Developing Simulation Techniques To Improve Detector Sensitivity For Neutrino Recoil Interactions

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Improving tracking capabilities for detecting low energy neutrinos would enable a broad range of physics measurements.Coherent Elastic Neutrino Nucleus Scattering (CEνNS) can be used as a tool to study neutrino properties and physics beyond the standard model. Low energy neutrinos in the MeV range that interact with particles generate nuclear recoils that leave small ionization tracks in an argon time projection chamber detector. Simulation studies that model the propagation of nuclear recoils will provide the distribution of ionization energy which is necessary for determining the thresholds and spatial resolution for a detector. Using the Stopping and Range of Ions in Matter (SRIM) simulation program, we obtained detailed collision data that modeled the propagation of nuclear recoils in gaseous argon. The trajectories significantly varied at each energy level, generating a wide distribution of ionization tracks for each nuclear recoil energy. Analyzing the spread in the distribution of ionization data provided a measure of how well certain ionization tracks and energies can be distinguished. Nuclear recoil energies ranging from 1-100 keV produced ionization tracks ranging from 10-350 μm in length and deposited ionization energy ranging between 1-60 keV. From these simulation studies, we obtained a fractional spatial resolution of $\sim$30% and a fractional energy resolution of $\sim$15%. These calculations suggest creating a detector capable of differentiating between nuclear recoil energies would require high spatial resolution on the μm scale with energy thresholds low enough to measure the 10s of keV energy deposits. We can implement these studies towards developing a gas electron multiplier based detector with 100 μm spacing capable of amplifying the signal produced by a low energy nuclear recoil.

I. INTRODUCTION

Neutrinos are among the most abundant and elusive particles in the universe. Created through various decay processes and weak interactions, these electrically neutral particles can carry information important to understanding the evolution of our universe, studying the last evolutionary stages of stars, and uncovering physics beyond the standard model. Because neutrinos are only detectable via the weak force, observing them quite is difficult and requires large target detectors. Time Projection Chambers (TPC) that utilize argon as a detection medium provide a fully active tracking detector capable of 3D track reconstruction from a neutrino interaction.

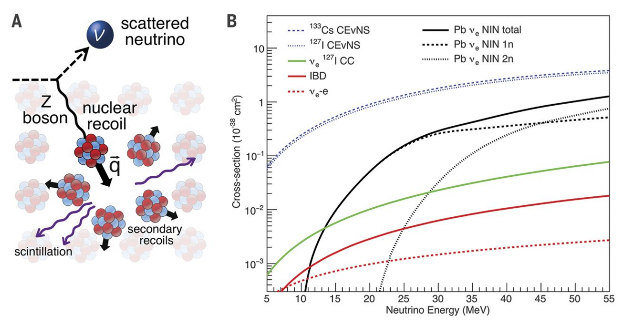


FIG. 1: A: CEνNS Interaction where nuclear recoil is the only detectable observable
B: Cross sections of CEνNS and other neutrino interactions such as inverse beta decay and neutrino-electron scattering, and charged current interactions [2]

A. Low Energy Neutrino Interactions

A neutrino interaction that occurs relatively frequently and is well predicted by the standard model is Coherent Elastic Neutrino-Nucleus Scattering (CEνNS). CEνNS is a neutrino interaction that is difficult to detect and has only been first observed recently through the COHERENT collaboration in 2017 [4]. This process is induced when a low energy neutrino (in the MeV range) scatters off an entire nucleus coherently.

While higher energy neutrinos interact with the individual nucleons of an atom, low energy neutrinos will scatter off the entire nucleus as a single particle exchanging a z boson, inducing a nuclear recoil in the 10s of keV range. The scattering cross section of the CEνNS interaction is proportional to the number of neutrons squared which makes the probability of this interaction relatively large compared to other interactions detected, such as inverse beta decay [2]. The nuclear recoil signal is the only detectable observable from neutrinos of low energies.

These nuclear recoils produce ionization energies that are difficult to measure with current detector thresholds.

In addition to low energy neutrinos, current dark matter candidates such as Weakly Interacting Massive Particles (WIMPs) can also interact coherently with an atom and generate a low energy nuclear recoil. This identical signal proposes the issue of a 'neutrino fog,' which describes a theoretical lower limit to which we can distinguish WIMP particles with a neutrino background. [1] Directional detection of nuclear recoils can help suppress neutrino fog backgrounds from dark matter searches and is therefore an area of active improvement for noble gas detectors.

