singles cut's efficiency is the ratio of "random" events that do not deposit energy more than the singles cut threshold in more than one detector to the total number of the random events. The efficiency is independently calculated for every series. The fraction of random events with single detector interaction gives the efficiency for singles cut. The average efficiency throughout the data period is 98.27 ± 0.01 . The uncertainty is small due to the high statistics of randomly triggered events.

Similarly, the efficiency of the veto cut is estimated using the number of random events removed due to accidentally-coincident activity in the veto paddle. The average efficiency throughout the data-taking period is 98.77 ± 0.01 . The uncertainty is small due to the high statistics of randomly triggered events. The analysis efficiency for these cuts are shown in Figure 4.10 (a).

4.7.2 Trigger Efficiency

Events for which the analog, filtered, and summed phonon pulses exceed a specified threshold voltage prompt the DAQ to trigger event readout. There are some events with energy deposition near the trigger threshold for which the probability of triggering is between zero and one. The trigger efficiency is the probability of DAQ to trigger low energy depositions as a function of event energy.

The ^{252}Cf calibration data, as it has high quality and high statistics data, is typically used to calculate the trigger efficiency. The ^{133}Ba calibration data was not used for this calculation as these calibration data saw an unexpected rise in the trigger rate after the first 30 minutes of the calibration run [85]. Only “good” ^{252}Cf -calibration events (passing general quality cut and phonon pulse shape cut) that triggered the non-CDMSlite detector are considered for this analysis. The calibration data were read out from a group of selected detectors; only “good” events from the detector above and below the CDMSlite detector (T5Z1 and T5Z3) were available for the efficiency calculation. Events triggering T5Z1 or T5Z3 are taken as an unbiased sample of events that can be used to estimate the CDMSlite detector’s trigger efficiency. The fraction of those considered events that also triggered the CDMSlite detector is taken as trigger efficiency. The efficiency quickly rises from a low value to unity as shown in Figure 4.8. This LIP-search analysis uses 100 eV as the analysis threshold where the trigger efficiency is $\sim 100\%$.

4.7.3 Pulse-Shape Efficiency

There are three phonon pulse-shape-based analysis cuts used in this analysis. A fake set of data was generated by simulating individual phonon pulses, which are uniformly distributed throughout the energy region. A fake pulse is created by combining (1) a noise trace obtained from the random-triggered event, (2) a slow pulse template with user-defined amplitude, and (3) a fast pulse template with user-defined amplitude. A standard pulse template is created combining slow pulse with noise trace to simulate each phonon pulse. Along with a standard pulse template, two other pulse templates are generated by a linear combination of fast (T_{fast})

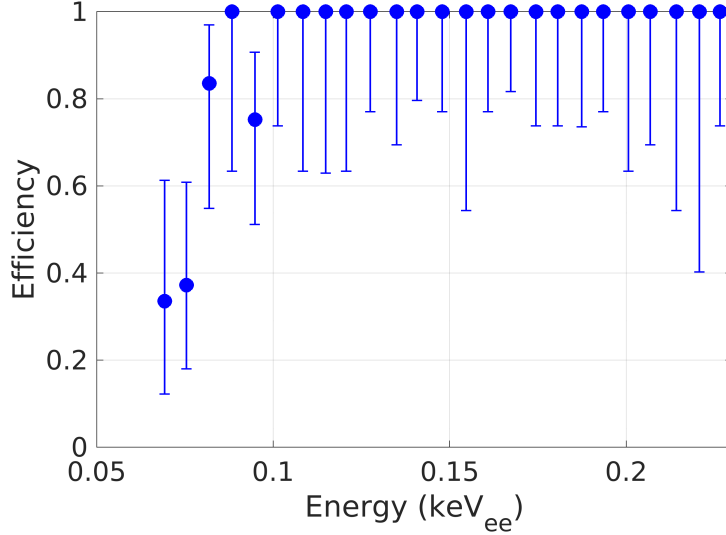


FIGURE 4.8: Binned trigger efficiency for Run 2 Period 1 data. This LIP-search analysis uses 100 eV as the analysis threshold where the trigger efficiency is $\sim 100\%$.

and slow pulse (T_{slow}) template. They are (1) peaky and (2) non-peaky templates.

$$T_{peaky/non-peaky} = T_{slow} \pm 0.125 \times T_{fast} \quad (4.5)$$

The fraction of the simulated pulses passing the cuts is used to determine the efficiency of these cuts. The efficiency for all three cuts is calculated individually. Figure 4.10 shows the combined analysis efficiency for all three cuts as a function of energy. More information on the efficiency calculation can be found in Ref. [74].

The pulse-shape cut efficiency calculation includes both statistical and systematic uncertainties. The statistical uncertainty for energy-bin is the fraction of a total number of fake events with a simulated pulse within an energy-bin that passes the cuts. The systematic uncertainty arises due to differences in three different pulse-shape templates that were used in the simulation of fake pulses. The maximum and minimum value (from all three) of efficiency obtained for each energy bin is used as an uncertainty. Both of these uncertainties are linearly combined to obtain the final pulse-shape efficiency. The mean uncertainty per bin for energy range of 100 eV_{ee} to 400 eV_{ee} is $\sim 1.2\%$. The uncertainty for the energy region

greater than 400eV_{ee} is negligible. The analysis efficiency along with uncertainties for the cuts are shown in Figure 4.10.

4.7.4 Radial Cut Efficiency

The efficiency of the radial cut is calculated using the fraction of events with correct energy construction that passes the radial cut. ^{71}Ge electron capture peaks are used as dark matter proxy for this calculation. These peaks have a known half-life of 11.43 days, which allows them to be identified in the energy spectra. Figure 4.9 shows the distribution of events from an activation peak in the radius vs. energy plane due to a non-uniform electric field. In the figure, R labels events from the activation with reduced NTL- amplification, P are events in an activation peak where P_i fraction passes the radial cut, and P_o fails the cut. P_i is the only fraction of events in the peak that passes the radial cut out of total $(R + P_i + P_o)$ expected events. So, the final radial cut efficiency can be written as :

$$\epsilon = \frac{P_i}{(P_i + P_o + R)} = \frac{P_i}{(P + R)} \cdot \frac{P}{P} = \frac{P}{R + P} \cdot \frac{P_i}{P}. \quad (4.6)$$

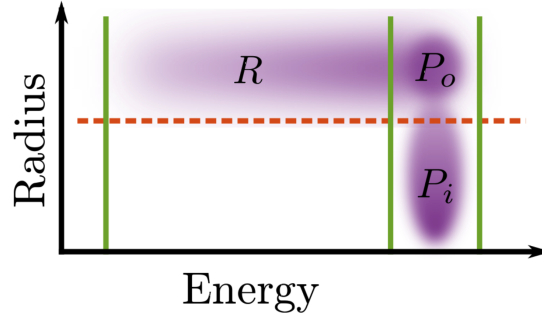


FIGURE 4.9: Distribution of events from the activation peak in radius vs energy plane due to non-uniform electric field at higher radius of detector.

The first term of efficiency is known as “energy efficiency”, representing the fraction of events lost due to reduced NTL-amplification. The second term is known as “peak efficiency,” representing fraction of events with correct energy reconstruction lost due to the radial cut.

The “energy efficiency” is energy independent and is calculated for the K- shell peak. The

efficiency calculated for K-shell was used for the entire energy window. The total number of events for the K-shell peak would be the number of events found at K-shell added with the number of events with reduced NTL amplification distributed in lower energy regions. The number of incorrectly constructed K-shell events was estimated using the constant half-life of the activation peak. All other events due to other dominant backgrounds are assumed to have a constant rate throughout the data period. The “energy efficiency” is calculated to be $86.4\% \pm 0.9\%$. More information of “energy efficiency” calculation can be found out at [55].

The “peak efficiency” is the probability of a correctly reconstructed event passing the radial cut. This is an energy-dependent efficiency, which means the efficiency should be calculated for the entire energy window. For a large energy range, the efficiency can be simply calculated by estimating the fraction of total events lost due to the radial cut. Mathematically,

$$\epsilon_{peak} = \frac{N_i}{N_i + N_o - N_b}, \quad (4.7)$$

where N_i is a number of events passing the cut, N_o is a number of events failing the cut, and N_b is a number of background events. This method needed modification for the lower energy region where most of the events are due to incomplete NTL-amplification. A pulse simulation, similar to one discussed in Section 4.7.3, is used to estimate the efficiency. Each data event has simulated pulses for all four channels. The pulse template, T_{2T} were constructed as

$$T_{2T} = (a_s T_{slow} + a_f T_{fast})/E_t, \quad (4.8)$$

where $a_s(a_f)$ are amplitude for slow(fast) templates and E_t is the total reconstructed energy for each event for the particular channel. The template is then scaled to the appropriate energy. The noise template obtained from the randomly triggered events is added with an event template to obtain a simulated pulse event. Those simulated pulse events are then processed to reconstruct their energy deposition and radial parameter. Now the “peak efficiency” for these simulated pulses would be a simple ratio of the number of the events passing the radial cut to the total number of events within that energy bin. Figure 4.10

shows the efficiency as the function of energy. The final radial cut efficiency is the product of “energy efficiency” and “peak efficiency.” The statistical uncertainty in the final efficiency is dominated by the statistical uncertainty in the peak efficiency.

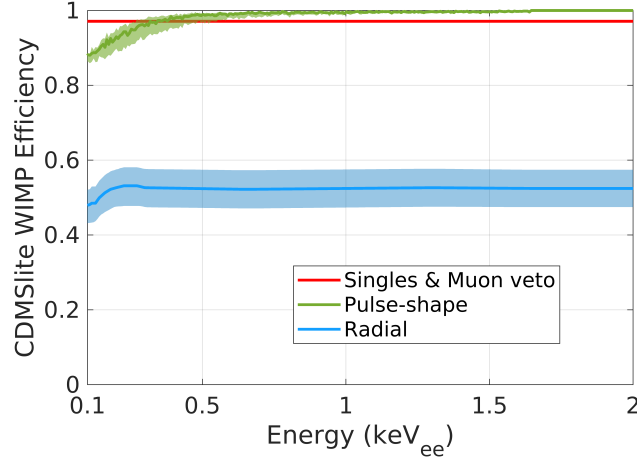
4.7.5 *Final CDMSlite Efficiency*

All the efficiency for the applied selection criteria is combined to obtain the CDMSlite WIMP-search analysis. The radial cut has the biggest impact with an efficiency of $\sim 50\%$. Figure 4.10 shows the final CDMSlite WIMP analysis efficiency for Run 2 Period 1. The LIP-search analysis also uses this efficiency along with correction factors for two of the selection criteria. Some jaggedness was observed in the efficiency curve, so it was smoothed before using it for this analysis¹. The uncertainty on the final efficiency is one of the primary sources of uncertainty in the LIPs sensitivity calculation. The product of the LIPs-specific correction factor (see Section 4.8) and this efficiency is the final analysis efficiency for the CDMSlite LIP-search.

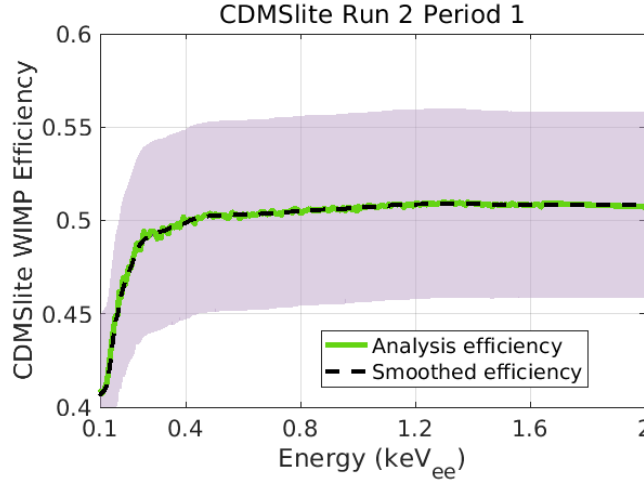
4.8 LIPs-Specific Efficiency

LIPs with smaller f have a small interaction cross-sections. This analysis is primarily focused on LIPs with smaller fractional charges. Like WIMP interactions, LIPs with small f rarely interact with a detector. Because of its electric charge, a LIP is expected to deposit energy through electromagnetic interactions with electrons in the detector. The fact that the CDMSlite detector cannot differentiate between an electron recoil and a nuclear recoil means all the physics cut defined for WIMPs can be used to search for LIPs with small f . For LIPs with small f , the analysis efficiency for retaining LIP events is expected to be the same as that for WIMP events with identical deposited ionization energy. However, LIPs with larger f have larger interaction cross-sections and interact more often with the medium through which they travel. LIPs with larger f might interact with multiple detectors or multiple times within the same detector. This means the probability of the singles cut or the radial cut rejecting

¹ The efficiency curve was smoothed by ‘smooth’ function using ‘movmedian’ method in Matlab.



(a)



(b)

FIGURE 4.10: (a) The calculated analysis efficiency for singles and muon vet (in red), pulse-shape cuts (green), and radial cut (in blue). The efficiency for the triggered threshold is not shown in the figure because its efficiency is 1 for the chosen analysis energy range. The shaded areas show the uncertainty in the efficiency. All these efficiencies are combined to obtain the CDMSlite WIMP-search analysis efficiency. (b) The final analysis efficiency (green) obtained for the WIMP-search after combining all the efficiencies shown in Figure (a). LIP-search will also use this efficiency as it uses all the selection criteria defined for WIMPs search. The efficiency has some jaggedness in the low energy region, so the efficiency was smoothed (black dashed) before using it in this LIP search analysis. The grey shaded area represents 1σ the uncertainty in the efficiency calculation. This uncertainty is one of the primary sources of uncertainty for LIPs intensity limit calculation.

a LIP event is higher for LIPs with larger f . This results in a LIP-specific inefficiency for these cuts when used for LIP-search. The Monte Carlo simulation, using GEANT4, is used for the calculation of efficiency correction factors that are independent of the deposited energy. The correction factors are the function of LIP's charge and $\beta\gamma$. This section describes this additional inefficiency and the correction factor calculated to incorporate this inefficiency.

4.8.1 *Singles Cut*

LIPs with larger f can interact with multiple detectors and deposit relatively larger energy in those detectors. The singles cut will reject a LIPs event if it deposits energy greater than the single's cut threshold in any veto detector (any detector other than the CDMSlite detector).

A GEANT4 based Monte Carlo simulation is performed to compute this addition LIPs-specific inefficiency for the singles cut. In GEANT4, detectors were arranged in 5 vertical stacks that mimic the Soudan detector deployment. LIPs with a variety of $\beta\gamma$ and f are simulated towards the detector configuration from a surface of a sphere sufficiently big enough to enclose those detectors. Singles cut correction factors for both angular distribution considered, isotropic and cosine squared, are calculated differently. Simulated LIPs, when interacting with a detector, deposit energy into the detector as they lose some of their kinetic energy. The LIPs-specific efficiency correction factor for the singles cut is the ratio of the number of simulated events registering more than threshold energy in the CDMSlite detector and at least one other veto detector to the total number of events interacting with the CDMSlite detector.

The calculation of LIPs-specific singles cut correction factor can be summarized in three steps:

1. Simulation, energy deposition and smearing for detector energy resolution
2. Selection of singles cut energy deposition threshold for veto detectors
3. Efficiency calculation

Simulation, Energy Deposition and Smearing for Detector Energy Resolution

Due to the low interaction cross-section of LIPs, a large number of LIPs ($> 10^8$) were simulated for each value of $\beta\gamma$ and f considered. Depending upon the choice of angular distribution, these LIPs generated various possible trajectories through detector configuration. These LIPs deposited energy in any detector with which they interacted. All the energy deposited in the detector needs to be smeared by the detector's resolution to resemble the reconstructed deposition in the detector. The energy deposited in the CDMSlite detector was smeared using the CDMSlite detector resolution function described in equation 4.10. The resolution (σ_T) for the simulated energy deposition (E_{sim}) is given by

$$\sigma_T = \sqrt{\sigma_E^2 + BE_{sim} + (AE_{sim})^2} \quad (4.9)$$

where values of σ_E^2 , B and A are defined in Section 4.10. The amount by which the simulated energy deposition is smeared is randomly chosen². Mathematically, the smeared energy deposition ($E_{smeared}$) is computed as:

$$E_{smeared} = E_{sim} \pm R\sigma_T \quad (4.10)$$

where R is a random number, following a Gaussian distribution with mean at 0.

Because most LIP interactions deposit little energy, as shown by Figure 3.1, the simulation predicts there to be more events just below the 100 eV analysis threshold than just above it. Smearing will push a greater number of just-below-threshold energy depositions above the 100 eV threshold than just-above-threshold energy depositions below 100 eV. It was computationally expensive to smear all events depositing energy in the CDMSlite detector as it was a very high statistic simulation. A study was done to identify the range of pre-smeared energy depositions that could, after smearing, fall within the analysis energy deposition window. The study considered 10^8 simulated events for a minimum ionizing LIP of $f = 10^{-3}$ were incident towards a detector identical to the CDMSlite detector. The study found that

² A Matlab function "normrnd" is used such that $E_{smeared} = normrnd(E_{sim}, \sigma_T)$

only $\sim 0.1\%$ of simulated events with an energy deposition less than 70 eV can fall inside the analysis window after smearing. Also, negligible events with simulated energy depositions energy greater than 2100 fall inside the analysis range. So, we smeared events with only energy deposition between 70 eV to 2100 eV. Table 4.2 and 4.3 show the result of this study.

Simulated energy deposition range (eV)	Number of simulated events	Number of simulated events within the analysis window after smearing
90-100	183216	62568 ($\sim 34\%$)
80-90	202352	21957 ($\sim 10\%$)
70-80	229054	4076 ($\sim 1.8\%$)
60-70	269801	352 ($\sim 0.1\%$)
2000-2100	1687	277 ($\sim 16\%$)
2100-2200	1534	3 ($\sim 0.2\%$)
2200-2300	1423	0 (—)

Table 4.2: Shows the probable number of events that can get within analysis energy range (100 eV – 2000 eV) after smearing the energy deposition with resolution of the detector.

Simulated energy deposition range (eV)	Number of simulated events	Number of simulated events outside the analysis window after smearing
100-110	159851	54349 ($\sim 34\%$)
110-120	141265	14016 ($\sim 10\%$)
1800-1900	1921	47 ($\sim 0.03\%$)
1900-2000	1790	284 ($\sim 16\%$)

Table 4.3: Shows the probable number of events that can get out of analysis energy range (100 eV – 2000 eV) after smearing the energy deposition with resolution of the detector.

All simulated events with an energy deposition within the analysis energy range in the CDMSlite detector (after smearing) are only considered for further analysis (from here on these events are called “simulated CDSMLite events”). All the non-zero energy deposition in other detectors were smeared with their energy resolution. The resolution (σ) for other iZIP detectors is given by

$$\sigma = \sqrt{A + BE_{sim} + CE_{sim}^2}, \quad (4.11)$$

where σ is resolution and parameters A, B and C are defined in Table 4.4. This calculation of resolution is discussed in Daniel Jardin's thesis [86]. Events are multiple-detector hit events only if they deposit energy greater than the single's cut energy threshold in any other detector along with the CDMSlite detector. The following section discusses how the energy thresholds for the singles cut are chosen for each detector.

Det	A [keV _t ²]	$\pm 1\sigma$	B [keV _t]	$\pm 1\sigma$	C	$\pm 1\sigma$
1	0.155393	0.0691325	9.60343e-11	0.00885466	0.000506287	3.0612e-05
2	0.082099	0.000138586	0.0108455	0.00183727	0	2.22402e-06
3	0.0846805	0.000118728	4.71845e-10	0.0108038	0.000702979	3.1949e-05
4	0.0328312	5.00053e-05	0.0100053	0.000280728	0.000244885	6.96688e-06
5	0.0411937	6.97124e-05	0.000549462	0.0010887	0.000361038	2.63019e-05
6	0.10674	0.000583262	0.144297	0.0521945	-4.49364e-05	7.14893e-05
7	0.327138	0.000644738	-0.0137804	0.00904437	0.000520678	3.12901e-05
8	0.0195073	6143.36	0.00802392	6145.57	0.000549911	6148.36
9	0.13223	0.206687	5.55112e-12	0.0310852	0.000572963	4.26256e-05
10	0.102399	0.000197759	0	0.00170764	0.000415507	8.16471e-05
11	0.0788837	0.000225082	0.0141565	0.00469563	0.000321161	1.91979e-05
12	0.0480589	9.00865e-05	0.00535584	0.00251146	0.000389617	5.05697e-05
13	0.492861	0.000972852	0.0238974	0.0313525	0.000810142	0.000199669
14	0.0343254	7.40223e-05	0.0141611	0.00260691	0.000314387	2.2043e-05
15	0.046846	8.63333e-05	0.0191361	0.00429152	2.90118e-05	4.67514e-05

Table 4.4: Parameters for phonon resolution, with 1σ uncertainties, of all the iZIP detectors. The detector number 14 is the CDMSlite detector and the numbers shown here in the table are when the detector was run as a iZIP detector. The resolution of all other detectors are calculated using the parameters in the table.

Selection of Singles Cut Energy Deposition Threshold for Veto Detectors

The singles cut thresholds for all the detectors are time-variant; detector energy thresholds change with each time block as discussed in Section 4.6.2. A simple algorithm is devised to include all these thresholds from all these time blocks. The total number of time blocks and live time for each time block for each detector might differ, but the total live time of all the

time blocks is equal to the total live time for the CDMSlite detector. A set of thresholds for each event is picked based on the probability of each time block's threshold being chosen weighted by its live time.

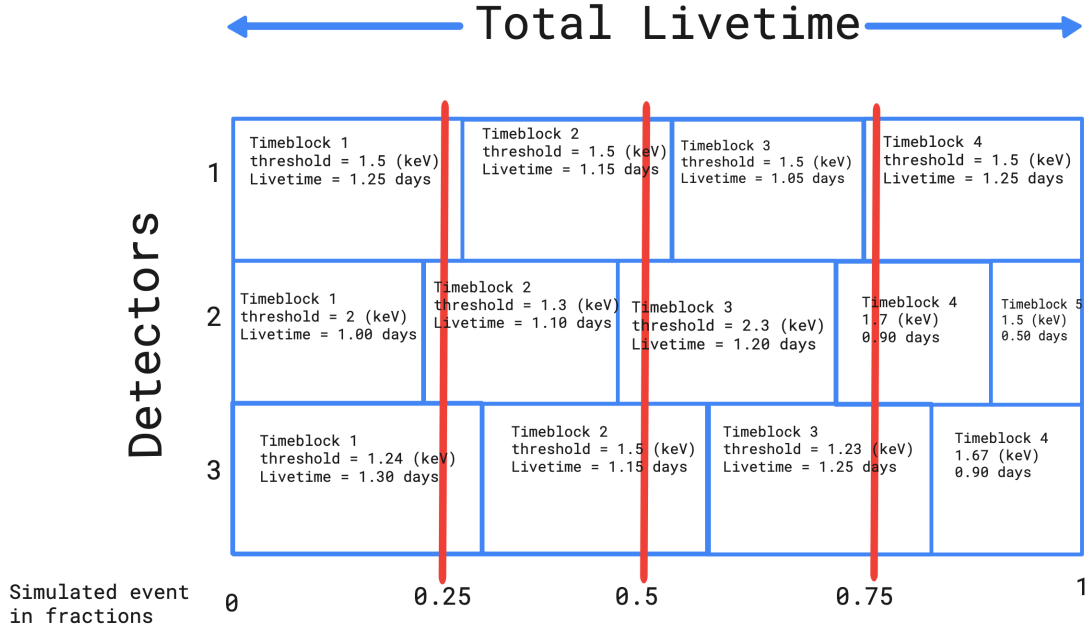


FIGURE 4.11: Cartoon illustrating the selection of the singles-cut threshold for each simulated event. The total live time for the CDMSlite detector is divided into time-block (a group of series where the particular detector is behaving similarly). Each detector had different sets of time blocks, with each time block having different singles cut threshold. The thresholds for each detector are calculated for each event by weighting their live time. The cartoon only shows three detectors as representation, but the analysis uses all fifteen detectors. The cartoon shows that if 100 events are simulated, then the first event will use a singles cut threshold from time block 1 for all three shown detectors. The 25th event, which will have live time equivalent to $1/4^{th}$ of total live time, will use threshold from time block 1 for detector 1, time block 2 for the second detector, and time block 1 for the third detector. Similarly, thresholds are picked from all the time blocks for other simulated events.

