

MEASUREMENT OF COSMOGENIC PRODUCTION RATES IN GE WITH CDMSlite

by

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Abstract

The majority of matter in the Universe is non-luminous, non-baryonic, and as of yet undiscovered. The SuperCDMS experiment searches for this “dark matter” in the form of Weakly Interacting Massive Particles (WIMPs), operating semiconducting detectors at cryogenic temperatures to measure energy deposits from dark matter interactions. These efforts have resulted in world leading limits on the interactions of dark matter with ordinary matter. The next phase of SuperCDMS is under construction at SNOLAB near Sudbury, ON.

Interaction of cosmic rays with detector material can result in the production of radioactive isotopes, the decay of which results in background in the measured energy spectrum. Tritium is expected to be the limiting background for SuperCDMS SNO-LAB. Production rates of tritium and other cosmogenic isotopes are not well known, with a wide spread in theoretical calculated rates and only a single measurement previously published for tritium. The work in this thesis details the measurement of cosmogenic production rates using low energy spectra measured by SuperCDMS.

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List of Acronyms

BBN	Big Bang nucleosynthesis
CDF	cumulative distribution function
CDM	cold dark matter
CDMSlite	CDMS low ionization threshold experiment
CMB	Cosmic Microwave Background
DM	dark matter
EC	electron capture
ER	electron recoil
GS	ground state
HDM	hot dark matter
HV	high voltage
iZIP	interleaved Z-sensitive ionization and phonon
JFET	junction gate field-effect transistor
KK	Kaluza-Klein
LHC	Large Hadron Collider
LKP	lightest Kaluza-Klein particle
LSP	lightest supersymmetric particle
LSS	large scale structure
MACHO	MAssive Compact Halo Object
MOND	MOdified Newtonian dynamics

MSSM	minimal SUSY model
NR	nuclear recoil
NTL	Neganov-Trofimov-Luke
PDF	probability distribution function
QET	Quasiparticle-trap-assisted Electrothermal- feedback Transition-edge-sensor
SM	Standard Model
SuperCDMS	Super Cryogenic Dark Matter Search
SUSY	supersymmetry
TES	Transition Edge Sensor
UED	Universal Extra Dimensions
WDM	warm dark matter
WIMP	Weakly Interacting Massive Particle

Part I

Introduction

Thesis Motivation

Despite the many successes of the Standard Model (SM) of Particle Physics, one of its significant shortcomings is the inability to account for dark matter, a non-luminous, non-baryonic type of matter constituting approximately 25% of the energy density of the Universe [1, 2]. While dark matter itself has not been directly observed, its presence and properties can be inferred through various astrophysical observations.

This thesis begins with an overview of evidence for the existence of dark matter, as well as some properties of dark matter that can be inferred from this evidence. A variety of well motivated candidates for dark matter are presented.

The Super Cryogenic Dark Matter Search experiment looks for dark matter, primarily in the form of Weakly Interacting Massive Particles. The experiment is kept deep underground in order to shield from cosmic rays, which are a significant source of background on Earth's surface. However, exposure of material to cosmic rays results in the production of isotopes within the material. If radioisotopes are produced in detectors while they are being fabricated and tested on Earth's surface, their decay results in background in sensitive experiments.

Production rates of radioisotopes in germanium are not well understood. In the main work of this thesis, CDMSlite data is used in order to measure cosmogenic production rates of radioisotopes in the CDMSlite detectors while above ground.

Chapter 1

Missing Matter

Here a brief review of dark matter is given. Some of the most compelling evidence for dark matter is described in Section 1.1, and Section 1.2 motivates the need to search beyond the SM for answers. In Section 1.3, freezeout and the dark matter (DM) temperature scale are introduced in the context the thermal history of the early Universe. Well motivated particle candidates for dark matter are discussed in Section 1.4; non-particle solutions are discussed in Section 1.5. Finally, the main experimental search channels for DM are described in Section 1.6.

1.1 Evidence For Dark Matter

Current evidence for the existence of dark matter comes from gravitational observations on various scales. Rotation curves of galaxies provide information of the dark matter content of a single galaxy; information on a larger scale comes from measurements gravitational lensing by objects such as galaxy clusters. On the largest scale, the entire dark matter content of the Universe can be inferred using anisotropies in the Cosmic Microwave Background (CMB).

1.1.1 Galactic Rotation Curves

Convincing evidence for dark matter on galactic scales comes from measurements of galactic rotation curves, which show the relationship between the orbital velocity and the radial distance of visible stars or gas from the centre of a galaxy.

In the 1930's, observations of the M31 disk found that the outer regions of the galaxy were moving at higher velocities than anticipated from the distribution of visible matter [3]. This observation was confirmed over thirty years later [4, 5]. The expected curve falls as $r^{-1/2}$ for distances greater than the main galactic distribution (Kepler's laws), yet the velocity of objects remains approximately constant up to large distances from the centre of the galaxy. Figure 1.1 depicts a rotation curve fit by three different components: gas, visible matter, and a dark halo contribution that accounts for the unexpected behaviour at large radii.

Under the assumption of a spherically symmetric matter distribution, the mass within a radius r is

$$M_{<}(r) = 4\pi \int_0^r \rho(r') r'^2 dr' \quad (1.1)$$

where $\rho(r)$ is the matter density distribution. The flat behaviour implies a mass distribution $\rho(r) \propto r^{-2}$, suggesting a spherical halo of dark matter surrounding the galaxy. Thus the observed flatness of rotation curves not only demonstrates the existence of dark matter, but also fixes the local dark matter density.

Some theories avoid introducing dark matter altogether by instead modifying gravity to account for the observed behaviour in rotation curves (see Section 1.5.2). However, recent measurements of radial velocities in the NGC1052–DF2 galaxy [7] display

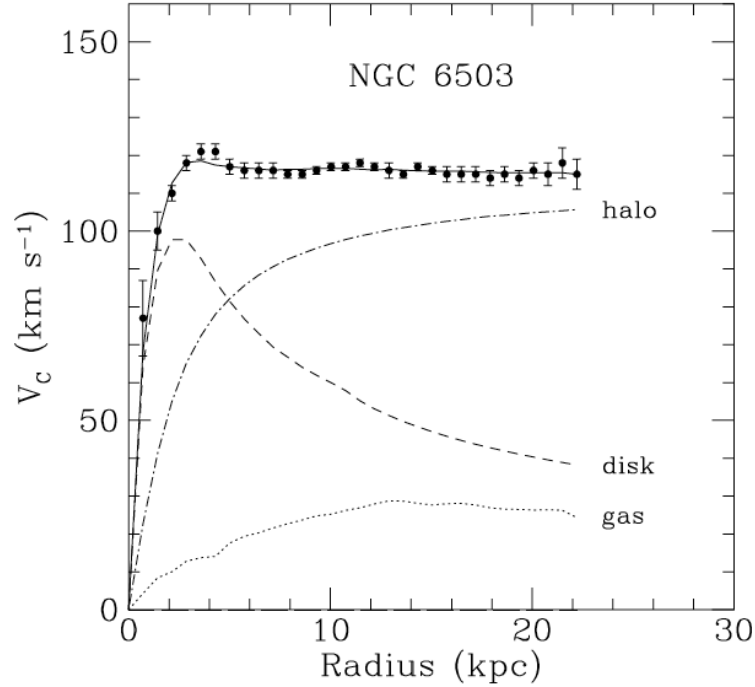


Figure 1.1: Fit to measured rotation curve, consisting of three components: gas, visible components (disk), and a dark halo component [6].

the behaviour expected based on the visible components. This galaxy is a rare exception, and if the measurements are confirmed this would be incompatible with models of gravitation that have been introduced to explain the deviation from expected behaviour in other galaxies.

1.1.2 Gravitational Lensing

Gravitational lensing is the bending of light in a strong gravitational field, a phenomenon most readily observed when light passes through very massive and/or dense objects like the central region of a galaxy or galaxy cluster [8, 9].

If the lensing effect is sufficiently strong, light rays from an object lying beyond the cluster will arrive at detectors on Earth from multiple different directions. The

result is multiple images of the same object. Arcs may also result as light from different sides of the same galaxy travels along slightly different paths. Figure 1.2 shows Hubble Space Telescope observation of the Abell 2218 galaxy cluster, in which arcs and multiple images are present [10].

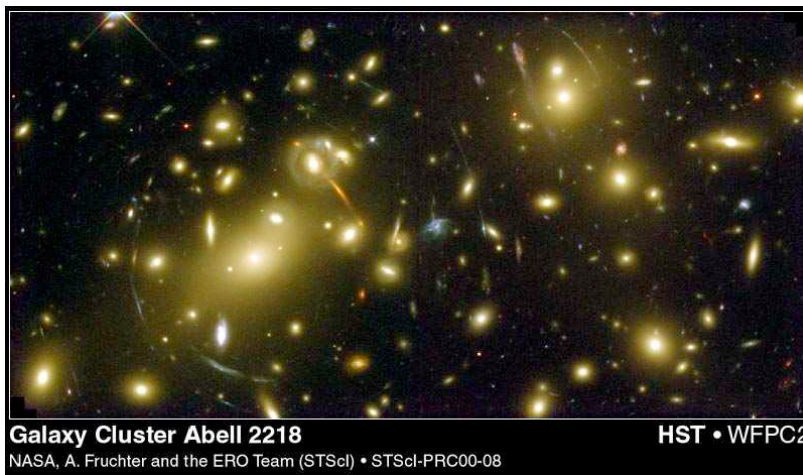


Figure 1.2: Lensing observed in the Abell 2218 cluster by the Hubble Space Telescope (credentials are indicated in the image).

Using measurements of gravitational lensing, the total mass M of a galaxy cluster can be inferred to be much larger than the observed baryonic mass (stars and gas). A much weaker and transient effect may be observed when light from an individual star is bent by a less massive lens such as a MAssive Compact Halo Object (MACHO, e.g. a brown dwarf or another non-luminous object of comparable mass) [11, 12]. The expected effect is the occasional brightening of stars from nearby galaxies. Observations lead to an exclusion of MACHOs as the dominant form of dark matter in the galaxy in the mass range $0.6 \times 10^{-7} M_{\odot} - 15 M_{\odot}$ [13] (see Section 1.5.1).

1.1.3 Galaxy Clusters

Galaxy clusters are the largest gravitationally bound objects in the Universe, consisting of thousands of individual galaxies. The earliest evidence for dark matter came in 1933 when Fritz Zwicky famously used observations of redshift to infer that galaxies in the Coma Cluster were moving unexpectedly fast [14]. Applying the virial theorem, the total mass M can be inferred. A deficit is observed in the matter in the clusters when considering only the contribution from stars, requiring a cluster mass at least 400 times greater than that of the luminous components.

Further evidence for dark matter comes from differences in the observed matter distribution of the Bullet Cluster when measurements are made using X-rays versus gravitational lensing. The Bullet Cluster constitutes two galaxy clusters which collided ~ 100 Myr ago. Individual galaxies are expected to pass one another, whereas the intracluster gas should collide and stall in the centre of the clusters. Maps of the projected matter density (determined via gravitational lensing) indicate that the two dark matter halos have passed through one another unaffected. In contrast, observations by the Chandra telescope [15] of X-ray emissions from the intracluster medium show that the hot baryonic gas has decelerated and is located between the two halos as expected; this is the first known system where the dark and baryonic matter components have separated [16]. Furthermore, these observations provide stringent constraints [16] on dark matter self-interactions, which must be small.

An composite image of the collision is shown in Figure 1.3, where the baryonic distribution, as measured by X-ray observations, and dark matter distribution, as measured by gravitational lensing, are highlighted.

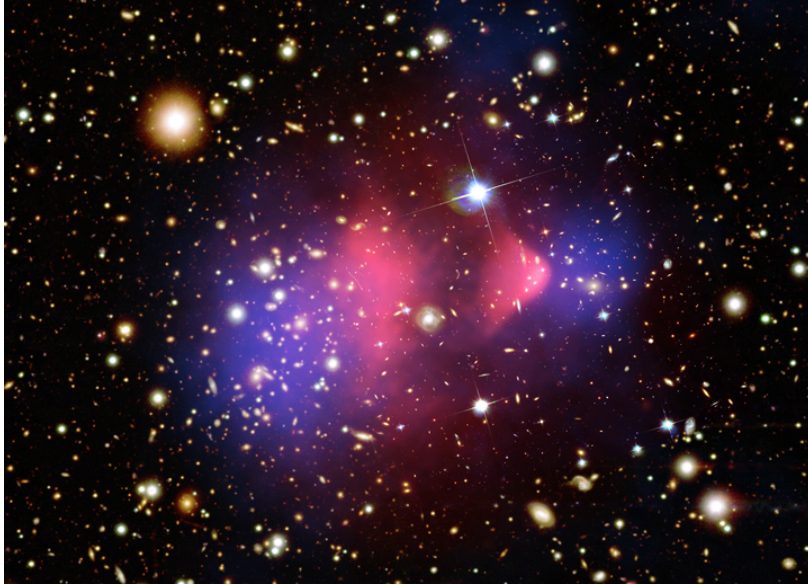


Figure 1.3: Composite image of the Bullet Cluster; the red and blue highlight represent the matter distribution as measured by X-ray measurements [15] (indicating the baryonic centre of mass) and by gravitational lensing [16] (indicating the true centre of mass, mostly accounted for by dark matter), respectively.

1.1.4 The Cosmic Microwave Background

The early Universe was very hot and dominated by thermal radiation, which would ionize any atoms that potentially formed. Eventually, the Universe cooled to a temperature where photons could no longer ionize the gas, and from this point onwards stable atoms could exist. Photons essentially stopped interacting, as there were no more charged particles and photons could not ionize neutral particles. These photons form the Cosmic Microwave Background (CMB), and are observable today.

Fluctuations of the matter density in the early Universe gave rise to the large scale structure (LSS) observed today, and correspond to small inhomogeneities in the CMB [17, 18]. Measurements of the CMB and LSS indicate that dark matter is non-baryonic. Furthermore, precise measurements of the abundance of dark matter can

also be determined.

For a homogenous, isotropic universe, the CMB should be a perfect blackbody power spectrum. This expectation is seemingly confirmed by observations indicating that the CMB is a blackbody power spectrum with temperature $T = (2.72548 \pm 0.00057)$ K [19]. However, anisotropies are observed in the temperature map at the level of 10^{-5} . These anisotropies in the power spectrum can be expanded in terms of spherical harmonics, giving an angular power spectrum.

The monopole and dipole components of the angular power spectrum correspond to the temperature of the perfect blackbody and to Doppler shift due to relative movement of our galaxy and the CMB. Insight into the physics of the universe when the photons essentially stopped interacting is contained within the higher moments. Figure 1.4 shows temperature anisotropies in the CMB after removing monopole and dipole components.

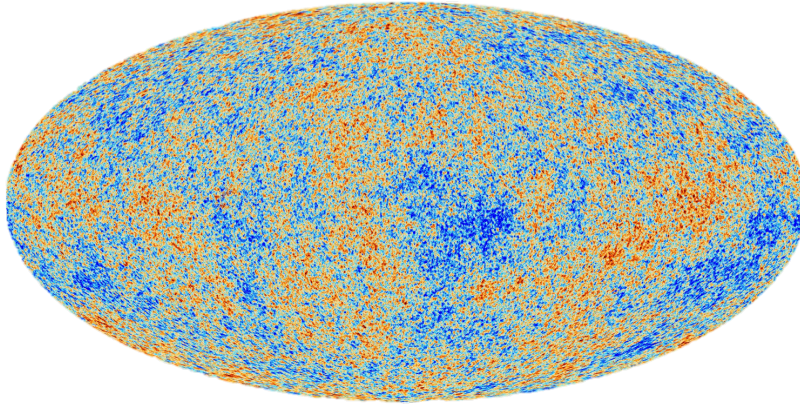


Figure 1.4: Temperature anisotropy of the CMB, from the Planck Collaboration [20].

Theoretical models of the angular power spectrum have dependencies on a variety of cosmological parameters, including fractional matter density, Ω_m , and fractional baryon density, Ω_b . These theoretical predictions can be fit to precise measurements of

the angular power spectrum, allowing these cosmological parameters to be determined [17, 18].

Measurements from WMAP give $\Omega_m = 0.265 \pm 0.01$ and $\Omega_b = 0.042 \pm 0.002$ [21], indicating the presence of non-baryonic matter that accounts for the majority of the matter density. Planck fits to the Λ CDM model (discussed in Section 1.3.2) give $\Omega_b = 0.0485 \pm 0.0033$, and $\Omega_{DM} = 0.258 \pm 0.018$ [2], where Ω_{DM} is the dark matter density.

1.2 Shortcoming of the Standard Model

There are no SM dark matter candidates. For agreement with data from the CMB, most DM should be non-baryonic [2]. Additionally, coupling of dark matter to the electromagnetic field must be non-existent, or extremely weak. Several studies [22–24] have considered the possibility of dark matter with very small electric charge fe (where e is the charge of the electron and $|f| \ll 1$), producing constraints on interactions of dark matter and photons.

Therefore, dark matter should interact with ordinary matter either via the weak nuclear force or another force with comparable or lower strength. Most leptons are charged, with the exception of the neutrinos. However, neutrinos cannot account for all dark matter because they are too light [25], and all other particles in the SM are either unstable or baryons. The conclusion is that dark matter cannot be composed of Standard Model particles.

1.3 Freeze Out and the Dark Matter Temperature Scale

1.3.1 Freeze-Out

As mentioned in Section 1.1.4, the early Universe was in a hot, dense state dominated by radiation. All particles were relativistic and in thermal equilibrium, maintained by scattering interactions. Equilibrium for a given particle species is maintained as long as its interaction rate, Γ , exceeds the expansion rate of the Universe. If Γ drops below the expansion rate, the species decouples from the thermal bath [26].

Particles are relativistic when the temperature is much greater than their mass ($m \ll T$). When relativistic particles decouple, their number becomes fixed by the thermal number at freeze out. The neutrinos are an example of particles that decoupled when relativistic.

As the Universe cools, if the temperature drops below the particle mass, the species becomes non-relativistic. Furthermore, the number density becomes Boltzmann suppressed, dropping exponentially as $e^{-m/T}$ in particle-antiparticle annihilations that are no longer balanced by particle production. These non-relativistic particles later decouple as the expansion rate of the Universe overtakes the interaction rate.

1.3.2 Hot, Cold, and Warm Dark Matter

There are three classes of dark matter based on a ‘temperature’ scale, which does not actually describe the dark matter temperature, but instead its velocity. Hot dark matter (HDM) was still relativistic at the time when the CMB photons stopped interacting, with mass up to a few tens of eV. Due to a large mean free path, HDM did not cluster and form clumps as small as galaxies. HDM is incompatible with data from LSS [27–29] and deep field observations [25], both of which provide upper

constraints on the allowed average DM particle velocity. Thus, only a small fraction of the DM density, which can be constrained by properties of the CMB, could be attributed to HDM. Neutrinos with low mass are an example of HDM candidates. Warm dark matter (WDM), like HDM, was relativistic at the time of decoupling, but is now non-relativistic.

In contrast, cold dark matter (CDM) decoupled from the thermal bath at freeze-out, and is more favoured by observations of the CMB than either WDM or HDM. A six parameter model that fits the data well is the Λ CDM model, in which a flat Universe is populated by radiation, baryons, CDM, and dark energy (described by a constant, Λ) [21].¹

1.4 Particles Beyond the Standard Model

1.4.1 Weakly Interacting Massive Particles

Weakly Interacting Massive Particles (WIMPs) are CDM candidates that arise in many well motivated theoretical models. In broad usage, WIMPs may refer to any non-baryonic massive particle that interacts either via the weak nuclear force or another force with similar or lesser strength. A more restrictive definition is a particle with mass in the range from around 2 GeV (the Lee-Weinberg bound [30]) to 100 TeV, a rough unitarity bound [31], with interactions dictated by the SM weak interaction.

The correct relic abundance of DM, as determined from measurements of the CMB [2], can be obtained through thermal freezeout for reasonable WIMP mass ranges and cross sections [26]. SM particles and WIMPs are assumed to have been in thermal

¹Dark energy, in contrast to dark matter, is non-clustering and homogenous; furthermore, dark energy has a striking impact on the expansion of the Universe.

equilibrium in the early hot Universe, where WIMP particle production results from SM-SM annihilations. Eventually, WIMPs freeze out as their interaction rate with ordinary matter is overtaken by the expansion rate of the Universe.

For WIMP masses around the electroweak scale, $\mathcal{O}(100)$ GeV, assuming a typical WIMP velocity of $0.1c$ results in a WIMP–WIMP annihilation cross section on the order of the weak interaction, $\mathcal{O}(10^{-26} \text{ cm}^3 \text{ s}^{-1})$ [32]. This remarkable coincidence is often referred to as the *WIMP miracle*.

Two prominent WIMP candidates arise from two qualitatively different theoretical frameworks, supersymmetry (SUSY) and Universal Extra Dimensions (UED):

Neutralinos: In supersymmetric extensions of the SM, each SM particle has an as yet undiscovered super partner with the same quantum numbers and gauge interactions, but with spin differing by $1/2\hbar$ and opposite R -parity. R -parity is defined $P_R = (-1)^{3(B-L)+2s}$ where s is spin, B is baryon number, and L is lepton number; $P_R = 1$ for SM particles and -1 for SUSY particles [33]. The lightest supersymmetric particle (LSP) is stable as a consequence of unbroken R -parity [34], and is often considered as a dark matter candidate.

For consistency with current non-observation, a supersymmetric dark matter candidate must have no electric or strong charge. Therefore, the only suitable supersymmetric dark matter candidates are the partners of the graviton, the gravitino $\tilde{G}$ with spin $3/2\hbar$, the spin $1/2$ partners of the neutral vector bosons B and W and the Higgs particles, called Bino ($\tilde{B}$), Wino ($\tilde{W}$) and Higgsino ($\tilde{H}_1, \tilde{H}_2$), or superpositions thereof called neutralinos ($\chi_{1,2,3,4}$), and the sneutrinos ($\tilde{\nu}_e, \tilde{\nu}_\mu, \text{ and } \tilde{\nu}_\tau$), which have a spin of 0 and are the superpartners of the standard model neutrinos.