B. Simulation Studies

Simulation studies of nuclear recoils in liquid and gaseous argon detectors and the ionization process aim to provide the necessary energy threshold and spatial resolution for a detector capable of detecting low energy nuclear recoils.

These simulation studies will emphasize two events from the nuclear recoil interaction: the propagation of the argon recoils at energies 1-100 keV in gaseous argon and the transport of the free electrons caused by the ionization process. From the nuclear recoil simulation, the trajectory information in addition to the energy loss are important outputs for obtaining spatial and energy resolution. The distribution of ionization energy loss produced by the nuclear recoil simulation will provide valuable input into simulating the electron transport. Simulations of the ionized electrons will provide a more detailed understanding of the ionization pattern created by nuclear recoils which will aid in particle identification in TPC detectors.

II. NUCLEAR RECOIL SIMULATION

The Stopping and Range of Ions in Matter (SRIM) is a software package that is capable of calculating different parameters for the transport of ions in a given target material and simulate these interactions through the use of its Monte Carlo based simulator, TRIM. TRIM produces collision plots that provide information on the energy loss from an incoming ion and the trajectories of an ion in a target medium and is a practical tool for tracking the spatial propagation of nuclear recoils in gaseous argon.

TRIM simulates the propagation of ions in a medium based on first principles, and allows for a more rigorous treatment of elastic scattering and energy distributions which is essential for simulating ions that experience numerous collisions in the process of slowing down [5]. TRIM also considers the energy loss induced on the target material and can track target collision cascades and energy lost to generating vacancies, phonon production, and to ionization.

A significant attribute of a nuclear recoil that penetrates an argon medium is its stopping power. The stopping power ($\frac{dE}{dx}$) is the amount of energy lost per unit distance and is what causes an atom to lose energy as it propagates. It is composed of the nuclear stopping power comprised of the elastic collisions with the target nuclei, and electronic stopping power caused by the inelastic collisions with the target electrons [5]. The stopping power increases rapidly at lower energies, and then eventually decreases after reaching a maximum known as the Bragg peak. At lower energies, the stopping power follows the falling side of the Bragg peak, where the energy loss decreases as the particle slows down [1]. In this lower energy regime, the nuclear stopping power is larger than the electronic stopping power and the energy with target nuclei is sufficient to produce cascades of secondary recoils, which contribute greatly to the the overall energy loss profile in the target.

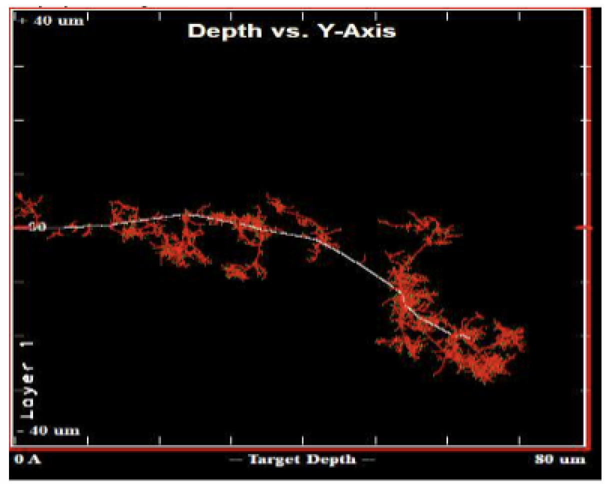


FIG. 2: Simulation of a single 30 keV nuclear recoil in gaseous argon: The white line shows the nuclear recoil trajectory, red cascades show secondary recoils

From figure 2, the initial recoil traveled a longitudinal range of 63.2 μm along the target depth at an initial energy of 30 keV at 1 atm. The energy loss from the initial recoil can be summed through energy loss due to ionization, which describes the interactions between the initial recoil and the target atoms, and energy loss due to kinetic energy of target atoms as a result of primary and secondary recoils. As the incoming nuclear recoil propagates through the gaseous argon, the energy from the collisions between the argon recoils and the target argon atoms is sufficient enough to generate cascades of secondary recoils. These secondary recoils contribute significantly to the overall energy loss. In the case of the 30 keV nuclear recoil, 61% of the energy lost due to ionization was from the secondary recoils, which signifies the importance of tracking the energy loss from both the incoming argon recoil and the secondary recoils for obtaining ionization distributions.

