Simulation Studies of Nuclear Recoils Resulting from Coherent Elastic Neutrino-Nucleus Scattering in Gaseous Argon

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(Dated: September 30, 2024)

Abstract

Neutrinos are light weakly interacting particles that play a crucial role in how the universe formed and how it operates today. One way in which neutrinos can interact with matter is called Coherent Elastic Neutrino-Nucleus Scattering (CEvNS), in which a neutrino interacts with the entire nucleus of an atom. Measuring CEvNS can find applications in particle physics, astrophysics and nuclear physics. In particular, the theoretically clean nature of this interaction makes it a good tool to search for deviations from currently known physics and thereby search for physics beyond the standard model. The principal challenge in detecting CEvNS arises from detecting the low energy nuclear recoils which range in energy from (10-100) keV. Key to many proposed applications is being able to detect the directionality of nuclear recoils arising from CEvNS. In order to be able to build a detector capable of sensing the directionality of these recoils, detailed simulations of these low energy processes within a detector medium are needed first. In this work, the Stopping and Range of Ions in Matter (SRIM) simulation tool is used to simulate nuclear recoils within gaseous argon. This program is capable of tracking energy losses caused by nuclear recoils, providing the trajectory of ionization signatures in the medium. The SRIM output data can then be used to make measurements of the intrinsic energy and directional resolution for nuclear recoils with energies ranging from 10-100 keV. Finally, this work also seeks to provide a preliminary calculation for the total number of scattering events that arise for a given nuclear recoil energy in gaseous argon assuming a neutrino flux produced by the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory.

I. INTRODUCTION

Neutrinos are the most abundant massive elementary particles in the universe, yet they remain highly mysterious. Many fundamental aspects of neutrinos are poorly understood, including their mass, oscillation, and their role on large cosmological scales. Studying neutrinos provides a way to probe physics beyond the standard model. Neutrinos only interact via weak force and gravity, making them notoriously difficult to detect.

One particular interaction of interest that neutrinos can engage in is known as Coherent Elastic Neutrino Nucleus Scattering (CEvNS). In this process, an incident neutrino exchanges a Z boson with the entire atomic nucleus and subsequently causes the nucleus to recoil at low energies (10-100 keV). Due to the coherent nature of this interaction, the cross section for this interaction is large for neutrino standards, making it more probable to occur compared to other neutrino interactions. Fig 1 shows a comparison of CEvNS cross section compared to more commonly studied charged currents as a function of neutrino energy [1].

Despite this, CEvNS remains one of the least studied neutrino interactions. In fact, the process has only been observed recently during the COHERENT Collaboration at Oak Ridge National Laboratory [2]. Further study of the CEvNS interaction is well motivated and can lead to a better understanding of neutrino physics. Since CEvNS is cleanly predicted by the Standard Model, it has also been proposed as a tool to further test the Standard Model and search for any deviations that could hint towards new physics. One particularly sought after measurement is the directionality of nuclear recoils resulting from CEvNS. One major reason for this is that measuring both the directional and energy spectrum of the recoils can provide information that the energy spectrum alone cannot. Assuming a known initial direction of neutrinos, it could allow for the direct energy reconstruction of the neutrino energy, which is vital for any neutrino experiment [3]. Measurements of deviations in the directional dependence predicted for CEvNS in the Standard Model have also been proposed as hinting towards new mediator particles beyond the Standard Model [4]. Beyond applications in particle physics, measuring the directionality of CEvNS even has utility in astrophysical searches for dark matter [5]. CEvNS serves an important background in these searches; thus understanding the directional dependence of CEvNS can help distinguish between neutrino

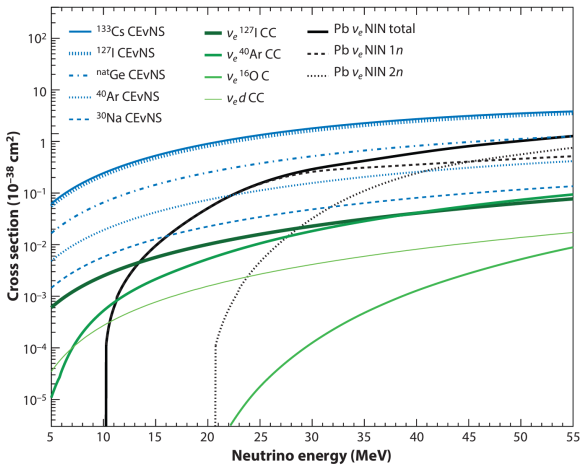

FIG. 1: CEvNS cross section as a function of neutrino energy compared to other neutrino interaction

and dark matter interactions with the detector. Potential applications in nuclear physics have been put forward as well. Since the neutrino interacts with the entire atomic nucleus during the interaction, but has a cross section which depends only on the square of the number of neutrons, CEvNS could be used as a tool to probe the neutron distribution of atoms [6].