Sneutrinos are already excluded by their non-observation [35, 36]; with current experimental sensitivities they should already have been observed. The gravitino is still a viable dark matter candidate, but only interacts gravitationally and is thus not a WIMP [37].

The spin 1/2 fermions mix to form four mass eigenstates (χ), the neutralinos. In the minimal SUSY model (MSSM), the LSP is generally assumed to be the lightest neutralino [34] ($\chi = \chi_1$), and is one of the best studied WIMP candidates. The lightest neutralino leads to the correct observed relic abundance of dark matter in various models [38, 39].

Kaluza-Klein: Extra spatial dimensions were introduced by Kaluza and Klein in the 1920's [40], an idea that lives on in UED, in which particles propagate in flat, compact extra dimensions of size $R \leq 10^{-18}$ m [41] with quantized momentum in units of $p^2 \sim R^{-2}$.

In minimal UED, the simplest model, there is a single extra dimension of size R compactified on a circle. All SM particles have infinitely many partner particles, one at each Kaluza-Klein (KK) level n with mass $\sim nR^{-1}$ and the same spin as the SM particle, in contrast to SUSY theories.

Much like the conserved R -parity in SUSY leads to the stable LSP, in minimal UED a discrete parity, the KK parity, is preserved. This implies that the lightest Kaluza-Klein particle (LKP) is stable, and potentially a viable dark matter candidate [42, 43].

1.4.2 Sterile Neutrinos

In the SM, neutrinos are massless and thus have a well-defined chirality. Neutrino interactions are only observable through the weak interaction, which exclusively couples to left-handed neutrinos and right-handed anti-neutrinos [44]. However, oscillation experiments have demonstrated that neutrinos are massive [45, 46]. A new massive neutrino species that mixes with the active neutrinos but does not participate in the weak interaction, and is therefore *sterile*, could be added to the SM.

A sterile neutrino with mass in the keV range was first proposed as a candidate for WDM [47], though the proposed mechanism was shown to be unable to simultaneously meet constraints from DM relic abundance and those from X-ray observations, and thus has been ruled out as the sole form of DM [48].

Sterile neutrino DM would be heavier, but less abundant than the HDM neutrino. The mass range is constrained below by the Tremaine-Gunn bound at ~ 300 eV [25], below which the phase space density of DM required by the observed amount of DM in dwarf galaxies would violate the Pauli exclusion principle.

Searches for sterile neutrino DM can look for X-ray signals from sterile neutrino DM decay, with lifetime $1/\tau_{DM}$ given by [49]

$$\tau_{DM} = \frac{1024\pi^2}{9\alpha G_F^2 \sin^2(2\theta) m_{DM}^5}, \quad (1.2)$$

where m_{DM} is the sterile neutrino mass eigenstate, θ is the mixing angle between the sterile and one of the three active (left-handed) neutrinos, α is the index of the neutrino mass eigenstate ($\alpha = 1, 2, 3$), and G_F is the Fermi constant. Some of the best constraints on θ and m_{DM} are from *Chandra* X-ray observations of Andromeda [50].

1.4.3 Axions

Axions are pseudo Nambu–Goldstone bosons² that were first postulated in 1977 by Peccei and Quinn as a solution to the strong CP problem [53]. A new global chiral $U(1)$ symmetry, the Peccei–Quinn (PQ) symmetry, was introduced, where axions are associated with the spontaneous breaking of this symmetry at a scale f_a [54, 55]. The axion field $a(x)$ then translates under a $U(1)_{PQ}$ transformation as $a(x) \rightarrow a(x) + \alpha f_a$. Interactions with ordinary matter are inversely proportional to f_a , and are thus highly suppressed for large values of f_a . The spontaneous breaking of the PQ symmetry introduces the axion mass [56],

$$m_a = 57.0(7)\mu\text{eV} \left(\frac{10^{11}\text{GeV}}{f_a} \right). \quad (1.3)$$

Despite being very light, the axion is a CDM candidate as it can be produced non-thermally; such axions may have been produced in the early Universe in sufficient quantities to account for a large amount of CDM in galactic halos [57–59].

The mass range generally considered open parameter space for axions is from 10^{-6} eV to 10^{-2} eV and from 10^2 eV to 10^6 eV [1]. The Axion Dark Matter eXperiment (ADMX) has set limits on axion dark matter, excluding masses between $1.9 \mu\text{eV}$ and $3.53 \mu\text{eV}$ [60, 61]. For an assumed local DM density of $0.45 \text{ GeV}/\text{cm}^3$, this corresponds to $f_a \approx 4 \times 10^{13} \text{ GeV}$.

²Nambu–Goldstone bosons are massless and arise in models involving the spontaneous breaking of a continuous symmetry. If the symmetry is also explicitly broken, then the boson is a pseudo Nambu–Goldstone boson, and is massive [51, 52].

1.5 Non-Particle Alternatives

1.5.1 MACHOs

There are models that account for the missing mass problem without requiring the introduction of new particles. Baryonic dark matter candidates, such as Massive Compact Halo Objects (MACHOs), emit little to no radiation. MACHOs could include objects such as neutron stars, black holes, or brown dwarfs [11, 12]. However, these objects (other than primordial black holes) are products of supernovae, which are rare.

The MACHO, EROS, and OGLE collaborations have performed microlensing studies of the Large Magellanic Cloud to search for such objects, and have shown that MACHOs could account for $3 \pm 0.2\%$ of the DM in our galaxy. Observations by MACHO rule out 100% MACHO contribution to DM at the 95% confidence level [62]. More recent observations by EROS lead to an exclusion of MACHOs as the dominant form of dark matter in the Milky Way in the mass range $0.6 \times 10^{-7} M_{\odot} - 15 M_{\odot}$ [13].

Not only are MACHOs as the sole type of DM ruled out by microlensing measurements, baryonic DM is ruled out by Big Bang nucleosynthesis (BBN). The baryon density affects the abundance of light elements predicted by BBN, and constraints on the baryon density from BBN [63] closely match that determined from measurements of the CMB [2]. However, primordial black holes are not baryonic, and are not affected by BBN and CMB constrains [64]. Some parameter space is still available for black holes as DM.

1.5.2 MOND

The previously described experimental evidence for dark matter and the proposed candidate particles all assume Einsteinian gravity. While one possibility to account for the apparent missing matter problem is to introduce dark matter, another possibility is to modify the theory of gravity. MODified Newtonian dynamics (MOND) reproduces many galactic scale observations, particularly galactic rotation curves, without the need for dark matter [65].

However, as MOND theories are non-relativistic, the existence of additional fields is required to embed MOND into relativistic field theory. Furthermore, MOND cannot explain away DM in galaxy clusters, and correct descriptions of LSS formation may still require a form of DM even in these theories [66]. Recent LIGO measurements of the speed of gravitational waves from the coalescence of binary neutron stars rule out many MOND theories [67].

1.6 Dark Matter Searches

Typical dark matter searches come in one of three forms: direct detection, indirect detection, and via production at colliders such as the Large Hadron Collider (LHC). These searches can be summarize pictorially with a diagram like the one depicted in Figure 1.5. Thus far searches have not found compelling evidence of a dark matter signal, and have only been able to exclude models or parameter space.

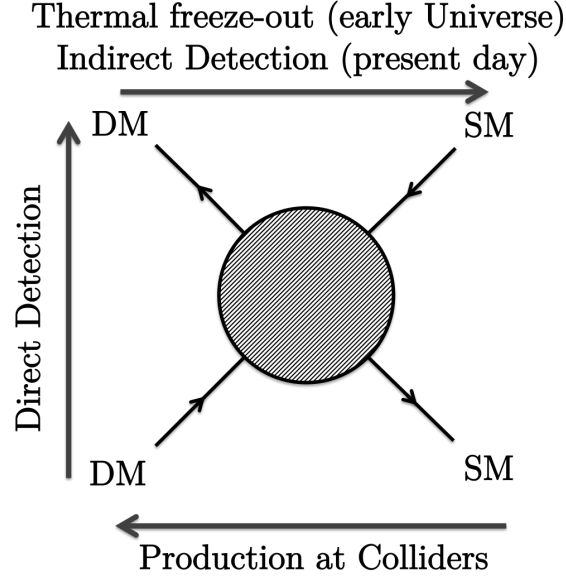


Figure 1.5: Schematic of different methods to search for dark matter. Arrow direction corresponds to time.

1.6.1 Indirect Detection

Indirect searches look for possible SM products of the decay or annihilation of DM. While indirect detection is favoured by the great abundance of dark matter in the Universe, SM interactions with DM are weak, leading to low production rates of SM particles from DM interactions. In many models, dark matter is stable, though there are models in which decay is possible. Typical products that indirect searches focus on are gamma rays, neutrinos, and cosmic rays, in particular anti-matter radiation [68]. Gamma rays are particularly useful for the indirect detection of DM, as photon sources point back to the signal origin, allowing signal sources to be mapped.

1.6.2 Production at Colliders

In particle beam collisions, the initial momentum transverse to the beam (transverse momentum) in the lab frame is zero, as is the total transverse momentum of all of the final products of a collision by conservation of momentum. Thus any net transverse momentum in the measured final particles implies that there is some missing transverse momentum, attributed to one or more particles whose presence could not be directly measured.

Dark matter could theoretically be produced through interactions of SM particles at colliders such as the LHC, but would not be detectable, so its presence would have to be inferred through missing transverse momentum. Experiments at the LHC are typically mono-X searches, where the production of a single SM particle is associated with some missing transverse momentum. Currently no collider searches for DM have observed a significant event excess over background [69, 70].

1.6.3 Direct Detection

Direct detection is the detection of DM through interactions of DM particles with detectors. In particular, WIMP searches typically look for evidence elastic scattering off of the nucleus, resulting in nuclear recoils. For DM with mass m_χ and density ρ_χ , the differential recoil event rate as a function of recoil energy E_R is

$$\frac{dR}{dE_R}(E_R) = \left(\frac{\sigma_0}{2\mu^2 m_\chi} \right) \times F^2(E_R) \times \left(\rho_\chi \int_{v \geq v_{\min}}^{v \leq v_{\text{esc}}} d^3v \frac{f(\mathbf{v}, t)}{v} \right) \quad (1.4)$$

where σ_0 is the DM-nucleon scattering cross section in the nucleon rest frame, μ is the reduced mass of the DM particle-nucleus system, F is the nuclear form factor, and $f(\mathbf{v}, t)$ is the DM velocity distribution. $v_{\min}$ is the minimum DM velocity, and v_{esc} is

the DM escape velocity, at which the DM particle would have enough kinetic energy to escape the galactic DM halo [71]. The differential recoil event rate is discussed in some detail for WIMPs in Appendix C.

Typical detection methods make use of heat, scintillation, and ionization signals that result from DM interactions. Some experiments utilize a combination of signals in order to discriminate backgrounds. Figure 1.6 summarizes a variety of direct detection experiments by detection technique. Common target materials include cryogenic semiconductors [72, 73], noble scintillators [74, 75], ionic scintillators [76, 77], and superheated fluids [78].

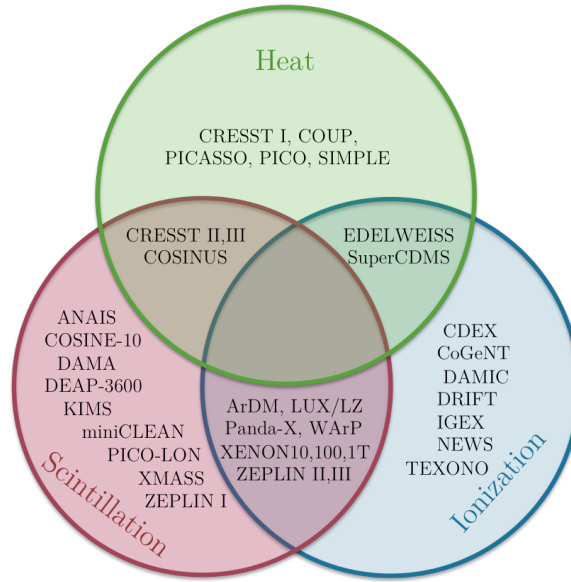


Figure 1.6: Summary of several direct detection experiments by signal type measured. Adapted from Ref. [79].

For high WIMP masses, there is agreement between all experiments on null results. However, in the low mass region there is tension in results, as some experiments claim an excess of signal over background [76, 77, 80], whereas other experiments see null

results in the same region. Figure 1.7 shows results from direct detection experiments for spin-independent scattering. Preferred regions where an excess of events was observed and upper limits in case of null-results are indicated.

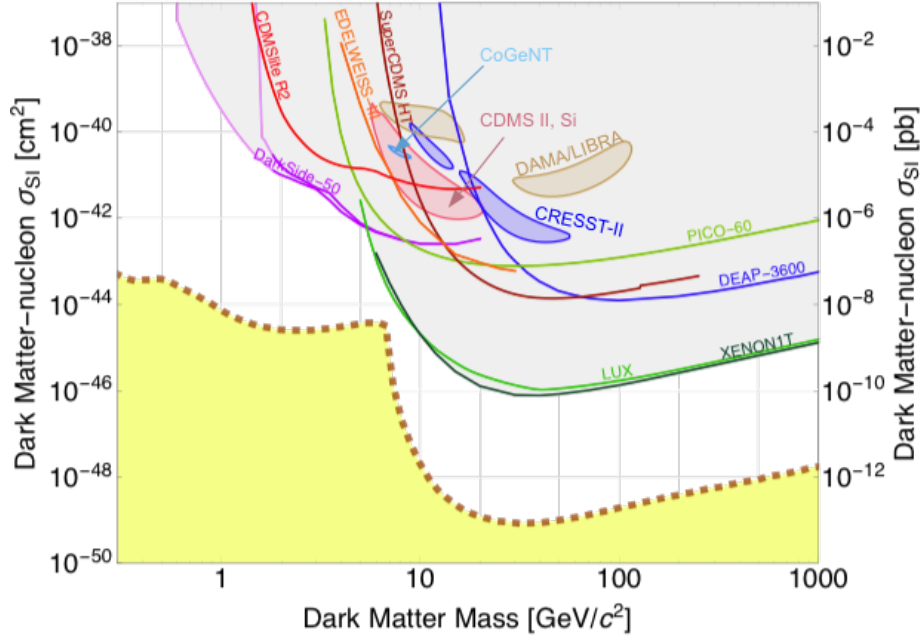


Figure 1.7: Current limits (solid lines) for DM direct detection spin-independent cross section as a function of DM mass. Closed contours correspond the WIMP interpretation of experiments who have observed an excess of events. The dashed line is the neutrino floor, below which there is an irreducible background from nuclear scattering of solar or atmospheric neutrinos [81]. Limits are given by CDMSlite Run 2 [82], SuperCDMS [72], EDELWEISS [73], PICO-60 [78], LUX [83], XENON1T [75], DEAP-3600 [74], DarkSide-50 [84], and CRESST [85]. Closed contours are given by DAMA/LIBRA [76], CoGeNT [86], CRESST-II [77], and CDMS II [80].

Chapter 2

SuperCDMS Experiment

The Super Cryogenic Dark Matter Search (SuperCDMS) experiment uses cryogenic semiconductor detectors to search for dark matter, mostly in the form of WIMPs, measuring nuclear recoils (NRs) and electron recoils (ERs) produced by dark matter particles scattering off of the detector nuclei. From 2012–2015, SuperCDMS operated 15 germanium detectors (~ 9 kg) at the Soudan Underground Laboratory in Soudan, MN, achieving world leading limits on interactions of dark matter with ordinary matter. Currently, SuperCDMS is preparing for the next generation of the experiment, SuperCDMS SNOLAB, which will be located at the Creighton nickel mine near Sudbury, ON, Canada.

2.1 iZIP Detectors

At Soudan, SuperCDMS used interleaved Z-sensitive ionization and phonon (iZIP) detectors made of ultra pure germanium cylinders, with diameter of ~ 70 mm and height of ~ 25 mm, amounting to a total mass of ~ 640 g [72]. A stack of 3 detectors formed a detector tower. The detectors were operated at temperatures of ~ 50 mK,

at which germanium has a band gap between the valance and conduction bands of 0.74 eV [87]. The interaction of a particle in these semiconducting detectors produces electron-hole (e/h) pairs. Phonons, quanta of vibration, are also produced, and the phonon signal is measured. A bias potential (a voltage applied between the flat faces of the detector) drifts the electrons and holes, which are collected on opposite sides, producing an ionization signal.

Each detector face is equipped with four phonon readout channels and two charge channels, which are photolithographically patterned onto the detector. An outer ring forms one channel of each type, while the inner area consists of the second charge channel and the three remaining phonon channels in segments of equal area. The top and bottom faces have a 60° relative offset for finer position information. A schematic of the channel layout is shown in Figure 2.1.

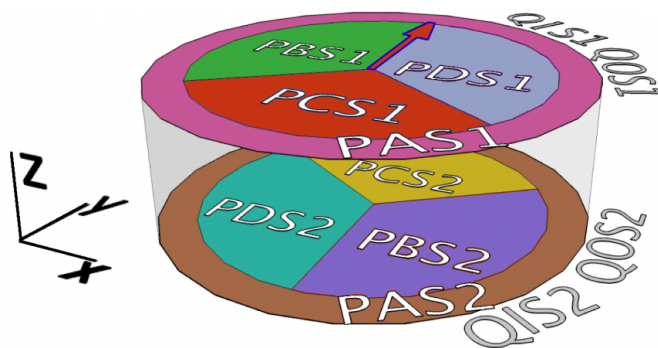


Figure 2.1: Phonon and ionization readout channels for an iZIP detector. The inner area consists of three phonon channels and one charge channel, and the outer ring is formed by one of each channel. The faces are rotated by 60° .

The two detector faces were held at opposite bias, ± 2 V, leading to a total bias $V_b = -4$ V across each detector. In an alternative operational mode, one side was held at ground and the other was biased to ~ -70 V. This high voltage (HV) setup is the CDMS low ionization threshold experiment (CDMSlite), described in Section 2.3.

2.1.1 Ionization Signal

In germanium, energy depositions exceeding the 0.74 eV [87] band gap by a sufficient amount will promote electron-hole (e/h) pairs to the conduction band. The number of pairs N_{eh} promoted is dependent on the energy and type of the interaction. The applied bias voltage drifts the charges to the detector faces. As the charges reach the detector surface, they induce image charges which generate a time varying current across a bias resistor, and the resulting voltage signal is read out through a junction gate field-effect transistor (JFET) amplifier circuit.

The amplitude of the ionization signal is a measure of the number of e/h pairs liberated in an interaction. For ERs, the number of pairs is $N_{e/h} = E_{\gamma}/\varepsilon_{\gamma}$, where E_{γ} is the deposited energy and ε_{γ} is the average single-pair excitation energy for an electron recoil, which is 3 eV in germanium [88]. For NRs, the number of liberated charges per energy is lower, resulting in inefficiency for the excitation of charges. The yield, Y , is a description of the charge excitation efficiency, defined to be unity for ERs.

2.1.2 Phonon Signal

Phonons in iZIP detectors are measured using Quasiparticle-trap-assisted Electro-thermal-feedback Transition-edge-sensors (QETs) held at superconducting temperatures. The QETs have large aluminium collector fins with thinly filmed tungsten Transition Edge Sensors (TESs). The superconducting temperature of the Al fins is 1.18 K, and that of the W is 80 mK [89]. If a phonon enters one of the fins it breaks up a Cooper pair and is absorbed. This generates Bogoliubov quasi-particles [90], which diffuse into the W, where they relax and break more Cooper pairs. The Cooper pair

breaking energy in W is much lower than in Al, thus the resulting quasiparticles are trapped and cannot diffuse back into the Al fins. In this manner, phonon energy is converted to quasiparticles which heat up the TES from superconducting to normal state, providing accurate measurement of the phonon energy [89].

Phonons are produced at several stages once an interaction occurs in the detector. Each of the following phonon types contributes to the total measured phonon signal.

Primary recoil phonons are emitted in electron recoils when the e/h pairs transition from the valance to the conduction band. The same is true in nuclear recoils, but additional phonons are produced by the movement of the recoiling nucleus. The energy in primary recoil phonons is proportional to the energy deposited by the incident particle.

Neganov-Trofimov-Luke (NTL) phonons: When electric charges move through an electric potential in a vacuum, they gain kinetic energy equal to the magnitude of the charge multiplied by the potential difference they have traversed. However, when the charge carriers drift through the same electric potential in material, collisions with lattice sites result in the charge carriers reaching a terminal velocity. Any excess work performed on these charges is then transferred to the lattice via the aforementioned collisions as phonons [91, 92]. The energy in these phonons is proportional to the applied voltage.

For a bias voltage V_b , the total energy E_t collected in phonons is the sum of the primary-recoil energy E_r and the energy from NTL phonons, $N_{eh}eV_b$,

$$E_t = E_r + N_{eh}eV_b. \quad (2.1)$$

Thus for large bias voltages (~ 70 V in CDMSlite mode), the measured recoil energy is greatly amplified, providing reach to energy thresholds much lower than those reached using lower biases (~ 4 V in iZIP mode).

As mentioned in Section 2.1.1, the average excitation energy per e/h pair is $\varepsilon_\gamma = 3$ eV in Ge. Thus the total number of e/h pairs produced in an ER is $N_{\text{eh}} = E_r/\varepsilon_\gamma$, and the total phonon energy measured for ERs is

$$E_t = E_r(1 + \frac{eV_b}{\varepsilon_\gamma}). \quad (2.2)$$

Nuclear recoils, on the other hand, promote fewer charge pairs than an electron recoil of equivalent energy: $N_{\text{eh}} = E_{\text{nr}}Y(E_{\text{nr}})/\varepsilon_\gamma$. The measured total phonon energy for NRs is

$$E_t = E_r(1 + Y(E_r)\frac{eV_b}{\varepsilon_\gamma}). \quad (2.3)$$

First introduced in Section 2.1.1, Y is the ionization energy produced per recoil energy (i.e. the ionization yield). For electron recoils, Y is defined to be unity. Discrimination between electron and nuclear recoils is achieved by computing the yield from the ratio of ionization signal to phonon energy. Figure 2.2 shows visible separate ER and NR bands, allowing discrimination between recoil types.