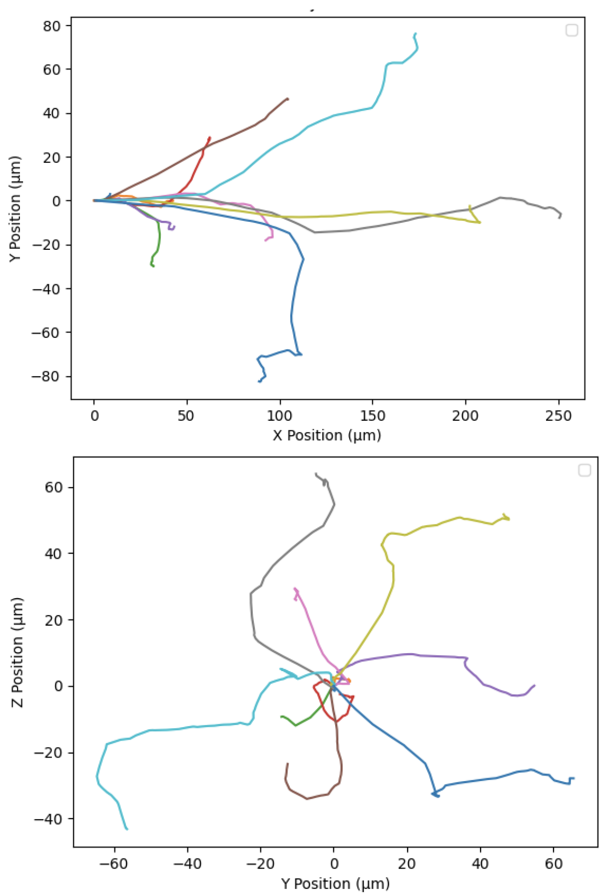


FIG. 3: *Upper:* 1-100 keV nuclear recoil trajectories projected on XY plane. Each trajectory color corresponds with a different recoil energy. This plot follows the nuclear recoil trajectory along the target depth
Lower: Lateral view of nuclear recoil projected on the YZ plane.

The propagation of nuclear recoils in gaseous argon at one atm varied significantly across energies ranging from 1-100 keV. Nuclear recoils at initial energies at 1-100 keV from these simulations exhibited a 10-250 μm track range. The initial beam path of the nuclear recoil is parallel to the target depth. The trajectories deviated from this initial path within a 60 μm range across the y and z axes. Overall, the trajectories lack a definite pattern and there is no distinct particle track that can be mapped for a single initial nuclear recoil energy. For this reason, it is important to obtain hundreds of simulations for each initial nuclear recoil energy so we can understand the spread in the distribution and gain intuition as to how nuclear recoils propagate and deposit energy.

A. Computation of Ionization Charge Distribution

Gaseous TPCs will detect the nuclear recoil through the drift electrons produced during ionization processes. Electronic stopping and nuclear stopping will both contribute to producing ionization in the gaseous argon medium and the secondary recoils will contribute greatly to the overall energy loss. For each simulation, SRIM provides distributions of the energy loss due to the ionization process from both the nuclear recoil and secondary recoils. As the nuclear recoil continues to propagate in the gaseous argon target, it will deposit its energy to ionizing electrons and induce secondary recoils that additionally deposit ionization energy. From analyzing the spread in data consisting of hundreds of simulations at each energy level, we can quantify the total ionization energy deposited. These calculations will provide the necessary resolution for an optimal detector.

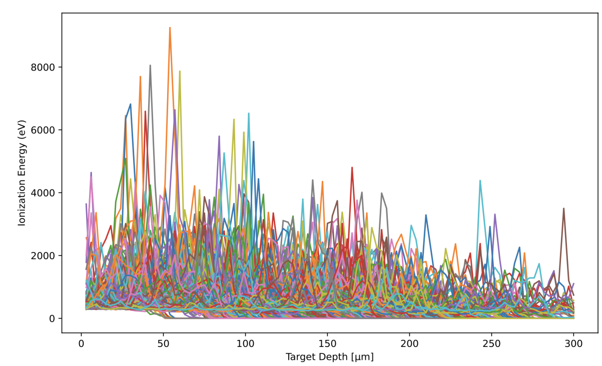


FIG. 4: Distribution of ionization energy loss at an initial nuclear recoil energy of 60 keV for 500 simulations

