Muon Spallation in Double Chooz

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This report presents my work for Double Chooz at MIT during the 2009 Summer REU program, funded by Columbia University. Double Chooz is a reactor neutrino experiment that aims to measure the mixing parameter $\theta_{13}$. The experiment detects electron antineutrinos via inverse beta decay. Neutrons and light nuclei made in muon spallation are a major background to the experiment. The delayed neutron emitter $^9$Li is especially problematic because it mimics the inverse beta decay signal. For this reason I studied muon spallation in Double Chooz, focusing on the production and subsequent decay of $^9$Li. There are two key differences between $^9$Li decay and inverse beta decay. The first is that $^9$Li is a $\beta^-$ decay, so it emits an electron, whereas inverse beta decay emits a positron. The second difference is the energy of the neutrons emitted. In $^9$Li decay the neutron energy is on the order of MeV, whereas the inverse beta decay neutron has a negligible kinetic energy. Since Double Chooz does not distinguish charge, the positrons and electrons are not easy to distinguish. First, I ran simulations of electrons and positrons in the Double Chooz detector and constructed a late light variable to distinguish them from electrons. This proved insufficient, so I wrote general software to simulate radioactive decays in the Double Chooz detector. In this report I present the deposited energy spectra of a few important decays.

1. INTRODUCTION

1.1. Neutrino Oscillations

Double Chooz is an antineutrino experiment that will measure or constrain the mixing parameter, $\theta_{13}$. This angle is one of three angles used to parameterize the neutrino mixing matrix, the mathematical representation of neutrino oscillations. Neutrino oscillation refers to the phenomenon in which the probability of detecting a neutrino as a $\nu_e$, $\nu_\mu$ or $\nu_\tau$ oscillates as the neutrino propagates through space. That is, at different points in space, the same neutrino might be detected as a different flavor ($e$, $\mu$ and $\tau$ are the three lepton flavors or families). Physicists interpret this process to mean that neutrinos have mass, this will be explained in more detail later in this section.

1.1.1. Significance and a Brief History of Neutrino Oscillations

The rules of elementary particles and their interactions are described by what is known as the Standard Model. The Standard Model was developed by particle theorists between 1960 and 1975 and nearly every experiment between then and now confirms its predictions. However, in 2001 SNO detected neutrino flavor change, which violates the Standard Model’s law of lepton family number conservation. In 2003 KamLAND confirmed neutrino oscillations by detecting the $L/E$ dependence characteristic of oscillation. These experiments presented the first conclusive evidence of physics beyond the Standard Model.

The consequence of neutrino oscillation is that an experiment that is sensitive to only one of the three neutrino flavors, say $\nu_e$, might conclude that some of the expected $\nu_e$’s have disappeared. Early Experiments were designed to detect the $\nu_e$ flux from the sun. Solar models gave a prediction for this value, but the Ray Davis experiment in the late 1960s showed a great deficit of solar neutrinos. He detected only $\frac{1}{3}$ of the predicted flux. Super-K later confirmed the deficit, and it became known as the ”solar neutrino problem.”

Neutrino oscillations were hypothesized, but because they violate Standard Model predictions they met harsh criticism. Finally, Sudbury Neutrino Observatory was constructed to determine whether the neutrinos were changing flavor. SNO used heavy water and was sensitive to signal from all 3 neutrino flavors. In 2001 SNO confirmed that solar neutrinos were indeed changing flavor [2]. This was a very exciting discovery for the field of physics, because there was and still is a lot to learn about the nature of the flavor change.

In 2003 KamLAND used reactor antineutrinos to test the nature of neutrino flavor change [1]. Figure 1 shows the results of this experiment. The plot shows the ratio of the anti-neutrino spectrum to the expectation for no-oscillation as a function of $L/E$. Here $L$ is KamLAND’s flux-weighted average distance from the reactors, 180km. The figure shows the $L/E$ dependence expected from neutrino oscillation.

Given that neutrinos oscillate, KamLAND was also able to use theoretical understanding of flavor oscillation to determine two of the parameters that describe the phenomenon [1]. For KamLAND, the probability that an electron antineutrino will remain an electron antineutrino is given by

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{1.27 \Delta m^2_{12} L}{E}$$

KamLAND used their measured neutrino energy spec-
trum and event rate to experimentally determine values for $\theta_{12}$ and $\Delta m^2_{12}$. A combined fit with solar neutrino data, especially SNO, improves these results.