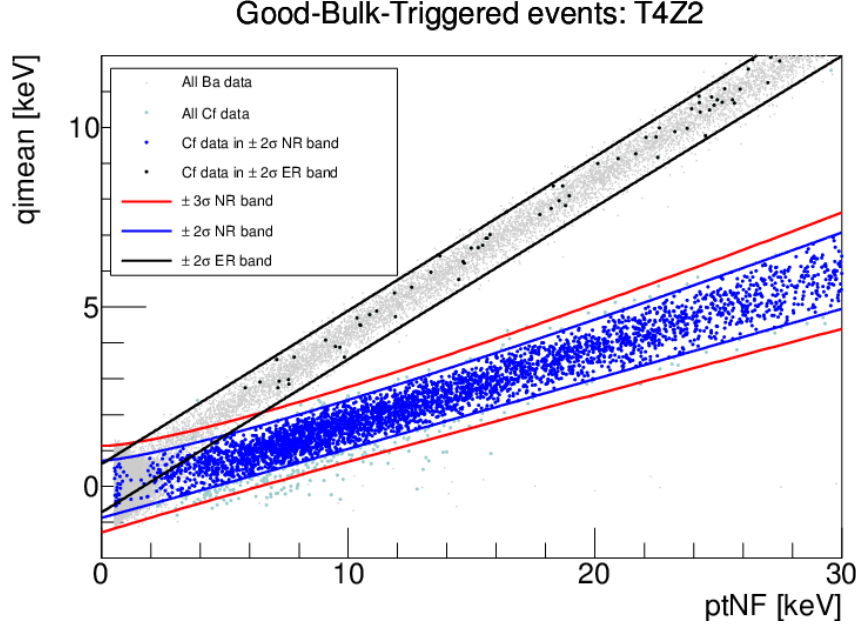


Figure 2.2: ER vs. NR discrimination using differences in yield [93]. The NR (blue) and ER (grey) bands are distinctly visible in the ionization energy vs. phonon energy plane.

Three energy scales are used for phonons, differing by the assumed recoil type:

- *Total phonon energy* makes no assumption the recoil type. This is the measured E_t in units of keV_t .
- *Electron equivalent energy* assumes an ER, with yield equal to unity. Denoting $g(V_b) = eV_b/\varepsilon_\gamma$, the energy is

$$E_{r,ee} = E_t/(1 + g(V_b)) \quad \text{with units } \text{keV}_{ee}. \quad (2.4)$$

- *Nuclear-recoil equivalent energy* assumes an NR. In this case the yield is below unity, and

$$E_{r,nr} = E_t/(1 + Y(E_{r,nr})g(V_b)) \quad \text{with units } \text{keV}_{nr}. \quad (2.5)$$

2.1.3 Signal Extraction

Heat signals measured in the phonon sensors are read out as electrical pulses with distinct shapes. Energy and position information can be inferred from these pulses; the total collected phonon energy is given by the integral of the pulse, while the pulse amplitude is approximately proportional to the energy [94].

To discriminate signal from noise events, make fiducial data selection criteria, and correct energy calibrations, three different template fits are performed for each event. The templates correspond to standard signal events, electronic glitches (characterized by quick rise and fall times), and low-frequency noise (LF noise) induced by the cryocooler.

Position and energy information are extracted from an event pulse using signal templates. An algorithm of note is the *two template optimal filter* (2T fit), first developed for CDMSlite Run 2 [94], which uses a linear combination of two templates. The first *slow* template is the average of many high energy traces from the ^{71}Ge electron capture line. The second *fast* template is developed based on the difference between the slow template and the traces used to define it, resulting in traces referred to as residual traces. The 2T fit returns both an energy estimator, as well as position information from the trace amplitudes and pulse start times in the different sensors.

Considering the geometrical layout of the sensors (see Figure 2.1), the position information from the 2T fit allows for the construction of a radial parameter that is a proxy (though an imperfect one) for radius. Events with a large value of the radial parameter correspond to events in the outer part of the detector. Identification of these events is essential for the rejection of events with reduced NTL amplification.

2.2 Calibration Data

^{133}Ba Gamma Ray Source: The ^{133}Ba gamma spectrum has several distinctive peaks, notably one at 356 keV. A ^{133}Ba gamma ray source is used for energy scale calibration and identification of the ER band in the ionization vs. phonon signal plane. In HV mode the detector saturates well below the 356 keV peak; an alternative method for energy calibration must be used [95]. However, the ^{133}Ba spectrum is used in Section 4.2 to extend the detection efficiency as a function of energy.

^{252}Cf Neutron Activation: A ^{252}Cf neutron source is used to determine the signal region of interest in the E_r vs. yield plane. Additionally, neutron capture on ^{70}Ge nuclei in the detector produces the radioactive isotope ^{71}Ge , which subsequently decays with 11.43 day half life via electron capture to the stable daughter product ^{71}Ga . K -, L -, and M -shell electron captures produce characteristic X-rays with energy 10.37 keV, 1.30 keV, and 0.16 keV, [96] and corresponding branching ratios 87.6%, 10.5%, and 1.8% [97], respectively. The lines from the electron captures are used to calibrate the ER energy scale in HV mode.

2.3 CDMSlite

The CDMS low ionization threshold experiment (CDMSlite) operates standard iZIP detectors at a relatively high bias voltage, employing the NTL mechanism to greatly amplify phonon signals. As the iZIPs were not designed for such use, modifications are required to run in CDMSlite mode. Three data sets were taken with two different iZIP detectors operating in HV mode.

2.3.1 Modifications to Traditional iZIPs

In order to operate a traditional iZIP in CDMSlite mode, adaptations are required. Instead of holding the charge readout electrodes on each side of the detector at different biases (see Section 2.1), the phonon and charge sensors on one side of the detector are held at bias potential. The sensors on the other side are held at ground. The readout electronics were not designed to for putting phonon sensors at potential, thus only the phonon sensors on the grounded side could be read out.

The detector housing is at ground. As shown in Figure 2.3, the applied electric field is not homogenous, with edge effects resulting in regions of reduced voltage at high radius. Thus in the outer portion of the detector, e/h pairs do not experience the full applied bias potential, and suffer from reduced NTL gain. These reduced NTL gain events are then reconstructed at the wrong energy, resulting in significant background.

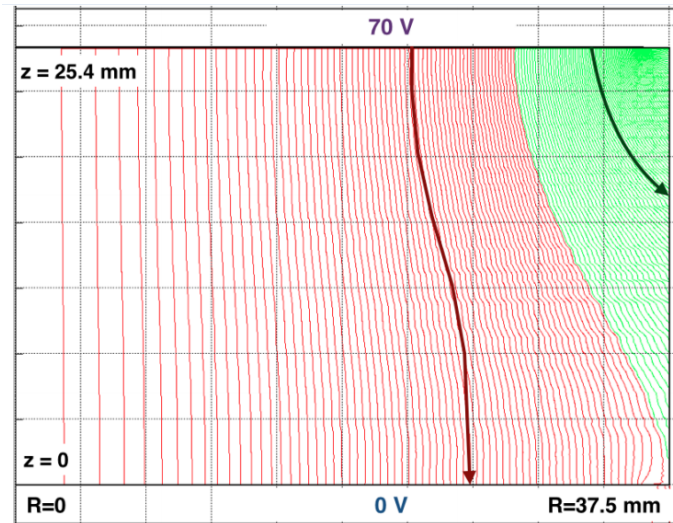


Figure 2.3: Electric field lines in the detector as a function of radius. Events in the green region do not experience the full 70 V bias potential.

2.3.2 Electron and Nuclear Recoils

In CDMSlite the charge signal is not measured, and the yield cannot be determined on an event-by-event basis. This becomes problematic for calibrating the ER and NR energy scales. Instead, theoretical models are used for the yield, typically that of Lindhard [98, 99]:

$$Y(E_{\text{r,nr}}) = \frac{k \cdot g(\varepsilon)}{1 + k \cdot g(\varepsilon)}. \quad (2.6)$$

Here $g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon$, $\varepsilon = 11.5 E_{\text{r,nr}} Z^{-7/3}$, Z is the atomic number of the detector material, and k is a constant (0.157 for Ge). From Equations 2.4 and 2.5, the NR energy scale can be described in terms of the ER energy scale

$$E_{\text{nr}} = E_{\text{ee}} \left[\frac{1 + \frac{eV_b}{\varepsilon_\gamma}}{1 + \frac{eV_b}{\varepsilon_\gamma} Y(E_{\text{nr}})} \right]. \quad (2.7)$$

The NR scale is important for WIMP scatters, whereas most backgrounds tend to be from ERs, hence the need for both energy scales.

2.3.3 CDMSlite Runs

Run 1 (2012): Proof of Principle

CDMSlite Run 1 was a proof-of-concept for the HV operational mode, operated for 15.7 livetime days of WIMP search in 2012. With a bias voltage of -69 V, a threshold of 170 eV_{ee} was achieved. Even without background subtraction and a small exposure of 6 kg days, the resulting WIMP limit was able to rule out portions of the CDMS II and CoGeNT signal contours [95].

Run 2 (2014): World Leading Limits

Following the success of the first run, CDMSlite Run 2 operated the same iZIP detector at a bias voltage of -70 V. Due to maintenance of the cryogenics, the run was split into two data periods, denoted Period 1 and Period 2. Improved methods of noise rejection resulted in lower thresholds than the first HV run, $75 \text{ eV}_{\text{ee}}$ and $56 \text{ eV}_{\text{ee}}$ for Period 1 and Period 2, respectively [82].

As ER/NR discrimination is lost in the CDMSlite operational mode, ER backgrounds are a significant problem and limit the experimental sensitivity. Run 2 saw great improvement over Run 1 in the reduction of backgrounds by developing a radial parameter for fiducialization, removing events with reduced NTL gain. The combination of lower energy threshold, reduced background, and a greater exposure of 70.1 kg days resulted in much greater sensitivity to spin-independent WIMP interactions than Run 1.

New parameter space for the WIMP-nucleon spin-independent cross section was excluded in the $1.6 - 5.5 \text{ GeV}/c^2$ WIMP mass range. The result remained world-leading in most of the mass range until the publication of results in 2018 by Darkside [84].

Run 3 (2015): Profile Likelihood Method

An alternative iZIP detector was operated in CDMSlite mode in 2015. The dataset was divided into two periods due to differences in cryocooler noise. The exposure was less than in Run 2, thus a significant improvement in sensitivity was not expected. Thus the Run 3 dataset was used as a test for the implementation of new analysis techniques. A salting approach was used to blind the DM search region, where fake

events (indistinguishable from real events) were added to the WIMP search data below 5 keV. Instead of determining limits in the standard manner for SuperCDMS, using the Optimum Interval method [100], a background model was developed for a profile likelihood fit. Final results are expected to be published shortly.

2.4 SuperCDMS SNOLAB

The planned SuperCDMS SNOLAB is the next phase of the experiment, and will be located 2 km underground at SNOLAB near Sudbury, Ontario. Detector towers will consist of stacks of six detectors, and a combination of germanium and silicon detectors will be used; the two materials provide complementarity in the search for sub-GeV DM [101] and non-standard interactions [102]. Motivated by the success of CDMSlite, both HV and iZIP operational modes will be implemented. Unlike SuperCDMS Soudan, where iZIP detectors were repurposed for HV mode, the new HV detectors are designed specifically for this operational mode.

2.4.1 Detector Design

HV detectors are intended to be operated with floated phonon sensors and an anticipated biasing scheme of ± 50 V, resulting in total bias of up to ~ 100 V [101]. As the ionization measurement in HV mode is rendered obsolete, the new HV detectors do not have ionization sensors; they are instrumented only with six phonon channels on either side. The channel layout for the HV and the iZIP detectors are shown in Figure 2.4.

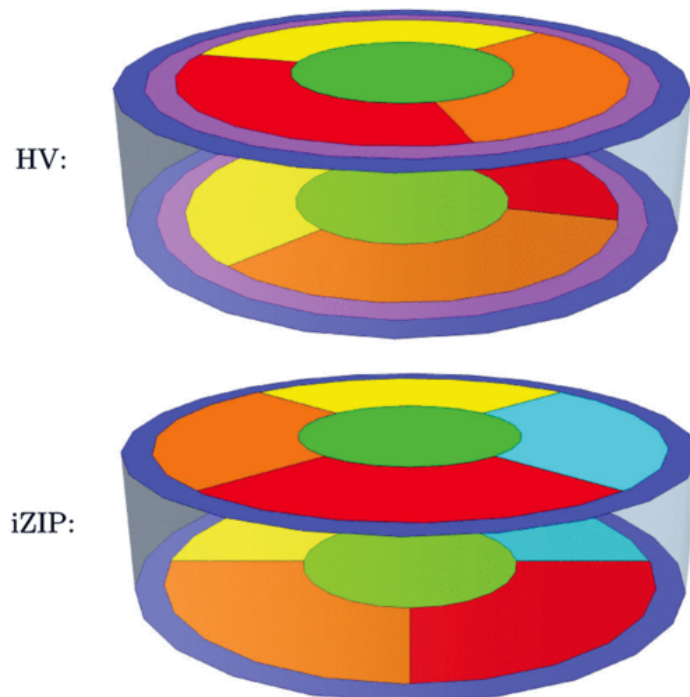


Figure 2.4: Channel layout for the HV (top) and iZIP (bottom) SuperCDMS SNO-LAB detectors [101]. For the HV detectors, a central channel is surrounded by three rings, the inner most of which is split into three equal segments. The two outer rings are designed to reject events near the edge of the detector, where reduced NTL gain is problematic. The three segment channels on the top surface of the detector are rotated 60° relative to those on the bottom surface. The phonon channels for the iZIP detectors consist of two rings arranged around an inner core. The inner ring is split into four equal segments. The outer ring also forms a charge channel, while the remaining area within the ring forms a second charge channel, totalling six phonon channels and two charge channels on either side. The bottom segments are rotated 45° with respect to the top segments.

2.4.2 Backgrounds in HV mode

Due to the lack of NR/ER discrimination, ER backgrounds cannot be rejected and thus the HV mode WIMP search is background limited. The experimental sensitivity is dependent on the ability to identify and constrain backgrounds.

Tritium is expected to be a limiting background in the HV detectors, particularly for Ge.¹ Tritium is produced, along with other potentially radioactive isotopes, by interactions of cosmic ray secondaries with the detector material while on the Earth's surface. Underground at SNOLAB, the 2 km rock overburden shields the detectors from continued production. However, tritium is a beta-emitter, decaying with a half life of 12.3 years. The half life is long enough that the isotope will not decay to negligible levels before data taking, but short enough that the decay rate is significant over the course of a run.

In order to constrain the expected amount of tritium contamination in the detectors, and therefore the effect of the experimental sensitivity, it is necessary to know the production rate of tritium and the location history of each detector. This is the motivation for this thesis, using CDMSlite data to determine the production rate of tritium, as well as other isotopes that may present as backgrounds at SuperCDMS SNOLAB.

2.4.3 CUTE

The Cryogenic Underground TEsting (CUTE) facility is intended to serve as a well shielded test facility to study detectors in low background conditions [103]. The facility is designed to hold a single detector tower, in which detector performance and background studies will be carried out. CUTE will be installed and operational at SNOLAB before SuperCDMS SNOLAB, with the possibility of performing some early DM search runs.

¹The Si detectors are also limited by ³²Si.

Part II

Analysis of CDM lite Data

Chapter 3

Cosmogenic Backgrounds

An important background in low-rate radiation experiments results from activation of the detector by cosmic rays. Section 3.1 gives an overview of the production of isotopes by cosmogenic ray secondaries, while Section 3.2 delves into more detail on the production mechanisms. In Section 3.3, radioisotopes relevant to CDMSlite are introduced, and the chapter closes with a summary of the literature on production rates in germanium.

3.1 Overview of Cosmogenic Production of Radioisotopes

Exposure of a detector to cosmic ray secondaries can result in the production of radioisotopes within the detector material. Fabrication and testing of the Super-CDMS detectors was performed on Earth's surface, where cosmic ray interactions are inevitable. Afterwards, the detectors were brought underground to Soudan mine, where the rock overburden provides shielding from cosmic rays. Radioisotope production stops, and the isotopes decay away. However, if the half life of an isotope is sufficiently long ($\gtrsim 100$ days), yet short enough that the decay rate is non-negligible

($\lesssim 15$ years), then the isotope may be present in sufficient quantity during data taking that its decay results in background events that make a significant contribution to the measured spectrum.

3.2 Production Mechanisms

There are several mechanisms by which radioactive isotopes are produced. Most cosmogenic production is dominated by spallation by high energy nucleons. As protons mostly interact in the atmosphere before reaching the Earth's surface, the proton contribution is subdominant to that from neutrons.¹ Other reactions, such as fragmentation and induced fission (or capture) may also be important for some nucleons. Negative muon and pion capture are generally subdominant processes [104].

The production rate R of an isotope in a material is related to the particle energy E , the production cross section $\sigma(E)$, and the particle flux $\phi(E)$ as

$$R = N \int \phi(E) \sigma(E) dE, \quad (3.1)$$

where N is the number of target nuclei. Minimizing the particle flux in the range in which the production cross section is significant (by reducing the incident particle energy, for example) or by removing the flux all together results in a reduction in production rate. The latter can be achieved by bringing the respective material deep underground.

¹This is only the case at sea level; flights at high altitudes will expose a material to a higher flux of cosmic protons.

3.3 Relevant Isotopes

Cosmogenic isotopes that can be produced in germanium are limited to those with mass less than the Ge mass. Table 3.1 lists all of the relevant radioisotopes that can be produced in germanium by cosmogenic activation, with half lives between 100 days and 15 years. Additionally, ^{71}Ge and ^{68}Ga are included, despite their short half lives. The former is produced via neutron capture on ^{70}Ge during ^{252}Cf neutron calibrations (see Section 2.2), and the latter is a daughter product of the longer-lived cosmogenically produced ^{68}Ge .

Tritium is of particular note. It has a relatively long half-life and, as a spallation product, it can be produced in any material. As discussed in Section 2.4, tritium is expected to be a limiting background for SuperCDMS SNOLAB.

3.4 Production Rate Literature

Published calculated or experimental production rates of radioisotopes by cosmogenic activation in natural germanium are sparse, and there is a wide spread in the available calculations. Only EDELWEISS [73] and SuperCDMS [105] have published measurements of the production rate of tritium in natural germanium. The latter publication includes the work performed for this thesis and the description here follows this paper very closely.

Calculated rates require cosmic ray flux spectra and production cross-sections, according to Equation 3.1. Typically, measured flux spectra and (semi-empirical) models for cross sections are used.

Isotope	Half life	Decay Type(s) + BR [%]				γ -radiation [keV] (branching ratio)	Q-value [keV]
		EC (GS)	EC (ES)	β^+	β^-		
^{71}Ge	11.4 d	100					232.6
^{68}Ge	270.3 d	100					107.2
^{68}Ga	68 m	8.9	2.2	88.9		511 (176%), 800 (0.4%), 1078 (3.5%)	2921
^{65}Zn	244.3 d	49	49	1.7		1116 (51%)	1352
^{63}Ni	101.2 y				100		67.0
^{60}Co	5.3 y				100	1173 (99.85%), 1333 (99.98%)	2823
^{57}Co	271.9 d		100			14 (9.54%), 122 (85.6%), 136 (10.6%), 692 (0.02%)	836.3
^{55}Fe	2.73 y	100					231.1
^{54}Mn	312 d		100			835 (100%)	1377
^{49}V	330 d	100					601.9
^{44}Ti	51.9 y		100			67.9 (93.0%), 78.3 (96.4%), 146.2 (0.092%)	267.4
^{45}Ca	162 d				100		259.7
^{22}Na	2.6 y		10	90		511 (180% ²), 1275 (100%)	2843
^3H	12.32 y				100		18.59

² 511 keV gamma rays from positron annihilation are produced in pairs, thus BR >100% are possible.

Table 3.1: Relevant cosmogenically produced isotopes in Ge. Half-lives are given in years (y), days (d) or minutes (m). EC decays can occur directly to the ground state (GS), or to an intermediate excited state (ES). The most common gamma rays (γ) that accompany decays to ES, and their branching ratios (BR), are also listed, as are Q-values. Isotope data are taken from Ref. [96].

Table 3.2 summarizes the available literature of calculated and experimental production rates in natural Ge. The different calculations vary in the neutron flux spectra used and in the measurements or models used for the cross sections (for details see caption of Table 3.2).

HV detectors at the future SuperCDMS SNOLAB will be background limited, thus an understanding of production rates of the expected cosmogenic isotopes will improve the sensitivity estimates. The sparse experimental production rates motivate the use of CDMSlite data to extract production rates of each of the isotopes in Table 3.2. A likelihood fit is performed to the CDMSlite Run 2 spectrum in order to determine the contributions of each background. The results are then used, along with the location history of the detector, to extract production rates in Section 5.3.4.

An important component of the likelihood fit is the energy-dependent signal efficiency, described in Section 4.1, which must be applied to the background spectral components. As the CDMSlite Run 2 WIMP search extended only up to 2 keV, this efficiency had not previously been studied at energies above this value, with the exception of a single point measurement at 10.37 keV. In order to separate tritium from Compton background, the fit region must extend to higher energies where the tritium component is negligible. The respective work is documented in Section 4.