Figure 4.11 shows a cartoon that illustrates the selection of the thresholds for each simulated event. For simplification, let us suppose there are N numbers of simulated events and the total live time of the CDMSlite detector is L . The live time is then uniformly divided into N bins. The cumulative sum of all the time blocks for these detectors should be equal to L .

The time block where each of those live time bins falls for each detector is determined. The singles cut threshold for that time block will be the threshold for that live time bin. The first simulated event will have a threshold from the first live time bin (L/N), the second event will have a threshold for the second bin $(2)L/N$, and so on. For the $N/4^{th}$ event, the figure shows that the $L/4$ live time falls on time block 1 for detector 1, time block 2 for detector 2, and time block 1 for detector 3. The energy threshold for the corresponding time blocks is selected as the singles cut energy threshold for each detector for that particular event. So, as the number of events progresses, the live time also progresses, and the thresholds change accordingly. After knowing the threshold, the energy deposition of simulated CDMSlite events in veto detectors is compared with these thresholds to count multiple events. Those simulated CDMSlite events that have energy deposited more than the threshold on at least one veto detector are deemed to be multiple-detector events.

Efficiency Calculation

The LIP-specific efficiency correction factor for the singles cut is calculated as the fraction of simulated single detector-hit events (non-multiple events) to all simulated CDMSlite events. Mathematically, the single detector-hit cut correction factor ($\epsilon_{\text{sdh}}(f, \beta\gamma)$) is

$$\epsilon_{\text{sdh}}(f, \beta\gamma) = 1 - \frac{N_{\text{md}}(f, \beta\gamma)}{N_{\text{CDMSlite}}(f, \beta\gamma)}, \quad (4.12)$$

where $N_{\text{CDMSlite}}(f, \beta\gamma)$ is the number of simulated LIP events depositing energy in the CDMSlite detector within the analyzed energy window (0.1–2 keV), and $N_{\text{md}}(f, \beta\gamma)$ is the number of LIP events that also deposit energy in at least one other detector above its threshold.

Figure 4.12 (a) shows the efficiency correction of the singles cut as a function of LIPs charge for a variety of $\beta\gamma$ values assuming an isotropic angular distribution. All the calculations shown in Figure 4.12 assumes LIPs of mass 100 MeV. The correction factor has the greatest impact on LIP detection efficiency for LIPs with $f = 1/100$ and quickly asymptotes

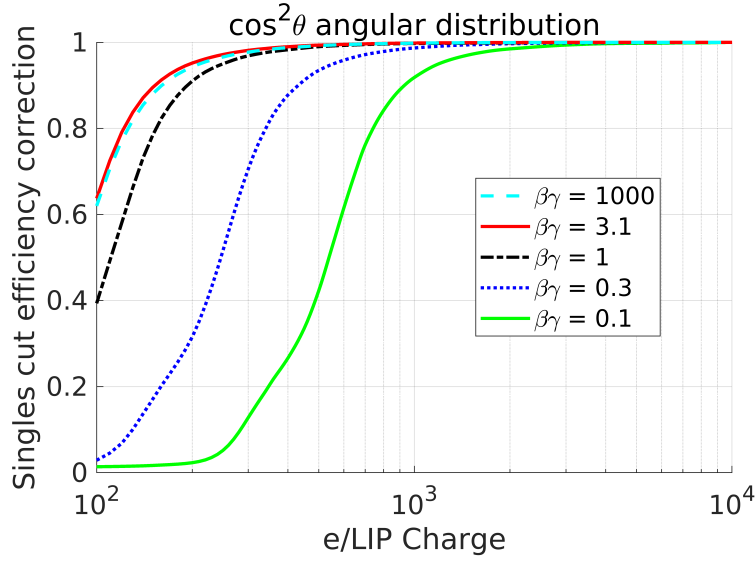
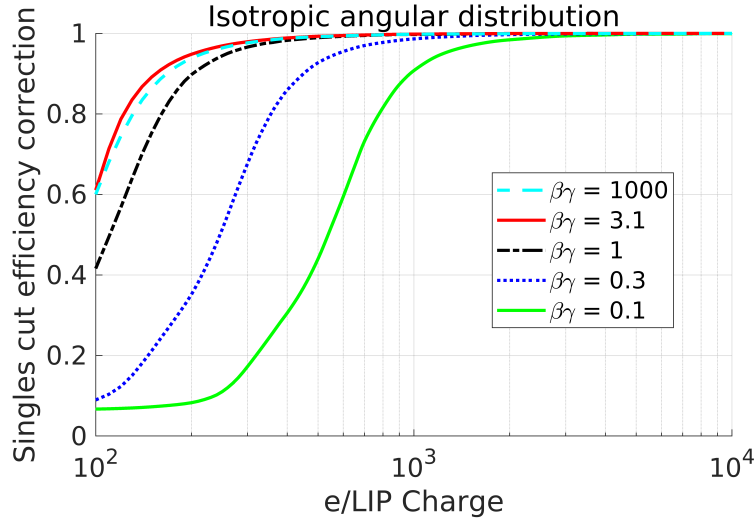


FIGURE 4.12: (a) Efficiency correction of the singles cut for the LIPs analysis assuming an isotropic angular distribution for a variety of $\beta\gamma$. The efficiency is lowest for $e/100$, where energy depositions are the largest, which increases the probability of a LIP to deposit detectable energy in at least one other detector. The efficiency rapidly rises as the LIP charge decreases for all $\beta\gamma$. High statistical simulation results in statistical uncertainties smaller than the width of curves. (b) This figure is identical to Figure (a) except it is for the $\cos^2\theta$ angular distribution.

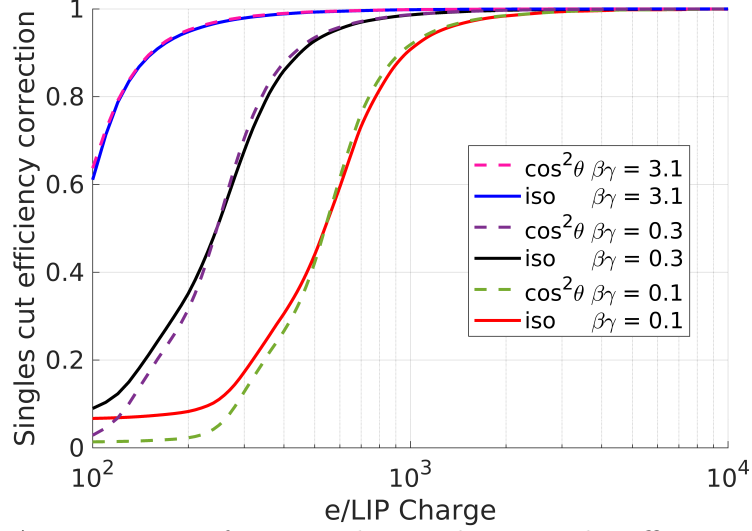


FIGURE 4.13: A comparison of LIP singles cut between the efficiency correction factors for a variety of $\beta\gamma$ values assuming isotropic and $\cos^2\theta$ angular distributions. The correction factors are generally equal for most of the considered LIPs except for the most highly ionizing LIPs considered (smaller $\beta\gamma$ with larger f), which has a smaller correction factor for the $\cos^2\theta$ angular distribution.

towards unity for smaller f . The behavior of the correction factor is expected because LIPs with larger f have a larger interaction cross-section, which means the probability of them depositing detectable energy in more than one detector is higher. For LIPs with smaller f , the correction factor increases towards one as the probability of LIPs depositing detectable energy decreases. Similarly, Figure 4.15 (b) shows the efficiency correction for $\cos^2\theta$ distribution, which has similar features.

The singles-cut correction factors for most of the considered LIPs are generally equivalent for the isotropic and $\cos^2\theta$ angular distribution. However, LIPs with smaller $\beta\gamma$ and larger f have smaller correction factors for the $\cos^2\theta$ distribution than the isotropic angular distribution. A typical LIP's trajectory, for the $\cos^2\theta$ distribution while passing through the CDMSlite detector usually takes it through the top and bottom detectors in its stack. The most ionizing LIPs considered herein have a larger probability of depositing detectable energy in those detectors, increasing the probability of rejection of these LIPs by the singles cut.

The uncertainty in the curve describing the correction factor as a function of f (for

an assumed value of $\beta\gamma$) is calculated assuming the binomial distribution. The Clopper-Person [80] method is used to calculate the 1-sigma confidence intervals³. The uncertainties are smaller than the width of the curves in both Figures 4.12 and 4.15.

4.8.2 Radial Cut

The radial cut rejects all events with a reconstructed position at a higher radius. These events are generally background events from incomplete NTL-amplification and side surface events. The position reconstruction is performed for each event based on the amplitude of deposited energy in each inner channel compared to the outer channel. The algorithm is based on the assumption of one interaction site within the detector.

LIPs with larger fractional charges can interact multiple times within the same detector. The interaction locations might be both within the fiducial volume or at a higher radius. The position reconstruction algorithm is not optimized for these multiple-site interaction events, and it will not be able to locate sites of these multiple interactions. We conservatively assume that all events with multiple interaction sites within a single detector are rejected by the radial cut.

The fraction of events that interact multiple times within the same detector is taken as the radial cut correction factor. A GEANT4 based Monte Carlo simulation is performed to compute this correction factor. LIPs were simulated towards one detector resembling a the CDMSlite detector with both isotropic and $\cos^2\theta$ distribution. The radial cut's efficiency correction factor ($\epsilon_{\text{fv}}(f, \beta\gamma)$) as a function of f and $\beta\gamma$ is given by

$$\epsilon_{\text{fv}}(f, \beta\gamma) = 1 - \frac{N_m(f, \beta\gamma)}{N_{\text{total}}(f, \beta\gamma)}, \quad (4.13)$$

where $N_{\text{total}}(f, \beta\gamma)$ is the number of simulated LIP events depositing energy in the CDMSlite detector, and $N_m(f, \beta\gamma)$ is the number of these interacting at more than one location in the same detector.

³ A Matlab function “binofit” is used such that $[mean\ uncertainty] = \text{binofit}(success, total\ trails)$.

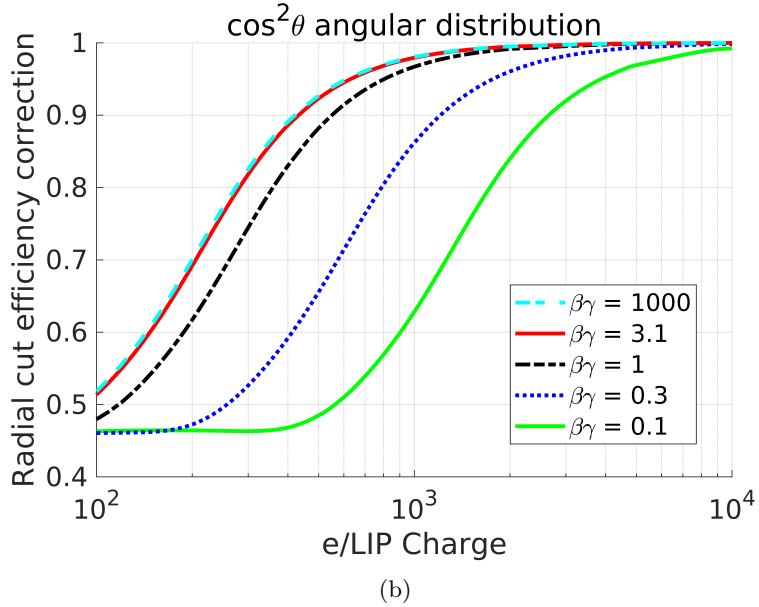
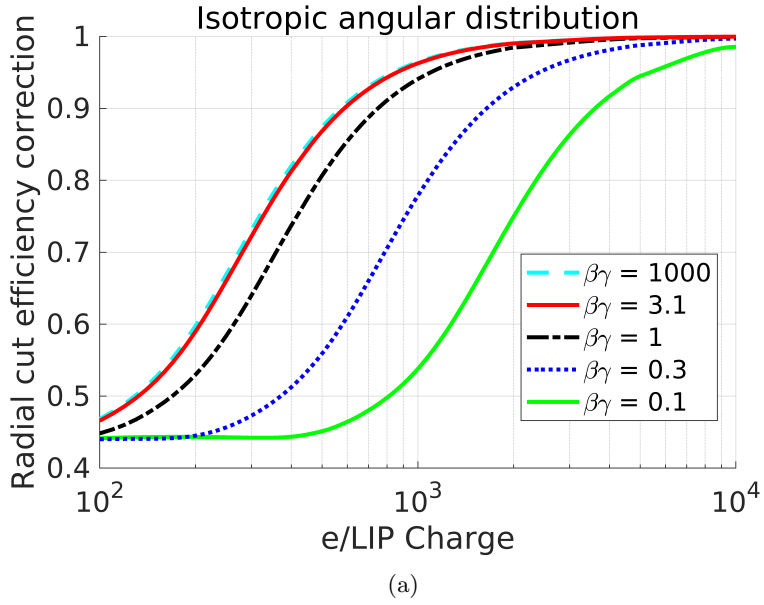


FIGURE 4.14: (a) Efficiency correction of the radial cut for LIPs analysis assuming an isotropic angular distribution for a variety of $\beta\gamma$. The efficiency is lowest for $e/100$ where energy depositions are largest increasing the probability of a LIP depositing detectable energy in at least one other detector. The efficiency rapidly rises as the LIP charge decreases for all $\beta\gamma$. High statistical simulation results in statistical uncertainties smaller than the thickness of curves. (b) The same LIP-specific efficiency correction but under the assumption of a $\cos^2\theta$ angular distribution.

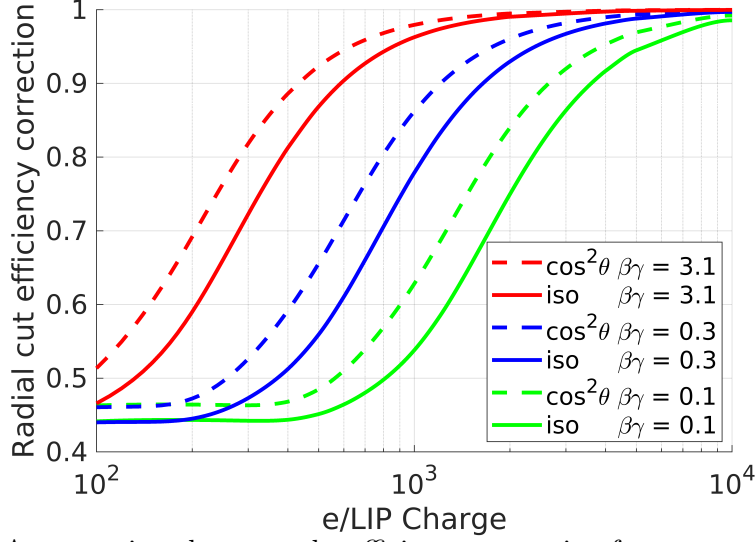


FIGURE 4.15: A comparison between the efficiency correction factor assuming isotropic and $\cos^2\theta$ angular distribution for a variety of $\beta\gamma$ values. The correction factors are smaller for isotropic angular distribution than for $\cos^2\theta$ angular distribution.

Figure 4.14 (a) shows the radial cut's efficiency correction as a function of LIPs charge for a variety of $\beta\gamma$ values assuming an isotropic angular distribution. All the efficiency curves shown in the figure assume LIPs of mass 100 MeV. The correction factor has the greatest impact on LIP detection efficiency for LIPs with $f = 1/100$ and quickly asymptotes towards unity for smaller f . The LIPs with larger f have a larger interaction cross-section, resulting in a higher probability of multiple interactions within the CDMSlite detector. For LIPs with smaller f , the correction factor increases towards one as the probability of a LIP interaction decreases. Similarly, Figure 4.14 (b) shows the efficiency correction for $\cos^2\theta$ distribution, which has similar features.

The efficiency correction factor for the radial cut under the assumption of an isotropic angular distribution is smaller than that under an assumed $\cos^2\theta$ angular distribution. This is because the typical LIP path length in a detector is larger under the assumption of an isotropic distribution; the cosine squared distribution has a reduced likelihood for the near-horizontal trajectories that typically have the longest path lengths in a detector. The probability of interaction increases with increased distance traveled through the detector, thereby increasing

the possibility for the radial cut to reject the event because of the multiple LIP interaction points, which means a smaller correction factor (greatest impact) for isotropic distribution.

The uncertainty in the curves is calculated assuming a binomial distribution using the same procedure used for singles cut. The uncertainties are smaller than the width of the curves in both figures 4.12 and 4.15.

4.8.3 Combined Singles and Radial Efficiency

The additional efficiency due to singles cut and radial cut are combined to obtain the total LIPs-specific efficiency for this analysis. The final LIPs- specific correction factor ϵ_{corr} is product of efficiency correction factors on singles cut and radial cut,

$$\epsilon_{\text{corr}} = \epsilon_{\text{sdh}}(f, \beta\gamma) \times \epsilon_{\text{fv}}(f, \beta\gamma). \quad (4.14)$$

The final LIPs-specific correction factor might be affected if there is some correlation between efficiency correction factor for singles cut and radial cut. So, a cross-check is performed to calculate the impact of the possible correlation between these factors using Geant4 simulation. Minimum ionizing LIPs with various fractional charges were simulated towards the detector configuration mimicking Soudan underground lab detector deployment. The singles cut efficiency was calculated under three different conditions: 1. Using events with energy deposition with CDMSlite energy range (as calculated in Section 4.8.1), 2. Using events with energy deposition with CDMSlite energy and passing radial cut, and 3. Using events with energy deposition with CDMSlite energy and failing radial cut. The difference in correction factor calculated using events that pass (condition 2) or fail radial cut (condition 3) is found to be less than 5% when compared to individually calculated correction factor (condition 1) as shown in Figure 4.16. The difference is much smaller than the uncertainty in the analysis efficiency obtained from the CDMSlite WIMP search. So, the impact of the possible correlation on the combined correction factor is not included in the sensitivity calculation.

Figure 4.17 shows the final efficiency correction as a function of a LIP charge for a variety of $\beta\gamma$ values under both angular distribution assumptions. Generally in comparison with

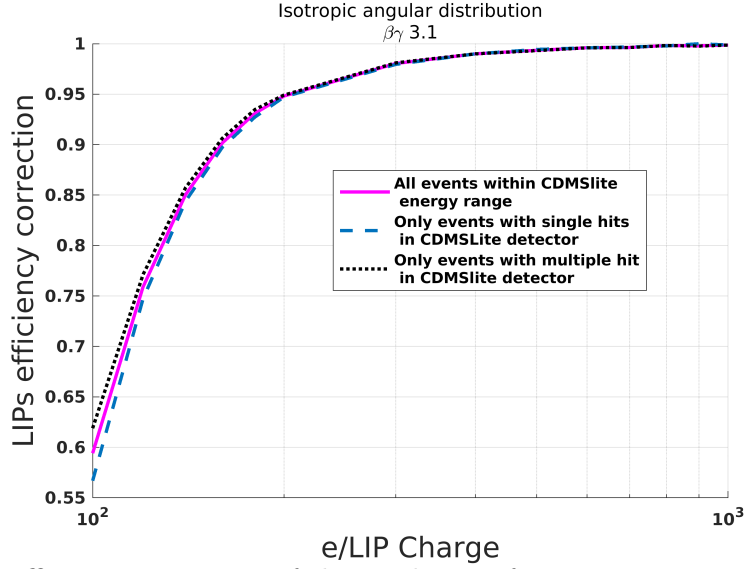


FIGURE 4.16: Efficiency correction of the singles cut for minimum ionizing LIPs assuming an isotropic angular distribution for a variety of f in magenta. The figure also shows the efficiency correction factor calculated for singles with only those event passing radial cut in dashed-blue and the efficiency correction factor calculated for singles with only those event failing radial cut in dotted-black. Both correction factor curves calculated using events passing or failing radial cut differ by less than 5% from the magenta curve calculated using all events.

$\cos^2\theta$ angular distribution, the isotropic angular distribution has a smaller correction factor, more significant one, due to a smaller correction factor for the radial cut. The correction factor for highly ionizing LIPs considered (small $\beta\gamma$ and larger f) is smaller under the $\cos^2\theta$ angular dependence due to dominance of correction factor from single's cut in that region. The uncertainty for all the curves is smaller than the curve's width due to high statistics simulation while calculating both the radial and singles cut correction factor.

The final efficiency correction factor is smaller under the assumption of an isotropic angular distribution for most of the considered values of f and $\beta\gamma$, as shown in Figure 4.18. The observed difference in these LIPs is from the difference observed in the radial cut's correction factor. But for some LIPs with smaller $\beta\gamma$ and larger f , the correction factor is smaller for $\cos^2\theta$ angular distribution. The singles cut correction factors are lower for these LIPs because of their larger interaction cross-section.

The final analysis efficiency is the product of LIPs-specific energy-independent efficiency

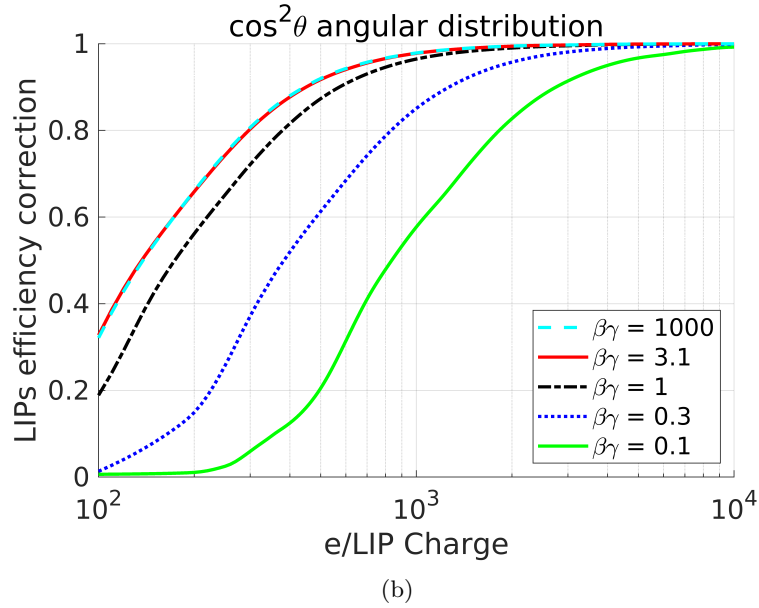
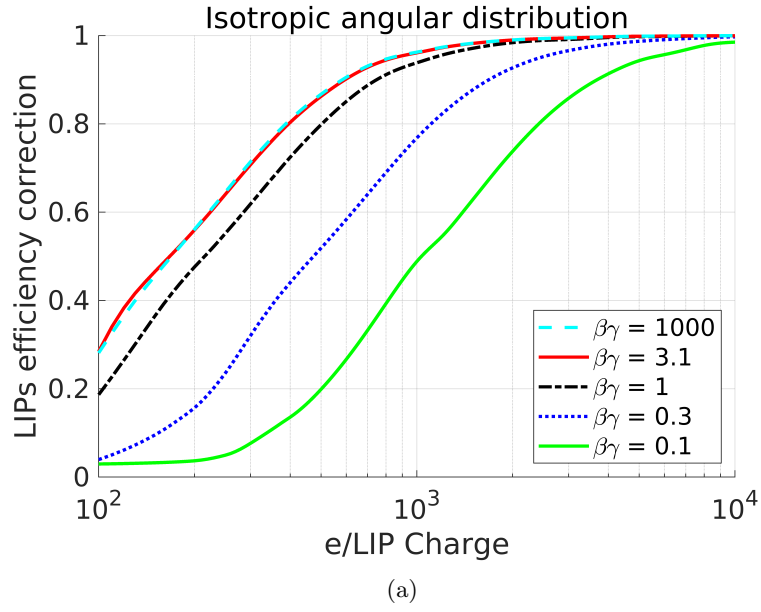


FIGURE 4.17: (a) The combined additional efficiency correction for LIPs which includes both singles cut and radial cut assuming isotropic angular distribution for a variety of $\beta\gamma$. This plot is simply the product of Figure 4.12 (a) and Figure 4.14 (a). (b) The combined efficiency for $\cos^2\theta$ angular distribution. This plot is simply the product of Figure 4.12 (b) and Figure 4.14 (b).