As previously mentioned, the cross-section for the CEvNS interaction is large due to the neutrino interacting with the entire nucleus. Despite this, the only observable trace left behind by CEvNS comes from the incredibly low-energy nuclear recoil. This presents a challenge in tracking the directionality of nuclear recoils that result from CEvNS. Since the nuclear recoil is a neutral current, reconstructing its track is much more challenging than that for charged currents. Measurements of directional information coming from nuclear recoil are currently only feasible in gas targets. One important reason for this is that measuring any component of the recoil track must be done on segmentation scales smaller than the recoil track itself, as well as diffusion scales. With such low energy recoils, using a gas detector can allow the recoil track to be long enough for this to be possible. It is also beneficial to use a noble gas detector as their inert nature causes them to refrain from participating in chemical reactions and allows for ease of electron transport. The focus of this paper will be to get an understanding of the observable signatures deposited by nuclear recoils in a gaseous argon target. In particular, I will make use of the Stopping and Range of Ions in Matter (SRIM) simulation tool to obtain electronic energy loss distributions and a distribution of nuclear recoil scattering angles across nuclear recoil energies ranging from 10-100 keV [7]. I also seek to provide a preliminary calculation of the expected event rate as a function of recoil energy as well as scattering angle. The ultimate goal of these simulations is to provide valuable information for what kind of detector should be built in order to track the directionality of recoils resulting from CEvNS. Before going into the details of the simulation studies of nuclear recoils in gaseous argon, it is essential to discuss the low-energy physics that produced the observable signature of the recoil track.

A. Physics of Recoil Cascades and the Ionization Process

Since the only observable trace produced by CEvNS comes in the form of the low-energy recoil, it is necessary to understand how this recoil deposits its energy in the detector medium. As the nuclear recoil travels through the target medium, it loses its energy in two primary forms. One is through ionization and excitation of neighboring target atoms and the other goes into the creation of secondary nuclear recoils. The energy lost to electrons can go into creating free electrons throughout the target, as well as creating photons as the electrons get put into excited states. The stopping power (dE/dx) of both the electrons and the atoms of the target conveys the instantaneous amount of energy lost to the target medium per unit distance. The amount of energy lost to electrons and nuclei varies as a function of both the recoil energy, as well as the composition of the target medium. Measuring the decrease of dE/dx along the recoil track can help determine the vector sign of the recoil track and therefore is essential for understanding where the nuclear recoil is in the target. It is also critical for getting a good angular and energy resolution. This informs us on what kind of detector needs to be built to distinguish both the energy as well as the scattering angle of the nuclear recoil.

To get a good energy resolution, measuring the amount of energy lost to the target electrons across 10-100 keV will be crucial. Likewise measuring the amount of energy lost to target nuclei as well as the locations of where secondary recoil cascades are produced along the track will be necessary for getting a good angular resolution. This is because the location of the recoil cascades give insight into where the nuclear recoil has traveled as it loses energy.

B. Simulation Techniques

The Stopping and Range of Ions in Matter (SRIM) simulation tool can be used to aid in our understanding of how nuclear recoils affect their target medium and will be the main tool used in this paper to calculate energy and angular resolutions [7]. SRIM is primarily used in applications involving ion implantation, sputtering, and ion transport in solids. But SRIM is also capable of simulating gas targets and can track a nuclear recoil travels as it moves through the target medium, as well as how the initial recoil deposits its energy throughout. The part of SRIM's simulation toolkit responsible for simulating this is called the Transport of Ions is Matter (TRIM). Both aspects of SRIM's simulation capabilities calculate the data using first principles, allowing for more accuracy and rigor. SRIM is capable of simulating any type of element for the initial ion fired into the target, but for the target itself there is a more limited selection of elements if the target is a gas. Fortunately argon is among the select few elements that can be simulated as a gaseous target. In general SRIM can only simulate noble gasses and hydrogen as gas targets. SRIM always assumes that the target is at STP. For argon gas, this determines that the density is 1.78 g/L. Various other parameters can be adjusted, such as the depth of the target, the energy of the initial recoil, the angle at which the recoil enters the target, and the type of damage calculation performed.