Reference	Method	Production Rate [atoms/(kg·day)]			
		^3H	^{55}Fe	^{65}Zn	^{68}Ge
Avignone (1992) [106]	calc.	178, 210	-	24.6, 34.4	22.9, 29.6
	exp.	-	-	38 ± 6	30 ± 7
Klapdor (2002) [107]	calc.	-	8.4	79	58.4
Barabanov (2006) [108]	calc.	-	-	-	80.7
Back (2007) [109]	calc.	-	3.4	29.0	45.8
Mei (2009) [110]	calc.	27.7	8.6	37.1	41.3
Cebrian (2010) [111]	calc.	-	8.0, 6.0	77, 63	89, 60
Zhang (2016) [112]	calc.	48.32	-	-	-
EDELWEISS (2017) [73]	calc.	46, 43.5	3.5, 4.0	38.7, 65.8	23.1, 45.0
	exp.	82 ± 21	4.6 ± 0.7	106 ± 13	>71
Wei (2017) [113]	calc. (a)	47.37	4.47	24.93	21.75
	calc. (b)	33.70/51.27	1.13/1.18	5.34/9.66	7.04/15.38
Amare (2018) [114]	calc.	75 ± 26	-	-	-
Ma (2018) [115]	calc.	23.68	4.15	40.47	83.05
SuperCDMS (2018) [105]	calc.	95	5.6	51	49
	exp.	74 ± 9	1.5 ± 0.7	17 ± 5	30 ± 18

Table 3.2: Published calculated (calc.) and experimental (exp.) cosmogenic production rates for ^3H , ^{55}Fe , ^{65}Zn and ^{68}Ge in Ge. The different calculated values from Ref. [106] use cosmic spectra from Lal [116] and Hess [117], respectively. Ref. [111] uses cosmic spectra from Ziegler [118] and Gordon [119]. The different calculations from Ref. [73] use cross sections from a semi-empirical model [120–124] and from the MENDL-2P database [125]. The experimental limit for ^{68}Ge reported in Ref. [73] is extracted assuming full saturation of ^{68}Ge at ground level at the time the crystal was grown. Calculations from Ref. [113] use (a) Geant4 and (b) Activia 1/2, and those from Table 1 of Ref. [115] use CRY to estimate the cosmic ray flux for Beijing at sea level and GEANT4 to determine the resulting activation.

Chapter 4

Signal Efficiency: CDMSlite Run 2

4.1 Published Efficiency

The following section describes the signal efficiency determined in Reference [82]. In selecting data for WIMP analysis, data selection criteria (*cuts*) were applied to remove certain types of background events. Doing so also removes a certain fraction of the events of interest. The energy-dependent signal efficiency is the probability that an event of interest is selected for analysis. The efficiency was determined by the sequential application of different selection criteria, described in the following sections.

4.1.1 Single-scatter and muon veto

Events coincident with the muon veto were removed, as were events with energy deposited in multiple detectors. Due to the low WIMP-nucleon scattering cross section, a WIMP is not expected to scatter more than once with the detector array. Therefore events in which more than one detector measures an energy deposit inconsistent with noise are rejected. This resulted in a constant signal efficiency of $(97.21 \pm 0.01)\%$, independent of the event energy.

4.1.2 Pulse Shape

Glitches and LF noise were identified by goodness-of-fit quantities for the respective templates (described in Section 2.1.3), resulting in three different cut criteria. The efficiency of each cut was determined using a Monte Carlo pulse simulation, in which experimental noise was combined with the standard pulse template, and then scaled to desired energies. The pulse-shape efficiency is significant below 0.5 keV, rapidly dropping for energies less than ~ 0.1 keV.

4.1.3 Trigger

Strict cuts remove events that could cause triggers from noise or cross talk in the CDMSlite detector in coincidence with the other detectors. ^{252}Cf calibration data are used to calculate the trigger efficiency as a function of energy reconstructed in the detector of interest. An unbiased sample of traces for the CDMSlite detector was extracted by looking at events triggered by other detectors. The fraction of events that trigger this detector was then determined as a function of reconstructed energy. A trigger efficiency of 50% is reached at 75^{+4}_{-5} and 56^{+6}_{-4} eV_{ee} for periods 1 and 2, respectively. Above ~ 80 eV, the trigger efficiency is essentially 100%

4.1.4 Fiducial Volume

Due to the inhomogeneous electric field distribution (see Figure 2.3), not all events receive equal NTL amplification; charge carriers from events in the outer portion of the detector are drawn to the sidewall, and do not experience the full potential across the detector. A cut on the radial parameter defines a fiducial volume and removes almost 90% of these events.

To determine the passage fraction of good events by this cut, ^{71}Ge electron capture events were used. These events are evenly distributed in the detector, and fall into one of three categories: those with reduced NTL gain, those with full amplification that pass the radial cut, and those with full amplification that fail the radial cut. Figure 4.1 shows a cartoon of the distribution of events in the radial parameter vs. energy plane as would be expected from a process that produces mono energetic events evenly distributed throughout the detector.

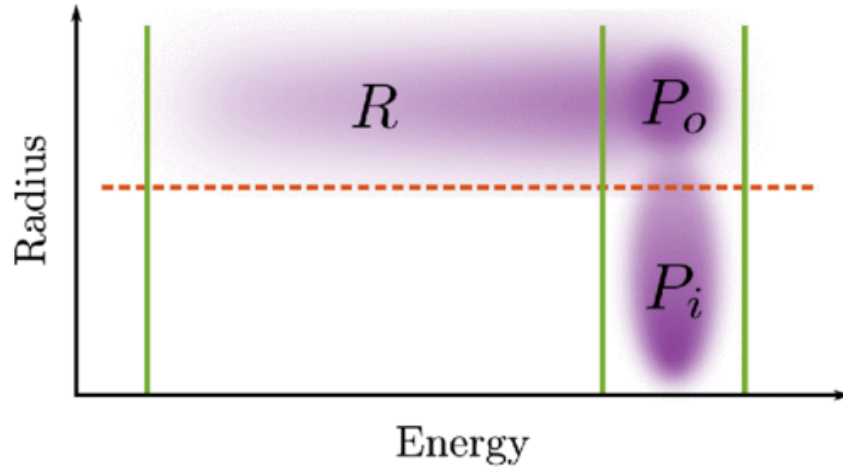


Figure 4.1: Segmentation of the reconstructed energy-radial parameter plane [94]. P_X are peak events reconstructed at the corrected energy: P_i are inner peak events passing the radial cut, P_o are events failing the cut. Region R corresponds to events failing the radial cut with reduced NTL gain.

The ^{71}Ge electron capture events are identified by partitioning the radial parameter vs. energy plane and fitting an exponential with the ^{71}Ge half life and a flat background to the event time in each partition. Given the classes of events described above, there are two components to the overall fiducial volume efficiency:

1. **Energy efficiency:** the fraction of events reconstructed at the correct energy,

$(P_o + P_i)/(P_o + P_i + R)$ (see Figure 4.1) and is 86%. Since this is an effect of

the electric field configuration, the energy efficiency is expected to be energy independent.

2. *Peak efficiency:* the fraction of events with full amplification that pass the radial cut. This can be calculated at the peak energies by taking the fraction of peak events passing the radial cut over all peak events, or $P_i/(P_i + P_o)$ using the convention of Figure 4.1. The number of background events in the inner part of the detector is negligible compared to the number of peak events, and the background in the outer part of the detector can be estimated from the background rate above and below the peak.

At lower energies, the peak efficiency is determined using a pulse simulation method. All events from the L -shell peak ¹ were used to create noise-free pulses by taking the composition of the fast and slow template pulse fits. These noise-free pulses were then scaled down to a desired energy, and a measured noise trace was added. The result is an artificial (yet realistic) event as could be expected to be observed from an interaction at the same location as the original event but at the chosen lower energy. Analyzing these simulated events in the same manner as real events allows the peak efficiency to be determined as a function of energy.

Combining the energy and peak efficiencies results in a final fiducial volume efficiency of $\sim 50\%$. Because of the saturation in the outer channel above ~ 2 keV_{ee}, the efficiency was only determined and published up to 2 keV. The efficiency was also measured at the 10.37 keV K -shell peak, and the efficiency was interpolated from

¹The K -shell could not be chosen due to saturation in the outer phonon channel above ~ 2 keV_{ee}

1.3 keV to 10.37 keV for energies between 1.3 keV and 2 keV, as done in Reference [82].

4.1.5 Combined Published Efficiency

Figure 4.2 [82] shows the effect of sequential application of the different data selection criteria on the efficiency. The total combined efficiency is $\sim 50\%$ for energies greater than 0.1 keV. The grey band on the signal efficiency is the combined 1σ uncertainty from all component efficiencies, but is dominated by the uncertainty from the fiducial volume criterion.

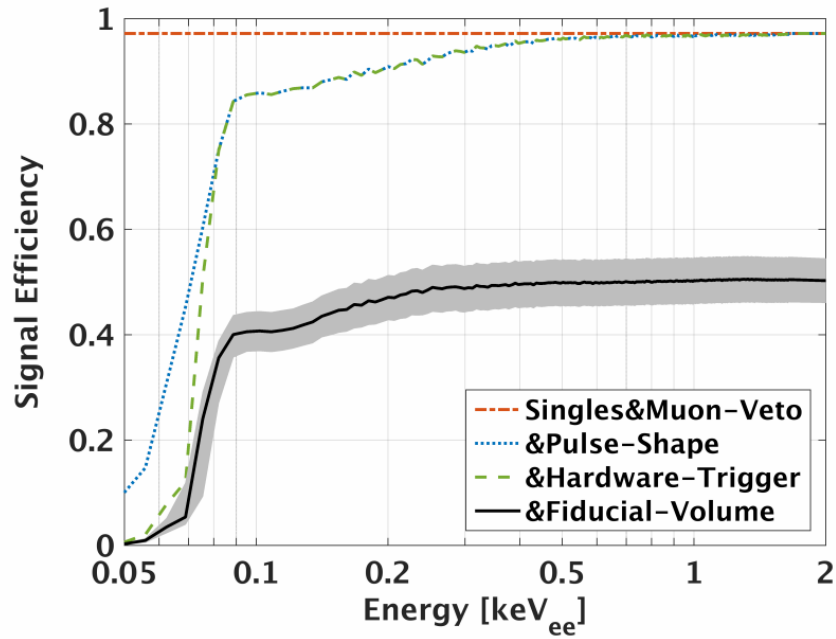


Figure 4.2: The published signal efficiency up to 2 keV [82]. Each component is incorporated sequentially, showing the resulting effect.

As the WIMP search region was restricted below 2 keV, the efficiency was not originally determined at higher energies, despite the measured fiducial efficiency at

10.37 keV. Above ~ 1 keV, only the singles and muon veto efficiency and the fiducial volume efficiency contribute to the total signal efficiency. As the singles and muon veto efficiency is constant with energy, the energy dependence of the efficiency at higher energies is determined by the radial cut.

4.2 Extending the Efficiency Above 10 keV

4.2.1 Motivating the Extension

Figure 4.3 shows the radial parameter as a function of event energy for both low background (WIMP search) data and ^{133}Ba calibration data taken during period 1. The fiducial volume cut is shown, with all events above the line removed from the analysis. At energies above ~ 20 keV, the upward trend of the distribution suggests rapidly decreasing efficiency.

Analysis of the CDMSlite Run 2 energy spectrum above 10 keV_{ee} necessitates extending the efficiency to higher energies. In the likelihood analysis described in Section 5.2.1, the contribution to the spectrum by tritium is determined. Tritium decays via β^- with an endpoint of 18.6 keV. In order to effectively separate tritium and contribution from Compton background, the fit range needs to extend to a region where the tritium contribution is negligible.

The fit is performed up to 20 keV, an energy selected as a compromise between high energy for tritium–Compton separation while avoiding the region of rapidly decreasing efficiency. Therefore, the signal efficiency must be determined up to at least 20 keV, but the extension is performed to 30 keV in order to properly capture behaviour of the efficiency at the edge of the interval to be used for the fit. As there are no electron capture peaks above 10.37 keV, an alternative method must be used for extending the

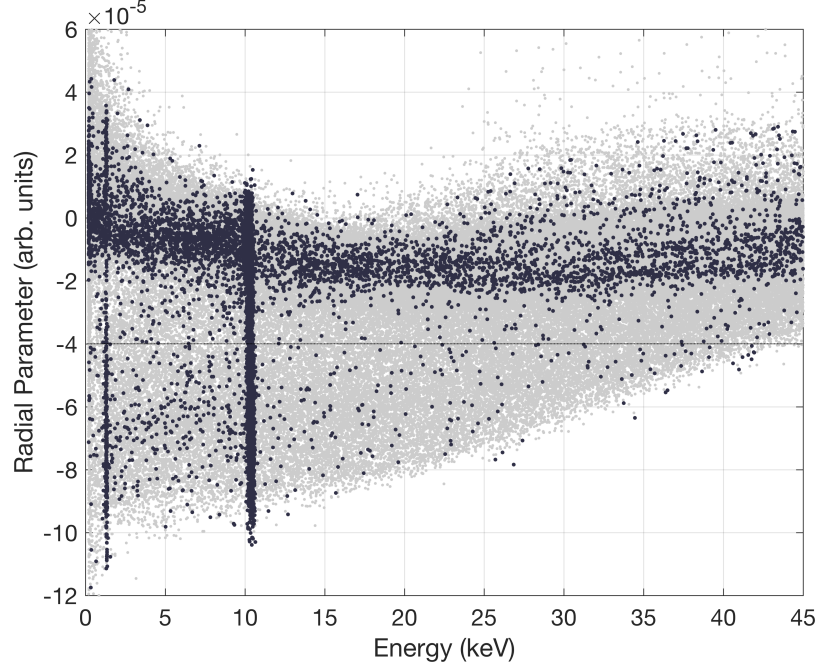


Figure 4.3: The CDMSlite Run 2 radial parameter as a function of energy for low background (dark points) and ^{133}Ba calibration data. The radial cut location for period 1 is indicated (solid line).

efficiency. The method of choice as described in the following sections is a comparison of simulated and measured ^{133}Ba calibration spectra.

4.2.2 Barium Simulation

A ^{133}Ba spectrum was simulated in GEANT4. The pulse shape parameters required for defining the radial parameter are not produced in the simulation, though the actual position of the event in the detector is given. The simulation also does not take into account the effects of reduced Luke gain at the edge of the detector. However, it is conceivable that other effects might lead to a distortion of the spectrum of deposited energies near the edge of the detector. Therefore, three different radial cuts, shown in Figure 4.4, motivated by the electric field configuration were explored, each removing

areas of reduced potential in the detector. The effect of each cut on the spectrum is compared to the full spectrum in Figure 4.5. No change in the shape of the simulated spectrum is observed within statistical uncertainty, motivating the use of the entire spectrum (with no radial cut) for maximum statistics.

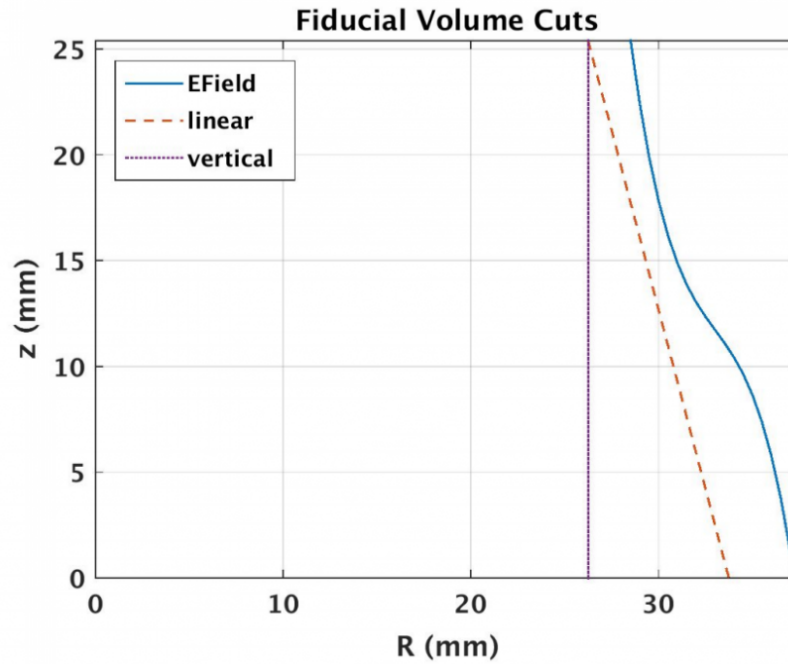


Figure 4.4: The three radial cuts tested on the barium simulation, removing regions where events experience a reduced potential.

4.2.3 Initial Hypothesis Efficiency

An initial hypothesis efficiency is constructed, set equal to the published efficiency up to 2 keV, the measured efficiency at 10.37 keV, and linearly interpolated between. Above 10.37 keV the efficiency is initially assumed constant. The resulting efficiency hypothesis is depicted in Figure 4.6.

The initial hypothesis efficiency is applied to the simulated spectrum, which is

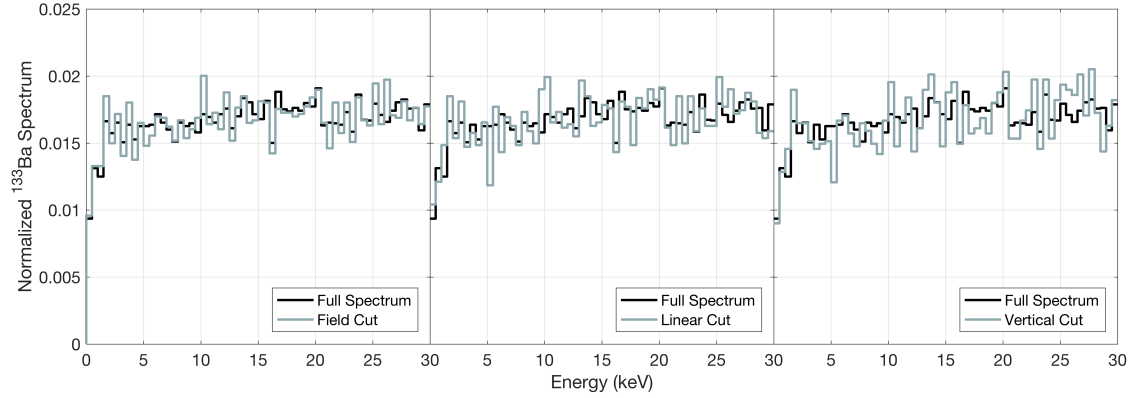


Figure 4.5: The three radial cuts applied to the barium simulation, each compared to the full spectrum. The radial cuts do not change the shape of the spectrum, motivating the use of full statistics.

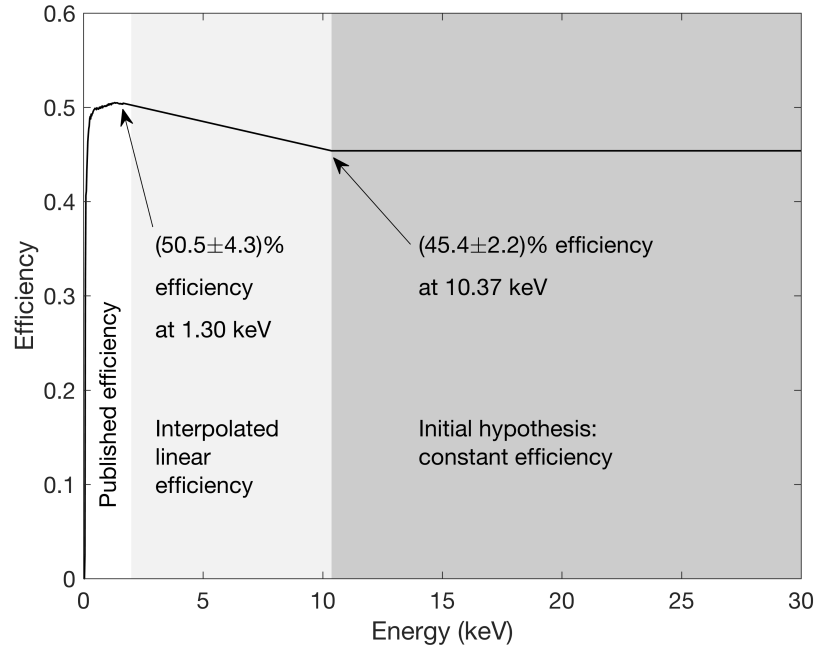


Figure 4.6: Initial hypothesis efficiency as a function of energy. This is the published efficiency up to 2 keV (white region), then linearly interpolated from 2 keV up to the efficiency measured at 10.37 keV (light grey region), and is assumed constant (dark grey region) above this energy.

then normalized to the measured spectrum between 3 and 10 keV. The upper bound is chosen as the efficiency is known up to 10.37 keV; the lower bound avoids low energy noise in the measured spectrum unaccounted for in the simulation. Systematic effects from the choice of normalization range are negligible, as discussed in Section 4.2.6.

Figure 4.7 compares the measured and the efficiency-corrected simulated spectra. Clear deviation can be seen above 20 keV, and a Kolmogorov-Smirnov (KS) test confirms that the spectra are not in good agreement. The initial hypothesis efficiency does not represent the data in this energy range, and an adaptation must be made.