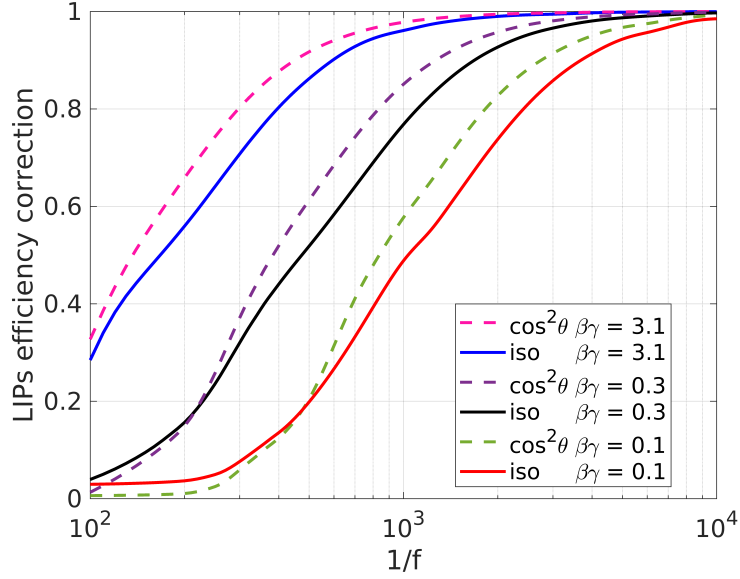


FIGURE 4.18: The comparison between the final LIPs-specific efficiency correction factor for a variety of $\beta\gamma$ values assuming isotropic and $\cos^2\theta$ angular distribution. The correction factor is generally smaller for isotropic angular distribution than for $\cos^2\theta$ angular distribution. However, for some LIPs with larger ionization cross-section, the efficiency is smaller for $\cos^2\theta$ angular distribution.

correction factor and the energy-dependent analysis efficiency calculated for the CDMSlite WIMP-search as shown in Figure 4.10.

Expected Sensitivity

The CDMSlite LIP-search analysis was performed in an “effective blind” fashion. The analyzers did not look at the data on which this analysis is based until the limit-setting framework was developed and all selection criteria, efficiencies, and expected sensitivities were calculated. The energy-deposition spectra obtained from the simulation of the CDMSlite Run 2 background model [79] is used to train the analysis and make sensitivity projections.

This chapter provides an overview of the CDMSlite background model and describes the calculation procedure to obtain the expected sensitivity.

5.1 Background Model

A background model was developed by the CDMSlite WIMP-search group for the CDMSlite Run 2 data spectrum. A maximum likelihood fit, including various cosmogenic isotopes and Compton sources, was applied to the Run 2 data spectrum to obtain the background model. The detailed discussion on the background model can be found in Ref. [79] and D. Barker’s thesis [84].

The components of the background model are mostly cosmogenic isotopes with a half-life ranging from ~ 100 days to about 15 years. These isotopes were produced in detectors due to cosmic activity before they were taken underground. The half-life of these isotopes is long

enough that they do not decay before the data taking period. It is also short enough to be considered as a significant source of background. These cosmogenic isotopes considered herein with medium half-life are: ^{68}Ge , ^{65}Zn , ^{55}Fe , ^{57}Co , ^{54}Mn and ^{49}V . ^{71}Ge (with a half-life of ~ 11.4 days) and ^{68}Ga (with a half-life of ~ 68 minutes) are also included in the background model. ^{71}Ge is produced during in-situ ^{252}Cf neutron calibration, while ^{68}Ga with a very short half-life is produced by the decay of ^{68}Ge . All these isotopes decay via electron capture giving discrete lines in the energy spectrum below $\sim 10 \text{ keV}_{ee}$.

Along with these isotopes, the background model also includes tritium (^3H) produced by cosmogenic sources. ^3H is modeled to undergo non-relativistic β -decay with a Q-value $\ll m_e c^2$, where m_e is mass of electron. The sources corresponding to the high energy γ that undergoes Compton scattering are also considered in this modeling. These high-energy γ are usually produced from radio-contaminants, including ^{238}U , ^{232}Th , ^{40}K , etc., in the experimental setup. The Compton background spectra were created using a GEANT4 based Monash model [87]. The Monash model accounts for the energy and direction of both scattered photon and ejected Compton electron. This model address the limitation of Compton electron directionality algorithms of other prior Compton scattering models.

Table 5.1 shows the total expected number of background events contributed for each background component included in the likelihood fit for a live time equivalent to that of the CDMSlite Run 2 Period 1. The model is created using the CDMSlite Run 2 data (combined Period 1 and Period 2) for an energy deposition below 20 keV_{ee} . The expected distribution for Run 2 Period 1 is calculated by weighting the total live time of the periods (Period 1 has 82% live time of the total Run 2). The table also has the uncertainty bounds on the number of events for these fitted background events. Figure 5.1 shows the maximum likelihood fit for each of the components. The background spectrum within the analysis energy range ($0.1 \text{ keV}_{ee} - 2 \text{ keV}_{ee}$) primarily consists of M and K-shell peaks due to an electron capture decay and a flat background due to tritium and Compton scattering.

Components	Best-fit # events	Uncertainty Range (68% C.L)	
		LL	UL
^{68}Ga	5.9	3.20	10.33
^{65}Zn	17.63	13.612	23.2
^{55}Fe	9.43	6.3	14.5
^3H	221.4	200	241
Compton (< 20 keV_{ee})	107.42	92.66	125.46
^{68}Co	1.64	-0.3	6.7
^{68}Mn	0.32	-1.7	4.9
^{68}V	1.8	0.2	6.5
$^{68}\text{Ge} + ^{71}\text{Ge}$ (Expected)	1584	1567	1598
$^{68}\text{Ge} + ^{71}\text{Ge}$ (Corrected after unblinding)	1352	1338	1364

Table 5.1: The number of events for each background component obtained after the maximum likelihood fit performed on the CDMSlite Run 2 data spectrum. The lower limit (LL) and upper limit (UL) are given with a confidence level (C.L) of 68%. There is no evidence for presence of ^{68}Co and ^{68}Mn which is clear from the negative lower bounds on their confidence intervals. The expected distribution of resulted in an over-prediction of activation peaks. This primary cause of this over prediction was due to the smaller amount of exposure of the detector to the ^{252}Cf source in Period 1 than Period 2 (see Section 6.3 for more detail). The expected rate is later corrected by weighting the live time within half-life of Cf calibration for both period.

5.2 Expected Sensitivity and Uncertainty

The LIPs expected sensitivity for various $\beta\gamma$ and f is computed using the simulated energy-deposition distribution obtained from the simulation of the CDMSlite Run 2 background model. For a reminder, the vertical intensity limit $I_v^{90}(f, \beta\gamma)$ for a LIPs (as described in Section 2.2 is

$$I_v^{90}(f, \beta\gamma) = \frac{N^{90}(f, \beta\gamma)}{\tau \int_{0.1 \text{ keV}}^{2 \text{ keV}} \underbrace{\epsilon(f, \beta\gamma, E) \frac{dP}{dE}(f, \beta\gamma) dE}_{\text{detection efficiency}} \int \underbrace{A(\theta) d\Omega}_{\text{geometric factor}}}. \quad (5.1)$$

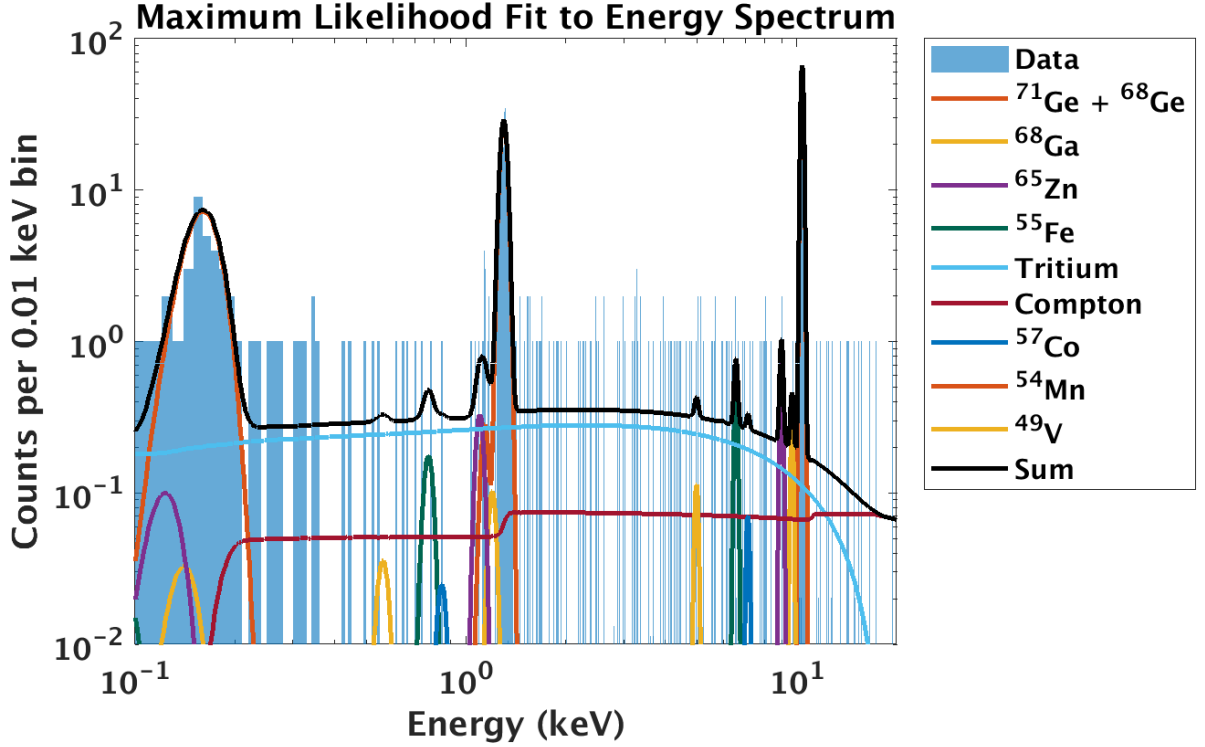


FIGURE 5.1: Maximum likelihood fitting to the CDMSlite Run 2 data spectrum with cosmogenic backgrounds and Compton Backgrounds.

where $N^{90}(f, \beta\gamma)$ is the 90% confidence upper limit on the expected number of observed LIPs, τ is the live time of the detector, $\frac{dP}{dE}(f, \beta\gamma)$ is the LIP energy-deposition distribution at LIP incident angle θ and $\epsilon(f, \beta\gamma, E)$ is the LIP-selection efficiency. The effective cross-sectional area of the detector surface at θ is $A(\theta) = \pi r^2 \cos \theta + 2rh \sin \theta$, where r and h are the detector radius and height, respectively. Three major elements for the calculation of expected sensitivity, as seen in Equation 5.5, are the LIP-selection efficiency, $\frac{dP}{dE}(f, \beta\gamma)$ and $N^{90}(f, \beta\gamma)$. The LIP-selection efficiency is product of the CDMSlite WIMP-search efficiency shown in Figure 4.10 and final LIPs-specific correction factor shown in Figure 4.17. $\frac{dP}{dE}(f, \beta\gamma)$ for different LIPs f and $\beta\gamma$ are described in Chapter 2. $N^{90}(f, \beta\gamma)$ is calculated using OI method (described in Section 2.3) on the simulated background distribution.

For each expected sensitivity calculation, 200 different sets of simulated energy-deposition distribution were generated. Each simulated distribution has a random number of events reflecting the expected range of the CDMSlite Run 2 Period 1 event energy distribution; Period 1 has 86.4% of total Run 2 exposure. The total number of events in each simulated background set was statistically varied. The uncertainty on the expected sensitivity is primarily due to uncertainty on the analysis efficiency, the energy thresholds of analysis and the signal model.

This section describes the simulated energy-deposition distribution, sources of uncertainties on expected sensitivity and then describes the resulting expected LIP sensitivity.

5.2.1 Simulated Energy-Deposition Distribution

The sets of energy-deposition distribution are generated from a random simulation of the CDMSlite background model. For each distribution, a normalized probability distribution function (PDF), within the analysis window of 100 eV_{ee} to 2 keV_{ee}, is generated where the contributions from each of the component are randomly chosen within its uncertainties (shown in Table 5.1). The resulting PDF is converted to the cumulative distribution function (CDF), which is then used to simulated the expected data spectrum. A sample background distribution is generated from simulation of CDF using total expected number of events in the data spectrum¹. The expected total number of events for Run 2 Period 1 is calculated based on the weight of livetime for each run; it has 86.4% of total Run 2 exposure. Figure 5.2 shows a PDF and a CDF generated from the background model for simulation of an expected energy-deposition distribution.

The total number of events for each spectrum was statistically varied within 1σ of expected total events, after applying all selection criteria, in the CDMSlite Run 2 Period 1. Figure 5.3 (a) shows a typical energy-deposition distribution and Figure 5.3 (b) shows the distribu-

¹ MATLAB function used:

$$\begin{aligned} randomCDFValues &= normalizedCDF(1) + (normalizedCDF(end) - normalizedCDF(1)) * rand(1, expectedNumbers); \\ simulatedBackgroundDistribution &= interp1(normalizedCDF, energyBins, randomCDFValues); \end{aligned} \quad (5.2)$$

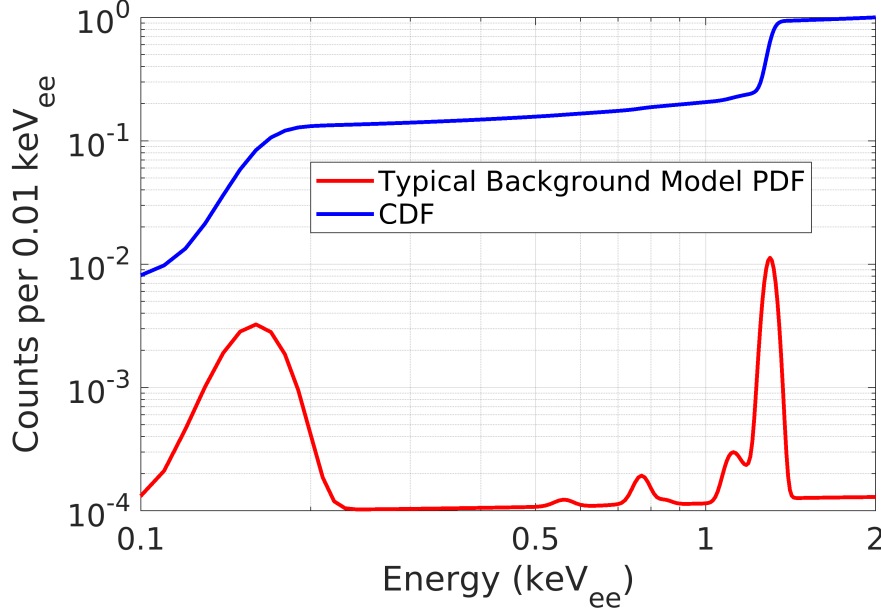


FIGURE 5.2: A PDF (in red) and CDF (in blue) generated from the CDMSlite background model. A PDF is generated for each expected energy deposition by varying each component’s contribution within its uncertainties. The CDF created from these PDF is used to simulate the expected data spectrum for the expected number of total events in the spectrum.

tion of the total number of events for 200 sets of simulated backgrounds energy-deposition distribution.

5.2.2 Sources of Uncertainty

Along with the statistical uncertainties in the expected number of background events, there are three significant sources of uncertainty that impact the expected sensitivity calculation. They are: (1) uncertainties in the analysis efficiency, (2) uncertainties in the energy calibration near thresholds, and (3) uncertainties in $\frac{dP}{dE}(f, \beta\gamma)$.

The impacts on expected sensitivity due to uncertainties in analysis efficiency, uncertainties in the energy calibration near thresholds and uncertainties in the simulated background are calculated together to eliminate any concerns about their correlation or anti-correlation. The resulting 1σ uncertainty on expected sensitivity due to uncertainties in the analysis efficiency, uncertainties in the energy calibration near thresholds and the statistical uncertainty

in simulated background distribution is $\sim 32\%$. The uncertainty due to the signal model is quadratically added, resulting in total uncertainties of $\sim 40\%$. This section briefly describes the estimates of these sources of uncertainties.

Uncertainty in the Analysis Efficiency

The uncertainty in the analysis efficiencies is one of the primary sources of uncertainty for the expected sensitivity calculation. The uncertainty in the efficiency is dominated by the statistical uncertainty in the radial cut, as seen in Figure 4.10. The uncertainty due to the LIPS-specific correction factor is negligible compared to that from the CDMSlite WIMP-search analysis efficiency. Due to high-statistics simulation, the uncertainty on correction factor is small. For each expected sensitivity calculation using a set of simulated background distributions, a randomly drawn efficiency is chosen from the samples created from CDMSlite WIMP search group [55]. Each sample of efficiency curve scales all the individual efficiency distribution from Figure 4.10 (a). Figure 5.3 (c) shows all 200 random efficiency curves used for the expected sensitivity calculation.

Uncertainties in the Energy Calibration Near Thresholds

The uncertainty in estimating lower and upper energy thresholds impacts the vertical intensity calculation. The upper and lower energy threshold for the analysis is 100 eV_{ee} and 2000 eV_{ee} respectively. The CDMSlite Run 2 Period 1 detector resolution (see Equation 4.10) is used to estimate this uncertainty on the lower and upper threshold:

$$\begin{aligned} \text{Lower threshold (eV}_{ee}\text{)} &= 100 + R\sigma_T \\ \text{Upper threshold (eV}_{ee}\text{)} &= 2000 + R\sigma_T. \end{aligned} \tag{5.3}$$

where R is a random number, following a Gaussian distribution with the mean at 0. For each set of expected sensitivity calculations, a random set of lower and upper threshold, varied within its uncertainties, is chosen as shown in Figure 5.3 (d) and Figure 5.3 (e) respectively. The resulting 1σ uncertainty on expected sensitivity due to uncertainties in the analysis effi-

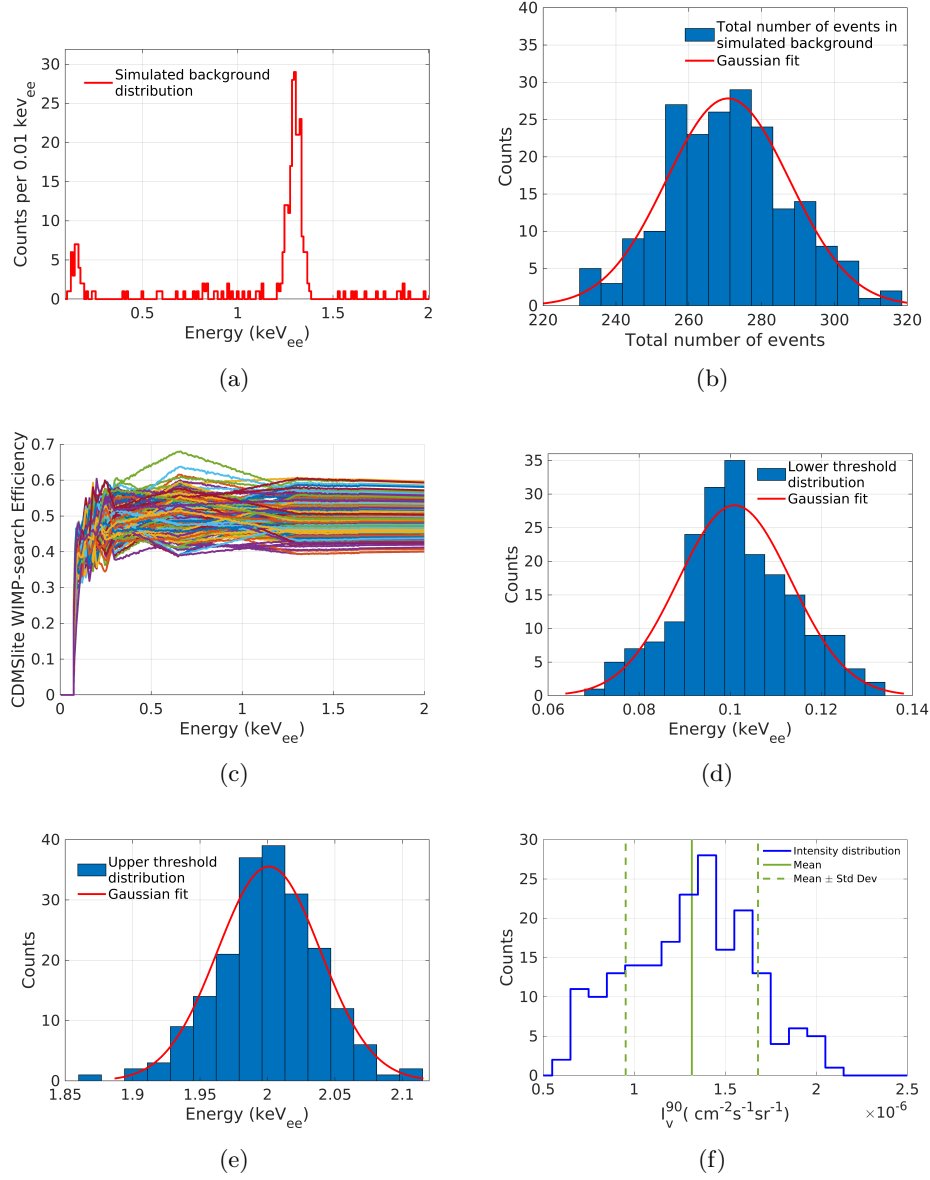


FIGURE 5.3: (a) A sample simulated background distribution which has a mean number (269) of total expected events. (b) The distribution of total numbers of events for all 200 sets of simulated background distributions. The total number of events is statistically varied. (c) 200 sets of efficiency curves used for each expected limit calculation. and (d) The distribution of the lower energy thresholds for each expected limit calculation. (e) The distribution of the upper energy thresholds for each expected limit calculation. (f) The distribution of intensity limits for LIPs with $\beta\gamma = 3.1$ and $f=1/1000$ computed using all 200 samples of background for which uncertainty in the analysis efficiency, uncertainties in the energy calibration near thresholds and statistical uncertainty in simulated background distribution are incorporated.

ciency, uncertainties in the energy calibration near thresholds and the statistical uncertainty in simulated background distribution is $\sim 32\%$ (shown in Figure 5.3 (f)).

The correct method of the measurement of uncertainty on thresholds should have been from the comparison of the activation peaks from the actual expected value. This was realized after the development of the limit setting framework and the unbinding of the data. The study performed by Samir [88] showed that the L-shell peak for Period 1 shifted by $\sim 2\sigma$. But, a similar calculation on Period 2 data showed that the same peak shifted by $\sim 5\sigma$. This brings in an additional systematic uncertainty. So, for this analysis, we decided to stay with uncertainty calculated using the above method (Equation 5.3) as it is still conservative to the uncertainty obtained from the comparison of the activation peaks from the actual expected value.

Figure 5.3 (f) shows the distribution of intensity limits for LIPs with $\beta\gamma = 3.1$ and $f=1/1000$ computed using all 200 samples of background for which uncertainty in the analysis efficiency, uncertainties in the energy calibration near thresholds, and statistical uncertainty in simulated background distribution are incorporated. The distribution is not a proper Gaussian because $N^{90}(f, \beta\gamma)$ doesn't have a linear relationship with the total number of events in the simulated background; instead it only depends on the shape of the simulated background. The mean of the distribution (green solid) is taken as the mean of expected intensity limit where as one standard deviation (green dashed) of the distribution is taken as total combined uncertainties due to uncertainty into the analysis efficiency, uncertainties in the energy calibration near thresholds and statistical uncertainty in simulated background distribution.

Uncertainties in the Signal Model

The uncertainties in the signal model are another significant source of uncertainty for intensity limit calculation. The impact of these uncertainties is studied independently and is added in quadrature to the uncertainties obtained from other sources discussed above. The impact of both statistical and systematic uncertainties on $\frac{dP}{dE}(f, \beta\gamma)$ on intensity limits are estimated;

the impact due to statistical uncertainty is found to be negligible whereas a systematic uncertainty of $\sim 24\%$ on the vertical intensity is estimated.