TRIM can output several types of files that store the information from the simulation. The type of files stored depends on which kind of damage calculation is selected. Since we need to get a map of the secondary recoils cascades, it is necessary to select "Detailed Calculation with full Damage Cascades" as the setting. The most important files generated from this setting are called: "COLLISON.txt" and "EXYZ.txt"; they store information about the secondary cascades and electronic energy losses respectively. The "COLLISON.txt" file records information whenever the initial ion collides with something in the target and gives locations of where secondary cascades are created which will be essential in studying angular resolution. The "EXYZ.txt" file records the position of the initial ion as it loses a certain amount of energy throughout its trajectory. It also records its electronic stopping power (energy lost per unit length to target electrons). This information, combined with the energy needed to ionize an argon atom is needed to get a map of the free electrons produced along the track. It will also be important in studying energy resolution. A guide on how to run SRIM through its python interface "pysrim" can be found here.

II. PRELIMINARY SRIM CALCULATIONS

Across nuclear recoil energies, the particle's trajectory, as well as the energy it loses to target nuclei and electrons vary significantly across events. For this reason, it is essential to get a distribution of events with nuclear recoil energies ranging from 10-100 keV. The amount of time it takes for the computation to complete scales with increasing energy. In this section, I will draw on simulated data samples with 500 events each for energies between 10-100 keV.

A. Distribution of Ion Trajectories

As a first preliminary calculation, I will focus on getting a sense of the distribution of trajectories that the nuclear recoils can take throughout the target. This can start to help us to understand the sizes of the recoil tracks and therefore can inform us of the necessary scales that measurements need to be made. Simulations of the trajectories of both the lowest and highest energies of nuclear recoils we are considering are shown (FIG 2 and 3). Each different color represents a distinct event from a sample of 100 events whose initial direction is aligned with the x-axis upon entering the detector medium. XY projections of each trajectory are also shown to demonstrate how they are spread out in the plane. The simulation for the lowest energy (10 keV), recoil tracks ranged in depth from 0.01 mm to 0.07 mm.

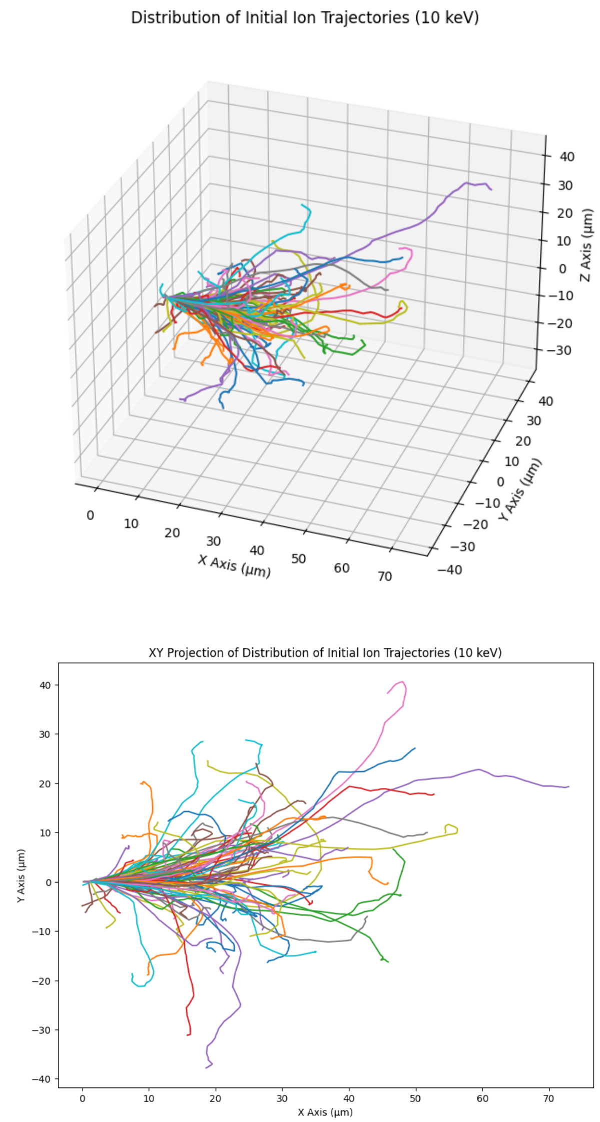

FIG. 2: Distribution of Ion Trajectories 10 keV (100 events). Above shows the trajectories in 3D and below is an XY projection

For the highest energy (100 keV) the maximum depth that the nuclear recoils could reach in the target was around 0.35 mm, a result consistent with that shown in Ref [3]. The recoils that traveled the least depth stopped in the neighborhood of 0.1 mm. This preliminary calculation hints towards a detector needed to be able to resolve recoil tracks ranging in depth from 0.01- 0.35 mm.