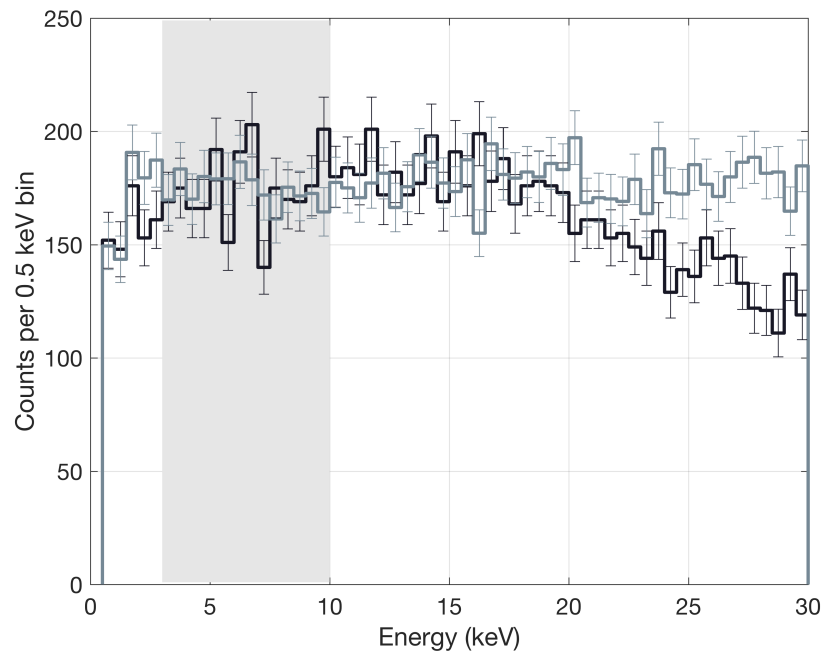


Figure 4.7: Measured (dark histogram) and simulated (light histogram) ^{133}Ba calibration spectra. The simulated spectrum is corrected by the initial hypothesis efficiency and normalized to the measured spectrum between 3–10 keV (grey region).

4.2.4 Adaptation to the Initial Hypothesis

While the simulated spectrum appears mostly flat to higher energies, the measured spectrum falls roughly linearly at high energy. A simple correction to the initial hypothesis efficiency is introduced. The initial hypothesis efficiency is multiplied by a piecewise function of energy, E , defined:

$$f(E) = \begin{cases} 1 & \text{if } E < A \\ 1 + B \times (E - A) & \text{if } E \geq A. \end{cases}$$

The parameters A and B are determined by a fit to the ratio of measurement to simulation. The fit values and 95% CL uncertainties are $A = 17.3 \pm 2.7$ keV and $B = -0.026 \pm 0.009$ keV⁻¹. A reduced χ^2 of 0.84 indicates that the fit is good. Figure 4.8 shows the ratio of the measured to simulated spectra with the resulting fit.

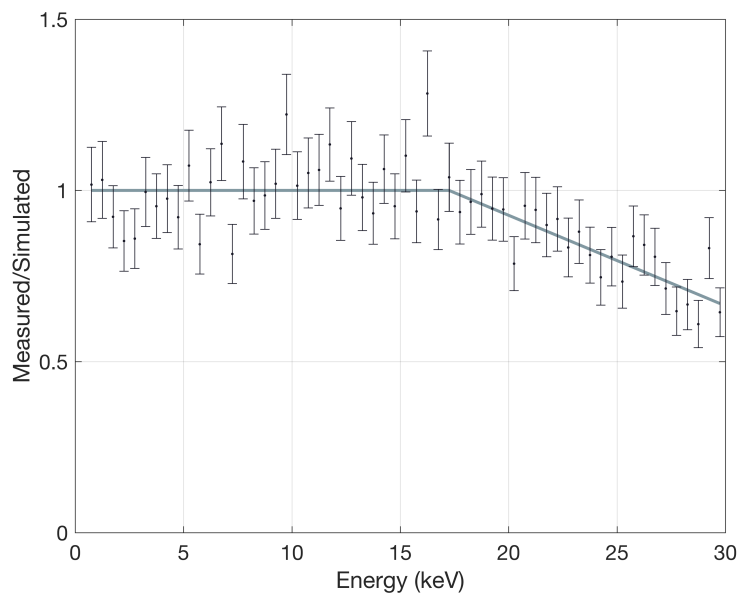


Figure 4.8: Ratio of measured and simulated ¹³³Ba calibration data (points) with the fit function $f(E)$ (line).

4.2.5 Final Efficiency

Application of the corrected efficiency to the simulated spectrum shows good agreement with the measured spectrum, as shown in Figure 4.9. A Kolmogorov Smirnov test with p-value 0.78 confirms that the simulated spectrum with the final efficiency applied is consistent with the measured spectrum.

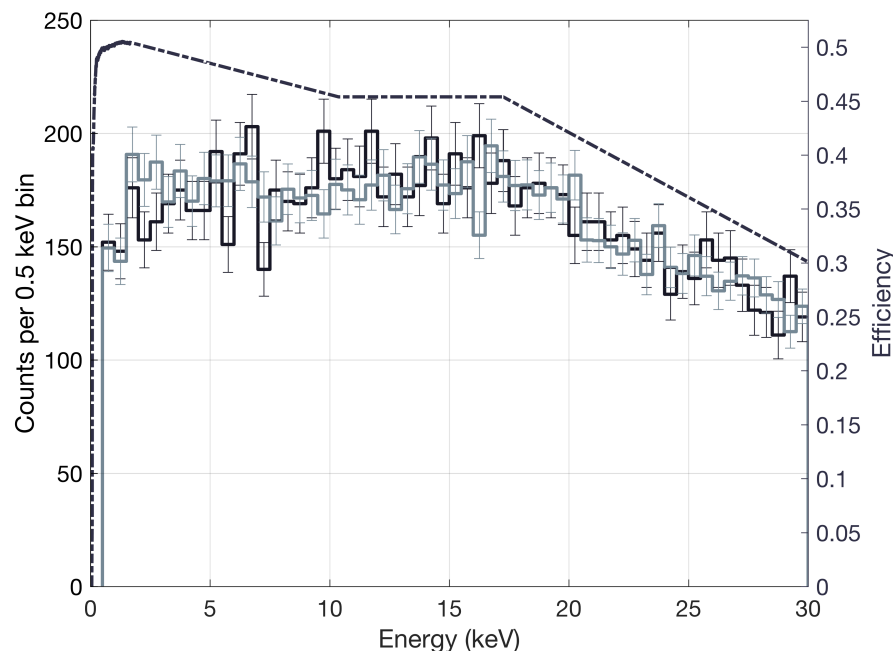


Figure 4.9: Final efficiency (grey) applied to the simulated ^{133}Ba calibration spectrum (light histogram), compared to the measured spectrum (dark histogram).

4.2.6 Systematic Effects

The choice of bin size and normalization range is explored to ensure that systematic effects are negligible. Varying the start point of the normalization range between 0.5 – 4.5 keV and the bin size between 0.1–1.5 keV produces fits with parameters within the 1σ uncertainty bounds. Thus systematic effects are not included in the stated uncertainty on the final efficiency.

Chapter 5

Cosmogenics in CDMSlite Run 2

A maximum likelihood fit is performed to determine the contributions of various backgrounds to the CDMSlite Run 2 spectrum. Each background is modelled as a probability distribution function (PDF). Considered backgrounds include spectral peaks generated by the X-ray/Auger cascades following EC decays, tritium beta decay, and interactions of gamma-rays which deposit fractional amounts of their total energy. The latter component is henceforth referred to as the ‘Compton’ component. Models for each of the backgrounds included in the likelihood fit are described in Section 5.1, while the results of the likelihood fit and a discussion of their uncertainties can be found in Section 5.2.

The contributions from backgrounds that result from the decay of radioisotopes produced by cosmogenic activation of the detector are then used in Section 5.3 to extract production rates of these isotopes in natural germanium at sea level.

In Section 5.4, a similar likelihood analysis is performed using the same background model while including a WIMP spectrum in order to improve upon the published CDMSlite Run 2 Optimum Interval (OI) limit.

5.1 Background Models

The background models take into account the energy-dependent resolution of the detector, described in Ref. [82]. The final efficiency determined in Section 4.2.5 is applied to the background models, which are then normalized to PDFs for the fit.

5.1.1 Electron Capture X-ray Peaks

Isotopes that decay by EC release an X-ray, or Auger electron cascade, with energy equal to the binding energy of the respective shell of the daughter isotope. For isotopes with atomic number less than that of Ge, only the K -, L -, and M -shells are relevant.

EC backgrounds are modelled as Gaussian functions at the K -, L_1 -, and M_1 -shell binding energies, with standard deviation set by the energy-dependent resolution. The amplitudes of these Gaussians are set by the ratios of the K -, L -, and M -shell branching ratios, which are calculated in Appendix A.

For most of the isotopes, the L_2 -shell can be ignored, as the branching ratios is on the order of $\sim 0.1\%$, compared to the $\sim 10\%$ L_1 -shell branching ratio. However, for Ge there are enough events that the L_2 -shell is included in the fit.

5.1.2 Tritium Beta Spectrum

Tritium beta decay is a super allowed process, thus the tritium beta decay spectrum can be written explicitly as a function of the electron kinetic energy, T_e , the energy measured by the detector. The spectrum is parameterized as

$$N(T_e) = C \sqrt{T_e^2 + 2T_e m_e c^2} (Q - T_e)^2 (T_e + m_e c^2) F(Z, T_e), \quad (5.1)$$

where C is a normalization constant, m_e is the electron mass, Q is the beta decay Q-value, and Z is the atomic number of the daughter nucleus [126]. $F(Z, T_e)$ is the Fermi function, for which the non relativistic approximation is appropriate (as the maximum kinetic energy, the Q-value, is 18.6 keV) [44]:

$$F(Z, T_e) = \frac{2\pi\eta}{1 - e^{-2\pi\eta}}. \quad (5.2)$$

Here $\eta = \frac{\alpha ZE}{pc}$, α is the fine structure constant, $E = T_e + m_e c^2$ is the total electron energy, and p is the magnitude of the electron momentum. This theoretical spectrum is then convolved with the energy-dependent resolution function.

5.1.3 Compton Background

The Compton spectrum was simulated in GEANT4 by D. Barker [127] using the Monash model [128]. The model takes into account properties of the outgoing gamma and the recoiling electron. When any electron is freed, the minimum energy deposited in the detector is the binding energy of the electron. This results in distinct steps arising at the K -, L -, and M -shell binding energies as fewer electrons are available for the scattering process. The relative size of these steps is partially affected by the number of electrons in each shell, and also by details of the electron wave functions.

5.2 Analysis of CDMSlite Spectrum

5.2.1 Likelihood Fit

The likelihood method is described in detail in Appendix B. The estimators in the likelihood fit are the number of events that each background contributes to the CDMSlite Run 2 spectrum. Figure 5.1 shows the results of the likelihood fit, and Table 5.1 gives the best fit number of events for each background with 68%, 90%, and 95% confidence intervals.

Component	# Events	Uncertainty Range					
		95 % CL		90 % CL		68 % CL	
		LL	UL	LL	UL	LL	UL
$^{68,71}\text{Ge}$	1932	1893	1967	1899	1962	1912	1949
^{68}Ga	7.2	0.9	18.0	1.8	16.1	3.9	12.6
^{65}Zn	21.5	11.9	35.1	13.4	32.8	16.6	28.3
^{55}Fe	11.5	3.8	23.6	5.0	21.6	7.7	17.7
^3H	270	222	318	230	310	245	294
Compton	131	95	175	101	168	113	153
$^{58,57,56}\text{Co}$	2.0	-2.7	11.2	-2.0	9.6	-0.3	6.7
^{54}Mn	0.4	-3.7	9.2	-3.1	7.7	-1.7	4.9
^{49}V	2.2	-2.2	10.7	-1.5	9.2	0.2	6.5
Sum	2378						

Table 5.1: Maximum likelihood fit results corresponding to the number of events that each background contributes to the measured CDMSlite spectrum with 70.10 kg-days of exposure [82]. Negative confidence intervals as listed in the bottom part of the table indicate that evidence for the presence of the respective isotope cannot be claimed.

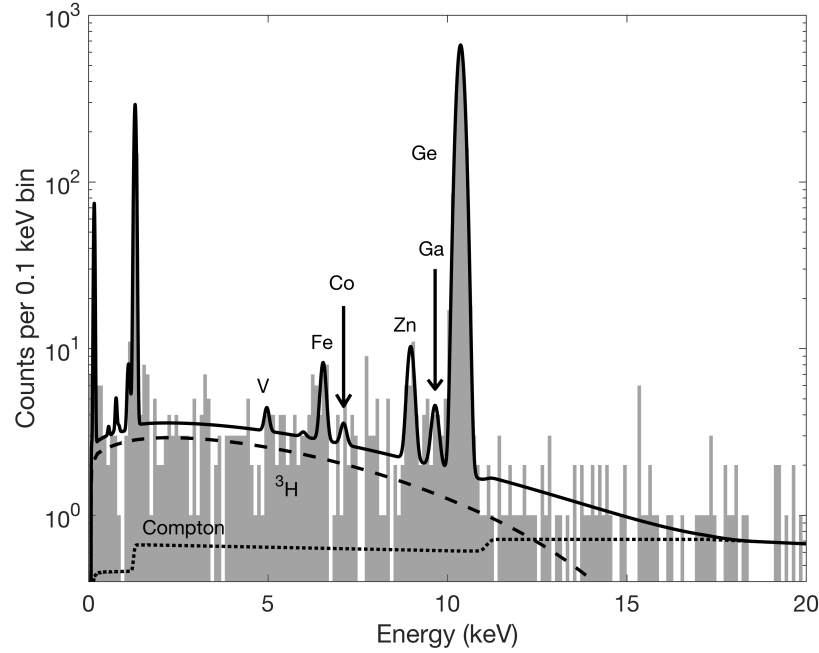


Figure 5.1: Results of maximum likelihood fit to the CDMSlite Run 2 spectrum. The L - and M -shell EC peaks (unlabelled) occur in the same order as the labelled K -shell peaks.

5.2.2 Uncertainty and Correlation

The uncertainty on the number of events for a given background is found by fixing the number of events and calculating the maximum likelihood. By calculating the maximum likelihood for a range of fixed event numbers, the likelihood PDF is determined as a function of number of events. This PDF is then converted to the cumulative distribution function (CDF), from which the 68%, 90%, and 95% confidence intervals can be determined. This procedure is demonstrated for tritium in Figure 5.2.

Correlations are also determined between the different backgrounds in a similar manner. Two backgrounds are held at fixed numbers of events while the maximum

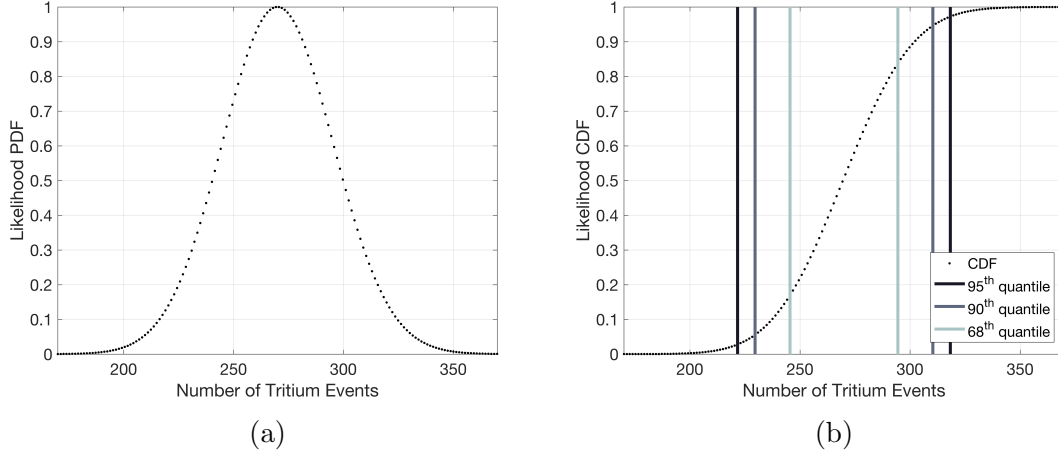


Figure 5.2: (a) Likelihood PDF over fixed values of the number of tritium events. (b) CDF determined from likelihood PDF over fixed tritium events. The 68%, 90%, and 95% CI are shown.

likelihood is calculated. This process is repeated over a grid of values of suitable range. The likelihood distribution is then determined from the grid using the Accept-Reject method: for each grid point a random number, z , between 0 and 1 is drawn. If the ratio of the likelihood at the chosen grid point to the maximum likelihood when all backgrounds float is greater than z , then the grid value is kept. If not, the value is rejected. All accepted values are then sorted, and the 2D confidence intervals are extracted.

Contours are drawn at the 68%, 90%, and 95% confidence levels. Contour plots are shown for tritium and germanium, and tritium and Compton contributions in Figure 5.3.

Additional contour plots are shown between background components from the Run 2 likelihood fit in Figure 5.4. Contours for the Co, Mn, and V components are not shown.

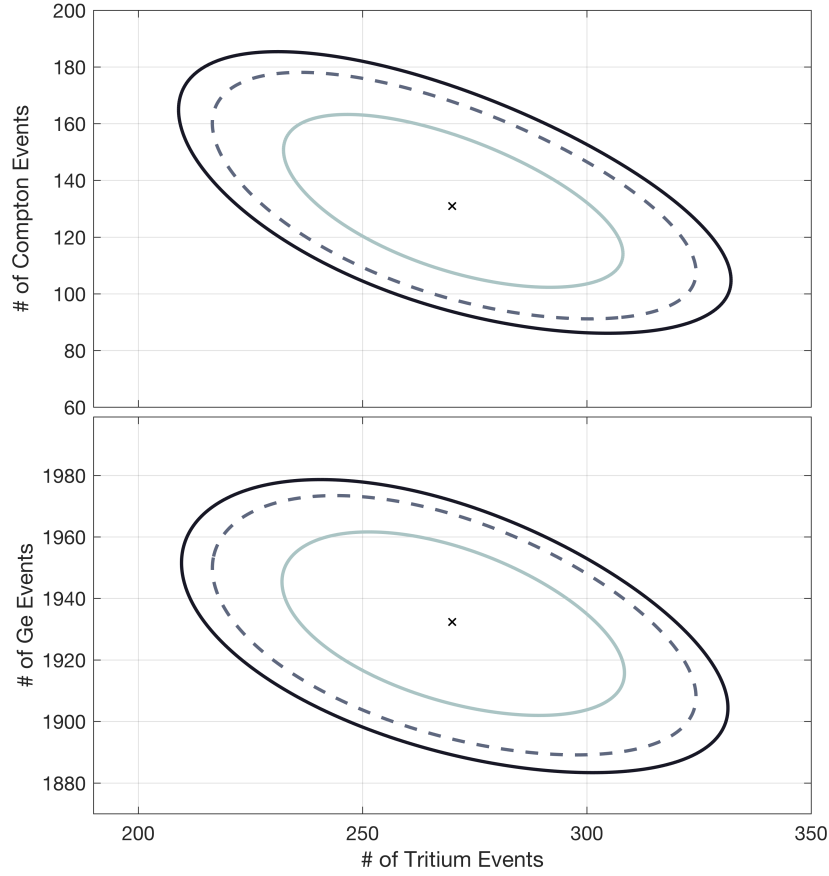


Figure 5.3: Correlation contours for tritium and Compton (top) and tritium and Ge (bottom). Contours are drawn at the 68% (inner, light), 90% (middle, dashed), and 95% (outer, dark) confidence levels.

5.2.3 Choice of Background Model and Systematic Uncertainties

β^- **Backgrounds:** Tritium is not the only isotope cosmogenically produced in germanium that undergoes β^- decay. However, whereas tritium has a relatively low Q-value of 18.6 keV, other isotopes that may be produced (and have half-lives in the relevant range) have much higher Q-values. Therefore, their spectra in

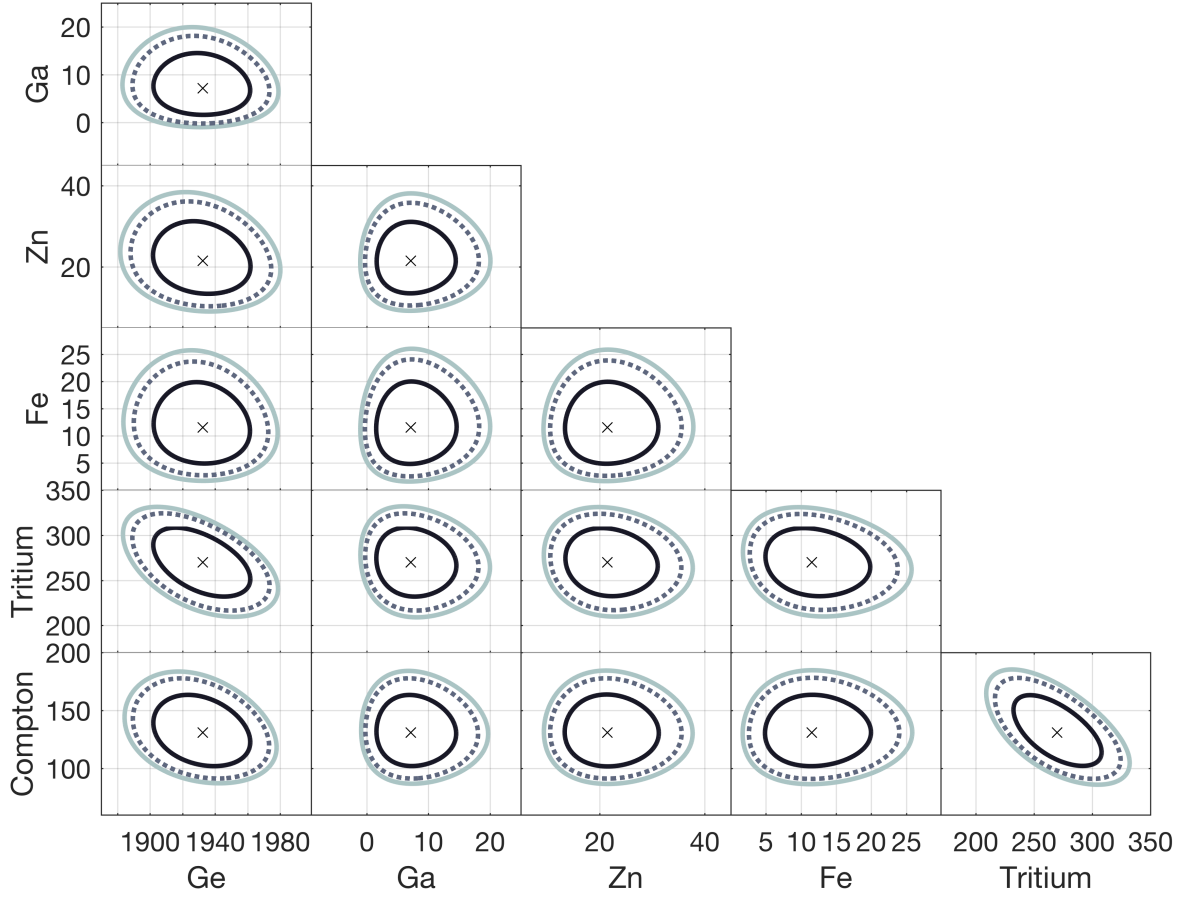


Figure 5.4: Correlations between components in the likelihood fit to the CDMSlite Run 2 spectrum. Contours are drawn at the 68% (inner, dark), 90% (middle, dashed), and 95% (outer, light) confidence levels.

the fit region are mostly flat and would be absorbed into the Compton component of the fit. Calculated production rates are available in literature for ^{60}Co and ^{63}Ni , ranging from 2.0 – 6.6 and from 1.9 – 5.2 atoms/(kg·day), respectively [107, 110, 111]. Assuming the highest of these production rates, both backgrounds combined would only contribute a few percent to the Compton component, thus neglecting these backgrounds as components in the likelihood fit is valid. The contributions of both isotopes are compared to the likelihood

fit results in Figure 5.5 (dashed lines).