Due to the large number of Monte Carlo events simulated to generate $\frac{dP}{dE}(f, \beta\gamma)$, the statistical uncertainty due $\frac{dP}{dE}(f, \beta\gamma)$ is small compared to that from other sources. In order to calculate the impact of statistical uncertainty of $\frac{dP}{dE}(f, \beta\gamma)$ on the vertical intensity limits, 50 different distributions of $\frac{dP}{dE}(f, \beta\gamma)$ are generated for LIPs with $f=10^{-3}$ and $\beta\gamma = 3.1$ assuming an isotropic angular distribution. Each of those $\frac{dP}{dE}(f, \beta\gamma)$ generated are used to calculate the vertical intensity limits for same randomly chosen simulated background distribution. Figure 5.4 shows the distribution of the vertical intensity calculated using 50 different sets of $\frac{dP}{dE}(f, \beta\gamma)$. The 1σ uncertainty on the distribution is $\sim 0.86\%$. The impact of this uncertainty is minimal when compared to that from the others and thus was deemed negligible.

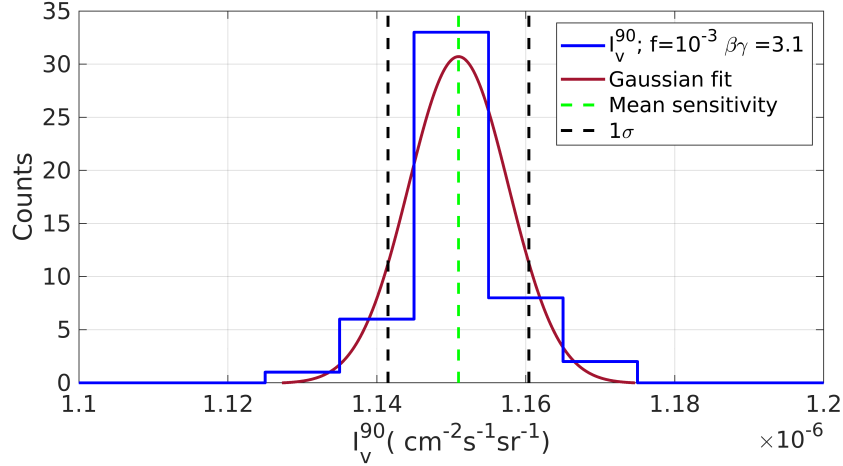


FIGURE 5.4: The distribution of the expected sensitivity calculated for 50 sets of $\frac{dP}{dE}(f, \beta\gamma)$ in blue. The distribution is fitted by Gaussian distribution in red and the mean of the fit is shown by a green dashed line. The black dotted lines represents 1σ values from the mean of the Gaussian fit.

The deviation of $\frac{dP}{dE}(f, \beta\gamma)$, obtained using GEANT4, from the true probability distribution is taken as systematic uncertainty. Since, there is no definite true probability distribution, the verified $\frac{dP}{dE}(f, \beta\gamma)$ obtained from GEANT4 simulated events is compared with that

obtained by the previous CDMS II LIP-search [15]. The systematic uncertainty on I_v^{90} is calculated by comparing sensitivity computed using both these methods. The difference in intensity limit is considered as the systematic error on $\frac{dP}{dE}(f, \beta\gamma)$.

Out of five possible methods to estimate the energy lost by a particle when passing through a detector described in Bischel [89], CDMS II used convolution calculations, and GEANT4 uses Monte Carlo simulation. Along with the ionization process, the GEANT4 method also includes additional physics processes, including the bremsstrahlung process and the pair-production process. Some differences in $\frac{dP}{dE}(f, \beta\gamma)$ for these methods are expected.

For the CDMS II, LIPs energy-deposition distributions are calculated by convolution of the single interaction PAI cross-section considering only ionization energy loss for minimum ionizing LIPs. Mathematically, the energy deposited due to a particle passing through a medium is estimated by the following function,

$$f(E) = \sum_{n=0}^{\infty} \frac{m^n e^{-m}}{n!} \sigma(E)^n \quad (5.4)$$

where n is number of interaction, m is average number of collision and $\sigma(E)$ is energy loss cross section for a single interaction calculated using PAI model as described in 2.2. Kunj's thesis [67] has more information on CDMS II probability distribution. This method generates mass-independent probability distribution functions (PDF) only for minimum ionizing LIPs ($\beta\gamma = 3.1$).

For Monte Carlo calculations, as in GEANT4, each individual interaction is simulated as a particle passes through the medium. The energy lost during each of these interactions is added up to obtain the total energy loss of the particle.

Along with different method of calculation of $\frac{dP}{dE}(f, \beta\gamma)$, these methods also uses different dielectric constants for ionization cross-section (described in Equation 2.2). Both sets of $\frac{dP}{dE}(f, \beta\gamma)$ obtained for CDMS II and GEANT4 are well validated. So, it is difficult to know which method provides more accurate $\frac{dP}{dE}(f, \beta\gamma)$ for LIPs. This LIP-search analysis takes the difference between these two methods as the systematic uncertainty on $\frac{dP}{dE}(f, \beta\gamma)$.

Figure 5.5 (a) shows the probability distribution function obtained from convolution method and GEANT4 method.

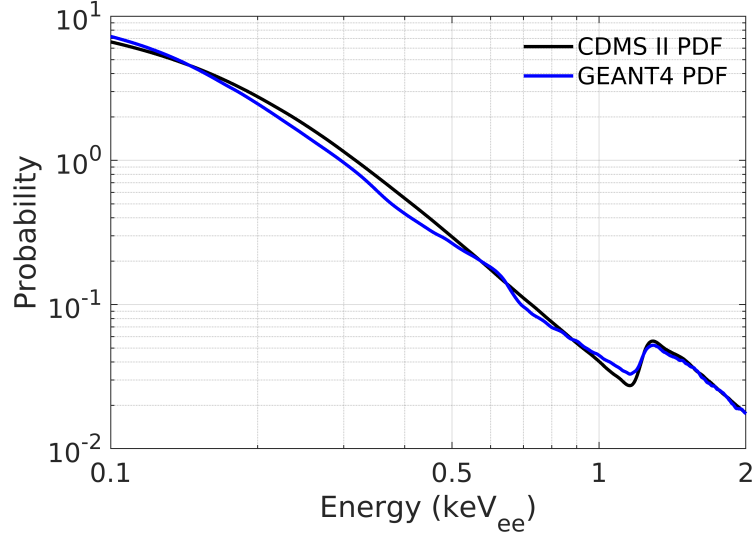
In order to estimate the impact of a systematic uncertainty on the I_v^{90} calculation, both of these $\frac{dP}{dE}(f, \beta\gamma)$ are used to calculate the I_v^{90} for LIPs with $f = 10^{-3}$, mass 100 MeV and $\beta\gamma = 3.1$. The intensity limits are calculated using both methods for 50 randomly simulated background distributions. The black histogram in Figure 5.5 (b) shows the ratio of the intensity calculated for GEANT4 method to CDMS II method. The histogram of the intensity ratio is fitted with a Gaussian red curve giving a mean value of 1.24 shown by a green-dashed line. So, the GEANT4 method is found to be $\sim 24\%$ less restrictive than the CDMS II method. This difference is taken as uncertainty on I_v^{90} for all considered values of LIP f , mass, and $\beta\gamma$.

5.2.3 Expected Sensitivity

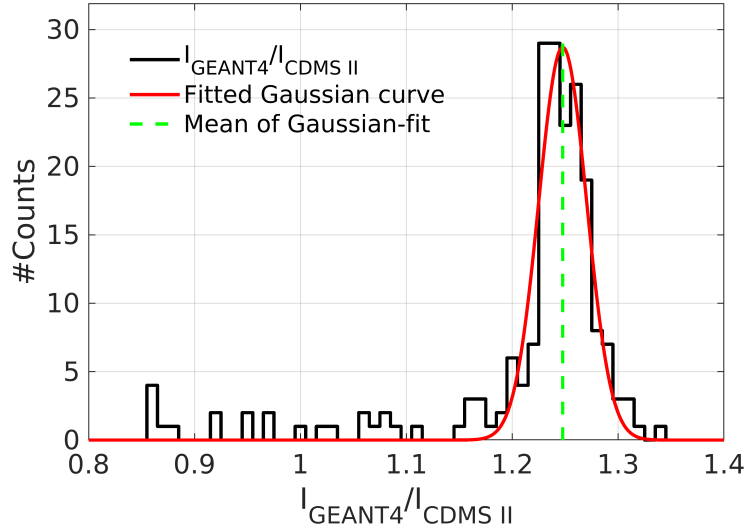
The expected sensitivity is calculated together with the estimation of the uncertainties for various LIPs f , mass and $\beta\gamma$. All 200 random sets of simulated backgrounds are used for the calculation. The mean of the I_v^{90} distribution thus obtained (using Equation 5.1) is taken as mean expected sensitivity, and the standard deviation of the distribution ($\sim 32\%$) is taken as the combined uncertainty on I_v^{90} due to uncertainty in analysis efficiency, energy threshold and the background distribution. Combining the uncertainty in $\frac{dP}{dE}(f, \beta\gamma)$ in quadrature with $\sim 32\%$, obtained from uncertainty in analysis efficiency, energy threshold and the background distribution, results in the final uncertainty estimate of $\sim 42\%$. Figure 5.6 (a) and (b) shows the expected sensitivity and the uncertainty band for assumed isotropic and $\cos^2\theta$ angular distribution.

The 90% confidence upper limit, $N^{90}(f, \beta\gamma)$, on the simulated background model is calculated using the Optimum Interval (OI) method [71]. For most assumed values of f , the $N^{90}(f, \beta\gamma)$ has a value that is typically between 20 and 60.

For larger fractional charged particles with $f \gtrsim 1/550$, the expected sensitivity is least restrictive for $\beta\gamma = 0.1$. This is because whenever these LIPs interact with the detector, they



(a)



(b)

FIGURE 5.5: (a) A comparison of the probability distribution function for minimum ionizing LIPs of mass 100 MeV with an isotropic angular distribution computed using CDMS II method (black) and GEANT4 method (blue). Both of these distribution functions have been smeared with the CDMSlite detector resolution. (b) A distribution of the ratio of the intensity limit (black) calculated using GEANT4 to that calculated using CDMS II method for 50 simulated deposition distribution. The histogram of the intensity ratio is fitted with Gaussian red curve giving a mean value of 1.24 shown by a green-dashed line. The limit calculated for GEANT4 method is $\sim 24\%$ less restrictive than CDMS II method.

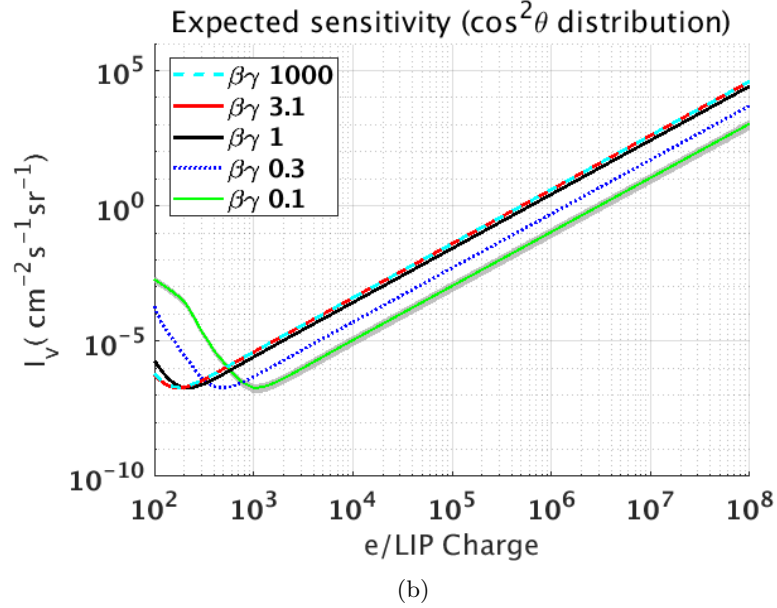
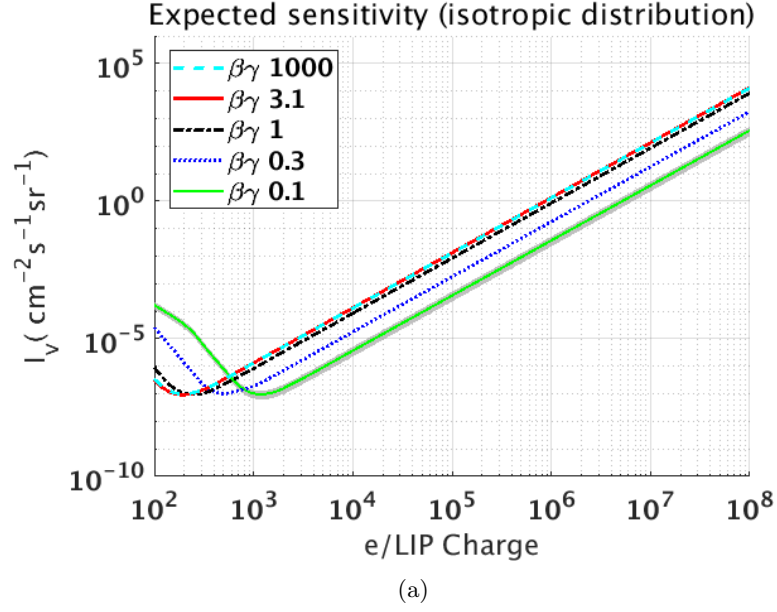


FIGURE 5.6: (a) A comparison of the vertical intensity for LIPs of various $\beta\gamma$ and mass 100 of MeV with an isotropic angular distribution. The combined uncertainty is shown by the shaded region which is similar for all the curves and is dominated by uncertainties in the CDMSlite Run 2 Period 1 efficiency, systemic uncertainty in the expected LIP PDFs, and statistical uncertainty in the background. For clarity, the uncertainty band is only shown for $\beta\gamma = 0.1$. (b) This figure is identical to Fig (a) except it is for an assumed $\cos^2\theta$ LIP incident angular distribution.

have a substantial probability of depositing energy larger than the upper energy threshold considered for this analysis. As a result, their probability of depositing energy within the analysis energy window, considered for this LIP-search analysis, is smaller than other $\beta\gamma$ values. For $f \lesssim 1/550$, the expected sensitivity is least restrictive for $\beta\gamma = 3.1$. As the interaction cross-section for these LIPs is small compared to other $\beta\gamma$ values, the probability of them depositing energy within the analysis energy window, after their interaction with the detector, is smaller.

For a very small fractional charge ($f < 10^{-4}$) with a single-interaction $\frac{dP}{dE}(f, \beta\gamma)$, the expected sensitivity is calculated by scaling the sensitivity limits obtained for $f = 10^{-4}$ by f^2 . For LIPs with a single-interaction $\frac{dP}{dE}(f, \beta\gamma)$ (described in Section 2.1.3), the amplitude of $\frac{dP}{dE}(f, \beta\gamma)$ are reduced by a scaling factor of f^2 without changing the shape of the distribution. It is computationally very expensive to compute $\frac{dP}{dE}(f, \beta\gamma)$ via Monte Carlo simulation for these small fractional charges. The expected sensitivity for these smaller fractional charge particles are calculated as:

$$I_v^{90}(f < 10^{-4}, \beta\gamma) = \frac{I_v^{90}(f = 10^{-4}, \beta\gamma)}{f^2}. \quad (5.5)$$

Since the simulated background distribution is obtained from the simulation of the background model developed from the CDMSlite Run 2 data, we expect the final intensity limit to be close to the expected sensitivity.

5.2.4 Comparison between Isotropic and $\cos^2\theta$ Angular Distribution

The expected sensitivity for assumed isotropic distribution has 3 times restrictive limits than that for $\cos^2\theta$ angular distribution as seen in Figure 5.7. For most of the LIP charges, the observed difference in expected sensitivity is primarily due to the difference in an effective cross-sectional area of the detector surface for both these distributions (more information in Chapter 2). For some larger fractional charges, the difference is less than a factor of 3 because those LIPs have a larger probability of depositing energy within the considered

analysis window for a $\cos^2\theta$ angular distribution than for an isotropic angular distribution.

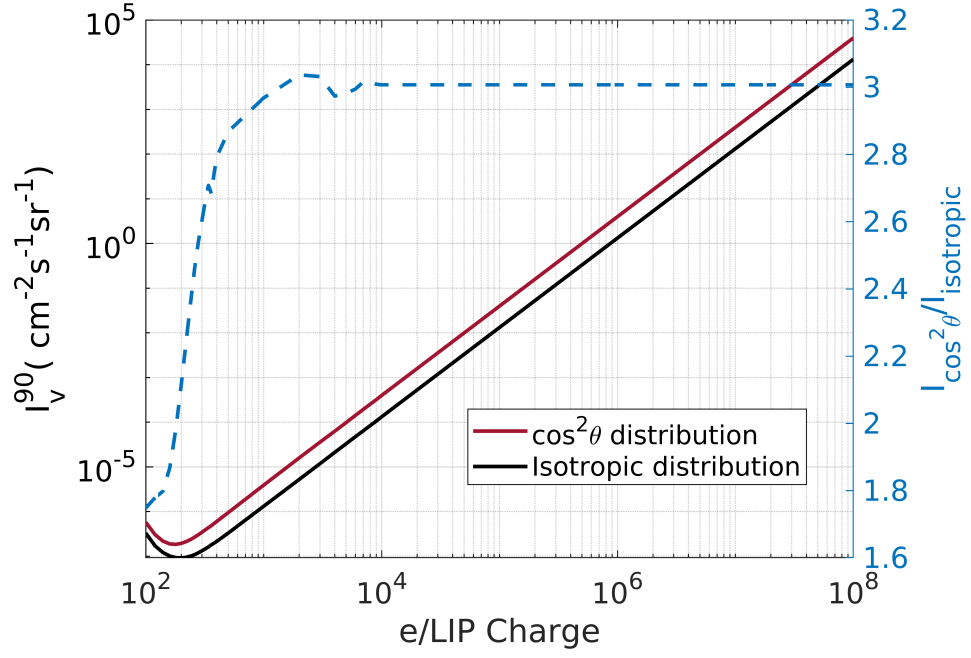


FIGURE 5.7: The comparison of vertical intensity limits for various LIPs charge with $\beta\gamma = 3.1$ and mass 100 MeV for $\cos^2\theta$ angular distribution (red) and isotropic angular distribution (black). The blue dotted curve is difference between both of these intensity limits.

6

Result

After developing the limit-setting framework and calculating the expected sensitivity, the LIP-search analysis was ready for the “quasi-unblinding” of the CDMSlite Run 2 Period 1 data. This chapter describes the unblinded Run 2 Period 1 data, the comparison of the data with the expectation, the computation of the LIP intensity limit, the comparison of LIP intensity with expected limit and some cross-checks on intensity limits.

6.1 CDMSlite Run 2 Period 1 Data

The CDMSlite Run 2 Period 1 data spectrum was unblinded for the first time by the analyzers after setting up the analysis framework. The CDMSlite Run 2 WIMP-search analysis used both Period 1 and Period 2 data sets. This combined Run 2 data set was already published before this LIP-search analysis began. The energy spectrum for only Period 1 is expected to be similar to the published Run 2 data spectrum as it is a smaller set of larger Run 2 data spectrum. Only events with energy depositions between 0.1 keV_{ee} and 2 keV_{ee} are selected. There are 32066 total raw events observed during the data taking run. After the application of the analysis cuts, the final data spectrum contains 180 events. Figure 6.1 shows the CDMSlite Run 2 Period 1 data spectrum within the analysis energy thresholds. Table 6.1 shows the remaining data events after successive application of the selection criteria (cuts).

The activation lines, L-shell at 1.30 keV_{ee} and M-shell at 0.16 keV_{ee} , from decays of intrinsic Ge radioisotopes are visible in the spectrum. The rate of events, after the application of all cuts, outside the activation peaks is $\sim 1 [\text{keV}_{ee} \text{ kg day}]^{-1}$.

Cuts	Total Events
Raw events	32066
&General quality cuts	5263
&Pulse-shape cuts	925
&Veto-coincident cut	906
&Singles cut	651
&Radial cut	180

Table 6.1: The number of surviving events, within the analysis energy thresholds ($0.1 \text{ keV}_{ee} - 2 \text{ keV}_{ee}$), after the application of each data selection criteria.

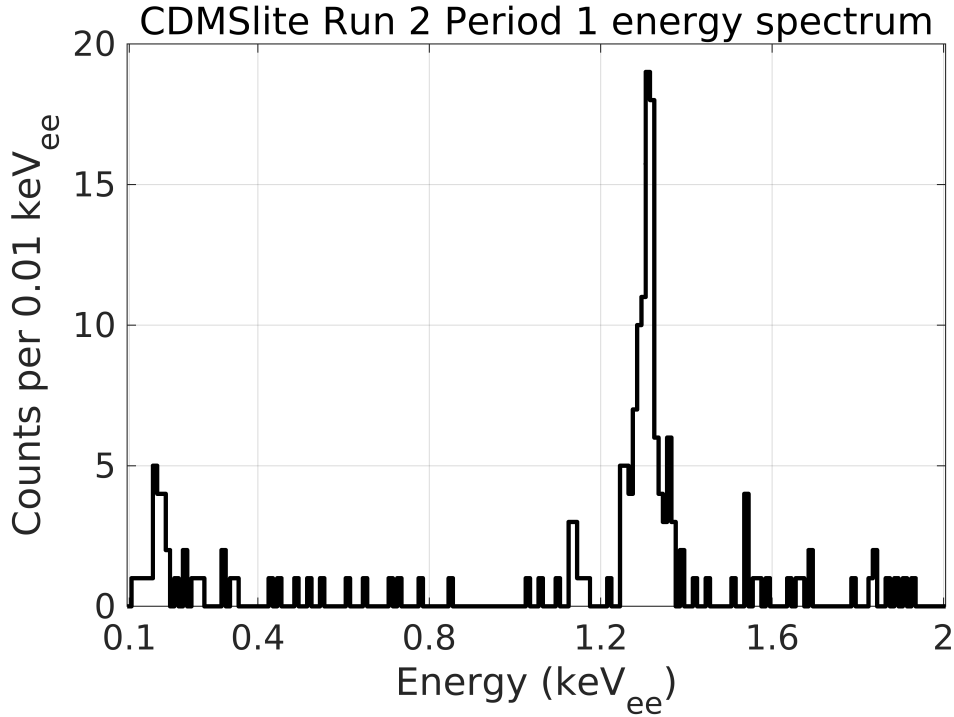


FIGURE 6.1: The energy spectrum obtained from the CDMSlite Run 2 Period 1 after applying all the analysis selection criteria. A total of 180 events survived the application of all the selection criteria. The activation lines, L-shell at 1.30 keV_{ee} and M-shell at 0.16 keV_{ee} , are visible in the spectrum.

6.1.1 Data Validation

Some cross-checks on the data spectrum were performed before the calculation of the final intensity limits. The cross-checks includes: (1) checking the shape and position of activation peaks and (2) comparing the data spectrum with expected background distribution.

Shape and Peak Position

The mean positions of the activation peaks are well-known; thus, a check is performed to compare the theoretical mean of peaks with that observed in the spectrum. The check is only performed for the L-shell peak due to a lack of statistics in the M-shell peak.

The L-shell peak is fitted with a Gaussian function plus one-degree polynomial as shown in Figure 6.2. The mean of the fit is 1.305 keV_{ee} , which has shifted by $\sim 0.5\%$ from the expected position of 1.299 keV_{ee} . This shift is relatively small when compared to uncertainties in the energy-scale used to estimate the threshold uncertainties (see Section 5.2.2).

Expected vs Actual Run 2 Period 1

The CDMSlite Run 2 Period 1 contains 80% of the total exposure of the CDMSlite Run 2 published data. There were 318 observed events in the CDMSlite Run 2 after the application of the selection cuts. From a simple weighting of exposure, one would expect 269 events in the CDMSlite Run 2 Period 1. However, the data spectrum for the CDMSlite only has 180 events. This section describes the cause of this significant discrepancy in the total number of events between the observed spectrum and the simulated background distribution.