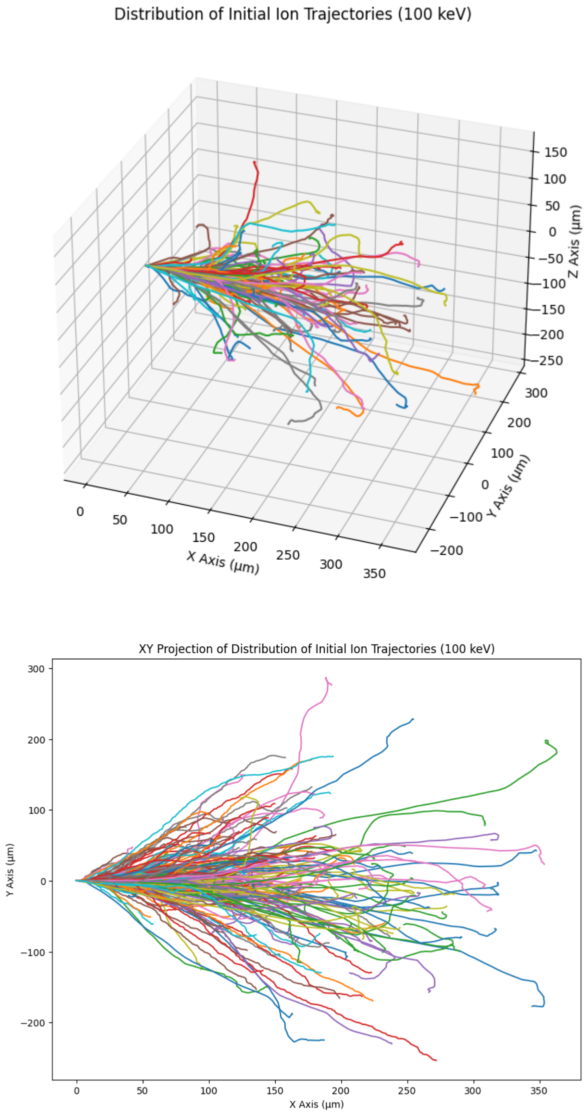

FIG. 3: Distribution of Ion Trajectories 100 keV (100 events). Above shows the trajectories in 3D and below is an XY projection

These calculations can also show visually how the trajectories spread out in the lateral plane (YZ plane). However, to get a better sense of how one can infer the directionality of these recoils, that is the angle in which they scatter from their initial direction, is more precise if one takes into account where target damage is created in the target.

B. Map of Recoil Cascades

As mentioned previously, one of the principal ways the nuclear recoil can lose its energy as it propagates through the target is to the target nuclei. This can result in creating even more nuclear recoils which in turn can cause secondary recoils themselves. These are referred to as recoil cascades or secondary damage cascades. SRIM takes track of where each secondary recoil is created every time the initial recoil collides with one of the target nuclei and stores the information in the ”COLLISON.txt” file. The first target nucleus that it collides with is referred to as the “Prime Recoil” by SRIM and every other recoil in the cascades that results from that recoil are simply regarded as secondaries. SRIM also keeps track of the amount of energy lost to each recoil cascade as well as the recoil energy of each secondary cascade. This will be essential when discussing angular resolution. To give an image of what this looks like in the target, one single trajectory is plotted for one energy (50 keV) (Fig 4).

