DUNE's Potential to Search for Neutrinoless Double Beta Decay

Elise Chavez
University of Wisconsin-Madison - GEM

Supervisors: Joseph Zennamo and Fernanda Psihas
Fermilab

August 07, 2020

Abstract

DUNE is projected to be the most capable GeV-scale neutrino experiment the world has seen, which means that it has the ability to search for physics we could not have hoped to observe with our current experiments. One such phenomena is neutrinoless double beta decay, an ultra-rare decay that would indicate new physics. It is a process that violates lepton number and hence is forbidden by the Standard Model, but as stated, it is super rare. The idea then is to take advantage of DUNE's size and capabilities to attempt to search for it by doping the liquid argon with xenon-136, a candidate isotope for the decay. This project, thus, aims to characterize the potential radiologic backgrounds that could come from DUNE itself and the environment to determine if searching for this decay is even feasible. In this paper, the following sources are examined at less than 5 MeV: radiation from the anode, radiation from the cathode, krypton, argon, radon, polonium, and, for the first time, neutrons. Ultimately, it has been determined that these sources do not provide a lot of apparent background that could disguise a neutrinoless double beta decay signal and that DUNE has great potential to search for this process. It must be noted that spallation from cosmic muons and solar neutrino backgrounds were not examined in this study.

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1 Introduction

In the new age of neutrino experiments, the advanced capabilities and the sheer sizes of developing projects have allowed physicists to explore more closely the laws of the universe and the things that make it up. One such process is neutrinoless double beta decay, an ultra rare process forbidden by the standard model. It is a very difficult process to detect due to it rareness, for context the current best limit on the half-life for xenon-136 to go through the decay is 10^{27} years, or 10^{16} ages of the universe. It is very very rare, but observing this decay would change completely the way in which we understand physics. It would indicate that there is new physics and that our current models need to change.

While the decay's rareness is an obstacle, there are several factors that can be exploited to make the chances of observation better. The first of those is amount of material. If there is more decay material, the probability of observation increases. Second is exposure time. If the material is left to decay for a long time, the probability again increases. Some of the other factors come from a detectors capabilities, such as energy resolution. All of these, help to increase the chance of observation. DUNE (Deep Underground Neutrino Experiment) is one experiment in development that may give us a fighting chance in observing neutrinoless double beta decay ($0\nu\beta\beta$). The idea is to dope the liquid argon in the far detector with xenon-136, a candidate isotope for this decay, and to use DUNE's exposure time and detector capabilities to increase our chances of detecting this decay, which would be monumental for physics. In addition, this would lower DUNE's capabilities to less than 5 MeV, as $0\nu\beta\beta$ occurs at 2.459 MeV for xenon-136.

This paper works to outline the full idea and potential backgrounds from the detector itself and from some parts of the environment that could disguise the $0\nu\beta\beta$ signal. The sources for such backgrounds are radiation from the anode, radiation from the cathode, krypton, polonium, argon, radon, and, for the first time, neutrons. The final states, or particles produced, will be analyzed and discussed along with their implications for this type of study in DUNE. The methods will be discussed in detail as this project worked with real DUNE simulations to obtain results as comparable as possible to DUNE's design.

2 Background

Before diving into all of the specifics of this project, there is a need for some background to completely understand the choices made and the ideas driving this project. First and foremost, it is important to understand $0\nu\beta\beta$ and what one needs to make it happen.

2.1 Neutrinoless Double Beta Decay

Neutrinoless double beta ($0\nu\beta\beta$) decay occurs when two neutrons in a nucleus decay into two protons and emit two electrons. This is depicted in Figure 1 and the Feynman diagram is given in Figure 2. As can be seen in the figures, this decay violates lepton number conservation. There are 0 leptons at the start but 2 in the final state. This is forbidden by the Standard Model. For this decay to occur in nature, the neutrino must be a Majorana particle meaning the neutrino must be its own anti-particle. Here, the electron neutrino and anti-electron neutrino annihilate leaving the two electrons as the final state.