The primary source of backgrounds in the data spectrum is the activation peaks obtained from the ^{252}Cf calibrations. There were five calibration periods (each calibration period of ~ 3 days of exposure) within the CDMSlite Run 2 data period. Out of those five calibration periods, only two periods are in the entire 97 days of live time for the CDMSlite Run 2 Period 1. Even though Period 2 had a shorter live time, the similar exposure to ^{252}Cf calibration resulted in a nearly equal number of events at the L-shell and the M-shell peaks for both periods. Therefore, our scaling of the number of events by a relative live time greatly

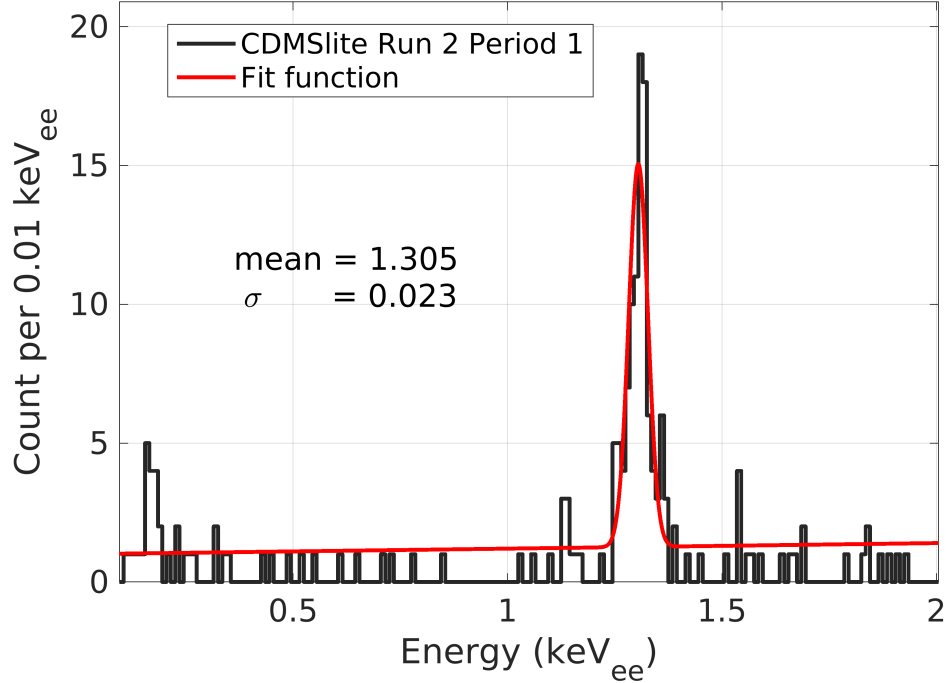


FIGURE 6.2: Energy deposition spectrum of the CDMSlite Run 2 Period 1 data with the L-shell (1.299 keV_{ee}) peak being fitted by a Gaussian plus one-degree polynomial distribution. The mean and σ of the fit are 1.305 keV_{ee} and 0.023 keV_{ee} respectively.

over-predicted the number of events in these peaks. Figure 6.3 shows the calibration periods in each periods of the CDMSlite Run 2 data. There is one calibration period at the beginning of Period 1 and one in the middle of the period. The relative impact of the ^{252}Cf calibration on the number of observed events passing the cuts is readily apparent.

The optimal LIP sensitivity is obtained from the events outside the peak in the spectrum. The number of events in the peaks, which are not the region of maximum sensitivity, has a minimal effect while calculating the upper limit on LIP-events using the Optimal Interval method. A check on the number of the events outside the peaks is performed to verify that the events outside the peaks match the expectation.

The total calendar time for Run 2 Period 1 is divided into four time blocks. The first time block has events between the calibration period and 11.3 days after the calibration (events after both calibration periods are included). The second time block has events within the

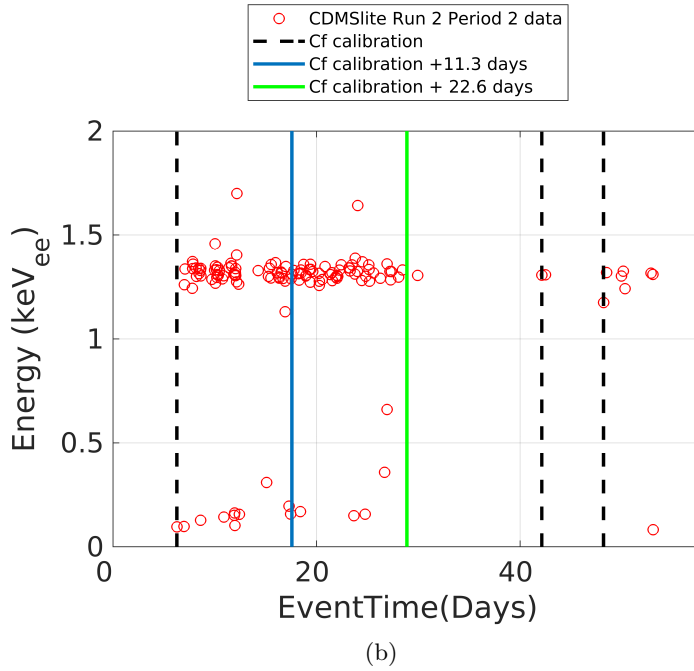
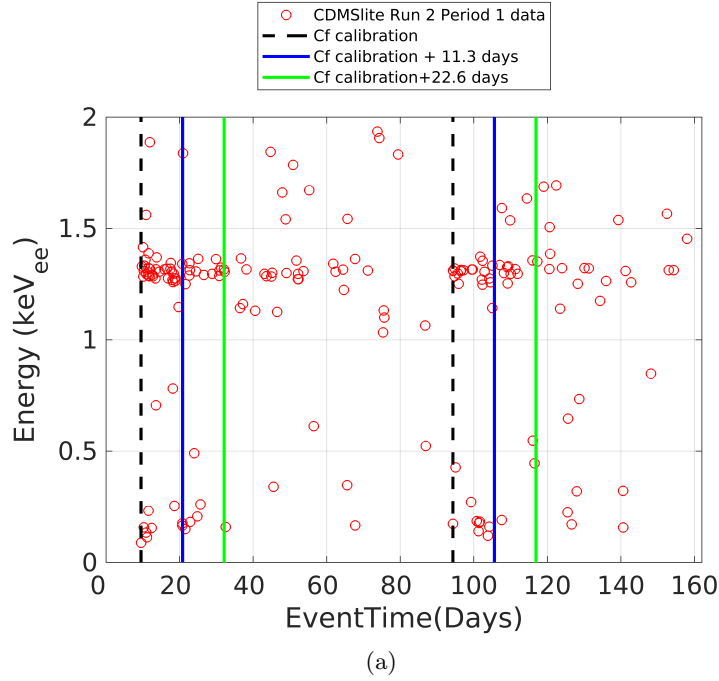


FIGURE 6.3: (a) The event distribution the events as a function of an actual time and the deposited energy. The red circles in the figure are the data points for Run 2 Period 1 after all the analysis cuts being applied. The dotted black lines represent the time at which the ^{252}Cf calibration was performed. The blue line represents the half-life of the calibration, and the green represents another half-life after the first half-life. (b) This is a similar figure to Figure (a), but for the CDMSlite Run 2 Period 2.

next 11.3 days after the first time block. Similarly, time blocks 3 and 4 are defined. Table 6.2 shows the distribution of the total number of events in each of these time blocks. The number of events in M, L, K-shell peaks (within $\sim 3\sigma$ from the mean of peaks) are decreasing with the time blocks which signifies the decrease of events observed after each half life of calibration.

Time blocks	Live time (days)	M-shell	L-shell	K-shell	Outside peaks (0.1 to 2 keV _{ee})
I	15.71	11	50	424	11
II	15.92	6	22	241	7
III	15.37	3	9	137	9
IV	15.14	0	13	78	9

Table 6.2: The event distribution while breaking the CDMSlite Run 2 Period 1 data into 4 half-lives of ^{78}Ge electron capture decay; the half life is 11.3 days. The number of events with in 3σ of M, L, K-shell peaks are decreasing with the time blocks which signifies the decrease of events observed after each half life of calibration. The total number of events outside these peaks within 0.1 to 2 keV_{ee} is statistically consistent (shown in Table 6.3), which shows that events in this energy region are not effected by the calibration.

The number of events outside the peak within our analysis window seems to be unaffected by the calibration as numbers are within statistical uncertainties for all four time blocks. The rate of events outside the peaks, where we will obtain optimal LIP-sensitivity, did scale with live time. The rate also matched the published rate of $\sim 1 [\text{keV}_{ee} \text{ kg day}]^{-1}$ for the CDMSlite Run 2 as described in Ref. [55].

Time blocks	Outside peaks events (0.1 to 2 keV _{ee}) scaled to 15 days of Live time $\pm 1\sigma$	Events per [keV _{ee} kg day] ⁻¹
I	10.5 $\pm$ 3.24	1.15 $\pm$ 0.35
II	6.59 $\pm$ 2.57	0.724 $\pm$ 0.28
III	8.78 $\pm$ 2.96	0.96 $\pm$ 0.32
IV	8.91 $\pm$ 2.99	0.98 $\pm$ 0.32

Table 6.3: The event distribution while breaking the CDMSlite Run 2 Period 1 data into 4 half-lives of ^{78}Ge electron capture decay; the half life is 11.3 days. The rate of events outside the peaks is statistically consistent and it did scale with live time.

6.2 Final Intensity Limits

The same procedure used to calculate the projected sensitivity is applied to the Run 2 Period 1 energy deposition distribution to calculate 90 % confidence-level upper limits on the LIP vertical intensity for a variety of f , mass and $\beta\gamma$. The uncertainty on the final limits is the same as that for expected sensitivity except for the statistical uncertainty on background distribution. The total uncertainty on the final limit is $\sim 37\%$.

Similar to that for expected sensitivity, the 90% confidence-level upper limit (N^{90}) on the number of LIP-candidate is calculated using the Optimum Interval (OI) method. As a reminder, while using the OI method for calculating the upper limit, all events were treated as LIPs events, and hence the observed limit is conservative. Figure 6.4 shows the N^{90} values calculated for various values of LIPs fractional charge for $\beta\gamma$ taking a value of 3.1 and with an assumed isotropic angular distribution. N^{90} has a maximum value of ~ 57 for $f = 1/300$ and the minimum value of ~ 41 for $f < 1/2000$. The N^{90} values for $f < 1/2000$ are expected to be the same as they have the same-shaped signal model, only differing in amplitude.

The intensity limit ($I_v^{90}(f, \beta\gamma)$) under the assumptions of minimum-ionizing LIP ($\beta\gamma = 3.1$) and mass 100 MeV for an isotropic distribution is shown in Fig. 6.5 along with limits from all prior direct searches for cosmogenic LIPs. This result is valid for all LIP mass considered in this analysis ($5 \text{ MeV}/c^2 - 100 \text{ TeV}/c^2$). LIPs with $\beta\gamma = 3.1$ for an assumed isotropic angular distribution is used for the direct comparison with prior experiments as all prior analysis have only set limits for these LIPs. This result sets the strongest constraint on energetic LIPs with $f > 1/160$, including a minimum vertical-intensity limit of $1.36 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at $f = 1/160$. This is the first analysis to extend the search to a very small fractional charge of $f = 1/10^8$. The grey band illustrates the 1σ uncertainty on the CDMSlite vertical intensity limit. This includes the uncertainty on the CDMSlite analysis cut efficiency, higher and lower energy thresholds and uncertainty in the LIP signal model.

The intensity limit on minimum ionizing LIPs for assumed isotropic distribution has ~ 3 times more restrictive limits than those obtained under the assumption of a $\cos^2\theta$ angular

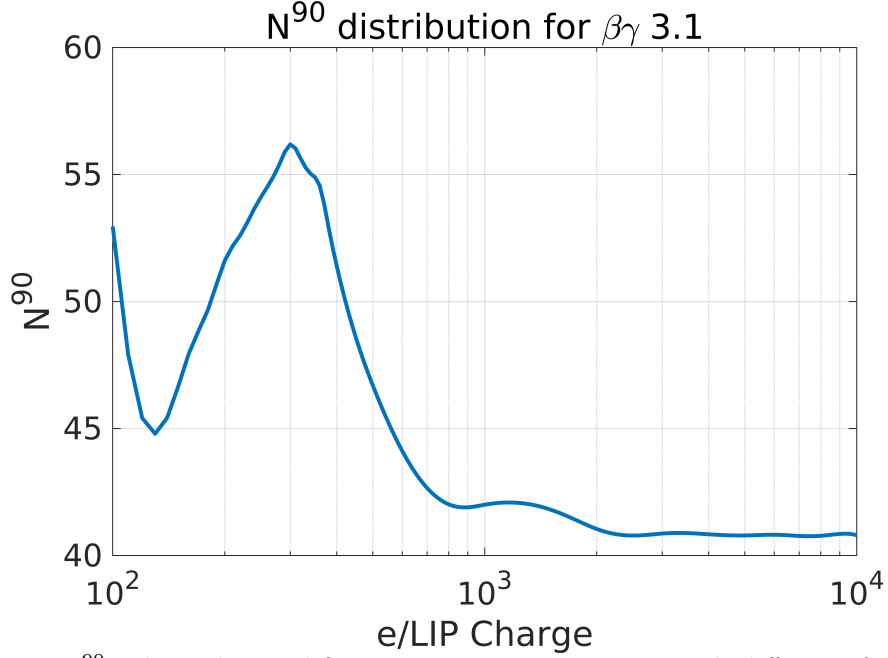


FIGURE 6.4: N^{90} values obtained for minimum ionizing LIPs with different f values and an assumed isotropic angular distribution.

distribution as seen in Figure 6.6. This factor of three obtained for the final limits is the same as obtained for expected sensitivity calculation (see Section 5.2.4).

The analysis is the first-ever LIPs-search analysis to marginalize over LIP $\beta\gamma$ and LIP mass. Figure 6.7 (a) and (b) shows the intensity limits for isotropic angular distribution and $\cos^2\theta$ angular distribution respectively for a variety of $\beta\gamma$ values. For all of these $\beta\gamma$ values, the isotropic angular distribution is about three times more restrictive than $\cos^2\theta$ angular distribution. These limits apply to the range of LIP masses considered in the analysis. The green band in the figure is the uncertainty on the intensity limit for $\beta\gamma$ value of 0.1. The uncertainty band is the same for all curves, but for the purpose of clarity, the band is only shown for $\beta\gamma$ of 0.1.

While a non-relativistic LIP ($f \sim 10^{-9}$, mass $\sim 511 \text{ keV}/c^2$) DM-electron scattering explanation of the DAMA [9] and CoGeNT [10] annual modulation signals has been proposed [7, 8], no search has probed this LIP parameter space. The result reported herein takes a first significant step towards searching for Dark Matter with fractional charge [7, 8] by setting the

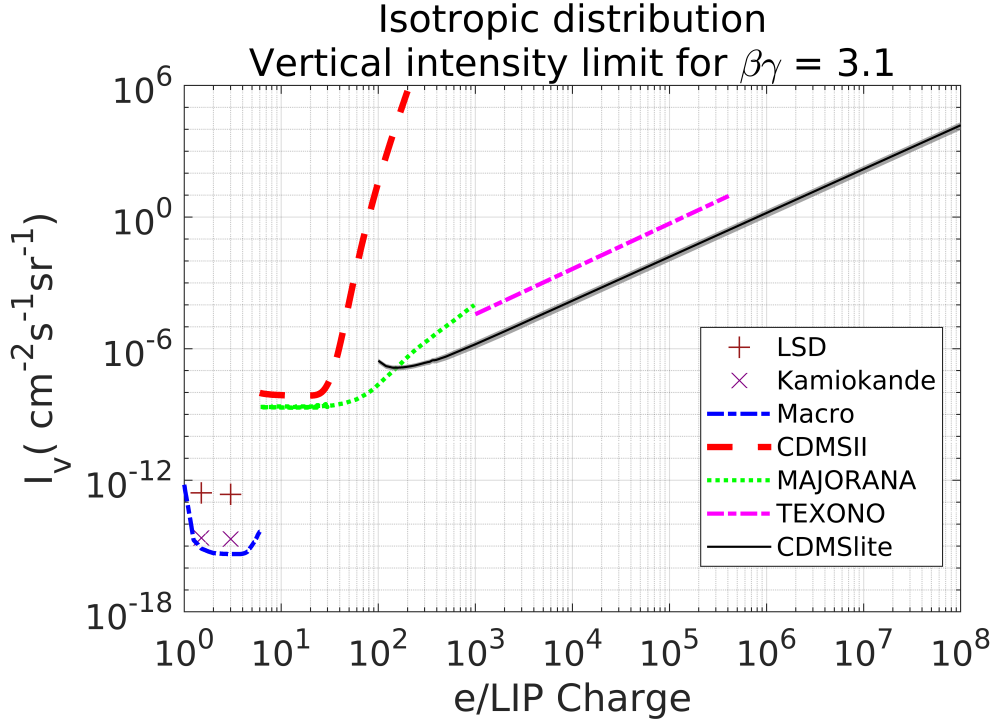


FIGURE 6.5: The figure shows the 90% confidence limit (in black solid) placed on the vertical intensity by our analysis of the CDMSlite under standard LIPs assumptions for minimally ionizing LIPs ($\beta\gamma = 3.1$) with the mass $100 \text{ MeV}/c^2$ and assuming an isotropic angular distribution. The grey band illustrates the 1σ uncertainty on the CDMSlite vertical intensity limit. For comparison, all prior results of experiments that performed direct searches for cosmogenic LIPs are also shown.

first limit on non-relativistic LIPs with $\beta\gamma$ as small as 0.1. These non-relativistic LIPs of $\beta\gamma$ of 0.1 still has far more energetic (~ 550 times) than that expected of galactically bound LIPs with $\beta\gamma$ of 0.0018.

6.3 Final Limits vs Projection

The final limit is expected to be close to the projected sensitivity as both calculations are based on a similar data spectrum. For all $\beta\gamma$ values, the comparison showed some discrepancies between the intensity limit and the expected sensitivity. The final intensity limit is found to be less restrictive than expected. The final limit is within 1σ value of the expected sensitivity for most of the LIP charge, except for LIPs with $1/160 < f < 1/500$ where the difference

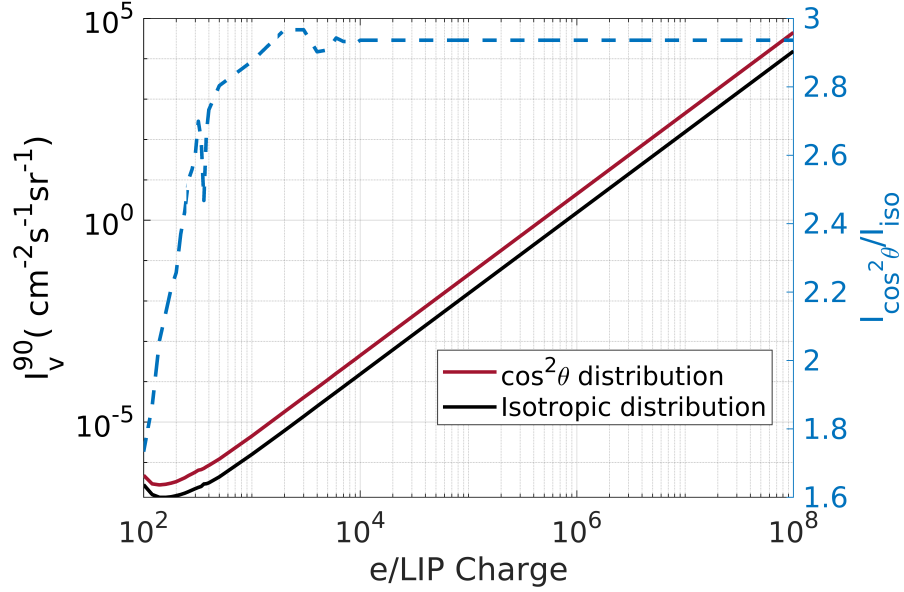


FIGURE 6.6: A comparison of vertical intensity limits for various LIPs charges with $\cos^2\theta$ angular distribution (red) and isotropic angular distribution (black) under the assumption of $\beta\gamma = 3.1$ and mass $100 \text{ MeV}/c^2$. The blue dotted curve is difference between these intensity limits.

is almost 2σ . A similar difference is observed for other $\beta\gamma$ values as well. Figure 6.8 (a) shows the expected limit and final intensity limit together for minimum ionizing LIPs. Figure 6.8 (b) shows the percentage difference between these two limits for various LIP charge.

The difference observed in intensity limits is due to the difference in the N^{90} value calculated for each LIP charge and $\beta\gamma$ values. N^{90} value is dependent on the signal model and the observed/expected data distribution. Since the same signal model is used for both calculations, the discrepancy is due to the difference in event distribution in the data spectrum and the simulated background distribution.

Figure 6.9 shows the comparison of data spectrum with a sample simulated energy distribution. The sample is chosen such that it has a typical N^{90} value. Three significant differences are observed between the data spectrum and simulated background spectrum: (1) the position of L-shell peak, (2) the number of events in L-shell peak, and (3) the data

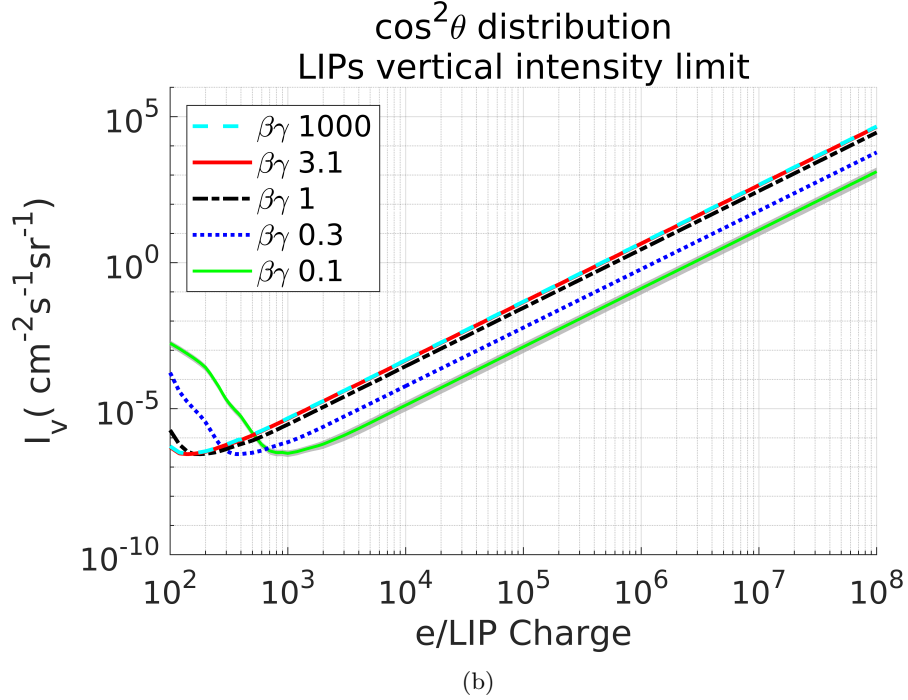
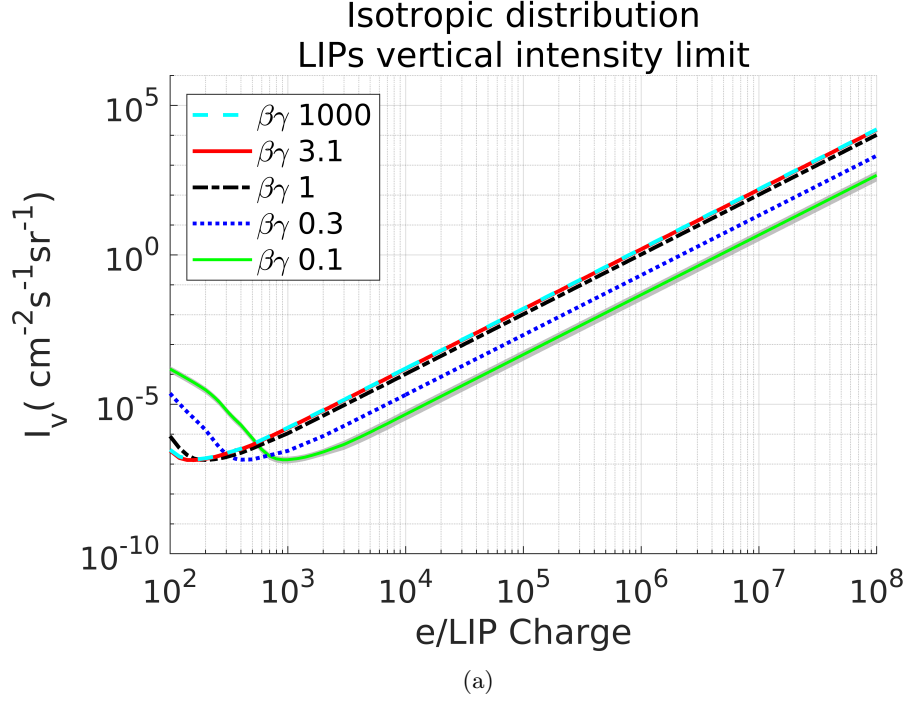


FIGURE 6.7: (a) The figure shows the 90% confidence limit on the LIPs vertical intensity as a function of LIP electric charge for various assumed values of $\beta\gamma$. The sensitivity limit are computed under the assumption of an isotropic angular distribution. The green band illustrates the 1-sigma uncertainty on the CDMSlite vertical intensity limit. (b) This figure is identical to Figure (a) except it is for $\cos^2\theta$ LIPs angular distribution.