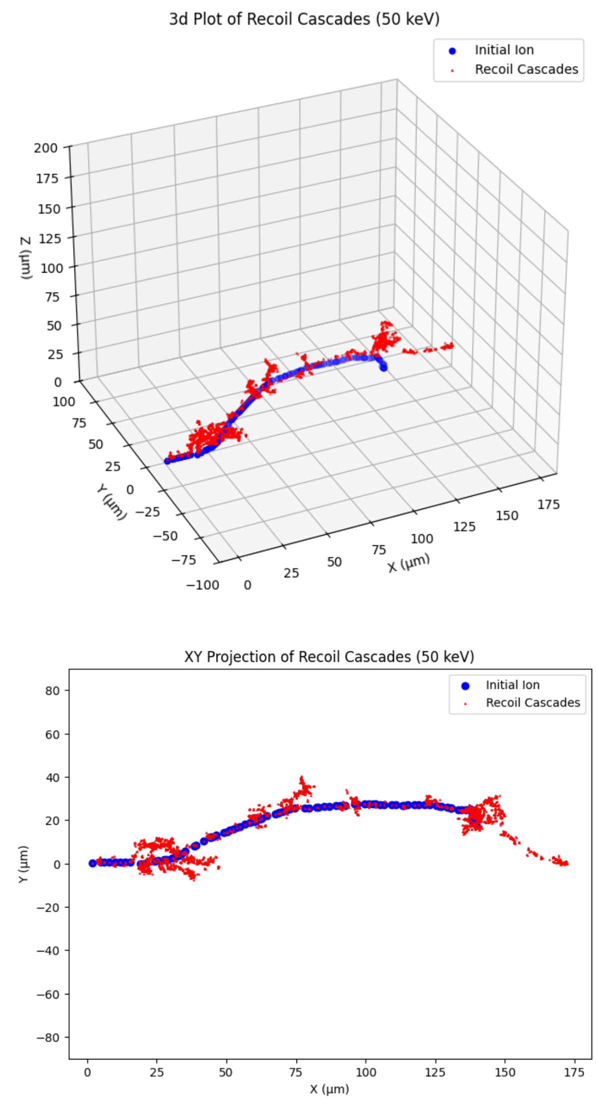

FIG. 4: Trajectory of a nuclear recoil and its secondary recoil cascades (50 keV)

The blue line represents the trajectory of the particle, similar to that in the previous section, and the red sites represent the sites at which the secondary cascades are created. Notice how these red dots cluster together at various points throughout the trajectory and then subsequently branch away. This is illustrative of the fact that the secondary cascades are responsible for a large portion of the energy loss of the initial nuclear recoil and are the main way the energy is distributed throughout the target. This will become more apparent when we look closer at the percentage of energy lost to target electrons compared to that of target nuclei. More importantly, the location of these cascades as well as the energy lost to them reveal footprints of the initial nuclear recoil as it advances into the target. These two pieces of information can then be used to define an overall scattering direction for the nuclear recoil.

III. ANGULAR RESOLUTION STUDIES

To be able to measure the directionality of these recoils, one needs to obtain a distribution of scattering angles. This can help inform us as to where the nuclear recoils are most likely to go relative to the initial direction of the neutrino. To calculate the scattering angle based off of the data given by SRIM, I first calculated an average position of each recoil cascade and then multiplied by the corresponding energy lost to that cascade. Then sum this up for every cascade and then divide by the sum of energy losses from each cascade.

$$\mathbf{R} = \frac{1}{E_{\text{tot}}} \sum_{i=1}^{n} \epsilon_i \mathbf{r}_i \tag{1}$$

Where $\mathbf{r}_i$ represents the average position of the ith recoil cascade and ϵ_i represents the energy lost to that cascade. The weighted vector sum $\mathbf{R}$ defines the overall direction that the particle scattering off into the detector. The scattering angle is then calculated by finding the angle between the overall direction and the initial direction of the nuclear recoil, which is set to be along the x-axis. This calculation is performed for 500 events at energy intervals of 10 keV for energies ranging from 10-100 keV. Distributions are plotted for each of these energy intervals in a 2D histogram (Fig 5).

The histogram shows that the scattering angles don't vary greatly across energies ranging from 10-100 keV of initial recoil energy. There is a higher concentration of events in the neighborhood of 20-25 degrees. It is then important to then define a fractional energy resolution for each event. This is defined to be the value in the distribution for which 68 percent of the data lies below. The uncertainty is defined as the difference between the value for which 78 percent of the data lies below and the value for which 60 percent of the data lies below.

The angular resolution values across energies are closely correlated and suggest that a detector would need to be able to detect particles deflecting within 40 degrees of the initial neutrino direction.

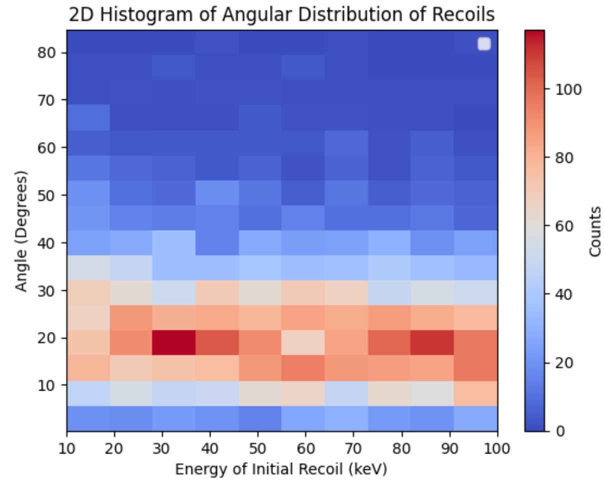

FIG. 5: 2D histogram of the distribution of scattering angles across 10-100 keV. Each column is a distribution over 500 events