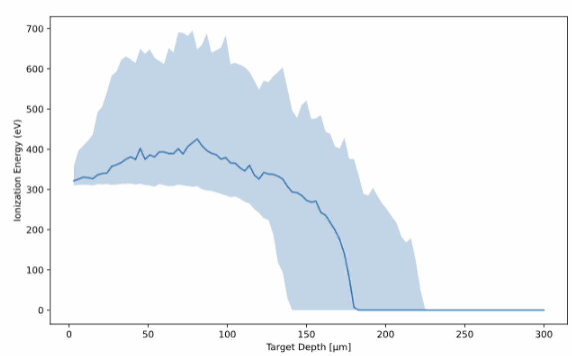


FIG. 5: Median ionization distribution at an initial nuclear recoil energy of 60 keV for 500 simulations

From figure 5, the spread in the ionization distribution across 500 simulations can be distinguished. The shaded region represents data within 50% of the median values and indicates a large spread across the distribution. As the nuclear recoil continues to deposit ionization energy, the ionization energy will reach zero, where the nuclear recoil will reach a maximum target depth. In this example, at an initial nuclear recoil energy of 60 keV, the nuclear recoil reaches a maximum target depth of $\sim$140 μm. This maximum target depth is correlated to the relative size of an ionization signature produced, which is important when considering the necessary spatial resolution for a detector capable of nuclear recoil tracking.

B. Resolution Calculations

In order to develop detectors capable of inferring directionality from keV nuclear recoils, information regarding the size of the ionization tracks produced is needed to guide the required spatial resolution for an optimal detector.

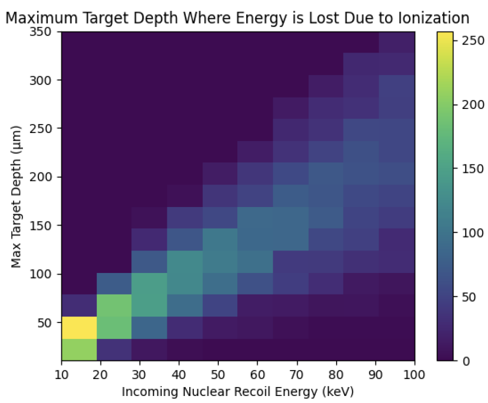
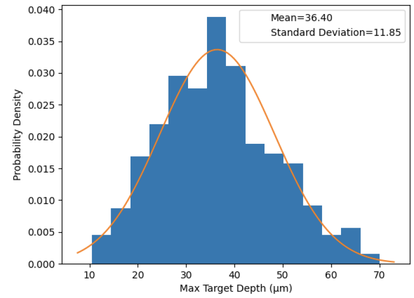


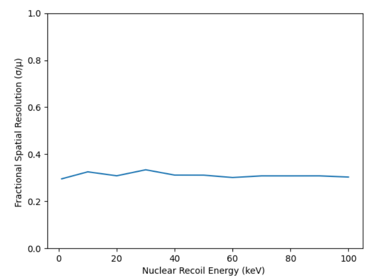
FIG. 6: Size of ionization signatures for each initial nuclear recoil energy. Each 10 keV bin contains 500 simulations

Across nuclear recoils ranging from energies 10-100 keV, the maximum target depth of the nuclear and the size of the ionization signatures of the nuclear recoils vary for each energy range, and the mean values for each distribution increases linearly. At each nuclear recoil energy, the data consisting of 500 simulations followed a normal distribution and therefore the standard deviation and the mean can be obtained to calculate the coefficient of variation. The coefficient of variation is defined as the ratio of the standard deviation to the mean. This ratio provides a measurement of how much the data is dispersed around the mean value and how accurately an ionization signature range can be distinguished within a given initial nuclear recoil energy.

The coefficient of variation will provide the fractional spatial resolution and give the upper and lower limits for differentiating the ionization tracks. This ratio will quantify how much an ionization track is smeared for a corresponding initial nuclear recoil energy. Across nuclear recoil energies within 1-100 keV, the fractional spatial resolution remained in between 29% - 33%. These calculations suggest developing a detector capable of resolving 10-350 μm ionization signatures and account for smearing as a result of the spread in the distribution.



(a) Distribution of 500 simulations at an initial energy of 10 keV. Gaussian fit is used to obtain fractional spatial resolution



(b) Fractional spatial resolution obtained by the ratio of the standard deviation and the mean at each energy bin

FIG. 7: Fractional spatial resolution calculation

To understand the distribution of ionization energy for obtaining necessary detector thresholds, we obtained the total ionization deposited for each simulation at each initial energy.