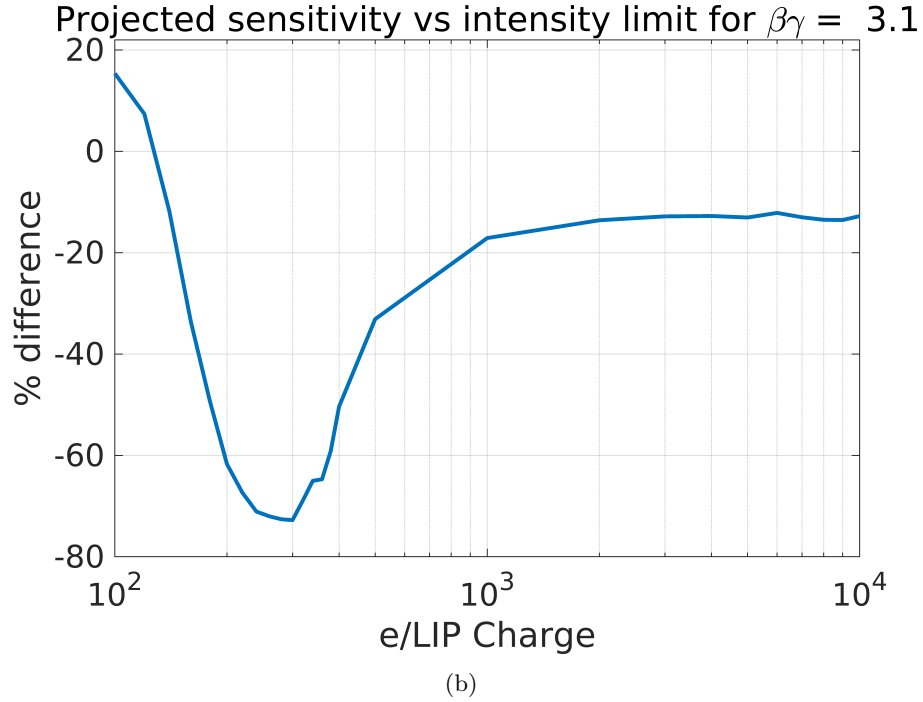
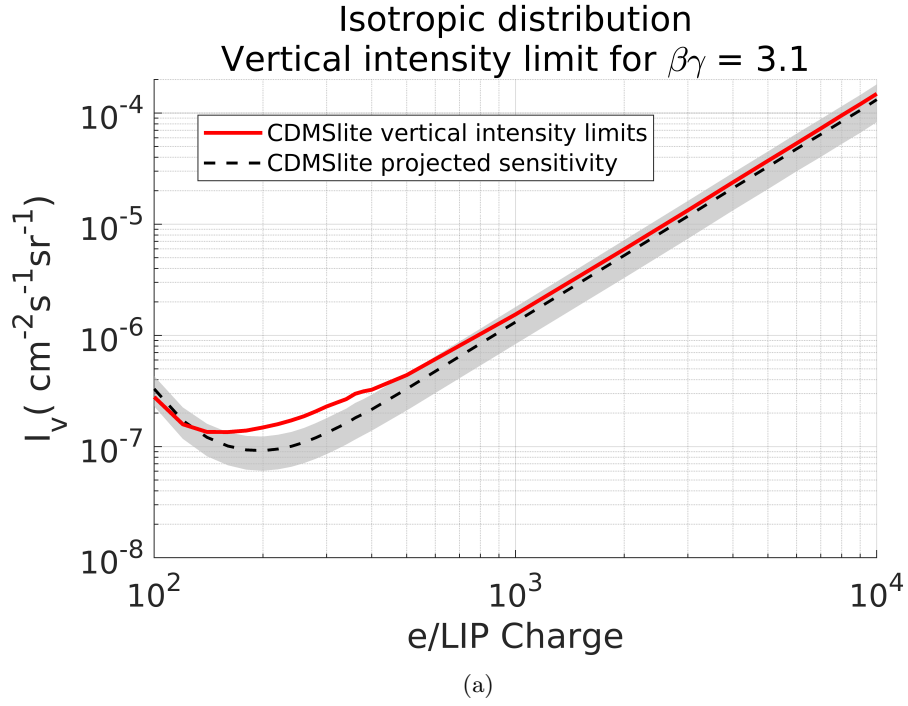


FIGURE 6.8: (a) A comparison between the expected sensitivity and the final intensity limits for minimum ionizing LIPs in an assumed isotropic distribution. The solid red curve is the final limits, and the dashed black curve is the mean expected limit with and 1σ uncertainty band is in grey. (b) This figure shows the percentage difference between the mean of expected limit and final limits.

spectrum seems to have more number of events just above the M-shell peak. As described in Section 6.1.1, the first two differences have minimal impact on the N^{90} calculation. A study showed that the dominant effect of worsening the intensity limit is due to the occurrence of more low-energy events, than we typically expected, above the M-shell peak.

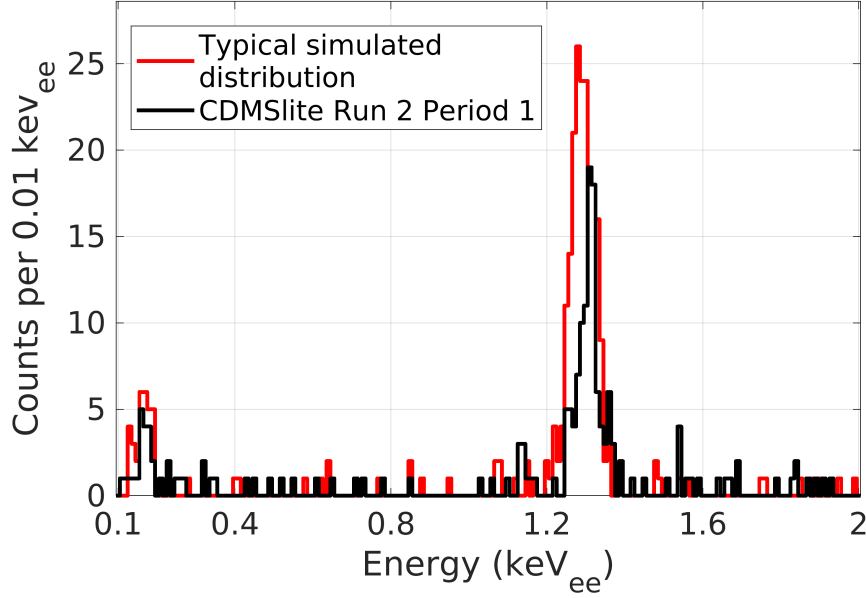


FIGURE 6.9: The energy spectrum obtained from the CDMSlite Run 2 Period 1 in red along with one of the typical simulated background distribution in blue.

This paragraph describes the procedure used to determine that the dominant impact on the vertical limit is due to unexpected events from 0.2 to 0.35 keV_{ee}. A portion of the data spectrum from a single slice in deposited energy is added to the typical sample background distribution to observe the impact due to that particular energy region on N^{90} calculation. A minimum ionizing LIP with $f = 1/300$ is chosen for the study, as it has the largest discrepancies between the limit and expected sensitivity as seen in Figure 6.8 (b). For minimum ionizing LIP with $f = 1/300$, the typical simulated background distribution has a N^{90} value of 35.47. The change in N^{90} value after the addition of the observed events from a slice of the energy deposition distribution to this simulated background is shown in Table 6.4.

The addition of 139 events between 1–2 keV_{ee} from the data spectrum to simulated back-

ground did not change the N^{90} value obtained from the distribution. This signifies that fewer events in the L-shell peak in the spectrum have minimal effect on the limit calculation. Similarly, the addition of 41 events from 0.1–1 keV_{ee} increased N^{90} values from 35.47 to 77.61. This signifies the distribution of the events in the lower energy range of the spectrum caused the discrepancies between the final limit and expected sensitivity. Further study showed that the ten events between 0.2–0.35 keV_{ee}, has the maximum impact on the N^{90} calculation. A similar study performed using minimum ionizing LIPs with $f = 1/200$ verified that the worsening of the limit is primarily due to the ten events observed between 0.2–0.35 keV_{ee}. This is not surprising because most LIPs have the maximum probability of deposition around the lower end of the range of recoil energies considered. Additional events around this region of optimal sensitivity can substantially increase N^{90} , which happened with the CDMSlite Run 2 Period 1 data set.

Portion of observed data added to a typical sample simulated distribution	Number of events added from the Period 1 data	Expected number of events in simulated data ($\pm 1\sigma$)	N^{90} value for combined spectrum
1 – 2 keV _{ee}	139	214 ± 16.1	35.47
0.1 – 1 keV _{ee}	41	53.64 ± 7.01	77.61
0.2 – 0.5 keV _{ee}	13	7.056 ± 2.41	70.06
0.35 – 0.5 keV _{ee}	3	3.45 ± 1.79	39.37
0.2 – 0.35 keV _{ee}	10	3.60 ± 1.8	62.52

Table 6.4: Some events from data spectrum is added to typical background-spectrum to observe the impact on N^{90} calculation. The 0.2–0.35 keV_{ee} part of observed spectrum is driving the reduction in sensitivity.

Figure 6.10 shows the PDF for minimum ionizing LIPs with electric charge $e/200$, $e/300$, and $e/400$ for the portion of the analysis region with the greatest sensitivity. LIPs probability distributions shown in the figure are scaled to unit probability within the analysis window. LIPs with electric charge $e/300$ are expected to sample this region the most, resulting in the greatest reduction in their sensitivity, as shown in Figure 6.8 (b).

Some of the possibilities for the presence of these unexpected events are: (1) an unlucky fluctuation of events in that energy region, (2) leakage of M-shell peak events, or (3) the

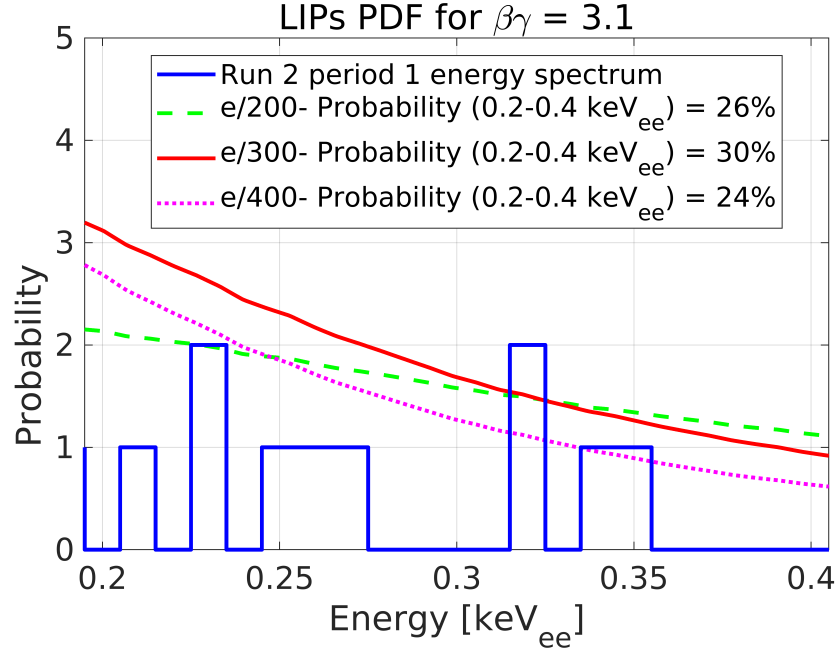


FIGURE 6.10: The PDF for minimum ionizing LIPs with electric charge $e/200$ (green dashed), $e/300$ (red solid), and $e/400$ (magenta dotted) for the portion of the analysis region with the greatest sensitivity. The energy distribution from the data spectrum between the energy range of $0.2\text{--}0.35\text{ keV}_{ee}$ is depicted by the blue histogram. LIPs with electric charge $e/300$ are expected to sample this region the most, resulting in the greatest reduction in their sensitivity.

background model does not fully describe data in this region. The background model typically expects 3.60 ± 1.8 events between 0.2 and 0.35 keV_{ee} . However, the data spectrum has nearly 4σ more events than expected by the background model. This suggests that the probability of the data spectrum being an unlucky fluctuation of expected events is minimal. 4 out of those ten events occurred within 11.3 days (half-life of ^{78}Ge) from ^{252}Cf calibration. Around 1.2 events were expected under the assumption that these events in-between the activation peaks are uniform in time. So, the possibility of these events being leaked M-shell events cannot be discarded although it would be easier to imagine how they leaked to lower energy than higher energy (un-rejected events with partials ionization collection). Also, the background model considered for this analysis only considered the cosmogenic isotopes, tritium and Compton effect. These events could be due to β s produced during radioactivity in the experimental site

or some other sources that the background model does not fully describe. The background model was devised to describe the Run 2 data but was not devised to allow a significant deviation from a flat distribution between these 0.2 and the 1.3 keV_{ee} peak. These events are not taken as a hint for LIP signals.

6.4 Intensity Limit Cross-checks

This section examines several cross-checks of the limit described in Section 6.2. These checks validate various decisions, suggest future improved approaches or identify problems of a sufficiently serious nature to necessitate revisiting the analysis. All the cross-checks are performed on minimum ionizing LIPs with an isotropic angular distribution, representing all other $\beta\gamma$ values.

6.4.1 *Final Limit vs. Relaxed Cuts Limit*

These checks are performed to check if there is a significant population of near signal events excluded and to test the robustness of the result. Two physics cuts with the more significant effect on the LIPs intensity limit calculation are the singles cut and the radial cut. The final intensity limit is compared with the intensity limits calculated for the data spectrum obtained: (1) without application of any physics cut, (2) without application of singles cut, (3) without application of radial cut. The comparison shows the improvement in the intensity limit after the application of these cuts.

Final Limit vs. No-Physics Cut Limit

A comparison between the intensity limit calculated for data spectrum without applying any physics cut, i.e., veto-coincident cut, singles cut, and radial cut, with the final intensity limit is performed to validate the decision to use these cuts for LIP-search analysis. All of these cut together removes 745 events with an LIP signal efficiency of $\sim 50\%$. The additional LIP-specific correction factor, especially for LIPs with larger f , further reduces the analysis efficiency. This check is performed to check if the application of these selection criteria helped

to improve the limit. This check also investigates the presence of a potential LIP-signal that may be lost due to the application of physics cuts.

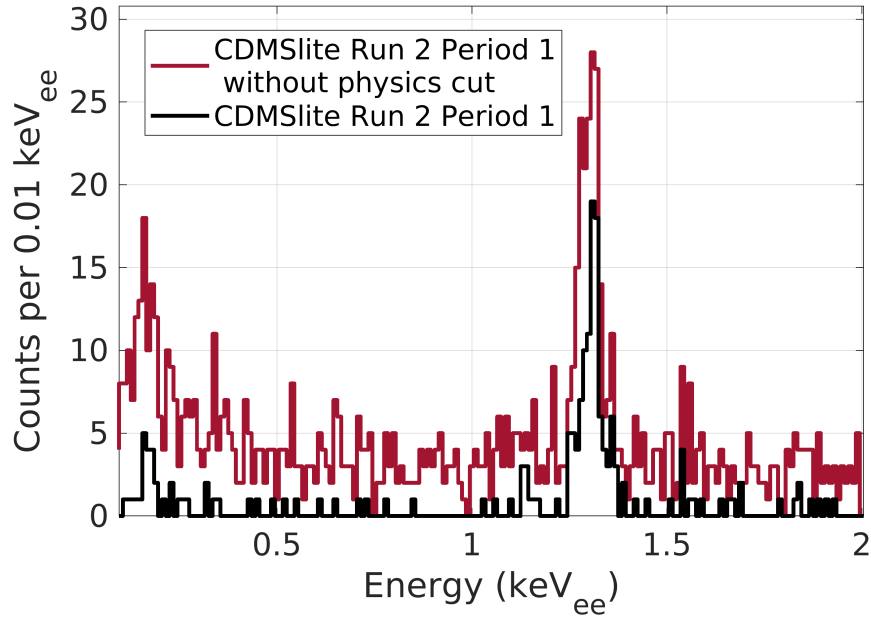
Figure 6.11 (a) shows the comparison of the data spectrum with (black) and without (red) application of physics cuts. There are 925 events in the spectrum without application of the physics cut. The physics cuts remove most of the events from the lower energy region, which is the area of optimal sensitivity for most of the considered LIPs in this analysis. Figure 6.11 (b) shows the comparison of the intensity limits calculated for two spectra described in Figure (a). The final intensity limit is ~ 2.1 times restrictive than the limit calculated for the spectrum without the application of the physics cut. This verifies the significance of these selection criteria as they helped improve the final limits and confirm no loss of potential LIPs signal.

Final Limit vs No-Singles Cut Limit

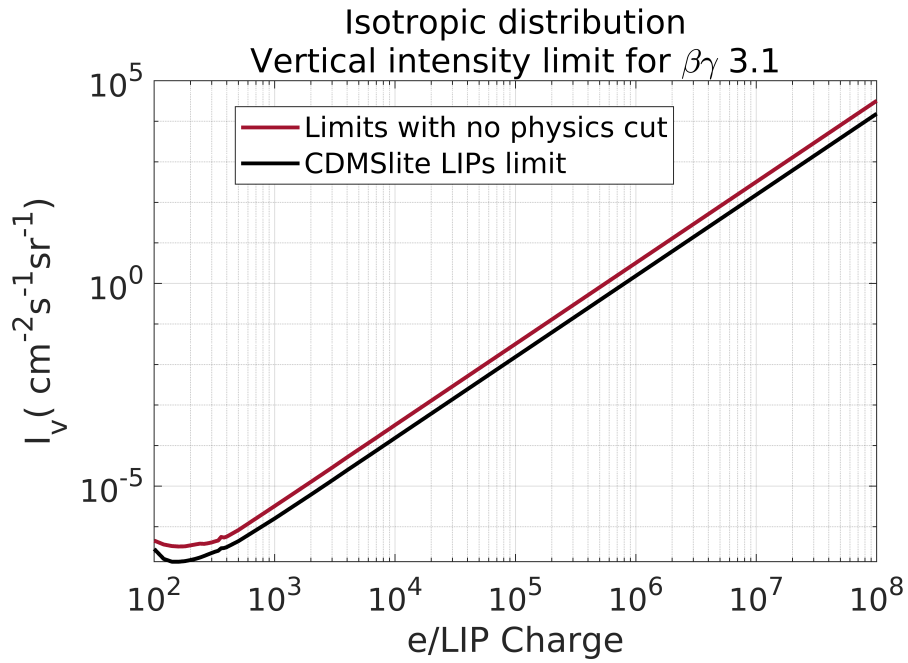
Similar to the check described above, the final intensity limit is compared with the intensity limit calculated for the spectrum obtained without the application of the singles cut. Figure 6.12 (a) shows both the spectra with (black) and without (red) application of singles cut and (b) shows the limit calculated for both of those spectra. There are 229 events in the spectra obtained without the application of the singles cut. For LIPs with $\beta\gamma$ value of 3.1, the final limit is nearly 1.2 times more restrictive which validates the robustness of the singles cut. For the largest fractional charge of $f=1/100$ considered, the limit becomes worse after applying the singles cut. This is because this LIP has a more significant probability of depositing energy greater than the upper energy threshold of this experiment, and the use of singles cut has minimal effect on it, but the more prominent correction factor of the singles cut causes it to have less restrictive limit after the application of the cut.

Final Limit vs No-Radial Cut Limit

In this check, the final intensity limit is compared with the intensity limit calculated for the spectrum obtained without the application of the radial cut. Figure 6.13 (a) shows both the spectra with (black) and without (red) application of radial cut and (b) shows the limit

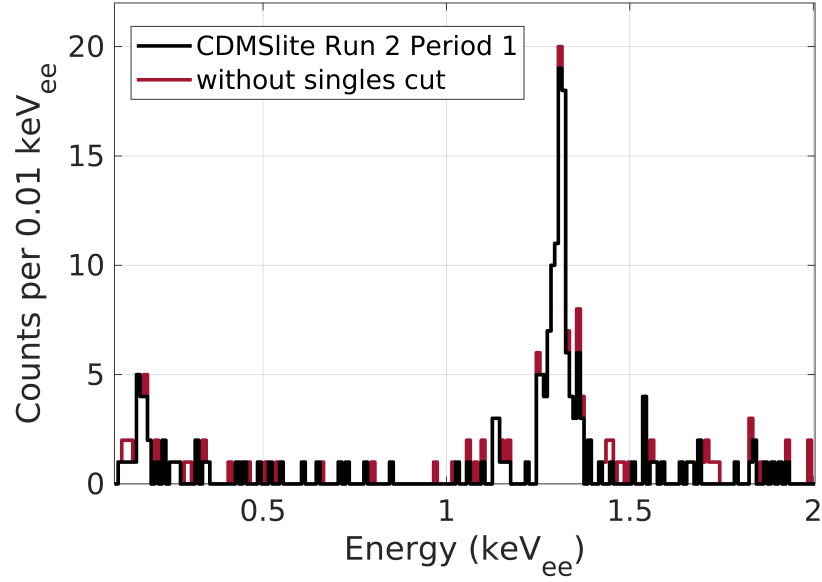


(a)

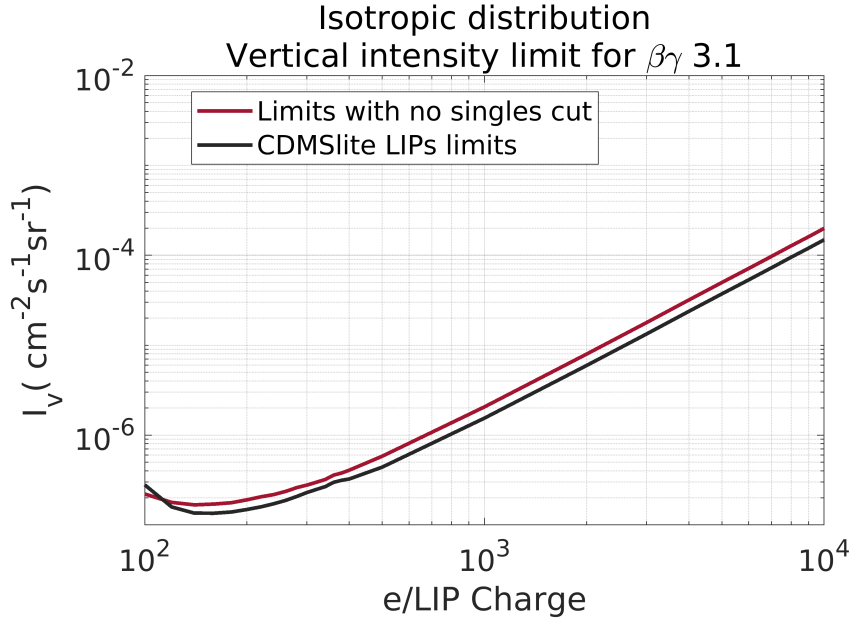


(b)

FIGURE 6.11: (a) This figure shows the energy spectrum of the CDMSlite Run2a data (black) compared with the data spectrum obtained after excluding all physics cuts (red). There are 925 events in the spectrum obtained after excluding all physics cuts. (b) This figure shows the comparison of LIPs vertical intensity (black) with the intensity calculated without utilizing the physics cut (red). The intensity for the spectrum excluding all physics process is nearly 2.1 times less restrictive than the black curve for most of the charges.