β^+ Backgrounds: As shown in Table 3.1, both ^{65}Zn and ^{68}Ga can undergo β^+ decay. As in the case of the β^- isotopes discussed above, these backgrounds are neglected in the fit as separate components, but their high Q-values (1352 keV and 2921 keV, respectively) result in relatively flat spectra in the fit region. Furthermore, using the results from the likelihood fit for ^{65}Zn and ^{68}Ga and scaling by the relative branching ratios of β^+ and EC ground state (GS) (with a correction discussed in Section 5.3.2), both backgrounds combined contribute less than 1 event to the fit region. Therefore, like the β^- emitters, they can also be safely absorbed into the Compton component. The calculated contributions are shown in Figure 5.5 (solid lines) with comparison to the likelihood fit results.

Surface Events from ^{210}Pb : the details of the spectral shape of contributions from ^{210}Pb contaminants on the surface of the detector housing and the germanium are a matter of current investigation but are generally expected to rise at low energy [129]. The total contribution from ^{210}Pb was estimated and found to be subdominant to tritium ($<10\%$ of tritium events given by likelihood fit) [130]. As the surface background spectrum is rising at low energies, its omission attributes extra events to the tritium contribution, leading to a moderate overestimate of the tritium production rate.

Instrumental Noise: events at low energies from instrumental noise are removed from the analysis by effective selection criterion, as described in Ref. [82]. This background can therefore be neglected in this analysis.

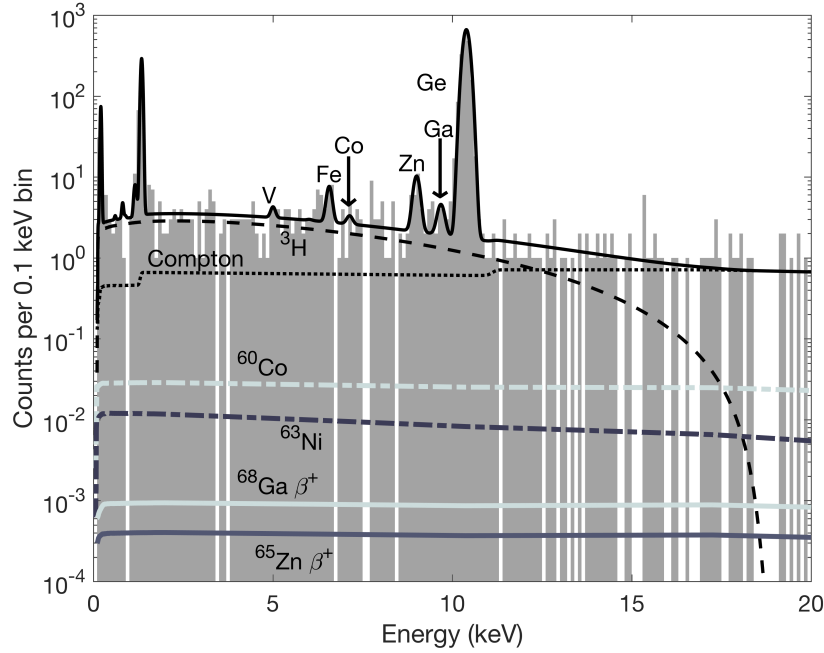


Figure 5.5: Contribution from β^- isotopes ^{60}Co and ^{63}Ni (dashed lines) compared to likelihood fit results. The contributions are determined using maximum production rates from literature. Also shown are contribution from β^+ isotopes ^{65}Zn and ^{68}Ga (solid lines) compared to likelihood fit results. In this case the contributions are estimated based on the likelihood fit results for the EC peaks for the respective isotopes and the corresponding branching ratios.

Unidentified Backgrounds: while there is no discernible evidence for other backgrounds in the spectrum, it is possible that there are unknown backgrounds that are unaccounted for. This could result in either an overestimation or an underestimation of the tritium component. As tritium is expected to be a limiting background for SuperCDMS SNOLAB [101], it is important not to underestimate the tritium rate. Therefore, in order to determine a conservative upper limit on the contribution of tritium to the spectrum, an alternative background model is fit to the spectrum. In this alternative fit, the Compton background

component is set to 0, and the upper limit of the fit range is reduced to 11 keV, below which the shape of tritium and the Compton components are most similar. Figure 5.6 shows the fit result. The tritium component determined by this fit is $\sim 30\%$ higher than that from the main fit.

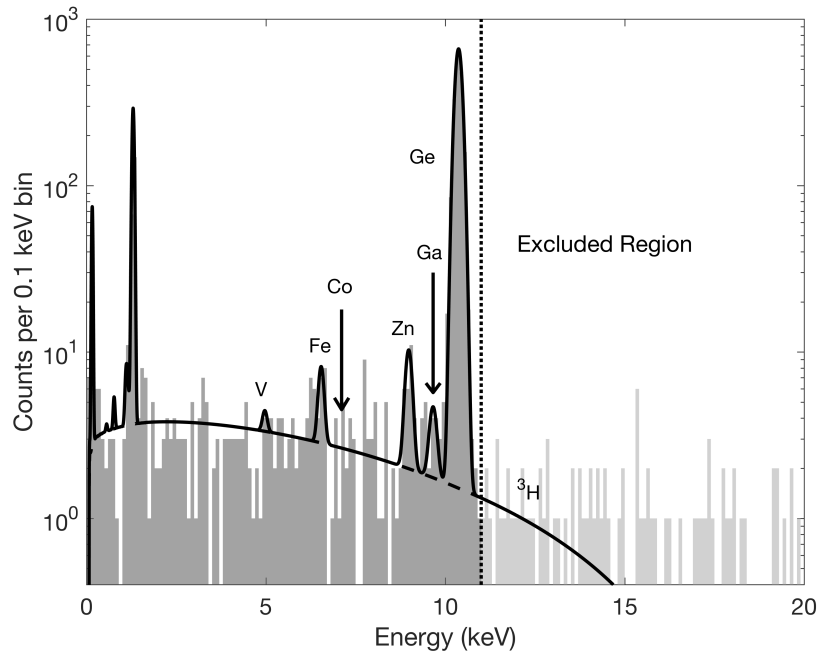


Figure 5.6: Results of maximum likelihood fit to CDMSlite Run 2 spectrum with Compton contribution set to zero. The dashed vertical line identifies the end of the fit region (0–11 keV).

5.3 Cosmogenic Production Rates

The results of the likelihood fit are used to determine the production rates of ^3H , ^{55}Fe , ^{65}Zn , and ^{68}Ge in germanium. From the best fit number of events in the spectrum, the total decay rate can be deduced. This requires accounting for the apparent reduction in rate due to imperfect signal efficiency and the branching ratio to the

decay mode of the spectral component in the fit.

5.3.1 ^{68}Ge from ^{68}Ga

Cosmogenically produced ^{68}Ge cannot be separated from the radiogenic ^{71}Ge (produced during neutron calibrations) in the likelihood fit. An attempt to separate the backgrounds using the time dependence of the two decays was made; however, uncertainty in the amount of ^{71}Ge produced in a calibration period before the detector was run in HV mode introduced significant uncertainty in the results. Instead, the likelihood fit result for the daughter product of ^{68}Ge , ^{68}Ga is used, providing a stronger result. While the branching ratio for ^{68}Ge to decay to ^{68}Ga via EC is 100%, the branching ratio for ^{68}Ga to EC is not, and must be taken into account.

5.3.2 Singles Peak Efficiency

In EC decay to an excited state, the X-ray/Auger electron cascade is accompanied by a gamma ray of known energy, which can either:

- interact only in the main detector (event in singles Compton spectrum);
- interact in the main detector and one or more of the other detectors (event in multiples Compton spectrum);
- escape the main detector but interact in one or more of the other detectors (event in multiples spectrum EC peak); or
- escape all detectors (event in singles spectrum EC peak).

In the last case, where the gamma does not deposit energy in any detector, the event ends up in the singles EC peak as if the decay had been to the GS with no

coincident gamma. Both ^{65}Zn and ^{68}Ga have EC decay modes to excited states. To determine the decay rates of these isotopes, the fraction of EC events that end up in the singles peak, the singles efficiency, must be found.

A simulation is performed in GEANT4 for each isotope, providing the energy of each particle in an event, the energy deposited in the detector by each of these particles, and the position in the detector where the energy is deposited. Only K -shell EC events are selected for analysis, as the singles efficiency does not depend on the shell energy.

As the simulation does not take into account the detector response, neither the radial parameter nor the multiples event criterion can be determined as in the main analysis. In the main analysis, an event is classified as a multiple scatter event if there is an energy deposit in one of the other detectors exceeding that detector's energy threshold; however, this threshold varies with time. Each simulated event is assigned a set of thresholds: the fraction of events that a single set of thresholds is assigned to is equal to the fraction of the livetime for which this particular set of thresholds was realized in during the measurement. A simulated event is characterized as a multiple if there is an energy deposit in one or more of the other detectors that exceeds the assigned threshold.

A radial cut is also developed for the simulated events. EC events that pass the singles cut are selected, and the x and y position of the energy deposit for each individual interaction in the event is used to create an energy weighted radius. For an event depositing total energy E and with n particles produced in the decay, where particle i deposits energy E_i , the energy weighted radius is

$$r = \sqrt{\sum_{i=1}^n L(i) \frac{E_i}{E} \left(\left(\frac{x_{1,i} + x_{3,i}}{2} \right)^2 + \left(\frac{y_{1,i} + y_{3,i}}{2} \right)^2 \right)}. \quad (5.3)$$

$L(i)$ corresponds to the Lindhard factor, equal to 1 for an electron recoil and assumed 0.3 for a nuclear recoil. Note that $E = \sum_{i=1}^n L(i) E_i$. The parameters $x_{1,i}$ and $x_{3,i}$ are the initial and final x positions (and similarly for the y position). Once the radial parameter has been determined, the energy efficiency at the energy corresponding to the K -shell is then found. The radial cut location is selected such that the fraction of events that pass the cut is equal to this efficiency. For a detector radius of 3.81 cm, the radial cuts are located at 0.0265 m and 0.0262 m for ^{65}Zn and ^{68}Ga , respectively.

For the remainder of the analysis, only EC K -shell events that pass the radial cut are selected, totalling N events. From these events, those with an energy deposit in the detector of approximately E_K are selected, giving all of the expected events in the K -shell peak, totalling N_K events. Within these events, those that also pass the multiples cut are selected, resulting in $N_{K,m}$ events. The total number of events in the singles peak is then $N_{K,s} = N_K - N_{K,m}$. The ‘singles efficiency’, or the fraction of EC events that are expected to end up in the singles peak, is then the fraction $N_{K,s}/N$.

The EC singles efficiency is then multiplied by the EC branching ratio to determine a total scale factor. For ^{65}Zn and ^{68}Ga , the EC branching ratios are 0.98 and 0.1111, respectively. Scale factors of 0.643 and 0.0964 were found.

5.3.3 Detector History

The location history of the detector is used in extracting the production rate. After the germanium crystal was pulled on November 24th, 2008, the detector was kept

in surface facilities at Stanford and Berkeley during fabrication and testing and, in between, in storage in an underground location at a depth of 16 m.w.e [131]. While on the surface, the detector was exposed to cosmic rays, and while in the underground tunnel, it is assumed that no cosmogenic isotope production occurred.

There is some uncertainty in one of the dates that the detector was brought underground due to a discrepancy in the history logs. The conflicting dates are two months apart; therefore, the average date is used in calculating the production rates and the discrepancy is propagated into the final uncertainty.

The detector was brought underground at the Soudan mine on October 25th, 2011, where it was kept until after the end of CDMSlite Run 2 , which started on February 4th, 2014. The exposure history of the detector is summarized in Table 5.2.

Time (days)	0	49	59	121±30	210	309	315	317	333	347
Location	S	U	S	U	S	U	S	U	S	U
Time (days)	366	434	438	497	498	791	829	1065	1898	
Location	S	U	S	U	S	U	S	M	Run Start	

Table 5.2: Run 2 detector location as a function of time. The top row gives the time in days after crystal pulling at which the detector was brought to the location indicated in the bottom row. Locations: S - surface (full exposure), U - underground (no exposure), M - Soudan mine (no exposure). As discussed in the text, the date of the 4th entry is uncertain due to discrepancies in different log entries. The average date is used with the indicated uncertainty spanning the full range of the discrepancy.

5.3.4 Extracting Production Rates

The event rates from the likelihood fit (scaled for 100% signal efficiency and with branching ratios accounted for) are used to determine the activity of each isotope as

a function of time during the run. If λ is the isotope lifetime, m is the detector mass, $L(t)$ is the fraction of the total time that the detector was active per unit time (thus the integral of $m \cdot L(t)$ over the entire run is the run exposure), and A_0 is the activity at the start of the run, the measured activity per kg at time t since the run start is

$$A_{meas}(t) = \frac{A_0}{m} L(t) e^{-\lambda t}. \quad (5.4)$$

This function is then normalized such that the area is equal to the event rate. Setting $t = 0$, A_0 can be solved for.

In periods with no cosmogenic activation, such as when the detector is stored in the underground tunnel or in Soudan mine, the activity of an isotope is governed by the simple exponential decay law

$$\frac{dN}{dt} = -N, \quad (5.5)$$

where N is the number of atoms at time t . Assuming N_0 atoms of isotope at a time t_0 , the number of atoms $N(t)$ at subsequent time t is

$$N(t) = N_0 e^{-\lambda(t-t_0)}. \quad (5.6)$$

In contrast, when the detector is stored above ground the activity is also influenced by the production rate P of the isotope

$$\frac{dN}{dt} = P - N, \quad (5.7)$$

from which the number of atoms as a function of time is

$$N(t) = (N_0 - \frac{P}{\lambda}) e^{-\lambda(t-t_0)} + \frac{P}{\lambda}. \quad (5.8)$$

Starting with $t = 0$ as the time at which the crystal was pulled, and an initial contamination of $N(t = 0) = 0$, the detector history is used to write the activity as a function of the production rate P . Using the calculated activity at the start of the run, A_0 , P can be explicitly determined. Figure 5.7 shows the activity of each isotope.

5.3.5 Resulting Rates

The measured production rates are shown in Table 5.3. For ^{68}Ge , two production rates are calculated under different assumptions: first assuming no contamination at the time of crystal pulling, and second assuming that the crystal is at full saturation when it is pulled. Either assumption is extreme, but the difference between the resulting rates is negligible compared to the statistical uncertainty from the fit. Also for tritium two values are presented: the rate determined using the best fit, and a conservative rate determined using the extreme assumption of no Compton contribution.

The production rate for tritium is lower than, but compatible with, the rate measured by EDELWEISS [73]. However, the production rates for the other isotopes are significantly lower than the rates from EDELWEISS.

5.4 WIMP Limit

The published CDMSlite Run 2 limit on spin-independent WIMP–nucleon interactions [82] was calculated using the Optimum Interval (OI) method [100], a standard limit setting tool for SuperCDMS DM searches. The Run 2 OI limit did not include

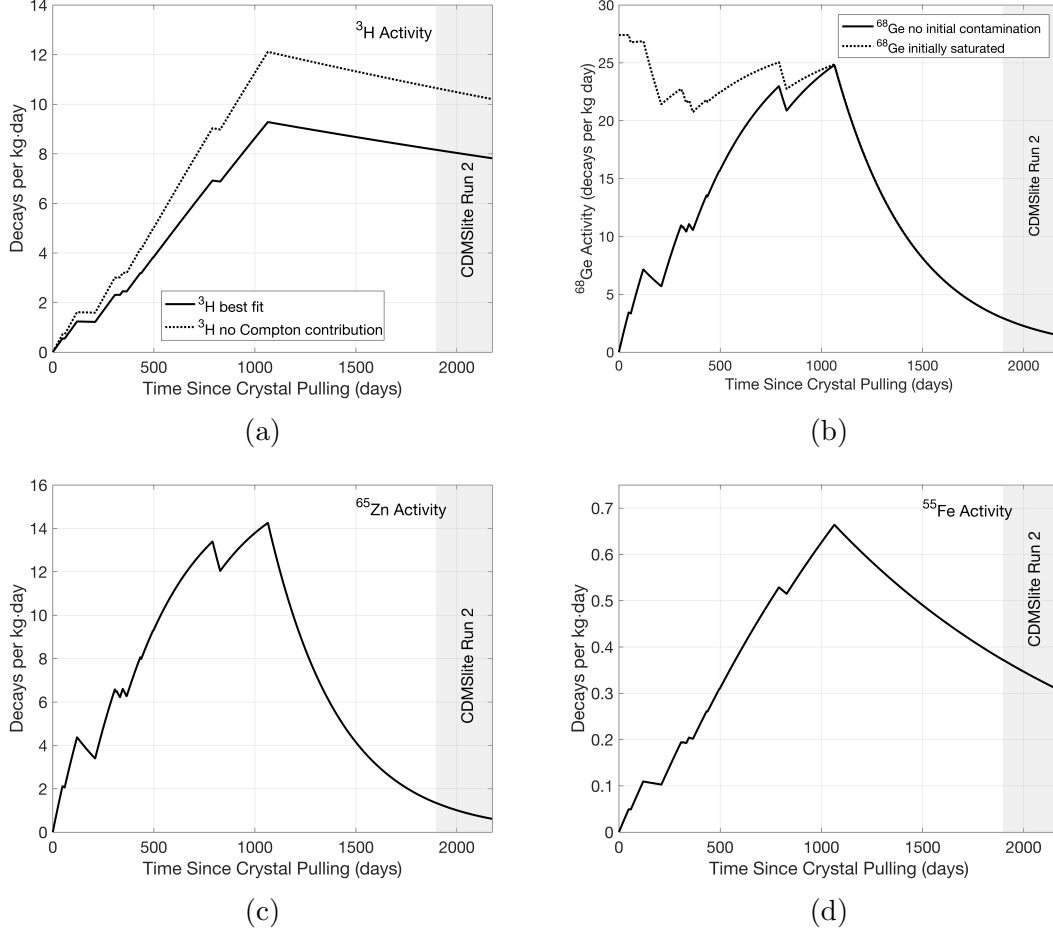


Figure 5.7: Activity of isotopes ((a) ^3H , (b) ^{68}Ge , (c) ^{65}Zn , and (d) ^{55}Fe) produced cosmogenically in Ge as a function of time in days since crystal pulling. In (a) the ^3H best fit (solid line) and fit without Compton component (dashed line) activities are shown; in (b) the ^{68}Ge activities under the assumptions of no initial contamination (solid line) and initial detector saturation (dashed line) are shown.

any background model. Here a likelihood approach is taken using the background model from the likelihood analysis for the extraction of production rates.

To compute the limit, an additional component corresponding to a WIMP spectrum is included in the likelihood analysis. Details about the calculation of the WIMP spectrum are given in Appendix C. The differential rate is calculated for a given WIMP

Isotope	Cosmogenic Production Rate [atoms/(kg·d)]	
	Measurement	Comment
^3H	74 ± 9	best fit
	(96 ± 10)	no Compton component
^{55}Fe	1.5 ± 0.7	
^{65}Zn	17 ± 5	
^{68}Ge	30 ± 18	no initial contamination
	28 ± 17	initially saturated

Table 5.3: Measured production rates and uncertainties (1σ) for cosmogenically produced isotopes in natural Ge at sea level. The second number for ^3H (in parenthesis) is deduced from the fit that neglects contributions from Compton scattering. The two values for ^{68}Ge make the two extreme assumptions that the concentration of this isotope during crystal pulling was either 0 or in equilibrium (saturated).

mass as a function of NR energy, and using $k = 0.157$ in the Lindhard model, the spectrum is converted to the ER energy scale and convolved with the energy-dependent resolution. The signal efficiency is then applied, and the spectrum is normalized. Figure 5.8 shows the resulting PDFs for several WIMP masses.

A likelihood fit is then performed for a variety of WIMP masses between 1.2 and 15 GeV/c^2 . The resulting fit to the spectrum is shown for a 15 GeV/c^2 WIMP in Figure 5.9.