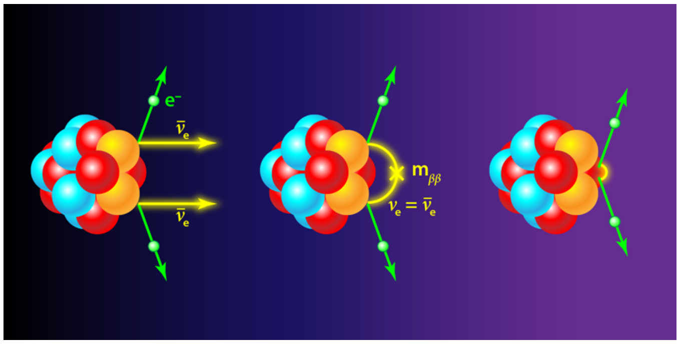

Figure 1: An atomic diagram of neutrinoless double beta decay. [4]

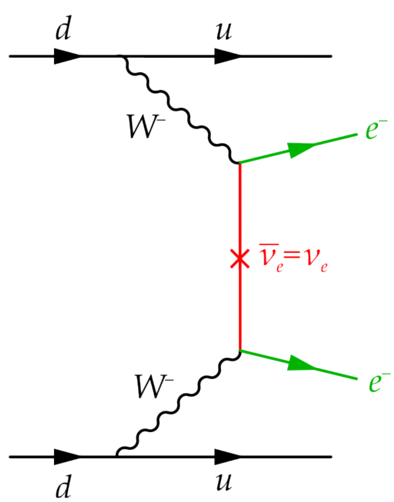

Figure 2: A Feynmann diagram of neutrinoless double beta decay. [5]

This means that observing such a decay would have vast implications for particle physics. It would mean that the Standard Model is wrong and demand change to it or the development of new theory. In addition, it could be a piece of the matter/anti-matter asymmetry puzzle. While it wouldn't directly be an answer, neutrinoless double beta decay would lead physicists to a new age of particle physics. Unfortunately, this decay is extremely rare with xenon-136 having a current $0\nu\beta\beta$ half life limit of 10^{27}, or 10^{16} ages of the universes as stated in the introduction. This makes observing the decay extremely difficult. There have been experiments that have tried and hence improved the half life limit over time. In the next section, the choice of DUNE and its potential will be discussed.

2.2 DUNE and Xenon-136

The future of neutrino physics lies in part with the Deep Underground Neutrino Experiment (DUNE) which will have both a near and far detector. The near detector will be located at Fermilab in Batavia, Illinois and the far detector will be located in South Dakota. The larger one being the far detector. A diagram of the entire experiment is given in Figure 3.

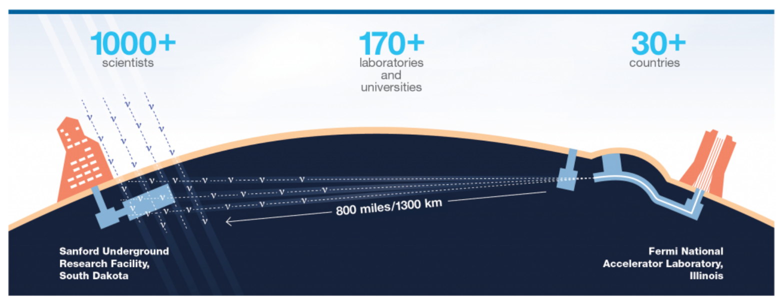

Figure 3: A diagram of the DUNE far and near detectors. [6]

The detectors will both contain time projection chambers (TPCs) immersed in liquid argon, called liquid argon time projection chambers (LArTPCs). There are expected to be two LArTPCs at first, with the plan being 4 total upon completion of the project. Each TPC will hold 20 kilotons of liquid argon. DUNE is also expected to run for a time period of about 5-10 years. Further, DUNE is expected to have a better sensitivity to the electron neutrino and hence electrons. This means a better sensitivity to the $0\nu\beta\beta$ signal.