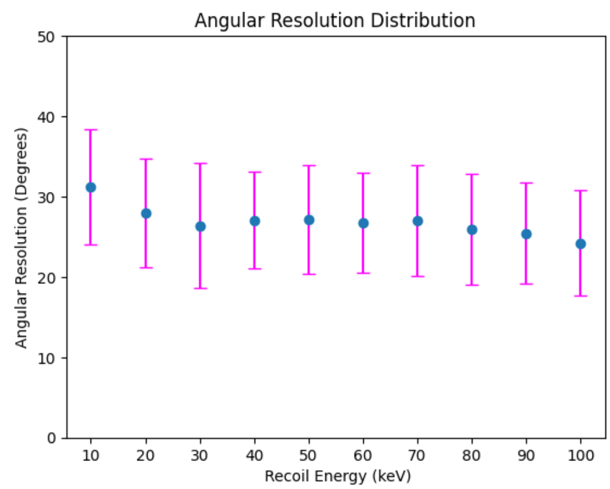

FIG. 6: Scatter plot of the angular resolution against its corresponding neutrino energy. The angular resolution is defined to be the value for which 68 percent of the data lies below.

IV. ENERGY RESOLUTION STUDIES

After calculating the angular resolution, the next essential thing to consider is the energy resolution. The amount of energy lost to target electrons is known to range across nuclear recoil energies and can therefore provide information about the energy of the initial recoil resulting from CEvNS. The total amount of electronic energy loss can be calculated from SRIM using the aforementioned "EXYZ.txt" file. This file records the electronic stopping power as a function of the position of the nuclear recoil. These measurements are made every time the initial ion loses a specific amount of energy specified by the user. This is shown visually for one event at 50 keV.

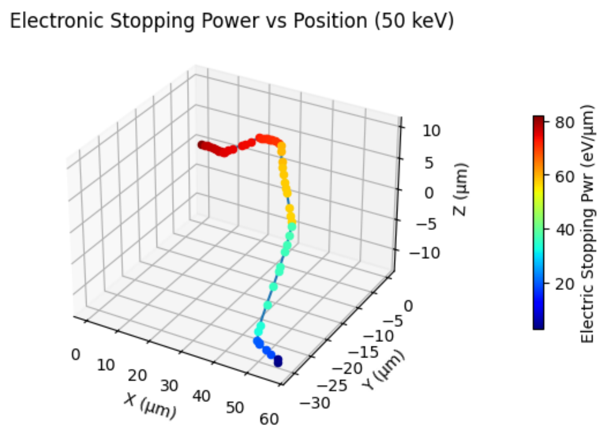

FIG. 7: Electronic Stopping Power plotted as a function of position. The colors get cooler as the particle moves through the target indicating a decrease in stopping power.

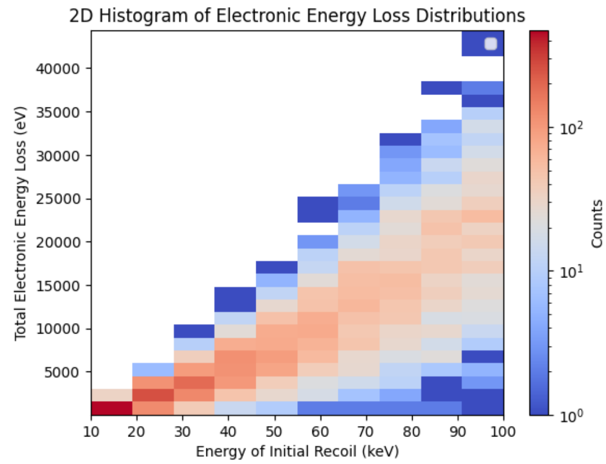

FIG. 8: 2D histogram of the distribution electronic energy losses across 10-100 keV. Each column is a distribution over 500 events. Note that the white boxes represent bins with zero counts.

Note how the electronic stopping power is greatest towards the beginning of the track and slowly dies off towards the end. Calculating the total electronic energy losses involves evaluating the distance between each successive energy loss and then multiplying by the electronic stopping power. This is done in discrete steps along the recoil track and then summed, with the smaller the energy interval specified by the user leading to a more accurate calculation of the sum. This calculation is also performed for 500 events at energy intervals of 10 keV for energies ranging from 10-100 keV. A 2D histogram of these distributions is also shown similar to that for the angular distribution (Fig 8).