The fit results are then used to determine the spin-independent WIMP-nucleon cross section. The results are shown in Table 5.4, and the resulting 90% upper confidence level limit is shown in Figure 5.10. Uncertainty in the Lindhard model (see Section 2.3.2) is calculated using a Monte Carlo approach. For each WIMP mass, different values of k (see Equation 2.6) are used and the corresponding 90% upper confidence level limits are calculated. The 1σ and 2σ uncertainty bands are extracted

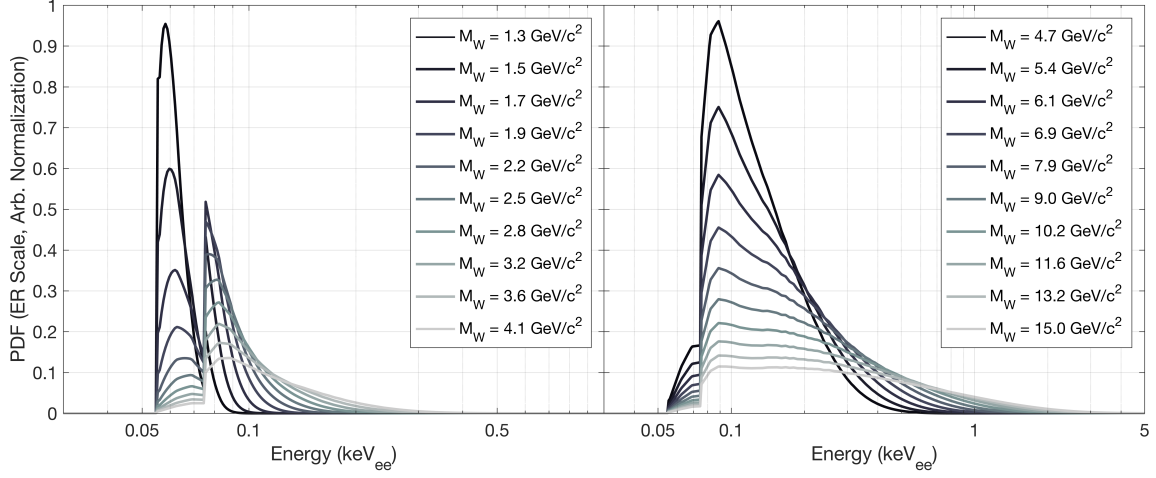


Figure 5.8: WIMP recoil spectra with resolution and efficiency applied.

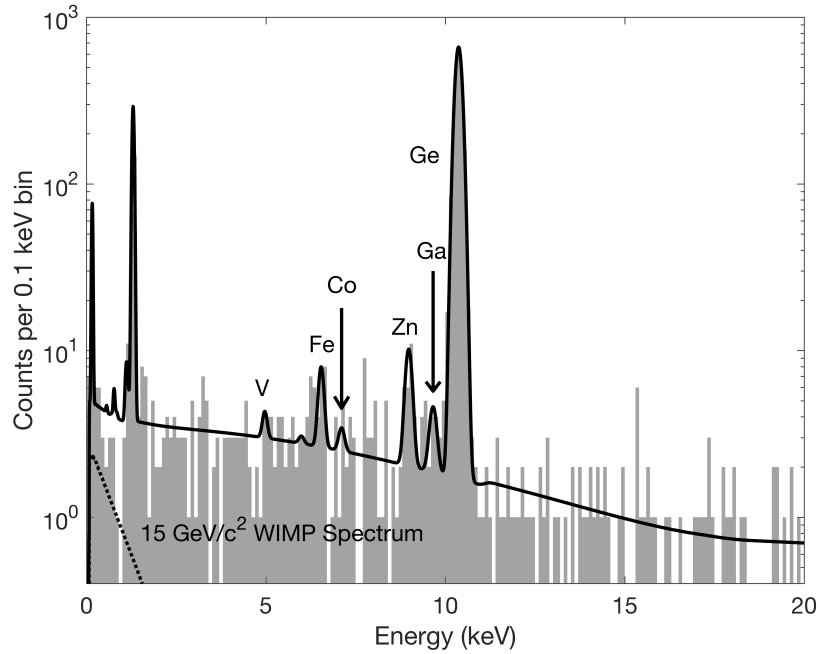


Figure 5.9: Maximum likelihood fit results to CDMSlite Run 2 spectrum for a $15 \text{ GeV}/c^2$ WIMP.

and shown in Figure 5.10. Not all systematics are considered, and this limit should be considered preliminary.

WIMP Mass (GeV/ c^2)	WIMP Events	Cross Section (cm ²)	WIMP Mass (GeV/ c^2)	WIMP Events	Cross Section (cm ²)
1.30	3.22	1.88×10^{-37}	4.71	16.20	8.29×10^{-42}
1.48	4.26	2.29×10^{-38}	5.36	17.86	6.75×10^{-42}
1.68	5.79	3.76×10^{-39}	6.09	18.84	5.50×10^{-42}
1.91	6.93	8.08×10^{-40}	6.93	19.22	4.58×10^{-42}
2.18	7.64	2.21×10^{-40}	7.88	19.17	3.85×10^{-42}
2.47	8.25	7.85×10^{-41}	8.96	18.96	3.32×10^{-42}
2.81	8.99	3.59×10^{-41}	10.19	18.89	2.93×10^{-42}
3.20	10.10	2.06×10^{-41}	11.60	19.16	2.69×10^{-42}
3.64	11.81	1.38×10^{-41}	13.19	19.78	2.58×10^{-42}
4.14	14.01	1.05×10^{-41}	15.00	20.65	2.51×10^{-42}

Table 5.4: Results from maximum likelihood fit to CDMSlite Run 2 spectrum with WIMP spectrum. Shown are the best fit number of WIMP events and the 90% upper confidence limit on the WIMP–nucleon scattering cross section as a function of WIMP mass.

The limit is an improvement upon the published OI limit in the mass range 3–15 GeV/ c^2 , but is not competitive with the DarkSide-50 limit [84]. Both DarkSide-50 and the OI limit are overtaken in a small region 1.3–1.5 GeV/ c^2 . Below this region the limits are not determined.

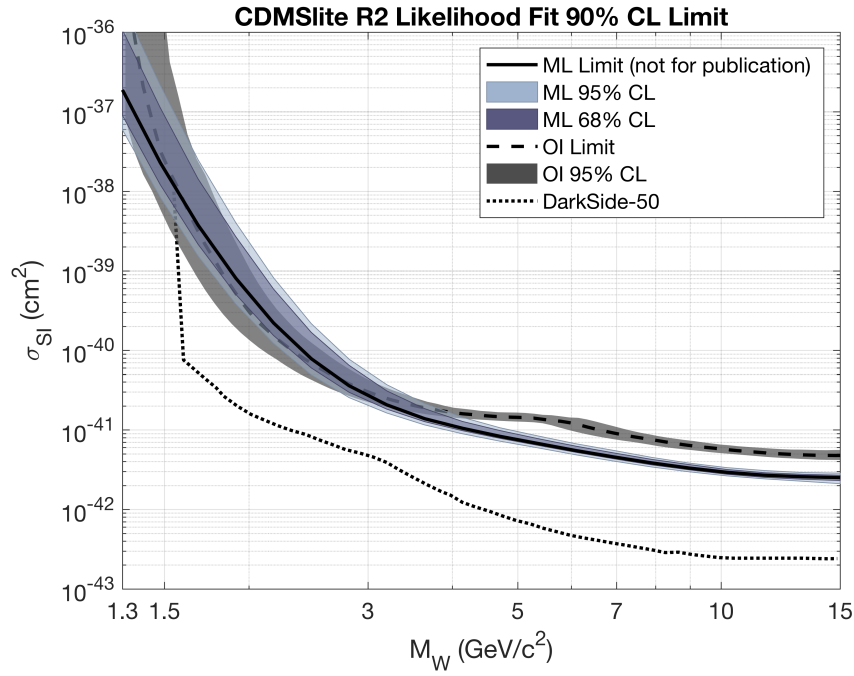


Figure 5.10: Spin-independent WIMP limit using maximum likelihood method (solid line) with 95% (light band) and 68% (dark band) CL bands. The OI limit [82] (dashed line) the DarkSide-50 limit [84] (dotted line) are shown for comparison.

Chapter 6

CDMSlite Run 3

A similar analysis is performed for CDMSlite Run 3. However, whereas an OI WIMP limit was determined for Run 2, in Run 3 a profile likelihood method is used. The likelihood fit is performed up to 25 keV, requiring extension of the signal efficiency as part of the main WIMP analysis. In this case the likelihood fit is not a part of the work for this thesis, only the extension of the signal efficiency.

Unlike in Run 2, where the radial cut was set flat as a function of energy, the Run 3 radial cut below 2 keV is defined such that fewer than 0.125 reduced NTL gain events are expected to pass the cut. Above 2 keV the radial cut is flat, resulting in a discontinuity at 2 keV.

6.1 Efficiency Extension

During the Run 3 analysis, the signal region was blinded with *salted* data (see Section 2.3.3). However, the salt was only included below 5 keV in WIMP search data, thus the results of the following analysis (which was performed before unsalting) are valid after unsalting.

The primary indication of the reduced radial cut efficiency above 20 keV in Run 2 was observed in the radial parameter vs. energy plane. However, this trend is not observed in the Run 3 plane, as shown in Figure 6.1. Note that the behaviour of the radial cut below 2 keV is a result of the change in cut definition (allowing fewer than 0.125 reduced NTL gain events to pass) from Run 2.

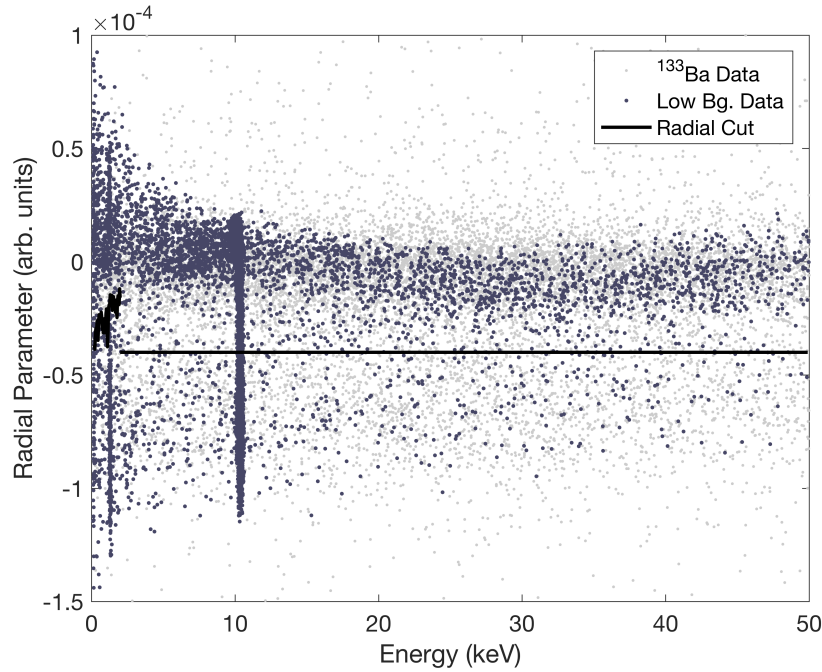


Figure 6.1: The CDMSlite Run 3 radial parameter as a function of energy for low background (dark points) and ^{133}Ba calibration data. The radial cut is also shown (solid line), with discontinuity at 2 keV.

An initial hypothesis efficiency is developed in the same manner as for Run 2, interpolating the efficiency between 2 and 10.37 keV and set constant at higher energies for each period (see Section 2.3.3). The efficiencies are weighted by the livetime of the respective period, with resulting efficiency shown in Figure 6.2. The erratic behaviour of the efficiency below 2 keV is a result of the definition of the radial cut.

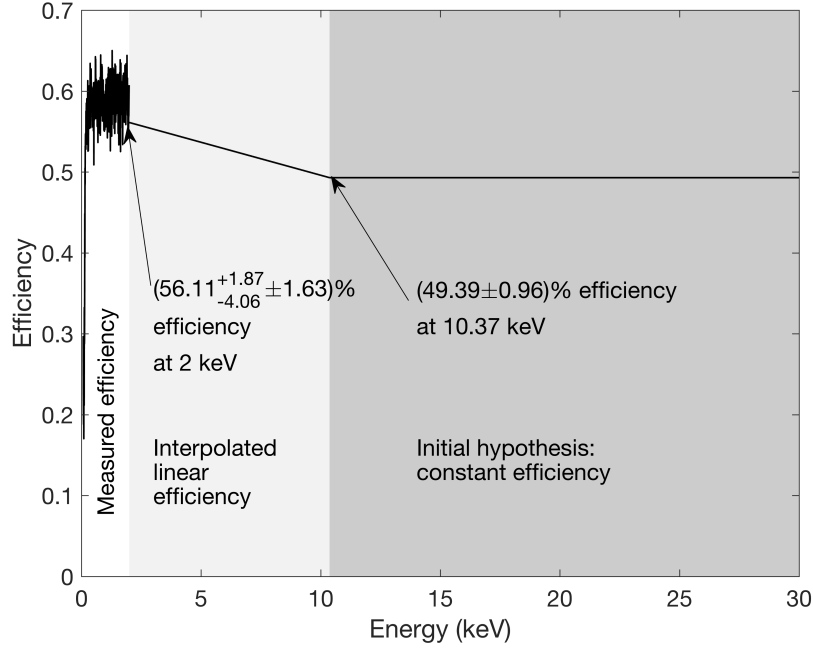


Figure 6.2: CDMSlite R3 initial hypothesis radial efficiency as a function of energy. This is the measured efficiency up to 2 keV (white region), then linearly interpolated from 2 keV up to the efficiency measured at 10.37 keV (light grey region), and is assumed constant (dark grey region) above this energy.

The weighted efficiency is applied to a simulated barium calibration spectrum and compared to measured data in Figure 6.3. Whereas in Run 2 the initial hypothesis efficiency clearly did not represent the data (see Figure 4.7), in Run 3 the spectra are compatible within statistics.

A KS test indicates that the hypothesis that the two distributions are drawn from the same spectrum cannot be rejected at any reasonable confidence level. Therefore, no further adaptations to the efficiency are required, and the final Run 3 efficiency used in this analysis is the initial hypothesis efficiency for each period.

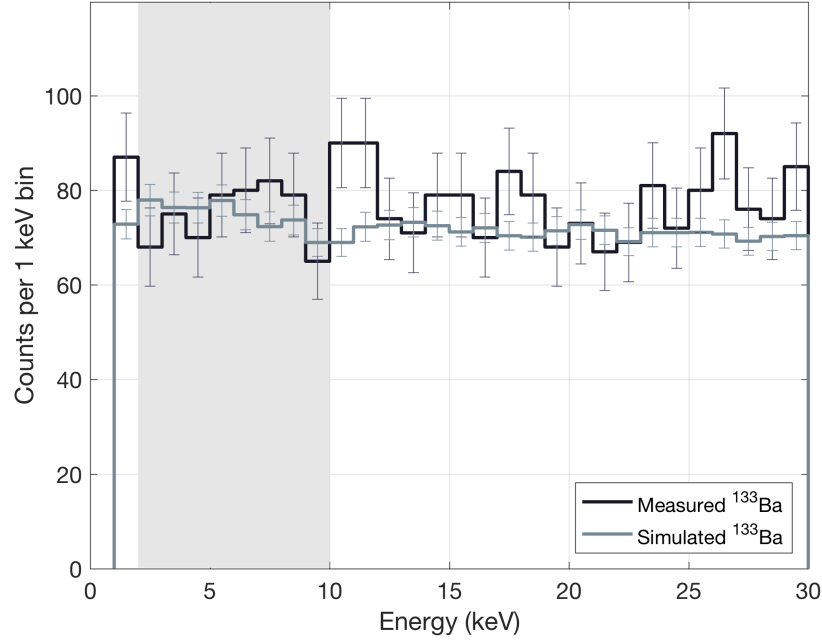


Figure 6.3: Livetime weighted initial hypothesis Run 3 efficiency applied to simulated barium calibration spectrum, normalized to the measured spectrum from 2–10 keV. The two spectra are compatible within uncertainty.

6.2 Likelihood Fit

As the CDMSlite Run 3 WIMP limit is set using a likelihood method, the results are directly used in this thesis. In order to determine the WIMP sensitivity before unsalting, a likelihood fit was performed between 5 and 25 keV, avoiding the salted region below 5 keV. The resulting event rates are shown in Table 6.1. It should be noted that, using CDMSlite Run 2 data, it was confirmed that differences in event rates from fits between threshold to 25 keV and 5 to 25 keV are negligible. Therefore, the Run 3 event rates between 5–25 keV are corrected for 100% efficiency and rescaled to the range 0–25 keV.

In CDMSlite Run 2 surface background from ^{210}Pb was neglected in the fit, but

in the Run 3 fit the surface background is explicitly included. The Run 3 detector was located at the top of a stack of detectors (see Section 2.1), whereas the Run 2 detector was in the centre of its respective stack. Therefore the Run 3 surface background includes a significant contribution from the top lid that is not present in the Run 2 spectrum.

Component	# Events	Uncertainty (1σ)
$^{68,71}\text{Ge}$	1984	32
^{68}Ga	2.4	2.2
^{65}Zn	8.6	2.9
^{55}Fe	3.5	2.4
^3H	49.9	17.5
Compton	156	13.8
Top Lid	37.5	13.1
Housing	2.9	5.6
Ge	5.6	2.4

Table 6.1: Maximum likelihood fit results with uncertainty. The numbers given are the number of events that each background contributes to the measured CDMSlite Run 3 spectrum between 5–25 keV. The last three rows correspond to surface background events.

6.3 Production Rates

Using the Run 3 detector history and the background event rates, production rates are extracted in the same manner as for Run 2. The resulting rates are compared to the Run 2 rates in Table 6.2.

The activity as a function of time in days since the Run 3 detector crystal was

Isotope	Cosmogenic Production Rate [atoms/(kg·d)]		
	CDMSlite R3	CDMSlite R2	Comment
^3H	50 ± 14	74 ± 9	best fit
^{55}Fe	1.1 ± 0.8	1.5 ± 0.7	
^{65}Zn	35 ± 12	17 ± 5	
^{68}Ge	48 ± 43	30 ± 18	no initial contamination
	44 ± 40	28 ± 17	initially saturated

Table 6.2: Measured production rates and uncertainties (1σ), for various isotopes in natural germanium at sea level, using data from both CDMSlite R2 and R3. The two values for ^{68}Ge make the two extreme assumptions that the concentration of this isotope during crystal pulling was either 0 or in equilibrium (saturated). The Run 3 fit includes surface background, while the Run 2 fit does not. Subtracting the $\sim 10\%$ estimated contribution to surface events from tritium, the tritium rates are compatible within 1σ .

pulled is shown for each isotope in Figure 6.4. For ^{68}Ge the rates assuming zero initial contamination and full saturation at the time of crystal pulling are both shown.

The production rates for ^{68}Ge and ^{55}Fe are consistent between the two runs within 1σ , while the rates for ^3H and ^{65}Zn are consistent only within 2σ . There were significant timing differences between the two runs. Run 3 was almost a year later than Run 2, and data taking occurred over a shorter continuous period of 96 days. Thus the shorter lived isotopes, ^{68}Ge and ^{65}Zn , have low expected event rates.

As surface background from Pb decays is included in the Run 3 fit, but not the Run 2 fit, the measured ^3H rate would be expected to be larger in Run 2. Assuming that the surface background in Run 2 accounts for 10% of the tritium events given by the likelihood fit (the estimated maximum effect of surface background), then the ^3H production rates from each run are compatible.

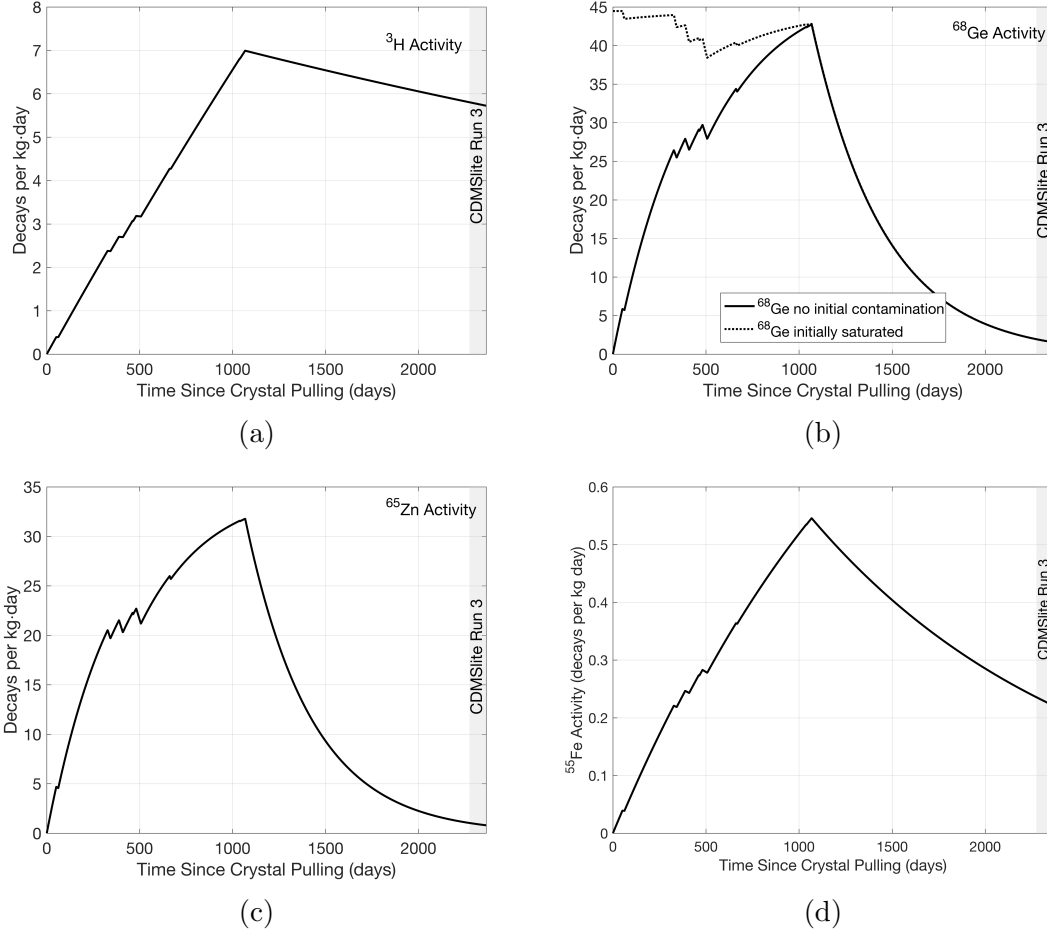


Figure 6.4: Activity of isotopes ((a) ^3H , (b) ^{68}Ge , (c) ^{65}Zn , and (d) ^{55}Fe) produced cosmogenically in Ge as a function of time in days since crystal pulling for CDMSlite Run 3. In (a) the ^3H best fit (solid line) and fit without Compton component (dashed line) activities are shown; in (b) the ^{68}Ge activities under the assumptions of no initial contamination (solid line) and initial detector saturation (dashed line) are shown.