To combat the rareness of the $0\nu\beta\beta$ decay, one can exploit the mass of decay material, exposure time, and detector capabilities to increase the chances of observation. The latter comes with the advanced capabilities and sensitivities of DUNE and the second comes from the planned run-length of the experiment. It is exploiting the mass of decay material that merits a more detailed discussion. Unfortunately, not all isotopes can undergo $0\nu\beta\beta$ decay. A nucleus would have two neutrons change into two protons, which is not always a physically allowed process. The nucleus must lose energy in order for this new state to be energetically favorable, and due to the complicated structure of the nucleus that is simply not the case for most nuclei. In Figure 4 are the few isotopes that can even undergo the decay.

Isotope	Natural abundance (%)	$Q_{\beta\beta}$ (MeV)
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Figure 4: A table of isotopes that can undergo neutrinoless double beta decay. [3]

The one isotope not on this list is argon, which means a different one would have to be used. The idea then is to dope the liquid argon with one of the potential candidates to enable DUNE to possibly observe this ultra rare decay. The question then becomes which one. Of the listed isotopes, only one would not destroy the detector: xenon-136. For the remainder of this paper xenon-136 will be simply referred to as xenon. The $0\nu\beta\beta$ decay for xenon is given below.

$$Xe(136,54) \rightarrow Ba(136,56) + 2e^{-} + 2.459MeV \quad (1)$$

It also turns out that xenon-136 actively enhances the detectors performance, which is another reason to use it. Putting this all together, the hope is to dope, by mole, the liquid argon with 2% xenon. To put this in context, the world's best $0\nu\beta\beta$ limits come from experiments that have had about 2 kg of decay material, DUNE would bring us to 100s of tons of decay material. Thus, DUNE can exploit its sheer size to exploit the mass of decay material.

This may seem like a fairly easy thing to do; however, doping the liquid argon is still in the research and development (R&D) phase of study. It is still unclear whether it is currently feasible to implement. This uncertainty also stems from how difficult it is to obtain xenon. In Figure 4, the natural abundance of xenon is 8.9%, but this is *all* xenon. Xenon-136's abundance is a big fraction of this, but Xenon will be hard to obtain. Thus, it is more than necessary to study the feasibility of this search for $0\nu\beta\beta$ decay which is the cornerstone of this project. We must know what to expect in DUNE.

2.3 The Purpose

The purpose of this project was to study and characterize the environmental radioactive decays in DUNE's LArTPCs which serve as background for the $0\nu\beta\beta$ decay. To understand whether this search should be pursued in DUNE, and if more efforts should be put into R&D for doping and acquiring xenon, we have to look at whether the radioactive background will greatly disguise the signal of two electrons at 2.459 MeV of energy. These background sources come from radiation from the cathode, radiation from the anode, krypton, radon, argon, polonium, and neutrons. Note this is the first look into what the background from neutrons in surrounding rock would look like at these energies. However, this study does not include backgrounds from spallation due to cosmic muons or solar neutrinos.

3 Methods and Data

The methods and data of this study have two distinct phases in terms of analysis, as such the specifics will be discussed separately. In general, the methods consisted of using the DUNE simulation framework to produce and analyze data for the potential backgrounds. This required knowledge and use of art and LArSoft as tools to create the appropriate trees of desired data as well as the use of ROOT to create histograms for these trees. The place where the two phases differ is how the data was acquired and what that data was.

3.1 DUNE Simulations Part I

The first set of data analyzed was from a DUNE simulation file, specifically this file came from the radiopurity files in the technical design report (TDR) for DUNE. This simulation was of a Nickel-59 source in one of the LArTPC modules proposed for the detector. It included radiation from the detector itself, including neutrons in the surrounding rock. These backgrounds were radiation from the cathode, radiation from the anode, argon, krypton, polonium, radon, and neutrons. This does not include background from spallation due to cosmic muons or solar neutrinos. In Table 1 below are the statistics from the simulation file. It is important to note that the data that came from this file represent an exposure of about 6.63e-10 for a 10 year period, meaning this is a very small portion of what can be expected for the full DUNE run.