Notice how the mean shifts up as the energy of the initial recoil moves up as expected. It can also be observed that these distributions are Gaussian and are therefore completely characterized by their mean and standard deviation. It is appropriate to then fit each distribution to a Gaussian curve (Fig 8). The information given by this Gaussian fit can thereby be used to characterize each distribution by its coefficient of variation. The coefficient of variation is defined to be the ratio between the standard deviation and the mean, and it is this value that will quantify the fractional energy resolution. Each coefficient of variation for each distribution is plotted against its corresponding initial recoil energies.

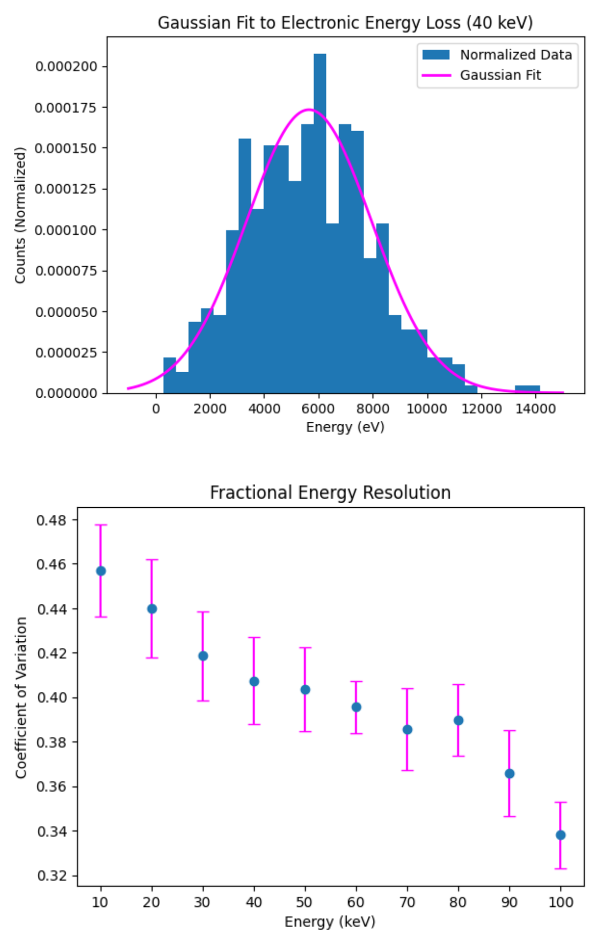

FIG. 9: A Gaussian fit is performed for each distribution. One example at 40 keV is highlighted. The coefficient of variation $\frac{\sigma}{\mu}$ is plotted against its corresponding energy.

The values of the coefficient of variation are seen to decrease as the energies get larger, though some statistical fluctuations are observed. This overall trend is not surprising as the graph demonstrates that the standard deviation gets larger with increasing energy. Despite that, the values of the coefficient of variation are close together ranging from 0.46 to 0.34. The low amount of energy lost at lower energies also suggests that a detector will need to be very sensitive to electronic energy losses in order to distinguish what the energy of the initial recoil was. This information combined with scattering angle is necessary to be able calculate the energy of the incident neutrino.

V. CALCULATION OF RECOIL SPECTRUM

One final thing to consider is the number of events one would expect to measure over a given interval of time for a particular detector. In order to perform this calculation, it is necessary to assume a neutrino flux given by a known source, which will be the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. This particular source of neutrinos is produced by pions decaying at rest (Fig 10).

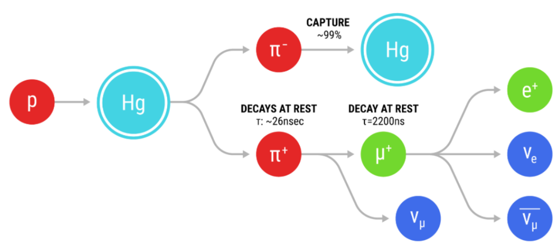

FIG. 10

FIG. 11: A schematic of how the neutrino beam is produced by SNS at Oak Ridge National Laboratory

It works by firing protons at a target of liquid mercury which creates a pair of charged pions. The negatively charged pion is captured back within the target about 99 percent of the time while the positively charged pion decays into an antimuon and a muon neutrino. The antimuon subsequently decays into a positron, electron neutrino, and a muon antineutrino. The relative abundance of each neutrino is about the same throughout the beam [8]. At about 20 m away from the source about 4 x 10^7 neutrinos pass through 1 cm^2 per second [9]. This information combined with the neutrino spectrum from a stopped pion source yields the neutrino flux. The neutrino spectrum for each flavor at a stopped pion source is well known and is given by Ref [6].