The confirmation of neutrino oscillation allows us to go forward and measure the various oscillation probabilities and the mass differences between the neutrino mass eigenstates.

1.1.2. Beyond the Standard Model

Neutrino oscillations are evidence of physics beyond the Standard Model. This means they might be a window into fascinating new physics, allowing us to understand and explain the nature of the universe better than we have before. Neutrino oscillations represent physics beyond the Standard Model in at least two ways. First, the Standard Model symmetry of lepton family number is violated by neutrino oscillation. Second, Standard Model neutrinos are massless and neutrino oscillation requires that neutrinos with a small but nonzero mass.

The Standard Model’s law of conservation of lepton family number states that neutrinos, which are leptons, cannot change flavor. This means that an electron neutrino must always remain an electron neutrino. However, the oscillations that we observe show that electron neutrinos, as they travel through space, have some probability of being detected as one of the other two neutrino flavors ($\mu$ or $\tau$). Thus these oscillations violate lepton family number conservation.

Furthermore, in the Standard Model neutrinos are massless, but neutrino oscillation implies that neutrinos have small, nonzero masses. Introducing a neutrino mass into the model is more difficult than it might seem. Theorists must now attempt to explain how the neutrinos acquire mass, and why that mass is so much smaller than the masses of all the other known particles. The most appealing explanation thus far is that neutrinos are Majorana particles and acquire mass via the see-saw mechanism. This theory can account for the incredibly small mass of the neutrinos, but it also requires the violation of lepton number conservation, another Standard Model symmetry.

The implication of neutrino mass by their oscillation is most easily explained when you consider a two-flavor system. Let us assume there are only two families of neutrinos: $\mu$ and $e$. This is a simplification because there are actually three known neutrino flavors, $e, \mu,$ and $\tau$. The neutrino can be described by a wave of either ‘mass states’ or ‘weak states.’ The weak states are the states that are described by neutrino flavor. The mass states, as the name implies, are described by the masses.

Since we are working with two weak states, we have two degrees of freedom in which we can describe our neutrino. The mass states and weak states can be thought of as different sets of basis vectors that describe this two-dimensional space. The neutrino can be described by either set of basis vectors, which are related by a simple rotation matrix. This means that any weak state is simply a linear combination of mass states.

Figure 2 shows a neutrino described by two different mass states. If both of the mass states that describe our neutrino were equal (say they are both 0), then the two mass waves have the same frequency. This would imply that the waves describing the neutrino are indistinguishable and no interference pattern is detected. The mass states would be equal to the weak states and so the rotation matrix would simply be the identity matrix, and the $\theta$ in this matrix would be 0. This scenario is exactly the one predicted by the Standard Model.

However, if the mass states are represented by slightly different masses, they would have different frequencies and the two waves would interfere with one another. Figure 2 shows what would happen in this case. As the waves constructively or destructively interfere, they have some

![FIG. 2: This image shows a combination of mass waves that start out describing a $\nu_\mu$. As the wave propagates it has some probability of being detected as a $\nu_e$. That is because these mass waves represent different masses and travel with different frequencies. The interference of the mass waves gives the probability of detecting a $\nu_e$.](image)
probability of being detected as the original $\mu$ neutrino flavor, but there is also a chance that this neutrino will be detected as an $e$ neutrino.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} e^{i\delta} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} \text{Flavor} \\ \text{Eigenstate} \end{pmatrix} = \begin{pmatrix} \text{Mixing Matrix} \\ \text{Mass Matrix} \end{pmatrix} \begin{pmatrix} \text{Eigenstate} \end{pmatrix}$$

FIG. 3: Neutrino Mixing in 3D

In order to explain $\theta_{13}$, the parameter Double Chooz hopes to measure, we must extend the two-state simplification to the current three state understanding. Though it is more difficult to visualize, the concept is the same. Here there are three dimensions so the mixing matrix is a $3 \times 3$ matrix (see figure 3). The weak eigenstates are related to the mass eigenstates by a unitary rotation matrix.

$$U = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}$$

FIG. 4: We break the unitary rotation matrix into three separate matrices whose parameters are more easily measured by experiments. The solar neutrino mixing angle, $\theta_{12}$ is measured to be about $33^\circ$. The atmospheric mixing angle, $\theta_{23}$, is measured to be maximal, $45^\circ$. $\theta_{13}$ is unknown, but constrained to $\theta_{13} < 13^\circ$.