Final State	Number of Particles
Photon	26,808
Electron	1,094,722
Positron	792
Alpha	37,419
Neutron	13
Proton	4
Other	5
Total	1,159,763

Table 1: A breakdown of the final states produced in the simulation.

Looking at this table, and given the breakdown of the possible sources, it is natural to wonder where some of the particles radiated from. Unfortunately, this is information that could not be determined from this file, the lineage of the particles was not properly stored. This means that the only thing to be done with this data was plot what was available and look at the picture as a whole. The variables available were energies, momenta, vertices, and other physical characteristics of the final states. The most important for this project was energies. The analysis of which is in the Analysis section. This brings us to the second phase of data.

3.2 DUNE Simulations Part II

Due to the lineage of the final states being broken, new files were produced from simulation that looked only at one source of background in the detector. For example, there is a simulation file from just radon as the source. This means that the final states of these sources could be analyzed with the parent information readily available, with the sources being the same as before. The tables below break down the statistics of this phase.

Radiation from Anode	
Final State	Number of Particles
Photon	459
Electron	2,955
Positron	0
Alpha	0
Neutron	0
Proton	0
Other	0
Total	3414

Table 2: Breakdown of final states for the anode.

Radiation from Cathode	
Final State	Number of Particles
Photon	3,515
Electron	34,018
Positron	5
Alpha	0
Neutron	0
Proton	0
Other	0
Total	37,538

Table 3: Breakdown of final states for the cathode.

Argon 42	
Final State	Number of Particles
Photon	388
Electron	2,359
Positron	0
Alpha	0
Neutron	0
Proton	0
Other	0
Total	2,747

Table 4: Breakdown of final states for the argon-42.

Argon	
Final State	Number of Particles
Photon	172,049
Electron	9,540,899
Positron	0
Alpha	0
Neutron	0
Proton	0
Other	0
Total	9,712,948

Table 5: Breakdown of final states for argon.

Krypton	
Final State	Number of Particles
Photon	28,764
Electron	1,109,420
Positron	0
Alpha	0
Neutron	0
Proton	0
Other	0
Total	1,138,184

Table 6: Breakdown of final states for krypton.

Neutron	
Final State	Number of Particles
Photon	542
Electron	2686
Positron	28
Alpha	0
Neutron	188
Proton	34
Other	667
Total	4,145

Table 7: Breakdown of final states for neutrons.

Polonium	
Final State	Number of Particles
Photon	0
Electron	0
Positron	0
Alpha	42
Neutron	0
Proton	0
Other	0
Total	42

Table 8: Breakdown of final states for polonium.

Radon	
Final State	Number of Particles
Photon	0
Electron	0
Positron	0
Alpha	36,992
Neutron	0
Proton	0
Other	0
Total	36,992

Table 9: Breakdown of final states for radon.

4 Analysis

Similar to the data, the analysis will be broken down into two the phases. For both phases, the information most valuable was the energy we can expect to be seen in the detector. This was obtained by taking the absolute value of the start energy minus the end energy. This is shown in the following equation.

$$Energy = |Start\ Energy - End\ Energy| \quad (2)$$

Here the start energy is the initial energy of the particle at production, and the end energy is the energy at the last place the particle was tracked. This gives us an idea of what energies we would be looking at as output from the LArTPC. The next two sections will provide the plots and discussions for each phase.

4.1 Results from DUNE Simulation Part I

First and foremost, below are the energy plots for the TDR simulation file. Recall Table 2, in it the protons, neutrons, and other particles make up 22 total particle. Individually, and combined, they do not have the statistics to produce any meaningful plots. Thus, they are not included. In these plots are a line at 2.5 MeV to indicate where the signal is expected to be. Due to energy smearing, the signal would not be a line at 2.459 MeV, instead it would be a peak at 2.459 MeV. Thus, this line gives us a point of comparison where the signal should peak.