$$f(E_{\nu_e}) = \frac{96}{m_\mu^4} E_{\nu_e}^2 (m_\mu - 2E_{\nu_e}) \tag{2}$$

$$f(E_{\overline{\nu_\mu}}) = \frac{16}{m_\mu^4} E_{\overline{\nu_\mu}}^2 (3m_\mu - 4E_{\nu_e}) \tag{3}$$

$$f(E_{\nu_\mu}) = \delta(E_{\nu_\mu} - E_\pi) \tag{4}$$

With $E_\pi = 29.8$ MeV and m_μ= 105.66 MeV. These equations give the probability that an neutrino with energy between E and E+dE will be emitted from the beam. Given this information, the neutrino flux is therefore given by:

$$\Phi(E) = C * f(E) \tag{5}$$

Where C is the total number of neutrinos per second per cm^2 that reach the target for a given flavor. The final piece of information needed to calculate the event rate per recoil energy is the differential cross section as a function of nuclear recoil for the CEvNS interaction. In its approximate form it is given by [1]:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} \frac{Q_w^2}{4} F(Q)^2 M(2 - \frac{MT}{E_\nu^2}) \tag{6}$$

M represents the mass of the target nucleus, G_F is the Fermi Coupling constant, T is the energy of the recoil, and E_ν is the energy of the neutrino. The weak nuclear charge Q_w can be approximated by the number of neutrons squared. Since this calculation is for 40 Ar, the number of neutrons is 22. The nuclear form fact F(Q) can be set to 1 for a coherent interaction. Putting everything together, the event rate per recoil energy can be calculated using the following formula.

$$\frac{dR}{dT} = N_t \int_{E_{min}}^{m_\mu/2} \Phi(E) \frac{d\sigma}{dT} dE_\nu \tag{7}$$

Where N_t gives the total number of target nuclei and $E_{min} = \sqrt{\frac{MT}{2}}$. Performing the calculation in Mathematica yields the following plot for the recoil spectrum. Note how the curves for the electron neutrino and the muon antineutrino follow similar trends. This is because of the similarity of the functional form of their neutrino spectrum. The muon neutrino is clearly different as its neutrino spectrum is a delta function due to the fact that this is produced from a pion decaying at rest.

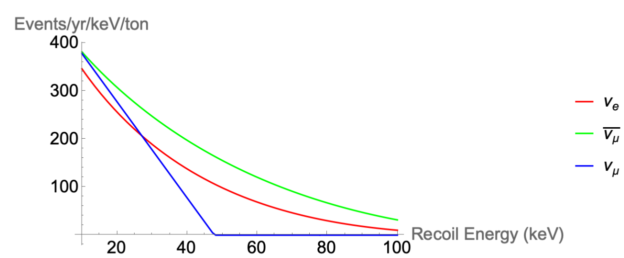

FIG. 12: The recoil spectrum as a fucntion of recoil energy is plotted for 40 Ar

VI. CONCLUSION

Using the SRIM simulation software package, calculations for the angular and energy resolution could be performed. SRIM was also used to get a preliminary calculation for the length of the recoil tracks and it was found that the recoils could penetrate up to about 0.35 mm into the target at the highest energy considered. Angular resolution studies also suggested building a detector of resolving nuclear recoils deflecting within 40 degrees of the initial neutrino direction. Studies of the energy resolution revealed the distribution of electronic energy losses across nuclear recoil energies and suggests the need for a detector with low energy thresholds in order to detect the ionization signature of some of the lower energy recoils. Due to the limitations of SRIM, it was not possible to be able to calculate the number of free electrons that were produced for a given recoil track, which would give more insight into how low this threshold needs to be. Finally calculations of an expected recoil spectrum assuming the SNS neutrino source at Oak Ridge National Laboratory were performed.

VII. ACKNOWLEDGEMENTS

I would first like to thank my advisor David Caratelli for guiding me throughout the project and introducing me to the wonderful world of neutrino physics. I'd also like to thank my graduate student mentor Alexander Antonakis for working closely with me on technical issues with running the simulation, helping me get started on the project, and for providing support throughout. I'd also like to thank the other undergraduates in the Caratelli lab for welcoming me and making me feel like a part of the lab. Finally, I would like to thank UCSB REU coordinator Sathya Guruswamy for organizing the program. This work was supported by National Science Foundation (NSF) REU grant PHY-2349677.

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