In practice, this unitary rotation matrix is broken down into three matrices, as figure 4 shows. There are three mixing angles in these matrices. $\theta_{12}$ has been defined by solar and reactor neutrino experiments. $\theta_{23}$ has been determined by atmospheric and accelerator neutrino experiments. The only mixing angle that is still undetermined is $\theta_{13}$, which is the one that Double Chooz will attempt to measure. $\theta_{13}$ has been constrained to $< 13^\circ$ and is thus the smallest mixing angle, which is why it has been so difficult to measure thus far.

The other unknown parameter in Figure 4 is $\delta$. This parameter represents a charge parity violating phase, which can be explored after $\theta_{13}$ is known. If $\delta$ is nonzero, that would mean that neutrinos violate charge parity conservation (a violation that is allowed by the SM). This violation would imply that neutrinos oscillate with a different probability than antineutrinos. This is the type of violation that is needed to explain why there is more matter than antimatter in the universe.

1.2. Double Chooz

1.2.1. Overview

Double Chooz is a neutrino physics experiment sensitive to only electron antineutrinos. The experiment is stationed in Chooz, France, near a nuclear reactor that provides electron antineutrinos with energies between 1.8 and 8.5 MeV. Double Chooz will consist of two identical main detectors, the Near Detector will be 300 meters from the reactor and the Far Detector will be 1000 meters away. Double Chooz is a disappearance experiment, expecting to observe fewer events at the far detector after correcting for solid angle.

Double Chooz is only sensitive to disappearance if $\sin^2 2\theta_{13}$ is greater than 0.02 to 0.03. The expected disappearance is described by equation 1. If Double Chooz detects a disappearance, we will conclude that the unobserved electron antineutrinos at the Far Detector oscillated to a different flavor of antineutrino, and thus were undetectable. We could then determine an experimental result for the probability of antineutrino oscillation to a different flavor. If this ‘disappearance’ effect is not observed in Double Chooz, an upper limit will be set on $\sin^2 2\theta_{13}$.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\tau) =$$

$$\sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} -$$

$$\frac{1}{2} \sin^2 \theta_{12} \sin^2 \theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{2E} \sin^2 \frac{\Delta m^2_{31} L}{2E} +$$

$$\left[ \sin^2 \frac{\Delta m^2_{21} L}{4E} \times$$

$$\left( \cos^4 \theta_{13} \sin^2 2\theta_{12} + \sin^2 \theta_{12} \sin^2 2\theta_{13} \cos^2 \frac{\Delta m^2_{31} L}{2E} \right) \right]$$

(1)

This probability is theoretically described by equation 1 and by fitting Double Chooz data we could find $\sin^2 2\theta_{13}$. This equation depends on other experimentally measured parameters. The survival probability of an electron antineutrino (1-equation 1) is shown in figure 5. This plot is shown for two different values of $\Delta m^2_{13}$. The first and smallest dip in the plot is the one controlled by $\theta_{13}$.

The magenta curve shows the original Super-K upper bound on $\Delta m^2_{13}$. The Chooz experiment was constructed with this value in mind, which made the far detector site at 1000 meters a perfect distance to measure the first dip in the plot. Minos is a more recent experiment that has a better fit for $\Delta m^2_{13}$. This updated plot is shown in blue in figure 5. This new data makes the location of the Double Chooz far detector less ideal, but Double Chooz should still measure a deficit if $\sin^2 2\theta_{13}$ is large enough.
1.2.2. Detection

The Double Chooz detector has many components. A diagram of the detector is shown in figure 6. The target volume is an acrylic cylinder in the very center of the detector, containing Gadolinium doped organic liquid scintillator. The target is contained within the gamma catcher, which is an acrylic cylinder filled with undoped liquid scintillator. The gamma catcher is surrounded by a buffer and is filled with plain mineral oil. The inner walls of the buffer contain photomultiplier tubes (PMTs) that detect light from the target. The two innermost components have acrylic walls so that the light can escape into the buffer. The outer components of the detector include shielding, an inner veto and an outer veto. The outer veto accurately tracks cosmic ray muons in order to veto them as they pass through Double Chooz.

The energy of the neutrino that produced the signal can be calculated using energy conservation:

\[ E_{\nu_e} = E_{e^+} - 0.8 \text{MeV} \]  

In this equation, \( E_{\nu_e} \) is the energy of the incoming antineutrino. The 0.8 MeV represents the rest energy of the positron, 0.5 MeV, less the energy lost by converting proton to neutron, 1.3 MeV. The neutron kinetic energy is neglected.