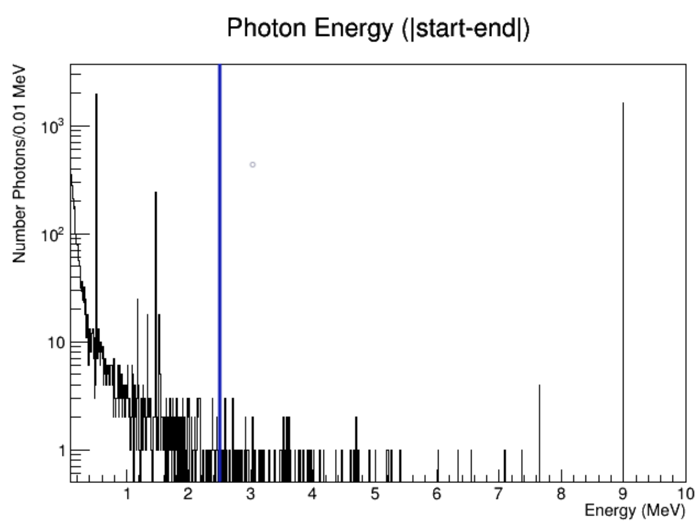

Figure 5: The energy distributions for the final states from phase 1 data. Here Photons are plotted from 0-10 MeV.

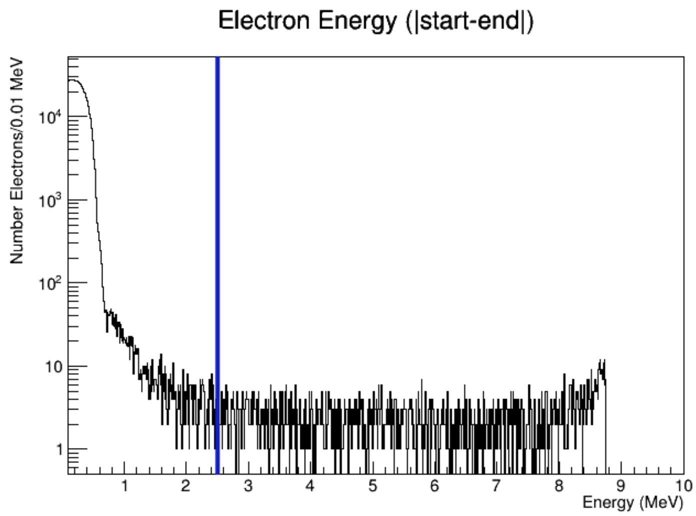

Figure 6: The energy distributions for the final states from phase 1 data. Here Electrons are plotted from 0-10 MeV.

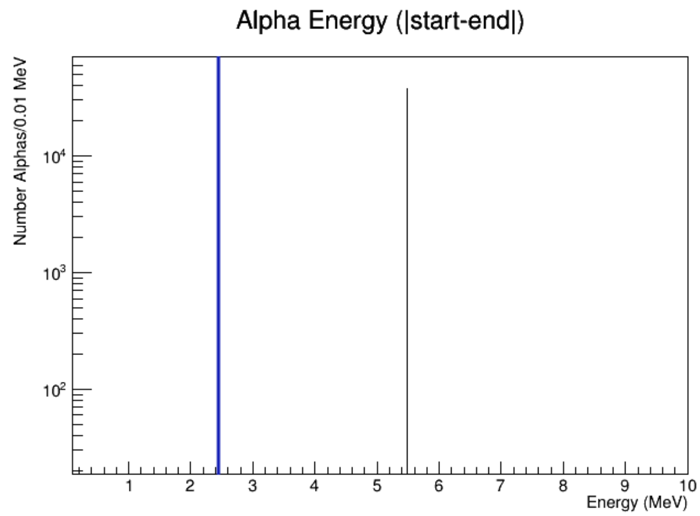

Figure 8: The energy distributions for the final states from phase 1 data. Here Alphas are plotted from 0-10 MeV.