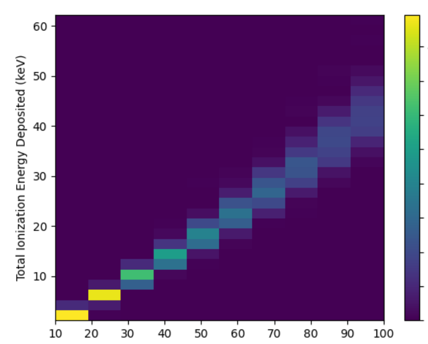
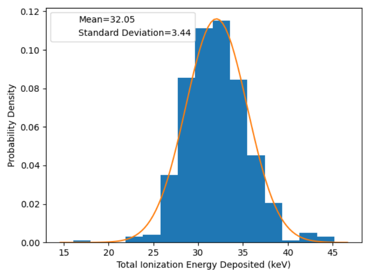
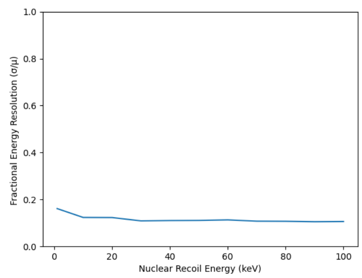


FIG. 8: Ionization energy deposited for each nuclear recoil energy. Each 10 keV bin contains 500 simulations

We obtained the fractional energy resolution to be $\sim$15% across nuclear recoil energies within 1-100 keV range. In order to distinguish between different energies of nuclear recoils and optimize detector performance, low



(a) Distribution of 500 simulations at an initial NR energy at 70 keV. Gaussian fit is used to obtain fractional energy resolution



(b) Fractional energy resolution obtained by the the ratio of the standard deviation to the mean at each energy distribution

FIG. 9: Fractional energy resolution calculation

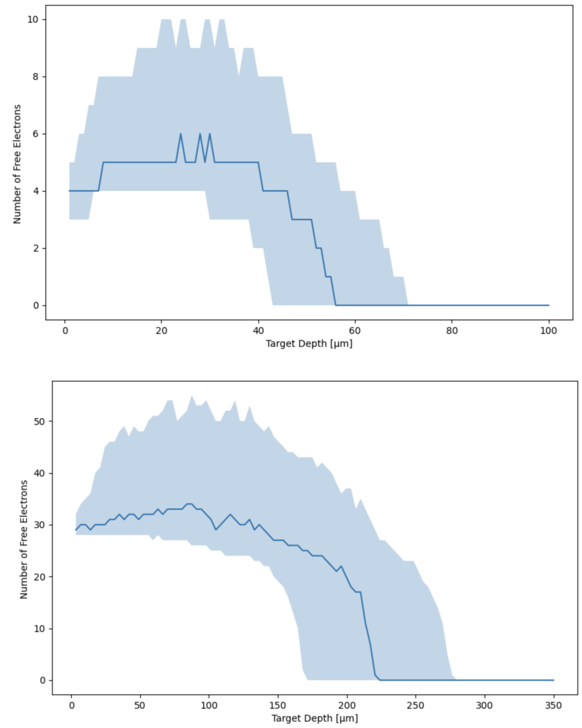


FIG. 10: Median number of free electrons produced across 500 simulations as a result of the ionization energy deposited. The number of electrons produced is found by dividing the ionization energy deposited by the energy required to ionize one argon atom (15.6 keV).
Lower: Initial Nuclear Recoil Energy 10 keV
Upper: Initial Nuclear Recoil Energy 100 keV

energy thresholds are needed to obtain detector sensitivity towards the tens of keV energy deposits from nuclear recoils.

III. ELECTRON TRANSPORT

The propagation of the free electrons produced as a result of energy lost to ionization is complex due to its interactions in the detector medium. As a result, the ionization signature produced by a nuclear recoil can be distorted by detector effects. At lower electron energies, elastic interactions between the electron and argon will occur and the argon-electron scattering interaction will impact the initial velocity of the electron. If the electron has enough energy, excitation or secondary ionization can occur and energy will be subtracted by the initial electron energy [3]. As a result of the detector's impact on the electron's transport, the ionization signature is smeared, affecting the detector's ability to resolve the ionization track. A thorough model of the electron cloud produced as a result of the nuclear recoil energy loss will guide the development of the necessary detector environments to improve nuclear recoil tracking.

The energy loss of the nuclear recoil decreases with time during its trajectory. As a result, more energy is deposited into ionization at the beginning of its propagation and thus more free electrons form. As the nuclear recoil loses energy in its path, elastic scattering dominates, hence, less free electrons are formed.