(a)



(b)

FIGURE 6.12: (a) This figure shows the energy spectrum of the CDMSlite Run2a data (red) compared with one of the data spectrum obtained after excluding singles cut (black). There are 229 events the spectra obtained without the application of the singles cut. (b) This figure shows the comparison of LIPs vertical intensity (black) with the intensity calculated after the exclusion of singles cut (red). The intensity calculated after the exclusion of singles cut is nearly 1.2 times less restrictive than the LIPs vertical intensity for $\beta\gamma$ value of 3.1. For the largest fractional charge of $f=1/100$ considered, the limit becomes worse after applying the singles cut because of its larger correction of singles cut efficiency.

calculated for both of those spectra. There are 229 events the spectra obtained without the application of the radial cut. The final limit is nearly 1.7 times more restrictive which validates the robustness of the singles cut.

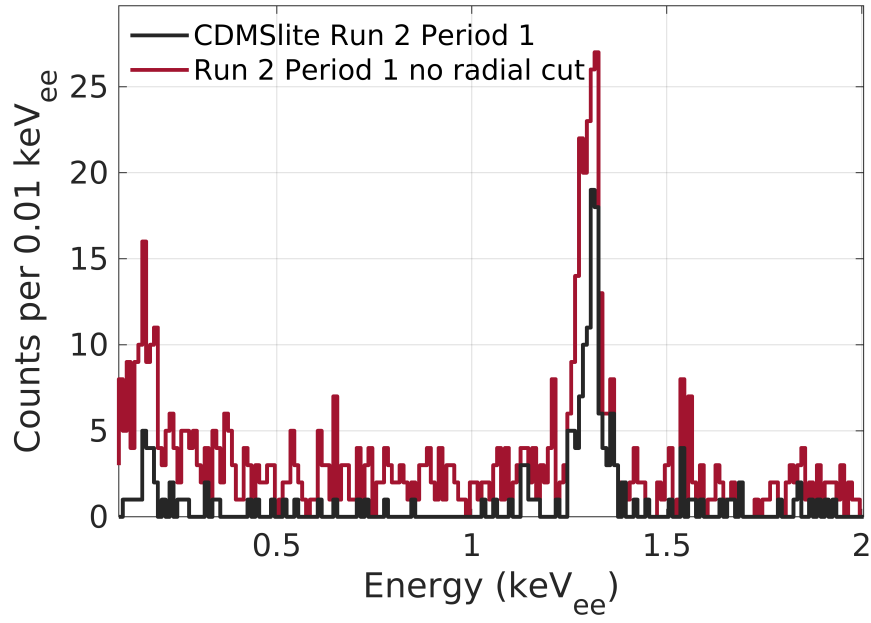
6.4.2 *Final Limits vs Extended Energy-Window*

A check is performed to observe the sensitivity of the LIP intensity limit on the choice of the low-energy analysis threshold. The intensity limit is calculated for minimum-ionizing LIPs using the data spectrum from 0.075 keV_{ee} to 2 keV_{ee}. As a reminder, the CDMSlite WIMP-search analysis utilized a low-energy analysis threshold of 0.075 keV_{ee}. So, this check is to evaluate the impact of our decision to use a more conservative low energy threshold of 0.1 keV_{ee}. This extending of the low energy threshold added one more event into the spectrum. Figure 6.14 (a) shows the data spectrum used for the limit calculation with a lowered energy threshold.

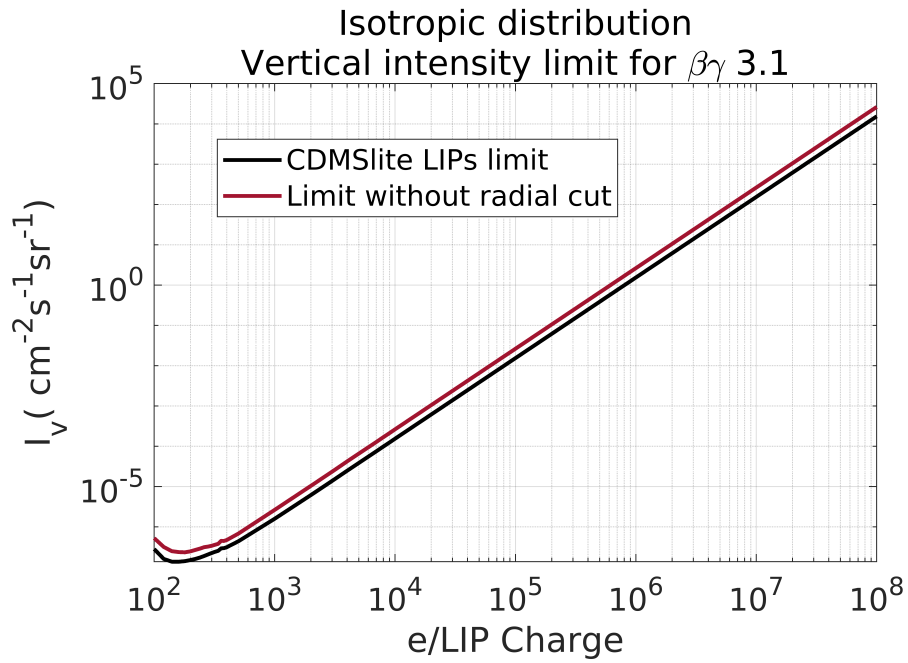
Figure 6.14 (b) compares the intensity limit calculated for extended energy window with the final intensity limit for minimum ionizing LIPs with an isotropic angular distribution. Extending the low energy threshold would have resulted in about 1.7 times stronger limit for most of the LIP charges. For LIPs with larger f whose optimal sensitivity is at the larger energy end of the spectrum, the intensity limit remains nearly the same. This check shows that the choice of a lower energy threshold of 0.1 keV_{ee}, for simplicity of the analysis, resulted in a 1.7 times worse limit.

6.4.3 *Final Limits vs 2 Half Lives Away from Cf Data*

The lower energy portion of the recoil spectrum considered is the most sensitive area for most LIPs for limit calculation. The M-shell activation peak dominates the lower energy portion. The number of M-shell events significantly decreases if data within 22.6 calendar days, two half-lives of ⁷⁸Ge electron capture decay, from ²⁵²Cf-calibration period is removed. We calculated the intensity limit using the data set with a reduced number of events in activation peaks.

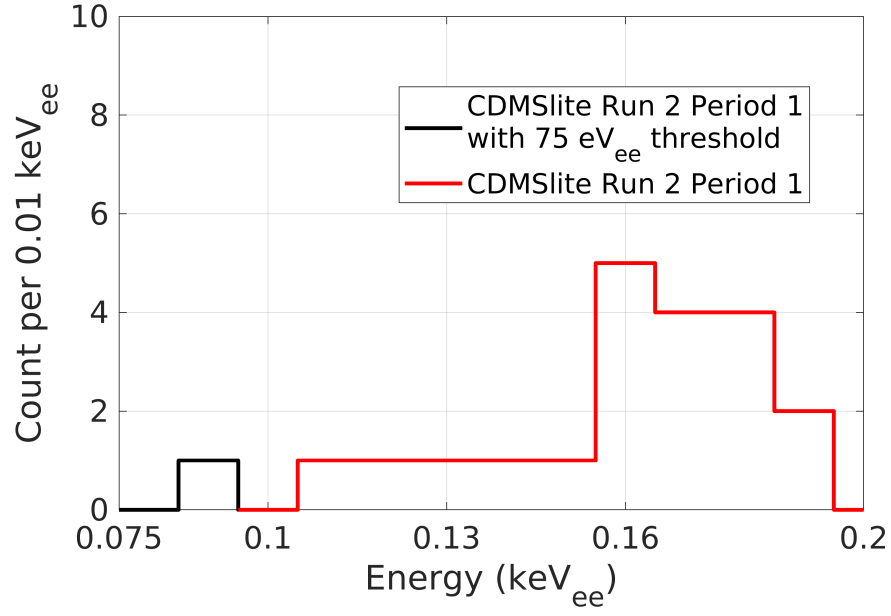


(a)

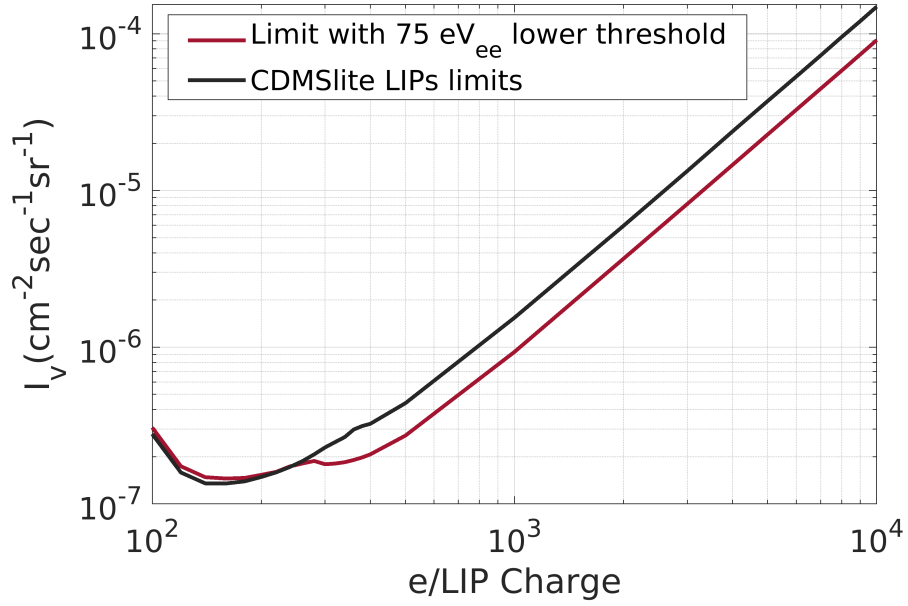


(b)

FIGURE 6.13: (a) This figure shows the energy spectrum of the CDMSlite Run2 Period 1 data (red) compared with one of the data spectrum obtained after excluding radial cut (black). There are 229 events in the spectra after excluding radial cut. (b) This figure shows the comparison of LIPs vertical intensity (black) with the intensity calculated after the exclusion of singles cut (red). The CDMSlite LIPs limits is nearly 1.7 times more restrictive than the limit for spectrum without the radial cut.



(a)



(b)

FIGURE 6.14: (a) This figure shows the energy spectrum of the data with an energy threshold of 75 eV_{ee} (black) and the CDMSlite Run 2 Period 1 spectrum in red. (b) This figure shows the comparison of the LIP vertical intensity (black) with the intensity calculated for spectrum with extended energy threshold (red). The intensity limit for an energy threshold of 75 eV_{ee} is nearly 1.7 times more restrictive than the CDMSlite LIPs vertical intensity for considered LIP charges with $\beta\gamma$ of 3.1.

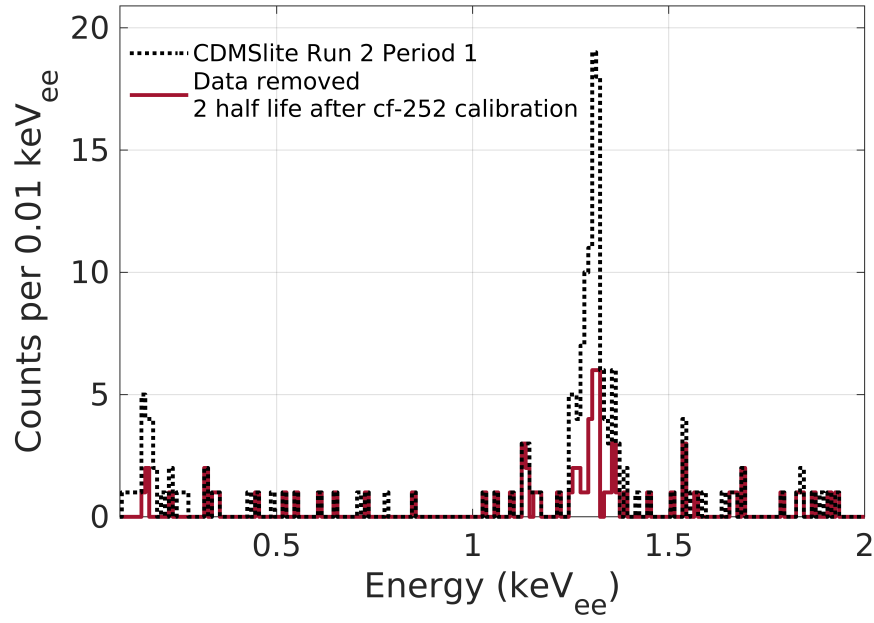
Figure 6.15 (a) shows the energy spectrum before (black dashed) and after (red solid) the removal of the events within 22.6 days from ^{252}Cf -calibration period. 90 events were removed after the application of these additional selection criteria which resulted in reduction of $\sim 38\%$ of total live time. 20 out of 34 events are removed between 0.1 to 0.5 keV $_{ee}$, which is the most sensitive area within our analysis range for limit calculation. Figure 6.15 (b) shows the limit (red) calculated for minimum ionizing LIPs with an isotropic angular distribution for the solid red spectrum shown in Figure (a) compared with the final intensity limit (black). The intensity limit improves by a factor of ~ 2 times for most of the considered LIPs after the application of this additional data-selection criteria. For LIPs with $f > 1/200$, the impact on the limit calculation is negligible as these LIPs are sensitive to the higher energy portion of the energy spectrum.

This analysis recommends an additional selection criterion to remove all the events in the time period following each Cf-calibration period for future analysis.

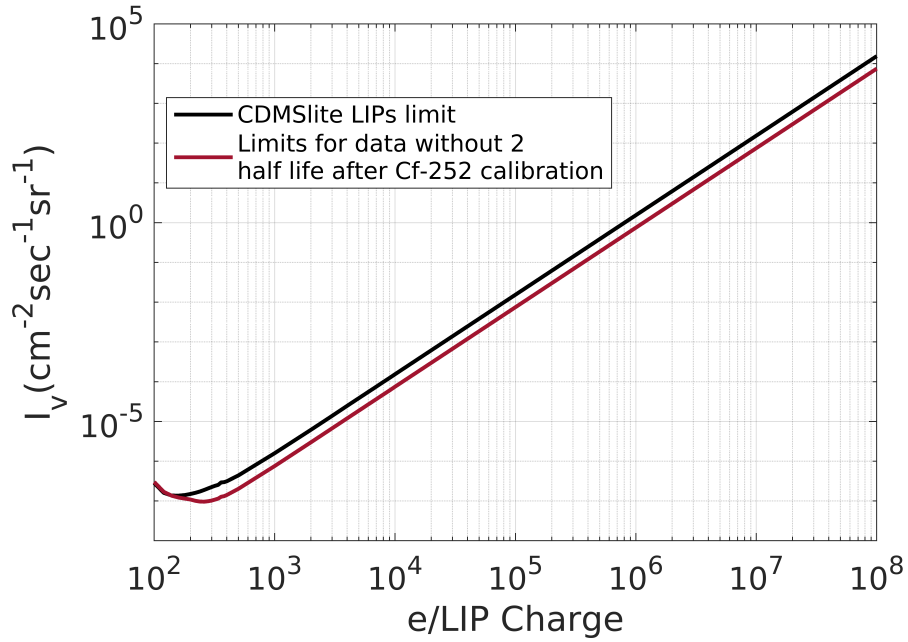
6.5 Summary

The thesis can be briefly summarized into the following point:

1. A LIP signal model is created for the first time using a GEANT4 Monte Carlo simulation. A LIP defined in GEANT4 interacts with an atom of the detector via ionization, bremsstrahlung, and pair production processes. All previous direct searches only considered depositions made through the ionization process. While using GEANT4, we can also generate signal models for various $\beta\gamma$ and LIP mass. This is the first direct LIP-search experiment to search for LIPs with various mass and $\beta\gamma$.
2. This work presents the first direct detection limits on the vertical intensity of cosmogenic LIPs with $f < 3.3 \times 10^{-6}$. The analysis also sets the strongest constraints on the intensity of minimum ionizing LIPs with $f < 1/160$. The low energy threshold of the CDMSlite detector allowed the analysis to compute the world-leading limits on LIPs.
3. This thesis also reports first-ever direct detection limits for LIPs with various $\beta\gamma$ from



(a)



(b)

FIGURE 6.15: (a) This figure shows the energy spectrum of the CDMSlite Run2a data (red) compared with one of the data spectrum obtained after the events within 22.6 days from ^{252}Cf -calibration period (black). (b) This figure shows the comparison of LIPs vertical intensity (black) with the intensity calculated for data spectrum in red. The intensity limit for spectrum obtained after removing events within 22.6 days from ^{252}Cf -calibration period is nearly 2 times more restrictive than the CDMSlite LIP intensity for $\beta\gamma$ of 3.1.

0.1 to 10^6 for mass range from $5 \text{ MeV}/c^2$ to $100 \text{ TeV}/c^2$. While non-relativistic LIPs have been proposed as a possible explanation for the DAMA [9] and CoGeNT [10] annual modulation signals [7, 8], no current result excludes this proposed explanation. Also, Munoz and Loeb [6] proposed a galactically bound dark matter model with the fractional charge to solve a baryonic temperature problem in the early universe. The result reported in the thesis represents a significant step towards searching for galactically bound dark matter with fractional charge by setting the first limit on non-relativistic LIPs with $\beta\gamma$ values as small as 0.1. This result reported sensitivity to $\beta\gamma$ values 30 times smaller than prior results. We still need a large factor of ~ 500 to search for galactically bound dark matter.

4. The angular distribution of incident LIPs is unknown. Plausible bounds on the angular distribution are isotropic and $\cos^2 \theta$. LIPs with smaller f have a small cross-section and are represented by isotropic distribution whereas LIPs with large f are represented by muon-like $\cos^2 \theta$ distribution. The vertical intensity limit for the $\cos^2 \theta$ distribution is ~ 3 times worse than that for the isotropic angular distribution for most of the smaller LIP charges considered.

6.6 Future Study

Some of the possible improvements for future study are listed below:

1. The analysis showed that the lower energy portion is the region of the optimal sensitivity for LIPs with smaller f . In one of the cross-checks performed on limits calculated for this analysis, lowering the lower threshold to 0.075 keV_{ee} from 0.1 keV_{ee} improved the limit by nearly 70%. So, data collected via a detector of an even lower threshold will improve the current final limit. The next version of the SuperCDMS experiment at SNOLAB, Canada, has a projected lower energy threshold of $\sim 3 \text{ eV}_{ee}$ for high voltage germanium detectors. The data collected from these extremely low threshold detectors should improve the sensitivity limit.

2. The LIP interaction probability increases as the distance traveled inside the detector increases. So, LIPs will have a greater probability of interacting with thicker detectors; thus, the intensity limits also improve for thicker detectors. SuperCDMS SNOLAB has a thick detector of 3.33 cm than compared to 2.54 cm of SOUDAN detectors. The LIP-search analysis using these thick detectors should lead to better sensitivity for LIPs.
3. This analysis uses a conservative OI method for calculating the upper limit on the possible number of LIPs. With a better understanding of the background, an analysis performed using the maximum likelihood method has a probability of discovery and would improve the intensity limits.

Appendix A

Energy Threshold and Live Time for Each Time Block for Singles Cut

Time blocks are detector-based groups of series of data taken as describe in Section 4.6.2. The total live time of CDMSlite Run 2 Period 1 is broken down into smaller time blocks where detector performance was comparable. The number of time blocks is different for each detector. For example, T3Z1 has 105 time blocks throughout the run, whereas T2Z2 has just 91 time blocks. I calculated the total live time for each time block which is also shown in Table A.1 and A.2 below. Williver [82] calculated singles cut threshold for each time block for all detectors, which is listed in Table A.3 and A.4. The singles cut threshold for each detector is defined using threshold and live time for each time block as described in Section 4.6.2.

T-B	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
1	0.02	0.12	0.12	0.02	0.12	0.02	0.12	0.02	0.02	0.02	0.12	0.12	0.12	0.02	0.02
2	0.12	0.12	0.12	0.12	0.12	0.02	0.12	0.02	0.12	0.02	0.12	0.12	0.12	0.12	0.02
3	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
4	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
5	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
6	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
7	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
8	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
9	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
10	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
13	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
14	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
15	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
16	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
17	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.11	0.12	0.12	0.12
18	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
19	0.12	0.12	0.11	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.03	0.12	0.12	0.12
20	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.12	0.12	0.12	0.11	0.12	0.11	0.12	0.12
21	0.11	0.12	0.03	0.11	0.03	0.12	0.12	0.12	0.11	0.12	0.12	0.01	0.12	0.11	0.12
22	0.12	0.03	0.12	0.12	0.12	0.11	0.03	0.11	0.12	0.11	0.03	0.12	0.03	0.12	0.11
23	0.03	0.12	0.01	0.03	0.01	0.12	0.12	0.12	0.03	0.12	0.12	0.07	0.12	0.03	0.12
24	0.12	0.01	0.12	0.12	0.12	0.03	0.01	0.03	0.12	0.03	0.01	0.06	0.01	0.12	0.03
25	0.01	0.12	0.07	0.01	0.07	0.12	0.12	0.12	0.01	0.12	0.12	0.07	0.12	0.01	0.12
26	0.12	0.07	0.06	0.12	0.06	0.01	0.07	0.01	0.12	0.01	0.07	0.12	0.07	0.12	0.01
27	0.07	0.06	0.07	0.07	0.07	0.12	0.06	0.12	0.07	0.12	0.06	0.11	0.06	0.07	0.12
28	0.06	0.07	0.12	0.06	0.12	0.07	0.07	0.07	0.06	0.07	0.07	0.09	0.07	0.06	0.07
29	0.07	0.12	0.11	0.07	0.11	0.06	0.12	0.06	0.07	0.06	0.12	0.11	0.12	0.07	0.06
30	0.12	0.11	0.09	0.12	0.09	0.07	0.11	0.07	0.12	0.07	0.11	0.11	0.11	0.12	0.07
31	0.11	0.09	0.11	0.11	0.11	0.12	0.09	0.12	0.11	0.12	0.09	0.05	0.09	0.11	0.12
32	0.09	0.11	0.11	0.09	0.11	0.11	0.11	0.11	0.09	0.11	0.11	0.12	0.11	0.09	0.11
33	0.11	0.11	0.05	0.11	0.05	0.09	0.11	0.09	0.11	0.09	0.11	0.11	0.11	0.11	0.09
34	0.11	0.05	0.12	0.11	0.12	0.11	0.05	0.11	0.11	0.11	0.05	0.11	0.05	0.11	0.11
35	0.05	0.12	0.11	0.05	0.11	0.11	0.12	0.11	0.05	0.11	0.12	0.11	0.12	0.05	0.11
36	0.12	0.11	0.11	0.12	0.11	0.05	0.11	0.05	0.12	0.05	0.11	0.11	0.11	0.12	0.05
37	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.12	0.11	0.12	0.11	0.11	0.11	0.11	0.12
38	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.06	0.11	0.11	0.11
39	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.09	0.11	0.11	0.11
40	0.11	0.11	0.06	0.11	0.06	0.11	0.11	0.11	0.11	0.11	0.11	0.07	0.11	0.11	0.11
41	0.11	0.06	0.09	0.11	0.09	0.11	0.06	0.11	0.11	0.11	0.06	0.07	0.06	0.11	0.11
42	0.06	0.09	0.07	0.06	0.07	0.11	0.09	0.11	0.06	0.11	0.09	0.07	0.09	0.06	0.11
43	0.09	0.07	0.07	0.09	0.07	0.06	0.07	0.06	0.09	0.06	0.07	0.12	0.07	0.09	0.06
44	0.07	0.07	0.07	0.07	0.07	0.09	0.07	0.09	0.07	0.09	0.07	0.11	0.07	0.07	0.09
45	0.07	0.07	0.12	0.07	0.12	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
46	0.07	0.12	0.11	0.07	0.11	0.07	0.12	0.07	0.07	0.07	0.12	0.07	0.12	0.07	0.07
47	0.12	0.11	0.07	0.12	0.07	0.07	0.11	0.07	0.12	0.07	0.11	0.07	0.11	0.12	0.07
48	0.11	0.07	0.07	0.11	0.07	0.12	0.07	0.12	0.11	0.12	0.07	0.06	0.07	0.11	0.12
49	0.07	0.07	0.07	0.07	0.07	0.11	0.07	0.11	0.07	0.11	0.07	0.07	0.07	0.07	0.11
50	0.07	0.07	0.06	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
51	0.07	0.06	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07	0.06	0.06	0.06	0.07	0.07
52	0.06	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.12	0.07	0.06	0.07
53	0.07	0.07	0.06	0.07	0.06	0.06	0.07	0.06	0.07	0.06	0.07	0.09	0.07	0.07	0.06
54	0.07	0.06	0.12	0.07	0.12	0.07	0.06	0.07	0.07	0.07	0.06	0.12	0.06	0.07	0.07
55	0.06	0.12	0.09	0.06	0.09	0.07	0.12	0.07	0.06	0.07	0.12	0.10	0.12	0.06	0.07
56	0.12	0.09	0.12	0.12	0.12	0.06	0.09	0.06	0.12	0.06	0.09	0.09	0.09	0.12	0.06
57	0.09	0.12	0.10	0.09	0.10	0.12	0.12	0.12	0.09	0.12	0.12	0.07	0.12	0.09	0.12
58	0.12	0.10	0.09	0.12	0.09	0.09	0.10	0.09	0.12	0.09	0.10	0.06	0.10	0.12	0.09
59	0.10	0.09	0.07	0.10	0.07	0.12	0.09	0.12	0.10	0.12	0.09	0.11	0.09	0.10	0.12
60	0.09	0.07	0.06	0.09	0.06	0.10	0.07	0.10	0.09	0.10	0.07	0.09	0.07	0.09	0.10

Table A.1: The total live time for each time block (1-61) throughout SuperCDMS Run 134 in units of days. All the live times are for these time blocks are used to calculate the singles cut threshold as described in Section 4.6.2. First Column (T-B) is the time block number, whereas 'Z' in all other columns represents detector number.