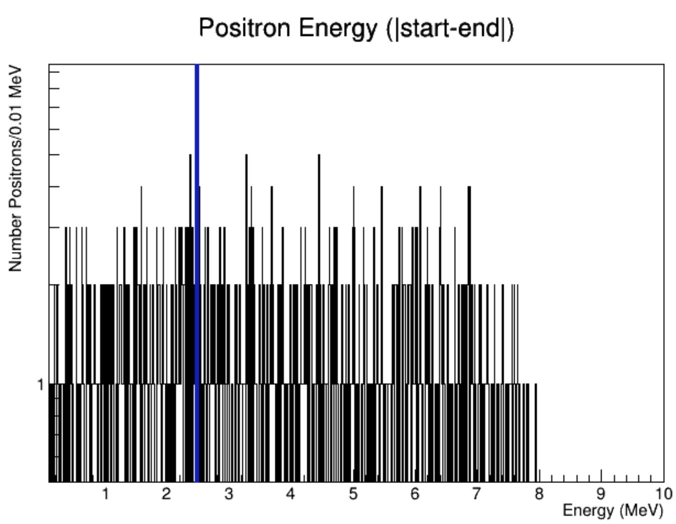

Figure 7: The energy distributions for the final states from phase 1 data. Here Positrons are plotted from 0-10 MeV.

These energy plots display all of the background decay products on one plot for each of the final states. In all four plots, it is clear that the energies of the decay products are not peaking at the $0\nu\beta\beta$ decay signal. Most importantly, the electrons in Figure 6 are not peaking near the signal. While there is a tail that might indicate a background of significance, the tail is not a majority of the events. It does not seem as if it would be able to disguise the signal. The photon plot is more a tool here than a direct analysis, this is because photons would not be seen in the DUNE LArTPCs. LArTPCs rely on the charge of particles to detect them, the photons will create high energy electrons that will ionize the liquid argon. What the photon plot does indicate is that the physics is making sense. There is a sharp line in Figure 5 at 9 MeV that is matched by the end of the electron's energy tail. This comes from Compton scattering. This just helps to ensure that the plots are representative of real physics, a sanity check if you will.

The other two plots, positrons and alphas, are helpful for background as they are charged. The positrons may look as if they heavily populate 2.5

MeV, but this plot has 700 positrons and it is in log scale. Thus, they also do not appear to populate the signal regions. The alphas, on the other hand, quite obviously are outside of the signal region. Alphas are monoenergetic, and they populate the 5.5 MeV energy. Thus, they also do not seem to disguise a signal.

4.2 Results from DUNE Simulation Part II

The second phase of analysis is on the data where the parent information is known. Again, the energy plots are displayed below. For this set of data, the plots with low statistics are the neutrons, protons, and positrons and hence they are not shown. In addition, this data has an other particle count of 667. These particles are a mixture of nuclei produced in the simulation and most seemed to be argon once they were examined. Again, there is a line at the expected signal peak energy of 2.5 MeV.