One of the main sources of background at Double Chooz is produced via cosmic ray muons, which travel through the detector depositing energy. In general, Double Chooz can tag these muons when they enter the detector and veto for a short period of time. However, cosmic ray muons and the shower of particles they create in the detector can also produce unstable, long-lived isotopes. These isotopes can generate false signals after the muon has passed. The largest source of this sort of background will be the decay of \(^9\)Li. \(^9\)Li \( \beta^- \) decays 100% of the time (in a \( \beta^- \) decay an electron is emitted), and about 50% of the time it also emits a neutron. Since Double Chooz has no way of distinguishing charge, the \( e^- + n \) signal will look very similar to the \( e^+ + n \) signal from inverse beta decay.
2. MUON SPALLATION IN ORGANIC SCINTILLATOR

The Double Chooz detectors will be filled with Gadolinium-doped organic liquid scintillator. Organic liquid scintillator contains mostly Hydrogen and 12C. When high energy cosmic ray muons pass through scintillator, they create hadronic and electromagnetic showers which serve as background to Double Chooz. Double Chooz’s outer veto tracks muons as they enter the detector. This will allow us to veto many of the particles made in the muon showers.

However, the interactions of muons and the particles created in their showers with 12C can produce radioactive nuclei. The table below shows some of these isotopes and their half-lives. The half-life of many of these isotopes is large compared to the muon rate and therefore cannot be vetoed effectively.

Since Double Chooz measures antineutrinos via inverse beta decay, any background must mimic the double coincidence signal described in the previous section. This coincidence means that only isotopes that decay and emit a neutron will be a concern to Double Chooz. Furthermore, Double Chooz detects reactor antineutrinos which are between 1.8 and 8.5MeV. For this energy range and with the double coincidence, the relevant isotope decays are those of 8He, 9Li and 11Li. Each of these decays can mimic the antineutrino signal. If the muon is detected by the outer veto, a three-fold coincidence with the muon can discriminate these decays from true antineutrino events.

To understand its background, Double Chooz needs to know how much of these radioactive isotopes will be produced within the detector. A few tests have been done to measure the spallation production yield in scintillation detectors. Hagner et al. [4] used a muon beam of 190 GeV and measured a combined value for the amount of 8He and 9Li produced in scintillator. More recently, KamLAND, at 2700 mwe with $<E_\mu> = 260$ GeV, published an analysis of their muon-induced isotope production, including results from their FLUKA simulation expectations.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>T $\frac{1}{2}$</th>
<th>E$_{\text{max}}$(MeV)</th>
<th>Decay Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^\beta^-$:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>0.02 s</td>
<td>13.4</td>
<td>e$^-$</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>13.80 s</td>
<td>11.5</td>
<td>e$^-$ with $\alpha$</td>
</tr>
<tr>
<td>$^{11}$Li</td>
<td>0.09 s</td>
<td>20.8</td>
<td>e$^-$</td>
</tr>
<tr>
<td>$^{9}$Li</td>
<td>0.18 s</td>
<td>13.6</td>
<td>e$^-$ with n</td>
</tr>
<tr>
<td>$^{8}$Li</td>
<td>0.84 s</td>
<td>16.0</td>
<td>e$^-$ with $\alpha$</td>
</tr>
<tr>
<td>$^{8}$He</td>
<td>0.12 s</td>
<td>10.6</td>
<td>e$^-$ with n</td>
</tr>
<tr>
<td>$^{6}$He</td>
<td>0.81 s</td>
<td>3.5</td>
<td>e$^-$</td>
</tr>
<tr>
<td>$^\beta^+$, EC*:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>20.38 min</td>
<td>0.96</td>
<td>e$^+$</td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>19.3 s</td>
<td>1.9</td>
<td>e$^+$</td>
</tr>
<tr>
<td>$^{9}$C</td>
<td>0.13 s</td>
<td>16.0</td>
<td>e$^+$ with p or $\alpha$</td>
</tr>
<tr>
<td>$^{9}$B</td>
<td>0.77 s</td>
<td>13.7</td>
<td>e$^+$ with $\alpha$</td>
</tr>
<tr>
<td>$^{7}$Be*</td>
<td>53.3 days</td>
<td>0.478</td>
<td>e$^+$</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Isotope</th>
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<th>$\mu$ shower</th>
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<tbody>
<tr>
<td>$^{12}$B</td>
<td>-</td>
<td>27.8 $\pm$ 1.9</td>
<td>42.9 $\pm$3.3</td>
</tr>
<tr>
<td>$^{9}$Li $^{(\text{combined})}$</td>
<td>3.16$\pm$ 0.25</td>
<td>2.2 $\pm$ 0.2</td>
<td>77 $\pm$ 6%</td>
</tr>
<tr>
<td>&gt;1.0 $\pm$ 0.3</td>
<td>8He</td>
<td>0.32 $\pm$ 0.05</td>
<td>0.7 $\pm$ 0.4</td>
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KamLAND does not quote a value for the production of 11Li because simulation indicates a very low yield. KamLAND’s 8He and 9Li yield results are shown. The units are $10^{-7}$ per muon per g cm$^{-2}$. Lithium-9 has a yield of $2.2 \times 10^{-7} \frac{1}{\mu(\text{g cm}^{-2})}$ and is thus the largest concern for background.