T-B	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
61	0.07	0.06	0.11	0.07	0.11	0.09	0.06	0.09	0.07	0.09	0.06	0.07	0.06	0.07	0.09
62	0.06	0.11	0.09	0.06	0.09	0.07	0.11	0.07	0.06	0.07	0.11	0.12	0.11	0.06	0.07
63	0.11	0.09	0.07	0.11	0.07	0.06	0.09	0.06	0.11	0.06	0.09	0.11	0.09	0.11	0.06
64	0.09	0.07	0.12	0.09	0.12	0.11	0.07	0.11	0.09	0.11	0.07	0.07	0.07	0.09	0.11
65	0.07	0.12	0.11	0.07	0.11	0.09	0.12	0.09	0.07	0.09	0.12	0.12	0.12	0.07	0.09
66	0.12	0.11	0.07	0.12	0.07	0.07	0.11	0.07	0.12	0.07	0.11	0.10	0.11	0.12	0.07
67	0.11	0.07	0.12	0.11	0.12	0.12	0.07	0.12	0.11	0.12	0.07	0.11	0.07	0.11	0.12
68	0.07	0.12	0.10	0.07	0.10	0.11	0.12	0.11	0.07	0.11	0.12	0.11	0.12	0.07	0.11
69	0.12	0.10	0.11	0.12	0.11	0.07	0.10	0.07	0.12	0.07	0.10	0.07	0.10	0.12	0.07
70	0.10	0.11	0.11	0.10	0.11	0.12	0.11	0.12	0.10	0.12	0.11	0.11	0.11	0.10	0.12
71	0.11	0.11	0.07	0.11	0.07	0.10	0.11	0.10	0.11	0.10	0.11	0.11	0.11	0.11	0.10
72	0.11	0.07	0.11	0.11	0.11	0.11	0.07	0.11	0.11	0.11	0.07	0.11	0.07	0.11	0.11
73	0.07	0.11	0.11	0.07	0.11	0.11	0.11	0.11	0.07	0.11	0.11	0.05	0.11	0.07	0.11
74	0.11	0.11	0.11	0.11	0.11	0.07	0.11	0.07	0.11	0.07	0.11	0.12	0.11	0.11	0.07
75	0.11	0.11	0.05	0.11	0.05	0.11	0.11	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11
76	0.11	0.05	0.12	0.11	0.12	0.11	0.05	0.11	0.11	0.11	0.05	0.12	0.05	0.11	0.11
77	0.05	0.12	0.12	0.05	0.12	0.11	0.12	0.11	0.05	0.11	0.12	0.12	0.12	0.05	0.11
78	0.12	0.12	0.12	0.12	0.12	0.05	0.12	0.05	0.12	0.05	0.12	0.05	0.12	0.12	0.05
79	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.05	0.12	0.12	0.12
80	0.12	0.12	0.05	0.12	0.05	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
81	0.12	0.05	0.05	0.12	0.05	0.12	0.05	0.12	0.12	0.12	0.05	0.12	0.05	0.12	0.12
82	0.05	0.05	0.12	0.05	0.12	0.12	0.05	0.12	0.05	0.12	0.05	0.12	0.05	0.05	0.12
83	0.05	0.12	0.12	0.05	0.12	0.05	0.12	0.05	0.05	0.05	0.12	0.12	0.12	0.05	0.05
84	0.12	0.12	0.12	0.12	0.12	0.05	0.12	0.05	0.12	0.05	0.12	0.07	0.12	0.12	0.05
85	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	31.02	0.12	0.12	0.12
86	0.12	0.12	0.07	0.12	0.07	0.12	0.12	0.12	0.12	0.12	0.12	61.46	0.12	0.12	0.12
87	0.12	0.07	31.02	0.12	30.44	0.12	0.07	0.12	0.12	0.12	0.07	4.31	0.07	0.12	0.12
88	0.07	12.73	61.69	0.07	62.04	0.12	24.54	0.12	0.07	0.12	30.32	4.51	9.38	0.07	0.12
89	12.85	43.52	4.25	30.44	8.95	0.07	20.37	0.07	30.44	0.07	62.27	9.26	15.74	30.56	0.07
90	17.59	36.34	4.35	62.27	8.78	31.02	3.09	31.02	50.00	30.90	8.72	21.41	8.29	61.92	93.29
91	62.04	4.84	9.48	4.36	22.57	61.34	3.77	61.57	11.92	61.46	9.03	0.62	3.34	8.95	3.74
92	8.95	4.11	17.01	4.35	—	4.59	8.81	4.97	5.19	8.95	17.48	—	3.89	31.37	4.41
93	9.48	8.90	4.81	31.37	—	4.35	7.33	3.75	3.87	9.14	4.19	—	4.19	—	31.37
94	2.62	6.17	—	—	—	8.90	2.91	8.44	8.90	12.73	0.62	—	14.93	—	—
95	18.63	16.20	—	—	—	12.50	8.98	17.71	6.17	4.54	—	—	8.63	—	—
96	0.62	—	—	—	—	5.13	6.76	4.24	15.63	2.67	—	—	12.27	—	—
97	—	—	—	—	—	2.67	5.30	0.97	0.62	1.18	—	—	11.57	—	—
98	—	—	—	—	—	1.17	2.23	—	—	1.08	—	—	1.88	—	—
99	—	—	—	—	—	0.97	7.30	—	—	—	—	—	7.30	—	—
100	—	—	—	—	—	—	3.80	—	—	—	—	—	9.38	—	—
101	—	—	—	—	—	—	4.28	—	—	—	—	—	2.60	—	—
102	—	—	—	—	—	—	3.08	—	—	—	—	—	10.46	—	—
103	—	—	—	—	—	—	11.16	—	—	—	—	—	6.75	—	—
104	—	—	—	—	—	—	4.29	—	—	—	—	—	1.17	—	—
105	—	—	—	—	—	—	3.74	—	—	—	—	—	0.97	—	—
106	—	—	—	—	—	—	0.97	—	—	—	—	—	—	—	—

Table A.2: The total live time for each time block (61-106) throughout SuperCDMS Run 134 in units of days. All the live times for these time blocks are used to calculate the singles cut threshold as described in Section 4.6.2. First Column (T-B) is the time block number, whereas 'Z' in all other columns represents detector number.

T-B	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
1	1.39	2.40	1.97	1.35	1.37	3.84	5.30	4.06	1.97	0.35	2.46	1.32	6.22	0.45	1.34
2	1.43	3.25	2.30	1.62	1.32	2.70	5.51	2.91	1.66	0.32	3.81	1.16	6.89	0.46	1.25
3	1.74	2.91	2.18	1.58	1.50	4.75	11.54	3.19	2.46	0.33	3.81	1.09	5.73	0.42	1.46
4	1.68	2.51	1.69	1.96	1.35	5.17	5.92	3.40	1.54	0.34	4.36	1.06	6.57	0.42	1.48
5	1.55	1.90	1.47	1.76	1.30	6.53	7.10	4.53	1.74	0.34	2.90	1.03	5.20	0.41	1.47
6	1.66	2.43	2.09	1.87	1.47	6.66	9.00	3.74	1.74	0.34	2.17	1.25	6.16	0.43	1.39
7	1.48	2.28	1.98	1.44	1.32	4.00	7.47	3.96	1.48	0.33	2.53	1.06	6.27	0.40	1.18
8	1.66	1.96	2.19	1.39	1.38	2.50	11.11	4.06	1.68	0.34	2.64	0.97	7.09	0.38	0.97
9	1.73	2.62	2.27	1.38	1.30	2.31	9.97	3.45	1.47	0.33	2.61	1.02	6.36	0.44	1.30
10	1.30	1.92	1.93	1.58	1.23	2.55	8.86	2.67	1.73	0.34	2.08	0.92	6.10	0.38	1.16
11	1.60	1.95	2.57	1.49	1.20	3.28	10.98	3.13	1.71	0.35	2.43	1.14	4.72	0.41	1.11
12	1.77	1.99	2.30	1.22	1.12	2.66	11.71	5.41	1.42	0.33	2.14	1.03	7.28	0.40	1.09
13	1.25	2.16	1.74	1.24	1.23	3.71	7.05	3.06	1.70	0.36	2.06	1.22	4.23	0.41	1.18
14	1.53	2.22	1.81	1.31	1.07	2.66	5.87	3.48	1.57	0.33	1.73	1.29	5.83	0.43	1.09
15	1.78	1.49	2.33	1.39	0.90	3.31	7.57	3.69	1.60	0.34	2.40	1.31	6.13	0.42	0.97
16	1.30	1.79	2.07	1.15	1.35	2.16	10.81	3.95	1.21	0.35	1.84	1.38	5.90	0.40	1.06
17	1.45	1.87	2.00	1.16	1.37	2.61	4.79	2.31	1.48	0.33	2.26	1.22	9.31	0.38	1.01
18	1.38	2.29	2.15	1.28	1.29	2.61	7.05	3.56	1.58	0.33	1.72	1.40	5.62	0.43	0.99
19	1.44	2.27	1.87	1.55	1.29	3.36	8.79	3.13	1.59	0.33	2.12	1.16	5.22	2.14	1.43
20	1.62	2.10	1.63	1.58	1.63	3.00	10.71	2.60	1.45	1.61	2.43	1.35	17.02	2.10	1.39
21	1.39	2.47	1.71	1.59	1.18	2.26	3.35	2.94	1.83	2.85	2.70	1.19	6.08	2.21	1.26
22	1.52	1.86	2.15	1.64	1.27	4.38	4.84	3.70	1.88	2.51	2.76	1.21	4.15	2.06	1.31
23	1.41	3.10	2.06	1.59	1.48	2.77	14.99	3.38	1.65	1.66	2.96	1.17	5.47	2.14	1.33
24	1.68	2.45	2.08	1.60	1.39	4.33	11.65	3.20	1.78	1.89	2.11	1.10	4.26	2.51	1.19
25	1.50	2.44	1.96	1.63	1.21	3.67	11.57	5.23	1.75	8.85	2.68	1.09	4.98	11.67	1.16
26	1.77	2.01	2.55	1.86	1.40	3.14	7.98	4.93	2.23	6.49	2.19	1.47	4.75	2.35	1.00
27	1.38	2.43	3.28	1.62	1.46	4.60	13.92	4.22	2.05	8.76	2.04	1.27	5.29	11.50	1.26
28	1.43	2.22	2.01	3.13	1.40	3.52	11.90	3.86	1.94	7.07	3.04	1.11	5.07	12.05	1.05
29	1.51	2.09	2.40	2.77	1.19	6.59	4.71	3.63	2.02	1.60	3.58	1.28	4.70	3.19	1.18
30	1.72	2.72	2.18	2.80	1.44	4.27	19.89	5.07	1.60	2.38	4.99	1.11	5.81	2.17	1.17
31	1.58	2.29	2.14	3.06	1.25	4.91	4.70	5.23	1.77	1.71	1.92	1.20	4.41	11.16	1.14
32	1.38	3.04	2.12	3.23	1.40	5.29	4.72	5.29	2.49	6.17	2.81	1.34	5.45	2.56	1.04
33	1.57	2.48	2.33	1.44	1.44	2.77	8.35	3.87	1.80	1.84	2.11	1.29	4.78	10.38	1.22
34	1.67	2.20	2.09	1.57	1.58	3.38	9.34	4.49	1.87	1.84	2.33	1.07	6.26	10.30	1.15
35	1.32	2.58	2.08	1.43	1.31	3.94	6.85	5.33	1.72	1.88	2.57	1.23	5.75	10.76	1.03
36	1.67	2.22	2.20	1.68	1.24	3.21	11.44	4.96	1.88	1.87	3.16	1.14	6.40	2.99	1.09
37	1.51	2.79	2.19	1.38	1.31	4.22	7.33	4.86	1.69	1.62	2.53	1.14	4.81	11.39	1.46
38	1.63	2.26	2.07	1.38	1.35	3.88	4.41	4.14	1.70	1.54	3.01	1.17	4.71	11.62	1.37
39	1.62	2.57	2.04	1.58	1.28	3.71	4.39	3.58	1.81	1.99	3.12	1.16	4.56	11.60	1.04
40	1.53	3.03	2.06	1.56	1.23	4.66	4.78	4.10	1.60	1.73	2.71	0.94	5.42	11.07	1.19
41	1.51	2.38	2.30	1.38	1.37	3.16	8.30	4.80	1.83	1.87	2.33	1.22	3.75	11.49	1.12
42	1.64	2.33	2.07	1.35	1.20	3.18	3.69	4.68	1.80	1.91	2.06	1.22	5.62	2.40	1.25
43	1.45	2.87	1.89	1.38	1.17	3.42	6.58	4.80	1.71	1.82	2.62	1.22	5.79	2.19	1.19
44	1.72	2.28	2.76	1.62	1.28	3.39	6.23	3.80	1.66	1.67	2.32	1.35	6.53	2.03	1.27
45	1.48	2.08	2.05	1.28	1.17	2.50	4.26	4.36	1.42	1.60	2.41	1.21	4.20	1.69	1.05
46	1.74	2.53	2.09	1.58	1.40	2.56	5.18	2.57	1.40	1.62	2.37	1.08	4.50	2.28	0.98
47	1.55	2.74	2.28	1.27	1.23	3.06	11.22	3.54	1.74	1.43	2.29	1.06	5.28	2.25	1.14
48	1.43	2.28	2.15	1.41	1.15	3.11	6.51	4.14	1.68	1.53	2.67	1.00	4.70	11.77	1.08
49	1.82	2.20	2.46	1.46	1.15	2.91	7.39	4.80	1.62	1.71	2.53	1.12	5.83	10.76	1.23
50	1.44	2.05	1.79	1.48	1.20	3.89	7.69	4.67	1.48	1.72	2.05	1.21	3.81	2.80	1.03
51	1.52	2.05	2.59	1.34	1.24	3.15	6.74	3.61	1.65	1.29	2.28	1.09	7.07	1.92	0.94
52	1.52	2.75	2.48	1.44	1.21	2.78	18.82	3.80	1.51	1.46	2.72	1.24	7.67	2.50	0.96
53	1.96	2.40	2.37	1.65	1.31	3.50	10.27	3.44	1.77	1.60	2.59	1.29	4.94	2.82	1.08
54	1.66	3.12	2.38	1.52	1.15	3.16	6.01	5.71	1.81	1.65	3.08	1.23	5.31	2.14	1.05
55	1.83	2.63	2.13	1.61	1.39	4.14	7.30	5.37	1.81	1.45	2.46	1.16	5.57	2.23	1.14
56	1.65	2.55	1.96	1.55	1.25	3.32	5.31	5.16	1.83	1.71	1.98	1.16	5.09	2.42	1.13
57	1.52	1.94	2.28	1.44	1.21	3.56	7.56	5.50	1.74	2.24	2.15	1.17	6.86	4.69	1.06
58	1.63	2.84	2.14	1.67	1.26	2.47	5.45	4.43	1.37	1.95	2.32	1.28	5.17	2.93	1.20
59	1.95	2.34	1.88	1.43	1.36	3.13	6.13	7.29	1.90	1.95	2.21	1.11	9.42	9.06	1.10
60	1.41	2.47	2.24	1.33	1.20	2.98	8.07	6.74	2.05	1.88	2.54	1.20	6.11	2.34	1.07

Table A.3: The singles cut energy threshold for each time block (1-60) throughout Super-CDMS Run 134 in keV units. All these thresholds are used for the calculation of the singles cut threshold as described in Section 4.6.2. First Column (T-B) is the time block number, whereas 'Z' in all other columns represents detector number.

T-B	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14	Z15
61	1.48	2.66	2.31	1.41	1.21	3.32	8.81	4.07	1.64	1.57	2.52	1.14	4.85	3.65	1.21
62	1.70	2.34	2.10	1.70	1.41	3.58	5.19	5.11	1.61	1.85	2.78	1.19	4.03	1.62	1.00
63	1.85	2.63	1.84	1.60	1.39	3.43	10.82	3.36	1.92	1.58	2.48	1.27	4.85	1.90	1.09
64	1.77	2.09	1.98	1.37	1.24	2.83	6.80	6.31	1.98	1.36	2.27	1.14	4.74	2.10	1.02
65	1.39	1.97	2.19	1.35	1.14	3.97	17.76	3.76	1.49	1.59	2.71	1.21	4.74	2.80	1.04
66	1.31	2.52	2.45	1.60	1.28	2.05	6.29	3.95	1.92	1.46	2.49	1.45	5.88	2.12	1.05
67	1.70	2.74	2.13	1.40	1.33	2.61	3.83	4.18	1.67	1.82	2.66	1.17	5.57	11.89	1.16
68	1.64	2.85	2.30	1.43	1.26	2.85	10.59	4.20	1.61	1.73	3.20	1.26	4.50	10.60	1.18
69	1.53	2.79	1.93	1.56	1.22	3.55	8.80	4.68	1.65	1.89	3.43	1.17	5.40	2.20	1.06
70	1.44	2.35	2.05	1.50	1.28	2.65	14.93	5.84	1.75	1.45	2.48	1.25	10.42	8.02	1.59
71	1.52	2.20	2.00	1.51	1.22	5.50	4.42	4.56	1.73	3.07	2.73	1.11	6.15	8.03	1.24
72	1.31	1.96	2.02	1.29	1.32	4.58	9.55	5.27	1.73	1.63	2.17	1.15	5.78	10.91	1.25
73	1.55	2.39	2.06	1.35	1.46	3.04	6.76	4.47	1.67	2.07	2.50	1.10	4.21	9.30	1.10
74	1.39	2.33	1.94	1.46	1.26	2.51	7.08	4.24	1.76	1.49	2.99	1.57	6.33	6.62	1.20
75	1.71	2.31	2.07	1.58	1.29	3.12	6.94	5.17	1.53	2.08	2.68	1.20	6.60	6.37	1.27
76	1.36	1.90	1.84	1.43	1.20	3.63	7.09	4.66	1.89	2.02	3.07	1.22	4.39	4.74	1.35
77	1.59	2.44	2.26	1.31	1.41	2.77	6.17	5.02	1.76	1.88	3.00	1.32	4.68	6.97	1.31
78	1.42	1.94	1.98	1.55	1.51	2.88	6.53	6.08	1.86	1.60	4.00	1.14	5.12	1.66	1.32
79	1.61	2.57	2.12	1.61	1.33	2.90	11.48	4.91	1.94	2.07	2.28	1.41	4.69	2.26	1.18
80	1.54	2.51	1.66	1.61	1.23	3.53	5.59	4.58	2.10	2.18	3.59	1.17	5.43	2.48	1.39
81	1.58	2.16	1.90	1.75	1.28	3.55	4.76	4.34	1.70	1.75	1.75	1.09	4.97	2.13	1.44
82	1.41	2.38	2.67	1.53	1.52	3.76	6.04	5.62	1.37	1.85	3.18	1.19	5.29	2.40	1.40
83	1.40	1.99	2.06	1.75	1.37	2.68	6.18	4.79	1.79	1.62	3.72	1.10	6.15	9.74	1.60
84	1.45	2.34	2.36	1.74	1.44	3.32	11.05	3.67	1.94	1.28	2.94	1.36	4.94	2.77	1.39
85	1.59	3.04	2.41	1.74	1.39	5.26	5.56	4.16	1.93	1.82	2.67	1.23	4.27	2.54	1.33
86	1.58	2.57	1.92	1.42	1.20	4.98	8.81	4.71	1.55	1.61	2.42	1.07	4.60	2.45	1.22
87	1.91	2.92	2.28	1.48	1.32	5.69	7.95	6.31	1.64	2.47	2.51	1.36	4.56	2.48	1.20
88	1.50	2.35	1.74	1.39	1.08	2.66	8.96	4.43	1.58	1.66	2.73	1.23	5.30	2.43	1.12
89	1.56	2.09	1.98	1.60	1.45	3.99	8.95	5.79	1.83	1.97	2.33	1.16	6.00	2.93	1.21
90	1.70	1.71	1.75	1.04	1.17	4.56	6.50	5.40	1.66	1.87	2.41	1.40	6.26	1.78	1.12
91	1.27	2.50	1.82	1.39	1.65	2.99	5.18	3.75	1.74	2.02	2.90	1.66	9.02	2.34	1.28
92	1.54	1.74	1.91	1.08	–	3.37	5.65	4.31	1.87	2.03	3.57	–	6.25	1.40	1.02
93	1.44	1.99	2.01	1.50	–	2.71	5.81	3.40	1.75	3.38	4.68	–	6.96	–	1.31
94	1.54	2.94	–	–	–	3.41	20.10	3.24	1.91	4.68	6.94	–	5.63	–	–
95	1.46	2.92	–	–	–	4.75	9.27	3.66	2.30	3.77	–	–	7.28	–	–
96	1.59	–	–	–	–	3.80	16.32	3.88	2.51	6.18	–	–	7.44	–	–
97	–	–	–	–	–	5.08	6.73	4.61	3.92	4.70	–	–	8.06	–	–
98	–	–	–	–	–	3.51	15.64	–	–	7.76	–	–	6.95	–	–
99	–	–	–	–	–	7.68	9.43	–	–	–	–	–	6.52	–	–
100	–	–	–	–	–	–	7.53	–	–	–	–	–	5.55	–	–
101	–	–	–	–	–	–	6.00	–	–	–	–	–	5.89	–	–
102	–	–	–	–	–	–	8.67	–	–	–	–	–	6.12	–	–
103	–	–	–	–	–	–	8.01	–	–	–	–	–	6.27	–	–
104	–	–	–	–	–	–	9.80	–	–	–	–	–	6.60	–	–
105	–	–	–	–	–	–	8.12	–	–	–	–	–	6.18	–	–
106	–	–	–	–	–	–	15.23	–	–	–	–	–	–	–	–

Table A.4: The singles cut energy threshold for each time block (61-106) throughout Super-CDMS Run 134 in keV units. All these thresholds are used for the calculation of the singles cut threshold as described in Section 4.6.2. First Column (T-B) is the time block number, whereas 'Z' in all other columns represents detector number.

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