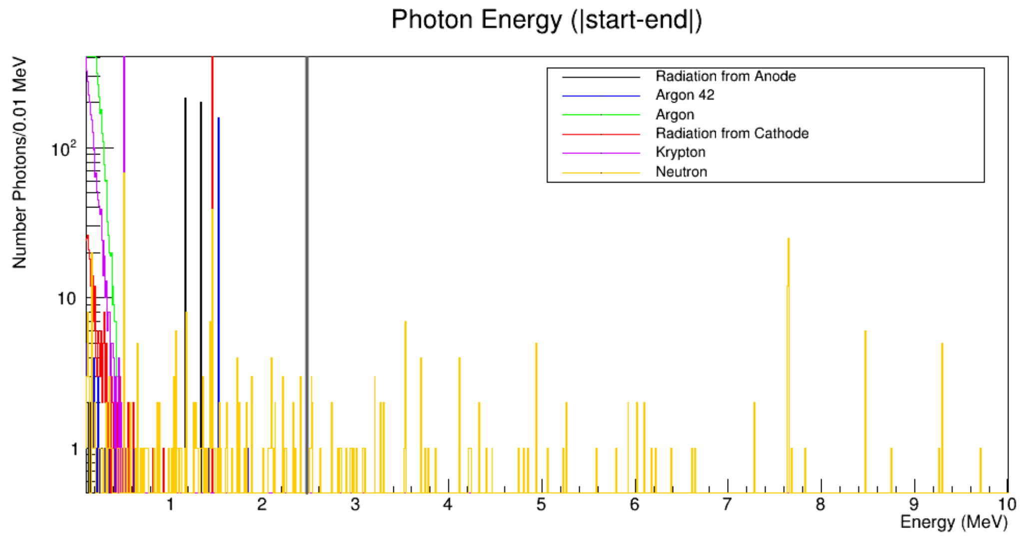

Figure 9: The energy distributions for the final states from phase 2 data. Here Photons are plotted from 0-10 MeV.

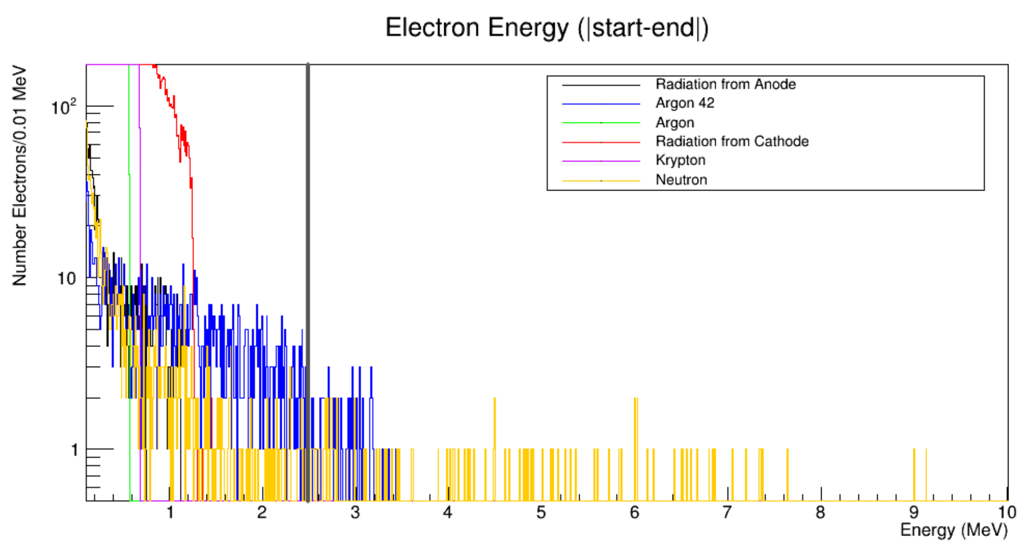

Figure 10: The energy distributions for the final states from phase 2 data. Here Electrons are plotted from 0-10 MeV.