Part III

Conclusion and Future Work

Chapter 7

Summary

The CDMSlite Run 2 and Run 3 spectra were analyzed to determine cosmogenic production rates for ^3H , ^{55}Fe , ^{65}Zn , and ^{68}Ge . While Run 2 required an extension of the signal efficiency, Run 3 did not as the main WIMP analysis already required the extended efficiency. Additionally, Run 3 includes contributions from surface background in the likelihood fit, whereas Run 2 does not; it is expected that the true contribution from tritium is somewhere below the value extracted from Run 2. The Run 3 WIMP analysis is awaiting publication, while Run 2 data was used here to produce an improved limit compared to the originally published OI limit.

When taking into account the surface event contributions, the results are compatible between the two measurements within 1σ , with the exception of ^{65}Zn , which is compatible within 2σ . The measured production rate for tritium is compatible with that from EDELWEISS, but the other rates are not. This is likely due to temporal and spatial variations in the cosmic radiation that led to a different activation pattern in EDELWEISS than in SuperCDMS; however, this is only a hypothesis. Further measurements and information on cosmogenic activation will be required to resolve this issue.

Chapter 8

Future Work

Further measurements of production rates are required in order to properly understand the rates. Using the HV detectors at SuperCDMS SNOLAB production rates in Ge could be measured.¹ Comparison between measurements of the same detector at different times should be made, as well as between different detectors. Production rates themselves are important for constraining backgrounds when setting limits.

The CUTE facility, introduced in Section 2.4.3, will be used to test the new detectors before SuperCDMS SNOLAB is operational. Testing will begin shortly after the detectors are brought underground, when the activity of any cosmogenically produced isotopes is at a maximum. This will require an adapted analysis, where isotopes with half lives as short as a few days will need to be considered.

Future analyses of the HV mode at SNOLAB may benefit from the techniques used in this thesis. The method of using ^{133}Ba calibration data to extend the CDMSlite efficiency may be used, as in CDMSlite Run 3, in profile likelihood limit setting. This circumvents the lack of electron capture peaks above 10.37 keV in Ge.

¹Production rates in Si are more challenging due to the ^{32}Si background, expected to be the dominant background in the Si detectors [101].

Chapter 9

Conclusion

Production rates, in atoms/(kg·day), of 74 ± 9 for ^3H , 1.5 ± 0.7 for ^{55}Fe , 17 ± 5 for ^{65}Zn , and 30 ± 18 for ^{68}Ge were determined using event rates determined from a likelihood fit to the measured CDMSlite Run 2 spectrum. Additional measurements were performed using event rates from Run 3, giving 50 ± 14 for ^3H , 1.1 ± 0.8 for ^{55}Fe , 35 ± 12 for ^{65}Zn , and 48 ± 43 for ^{68}Ge . The rates are in agreement to within 1σ for ^{55}Fe and ^{68}Ge . The Run 3 ^{65}Zn rate is higher, but within 1.3σ . While the ^3H rate is low, this is likely due to the inclusion of surface events in the likelihood fit; considering the respective estimate for Run 2 brings the rates to within 1σ .

Avignone has only rates for ^{68}Ge and ^{65}Zn for comparison to the work of in this thesis, and the ^{68}Ge rates are compatible. Only the ^3H production rates are consistent with those measured by EDELWEISS. As the experimental database of production rates in Ge consists only of those from Avignone [106], EDELWEISS [73], and CDMSlite Run 2, further measurements are required in order to better understand the rates.

Production of isotopes by cosmic rays is highly dependent on the cosmic ray flux (which is dependent on location, time of year, and shielding overburden) and the

isotope production cross sections. Better understanding of the dependence of cosmic ray flux on location is required, and of isotope production cross sections, are required in order to explain the discrepancies in observed production rates. The planned CUTE measurements will add to the global knowledge and make one step closer to an understanding of this complex problem.

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Appendix A

Electron Capture Physics

A.1 An Overview of Electron Capture

When a parent atom of atomic mass and number (A, Z) decays by electron capture, one of the inner shell electrons of the atom is absorbed by the nucleus, converting a proton to a neutron with the simultaneous release of an electron neutrino:

$$p + e^{-} \longrightarrow n + \nu_e. \quad (\text{A.1})$$

All of the energy of the decay is carried by the emitted neutrino, the emission of which causes the nucleus to recoil by conservation of momentum. The daughter isotope, $(A, Z - 1)$, may be left in an excited state, in which case de-excitation to the ground state occurs by the release of gamma rays.

As one of the electrons is now missing from an inner shell, the vacancy will be filled either by an electron from a higher energy level, accompanied by the emission of one or more X-rays, or the ejection of an outer electron, leading to an Auger electron cascade.

A.2 Calculation of Electron Capture Peak Branching Ratios

The PDF for an EC background implemented for the likelihood analysis consists of three Gaussian functions centred on the K -, L_1 -, and M_1 -shell binding energies of the daughter isotope, with the width set by the energy-dependent resolution function. For Ge, there is an additional Gaussian centred on the L_2 -shell. The relative normalization of each Gaussian is determined by the branching ratio to the respective shell. These branching ratios are calculated for each isotope.

The electron shells are summarized in Table A.1 for Ge, which has the highest $Z = 32$ of the EC backgrounds considered in this thesis, and so all other isotopes will have fewer electron shells to consider.

Shell	K	L ₁	L ₂	L ₃	M ₁	M ₂	M ₃	M ₄	M ₅	N ₁	N ₂
Orbital	1s	2s	2p _{1/2}	2p _{3/2}	3s	3p _{1/2}	3p _{3/2}	3d _{3/2}	3d _{5/2}	4s	4p _{1/2}
Number e Ge	2	2	4	2	2	4	2	8	2	2	2
Ga	2	2	4	2	2	4	2	8	2	2	1
Zn	2	2	4	2	2	4	2	8	2	2	-
Co	2	2	4	2	2	4	2	8	1	-	-
Fe	2	2	4	2	2	4	2	8	-	-	-
Mn	2	2	4	2	2	4	2	7	-	-	-
V	2	2	4	2	2	4	2	5	-	-	-

Table A.1: Electron shells, orbital, and number of electrons per shell the EC isotopes considered in this thesis.

The fractional capture probability for the i^{th} shell is denoted P_i ; by definition the sum of all P_i must be unity (for the isotopes in Table A.1 with no electrons in the N-shells, $P_N = 0$):

$$P_K + P_L + P_M + P_N = 1. \quad (\text{A.2})$$

For the L -shell and higher, the first sub-shell dominates the shell probability, the second sub-shell makes a small contribution, and any other sub-shells are generally negligible. Equation A.2 can be rewritten as

$$P_K = \left\{ 1 + \frac{P_L}{P_K} \left[1 + \frac{P_M}{P_L} \left(1 + \frac{P_N}{P_M} \right) \right] \right\}^{-1}, \quad (\text{A.3})$$

where the ratios P_L/P_K , P_M/P_L , and P_N/P_M can be written

$$\frac{P_L}{P_K} = k_{LK} \left(\frac{[Q - E_f] - E_{L_1}}{Q - E_K} \right)^2 \quad (\text{A.4})$$

$$\frac{P_M}{P_L} = k_{ML} \left(\frac{[Q - E_f] - E_{M_1}}{Q - E_{L_1}} \right)^2 \quad (\text{A.5})$$

$$\frac{P_N}{P_M} = k_{NM} \left(\frac{[Q - E_f] - E_{N_1}}{Q - E_{M_1}} \right)^2. \quad (\text{A.6})$$

Q is the energy available in the electron capture process, E_f is the energy of the final level (will be zero if the decay is to the ground state), E_i is the binding energy of the i^{th} shell of the daughter nucleus, and k_{jk} is a factor dependent on the geometry of the j^{th} and k^{th} shells of the parent atom. These geometrical factors are tabulated in Schönfeld [97], and are shown for the relevant isotopes in Table A.2.

For each isotope, the fractions P_L/P_K and P_M/P_L are calculated. As the N -shell contribution is negligible, it is ignored. It is also assumed that $P_L \simeq P_{L_1}$ and $P_M \simeq P_{M_1}$. This assumption is valid as $P_{L_2}/P_{L_1} \simeq P_{M_2}/P_{M_1} < 0.001$. Table A.3 shows the branching ratios and peak energies for the K -, L_1 -, and M_1 -shells. As the

Element (Z)	k_{LK}	k_{ML}	k_{NM}
Ge (32)	0.1110 (16)	0.167 (4)	0.078 (7)
Ga (31)	0.1101 (16)	0.165 (4)	0.069 (7)
Zn (30)	0.1091 (17)	0.163 (5)	0.063 (8)
Co (27)	0.1066 (16)	0.160 (6)	0.047 (12)
Fe (26)	0.1056 (16)	0.159 (6)	0.041 (13)
Mn (25)	0.1045 (17)	0.158 (6)	0.036 (13)
V (23)	0.1022 (19)	0.154 (7)	0.024 (11)

Table A.2: Tabulated values of k_{LK} , k_{ML} , and k_{NM} with uncertainty on last two digits in parentheses from Ref. [97].

branching ratios depend on E_f , for isotopes that can decay to either an excited state or the ground state, the ground state branching ratios are used. These are the events that are expected to result in the singles EC peak.

For the Ge isotopes, the L_1 and L_2 branching ratios are both calculated and used in the likelihood fit, as the large number of events in the Ge capture peak means that the L_2 contribution (0.1%) should not be neglected. While the branching ratios are shown for both ^{71}Ge and ^{68}Ge , as the dominant contribution to the peak is from ^{71}Ge , these are the branching ratios used in the Ge EC PDF in the likelihood fit. The ratio of the L sub-shells for germanium is [132]

$$\frac{P_{L_2}}{P_{L_1}} = \frac{f_{L_2}^2}{g_{L_1}^2} = 0.00895, \quad (\text{A.7})$$

where $f_{L_2}^2/g_{L_1}^2$ is the amplitude ratio of the components of the bound electron radial wavefunction.

Isotope	K			L ₁			M ₁		
	E [keV]	σ [eV]	BR	E [keV]	σ [eV]	BR	E [keV]	σ [eV]	BR
⁷¹ Ge	10.37	101	87.6 %	1.30	31.2	10.5 %	0.160	14.0	1.8 %
⁶⁸ Ge	10.37	101	86.5 %	1.30	31.2	11.5 %	0.160	14.0	1.78 %
⁶⁸ Ga	9.66	96.3	88.6 %	1.20	30.0	9.8 %	0.140	13.1	1.6 %
⁶⁵ Zn	8.98	91.8	88.6 %	1.10	28.8	9.8 %	0.122	13.1	1.6 %
⁵⁷ Co	7.11	79.2	88.8 %	0.84	25.5	9.6 %	0.091	12.3	1.5 %
⁵⁵ Fe	6.54	75.2	88.6 %	0.77	24.4	9.8 %	0.082	12.1	1.6 %
⁵⁴ Mn	5.99	71.3	89.6 %	0.70	23.4	9.0 %	0.066	11.7	1.4 %
⁴⁹ V	4.97	63.7	89.3 %	0.56	21.3	9.3 %	0.059	11.5	1.4 %

Table A.3: Data for the radioisotopes considered in this thesis that decay via electron capture: total X-ray/Auger-electron cascade energies E (keV) [96], measured experimental resolutions σ (eV) at those energies [94], and branching ratios (BR) [97], for the K -, L_1 -, and M_1 -shell capture peaks. For isotopes other than ⁷¹Ge and ⁶⁸Ge only these three peaks are relevant due to the low number of decays of these isotopes and the small branching ratios to other shells. However, for germanium the L_2 peak ($E = 1.14$ keV, $\sigma = 29$ eV, and BR = 0.1 %) cannot be neglected due to the high rate of Ge EC decays.

Appendix B

Likelihood Method

B.1 Background PDFs

The EC backgrounds considered in the likelihood fit are $^{68,71}\text{Ge}$, ^{68}Ga , ^{65}Zn , ^{55}Fe , $^{58,57,56}\text{Co}$, ^{54}Mn , and ^{49}V . A tritium beta spectrum and Compton components are also included. The likelihood fit requires 9 PDFs. The PDFs of the EC X-ray/Auger electron peaks are modelled as Gaussian functions centred on the K -, L_1 -, and M_1 -shell binding energies of the daughter isotope. The resolution is set by an energy-dependent resolution model [94]. For an isotope with daughter isotope binding energies E_K , E_{L_1} , and E_{M_1} for the K -, L_1 -, and M_1 -shells, the PDF is modelled as

$$f(E) = \frac{P_K}{\sqrt{2\pi}\sigma_K} \exp\left(-\frac{(E - E_K)^2}{2\sigma_K^2}\right) + \frac{P_{L_1}}{\sqrt{2\pi}\sigma_{L_1}} \exp\left(-\frac{(E - E_{L_1})^2}{2\sigma_{L_1}^2}\right) + \frac{P_{M_1}}{\sqrt{2\pi}\sigma_{M_1}} \exp\left(-\frac{(E - E_{M_1})^2}{2\sigma_{M_1}^2}\right), \quad (\text{B.1})$$

where the P_X is the probability to capture an electron from the X -shell and σ_X is the

resolution at E_X . E_X , σ_X , and P_X are listed in Table A.3. The L_2 - and M_2 -shells are neglected due to their small branching ratios; however, the L_2 peak cannot be neglected for Ge. Therefore for this background, the PDF is

$$f(E) = \frac{P_K}{\sqrt{2\pi}\sigma_K} \exp\left(-\frac{(E - E_K)^2}{2\sigma_K^2}\right) + \frac{P_{L_1}}{\sqrt{2\pi}\sigma_{L_1}} \exp\left(-\frac{(E - E_{L_1})^2}{2\sigma_{L_1}^2}\right) + \frac{P_{L_2}}{\sqrt{2\pi}\sigma_{L_2}} \exp\left(-\frac{(E - E_{L_2})^2}{2\sigma_{L_2}^2}\right) + \frac{P_{M_1}}{\sqrt{2\pi}\sigma_{M_1}} \exp\left(-\frac{(E - E_{M_1})^2}{2\sigma_{M_1}^2}\right). \quad (\text{B.2})$$

The energy dependent efficiency determined in Section 4.2.5 is then applied to each PDF, and the resulting functions are renormalized to PDFs that can be used in the likelihood fit. These PDFs, denoted $f_b(E)$ for background b , are then used to minimize the negative log-likelihood function with estimators n_b , the number of events that background b contributes.

B.2 Likelihood Function

For the measured event spectrum, with N events with energies E_i (where $i = 1, \dots, N$), the likelihood function is

$$\mathcal{L}(\nu, \vec{\theta}) = \frac{\nu^N}{N!} e^{-\nu} \prod_{i=1}^N F(E_i; n_b) \quad (\text{B.3})$$

$$= \frac{\nu^N}{N!} e^{-\nu} \prod_{i=1}^N \left[\sum_b \theta_b f_b(E_i) \right] \quad (\text{B.4})$$

$$= \frac{1}{N!} e^{-\nu} \prod_{i=1}^N \left[\sum_b \nu \theta_b f_b(E_i) \right], \quad (\text{B.5})$$

where ν and $\vec{\theta}$ are likelihood parameters corresponding to the number of events and a vector of amplitudes for the background PDFs, respectively.

As ν and $\vec{\theta}$ are independent, maximizing the likelihood involves maximizing the Poisson term and the PDF term separately. Maximizing the Poisson term gives

$$\frac{\partial \mathcal{L}_{Pois}}{\partial \nu} = \left[\frac{N \nu^{N-1}}{N!} e^{-\nu} - \frac{\nu^N}{N!} e^{-\nu} \right] = 0 \quad (\text{B.6})$$

$$\implies \nu = N. \quad (\text{B.7})$$

Thus the likelihood is maximized for $\nu = N$. Furthermore, as a constant, the $N!$ term can be dropped with no effect on the maximization of the likelihood. The resulting log-likelihood function is

$$\ln(\mathcal{L}(\nu, \vec{\theta})) = -\nu + \sum_{i=1}^N \ln \left[\sum_b \nu \theta_b f_b(E_i) \right]. \quad (\text{B.8})$$

Note that $\nu \theta_b$ is the number of events that background b contributes to the spectrum. As $\sum_b \theta_b = 1$, ν and θ can be parameterized by $n_b = \nu \theta_b$.

$$\ln(\mathcal{L}) = -N + \sum_{i=1}^N \ln \left[\sum_b n_b f_b(E_i) \right]. \quad (\text{B.9})$$

Appendix C

WIMP Physics

WIMP detection rates are dependent on properties of the galactic halo. These properties include the WIMP velocity distribution, $f(v_\odot)$, and matter density $\rho_\odot$ at the Earth's position in the galaxy, $r_\odot$. The following form of the WIMP spectrum uses the isothermal halo model, in which the WIMP distribution function is a Maxwell–Boltzmann distribution in the galactic rest frame.

The following derivation is from the work of Donato, Fornego, and Scopel [71]. The interaction of a WIMP of mass m_χ with matter (i.e. a detector) produces the recoil of a nucleus with energy E_R . The relevant quantity to consider is the differential rate, dR/dE_R , in the rest frame of the Earth. The differential rate can be expressed as

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \frac{m_N \sigma_0}{2m_{\text{red}}^2} F^2(q) \mathcal{I}(v_{\text{min}}, v_\odot, v_{\text{escape}}) \quad (\text{C.1})$$

where N_T is the number of target nuclei, ρ_χ is the local WIMP matter density, m_N is the mass of the nucleus, σ_0 is the point-like total WIMP–nucleus cross section, m_{red} is the WIMP–nucleus reduced mass, and $F(q)$ is the nuclear form factor, a function

of the momentum transfer ($q^2 = 2m_n E_R$). The nuclear form factor can be written as

$$F(q) = 3 \frac{j_1(qr_0)}{qr_0} \exp\left(-\frac{1}{2}s^2 q^2\right). \quad (\text{C.2})$$

Here $s \simeq 1$ fm is the thickness parameter for the nucleus surface, $r_0 = (r^2 - 5s^2)^{1/2}$, $r = 1.2 A^{1/3}$ fm (A is the nuclear mass number), and $j_1(qr_0)$ is the spherical Bessel function of index 1. The function $\mathcal{I}(v_{\min}, v_{\odot}, v_{\text{escape}})$ contains the details about the intergration of the WIMP velocity distribution function, $f(v)$, in the Earth's frame:

$$\mathcal{I}(v_{\min}, v_{\odot}, v_{\text{escape}}) = \int_{v_{\min}(E_R)}^{v_{\text{esc}}} v dv \bar{f}(v) \quad (\text{C.3})$$

where $v_{\min}(E_R) = (m_N E_R / (2m_{\text{red}}^2))^{1/2}$, and v_{esc} is the WIMP escape velocity from the halo. The function $\bar{f}(v)$ is defined as

$$\bar{f}(v) = 2\pi \int_{(\cos \theta)_{\min}}^{(\cos \theta)_{\max}} d\cos \theta f(v, \cos \theta). \quad (\text{C.4})$$

For a non-rotating model, $\mathcal{I}(v_{\min}, v_{\odot}, v_{\text{escape}})$ can be written as a function of dimensionless variables, $x^2 = 3v^2/(2w^2)$, $\eta = 3v_{\odot}^2/(2w^2)$, and $x_{\min} = (3mE_R/4m_{\text{red}}^2 w^2)^{1/2}$. Here w is the root mean square velocity of the Maxwell distribution in the galactic rest frame, and must be the same in all three parameters. Defining the function

$$\chi(x, y) = \frac{\sqrt{\pi}}{2} [\text{erf}(y) - \text{erf}(x)] \quad (\text{C.5})$$

where

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt, \quad (\text{C.6})$$

$\mathcal{I}(v_{\min}, v_{\odot}, v_{\text{escape}})$ can then be written as

$$\mathcal{I}(v_{\min}, v_{\odot}, v_{\text{escape}}) = \frac{N}{\eta} \left(\frac{3}{2\pi w^2} \right)^{1/2} \times \begin{cases} \chi(x_{\min} - \eta, x_{\min} + \eta) - 2\eta \exp(-z^2) & x_{\min} \leq z - \eta \\ \chi(x_{\min} - \eta, z) - \exp(-z^2)(z + \eta - x_{\min}) & z - \eta \leq x_{\min} \leq z + \eta \\ 0 & x_{\min} \geq z + \eta. \end{cases} \quad (\text{C.7})$$

The differential rate can then be calculated once values for σ_0 , ρ_χ , $v_{\odot}$, and v_{escape} are chosen. The choice of σ_0 is arbitrary as this will cancel out when determining the cross section limit, but the choice of the other WIMP parameters will affect the result. There is some uncertainty on these values. In the likelihood calculation of Section 5.4, the following values for the parameters are used:

Parameter	Value
σ_0	$1 \times 10^{-41} \text{ cm}^2$
ρ_χ	$0.3 \text{ GeV } c^{-2} \text{ cm}^{-3}$
$v_{\odot}$	220 km/s
v_{escape}	544 km/s

Table C.1: WIMP model parameters.

These WIMP velocity and matter density parameters are those used in the published CDMSlite Run 2 optimum interval limit calculation [82].