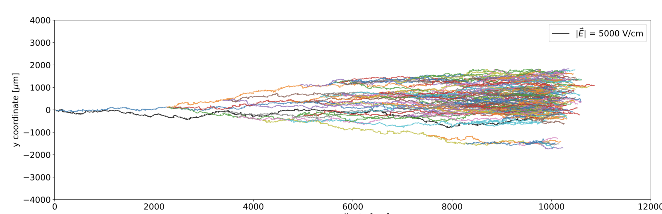


FIG. 11: TRANSLATE simulation: electrons in gaseous argon at a constant electric field of 5000 V/cm. Each branch is caused by secondary ionization where a new free electron is produced [3]

The TRANSLATE simulation package models the propagation of electrons in a liquid and gaseous argon medium at varying electric field strengths and accounts for the electron interactions with the argon medium throughout its trajectory [3]. The simulation of the secondary ionization, excitation, and electron-argon scattering interactions is important in understanding how a single electron drifts through a detector and the electron cascades it can produce. The number of free electrons produced and their positions along the target depth as a result of the initial nuclear recoil ionization energy deposition are valuable inputs to the TRANSLATE simulation tool.

From a simulated electron, we can track the cascade it produces and obtain a model for ionization signature from nuclear recoils and the detectors realistic response to the ionization charge distribution. Identifying features of electron propagation can help distinguish between particle tracks for identifying the interaction. Simulations that reproduce these interactions as a result of this complex microphysics can help gain an understanding of the number of free electrons produced and for matching electronic signal to the nuclear recoil interaction in the detector.

IV. DETECTOR R & D

These simulation studies and the resolution calculations can be implemented into developing a detector capable of nuclear recoil tracking and improving directional detection. A solution to improving detection of nuclear recoils that leave small energy deposits is electron amplification, specifically in a gaseous medium, where it is more practical for inferring directionality. A gaseous electron multiplier (GEM) based argon time projection chamber can provide the necessary amplification and sufficient gain to measure the ionization signatures from low energy recoils.

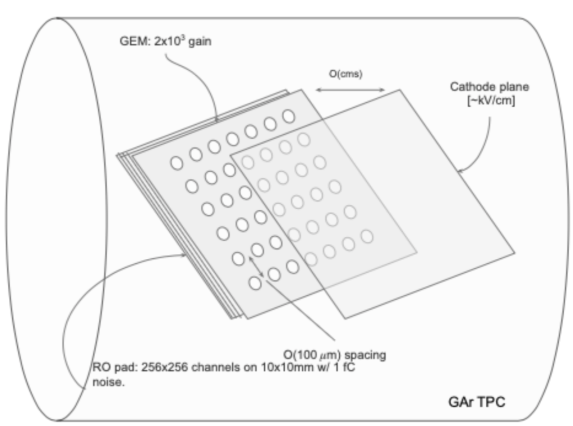


FIG. 12: Proposed GEM detector model with 100 μm spacing between holes on GEM foil

GEMs are a type of micro-pattern gaseous detector that can be used for μm-scale tracking. The GEM foil is a key component of the detector and is where electron avalanches will occur. The voltage potential placed within the foil creates a large electric field within the holes. As electrons drift across the detector volume from the electric field induced from the cathode plane, they will reach the holes of the GEM foil where the electric field is large enough to accelerate the electrons and cause secondary ionization processes. The result is a cascade of hundreds of electrons which will eventually drift to the readout plane where the signal will be detected. The development of a GEM detector will be guided by the sizes the ionization signatures produced and by the energy deposited from nuclear recoils to ensure the resolution is sufficient enough for μm tracking.

V. CONCLUSION

From the SRIM simulation tool, we have obtained distributions of the ionization energy deposited by nuclear recoils ranging from 1-100 keV in gaseous argon at 1 atm. Running hundreds of simulation for each energy level provided enough data to analyze the spread in the distribution to obtain measurements that quantified how well we can distinguish the ionization signatures for a given nuclear recoil energy. These ionization energy distributions provided the size of ionization signatures along the x axis; however, due to the limitations of the simulation program, we did not obtain y and z information regarding the ionization distribution for hundreds of simulations. The fractional spatial resolution we obtained suggests developing a detectors capable of resolving the μm tracks and accounts for smearing as a result of the variation of ionization tracks for a given nuclear recoil energy. The fractional energy resolutions calculated suggest that developing a detector with low enough energy thresholds is required to sense the tens of keV energy deposits.

VI. ACKNOWLEDGMENTS

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