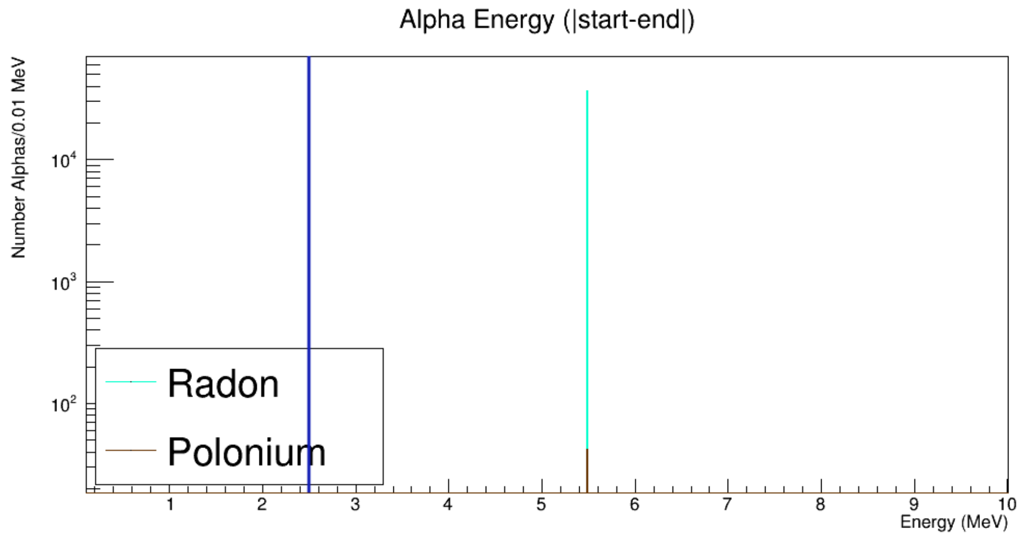

Figure 11: The energy distributions for the final states from phase 2 data. Here Alphas are plotted from 0-10 MeV.

It is important to note that in Figures 9 and 10 polonium nor radon produce any photons or electrons. They instead make up all of the alpha production in Figure 11. Here, the photons are again more a sanity check tool than what is most interesting. It is clear though, that if they will be detected, the photon energies are not peaking at 2.5 MeV. The alphas again quite clearly indicate that they will not disguise the signal. Here that indicates that neither polonium nor radon provide any significant background to the $0\nu\beta\beta$ decay signal.

Now, the most interesting of these plots is the electron energy plot. From what can be seen, the electrons would also not cause any confusion with the signal. These sources do not seem produce large amounts of electrons in the signal region. This is great news for the future potential of this study. In addition, the features of Figure 6 can be pieced together. The peak of the electrons at $\leq$1 MeV can be attributed to argon, krypton, and radiation from the cathode. These sources, thus do not produce many electrons at the energies we are concerned about. Neutrons also appear to be the culprit for parts of the tail, with a little contribution from argon-42.The rest of the sources appear to contribute to the $\leq$2 MeV electrons. Regardless, these source are not producing final states at 2.5 MeV in large quantities. What this also indicates, is that the nickel-59 source might have contributed to the tail of Figure 6 as well, which is not a common source of background in the proposed LArTPCs.

5 Conclusion

Overall, this project aimed to characterize the possible backgrounds that could come from the DUNE LArTPCs and the surrounding rock for $0\nu\beta\beta$ decay. These background sources include radiation from the anode, radiation from the cathode, krypton, argon, radon, polonium, and neutrons. These are the radio-isotopes expected to be at the edges of the detector with neutrons coming from the surrounding rock. The backgrounds not considered in this study are spallation from cosmic muons and solar neutrinos. The final results indicate that these sources do not produce a significant amount of final states at the signal energy region (2.5 MeV). This indicates that DUNE has a great potential to search for $0\nu\beta\beta$.

This also means that investing in the R&D is both worth the effort and necessary for this search to be realized in DUNE. In a similar vein, studies of this kind should be done extensively to truly understand what we should expect in doing this search in DUNE. This is one of the first to look at the neutron's background, which should be further investigated as this would help to fully characterize the neutron's potential background. In addition, looking into the backgrounds left out in this project would also be incredibly useful when considering the feasibility and potential of this search.

We are in exciting times for neutrino physics, and for detector physics. Much can and needs to be done in order to truly bring DUNE to the capability of searching for $0\nu\beta\beta$ decay, and much work needs to be done in determining whether these efforts will be fruitful. Fortunately, the results of this study indicate that they will in fact be fruitful. It seems that DUNE is able to distinguish the decay signal and it's radiological background, and could pave the way to discovering new physics that could change particle physics forever.

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