3. POSITRONS V. ELECTRONS

The first and most obvious difference between inverse beta decay, and the 9Li background decay is that in the former a positron is emitted, whereas in the latter an electron is emitted. My first attempt at differentiating between inverse beta decay and 9Li decay was to see whether electrons and positrons might leave a different signature in our detector. Both of the particles will deposit their kinetic energy within the detector, but only the positron will annihilate producing two 0.511 MeV gammas. I hoped to use this information to distinguish the two particles.

I simulated 1000 events of each particle in our detector, and then reconstructed them using Double Chooz software. Given a certain amount of light deposited in the detector, my goal was to be able to tell whether an electron or a positron had passed through. Thus I wanted to compare the two particles when the same amount of light was deposited in the detector. I simulated 4MeV total energy positrons and 5MeV electrons.

The signal from these simulations is displayed in figure 7. The plot shows that the two pulses appear almost identical.

To quantify any difference that might exist between the pulse shapes, I constructed a late light variable which sums the late light for each event. I defined late light as that deposited after $t_{\text{cutoff}} = 80$ ns. This required me to loop through all of the data on an event-by-event basis, employing Double Chooz data structures. The result of

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FIG. 7: The time distribution of pulses, these initial simulations appear very similar.

this study is shown in figure 8, which plots the fraction of late light in the pulse against total light.

FIG. 8: Results of late light study were inconclusive.

In these plots we compare each column, that is each section with a given amount of total light deposited. I expected the positrons to have more late light than the electrons, which would mean that the positron data would lie significantly above the electron data. As figure 8 shows, the difference is not enough to conclude which particle has been detected.

I then used higher level analysis to distinguish the particles. I reconstructed the events using an algorithm that accounts for pulse time and charge. I expected that the positron-electron annihilation would make positrons more difficult for Double Chooz software to reconstruct because three particles are depositing energy. Double Chooz has a reconstruction variable called Chi Squared that quantifies the uncertainty in the reconstruction.

I applied Double Chooz’s Readout System Simulation to the electron and the positron data to emulate what Double Chooz would detect if these were real events. I then reconstructed the events using Double Chooz software (RecoBAMA). The results of this test are shown in figure 9. The chi squared plots differ slightly, but not enough to differentiate between the two particles.

FIG. 9: Reconstruction Chi-Squared Distribution. There was no significant deviation found.

While these exercises allowed me to learn about Double Chooz software and data structures, the results were inconclusive. The next step was to fully simulate $^9\text{Li}$ decay so that I could compare the full decay to inverse beta decay. This decay is not already handled by Double Chooz software, so I wrote a generator to simulate isotope decay in the Double Chooz detector.

4. UNSTABLE ISOTOPE DECAYS

I wrote a general generator for unstable isotope decays in Double Chooz. In addition to $^9\text{Li}$, it can simulate unstable isotope decays like that of $^{12}\text{B}$, which can be used to calibrate the detector at higher energies than we can reach with typical gamma sources like $^{60}\text{Co}$.

4.1. The Physics of Isotope Decays

4.1.1. How and Why a Nuclear Decay Occurs

The chart in figure 10 shows the stable nuclei in the Z-N plane. If a nucleus is above the blue data, it is neutron rich and will $\beta^{-}$ decay. That means that it will convert a neutron into a proton in the reaction described by

$$n \rightarrow p + e^{+} + \bar{\nu}_{e}.$$
If a nucleus is below the blue data, it will undergo the opposite reaction, a $\beta^+$ decay, described by

$$p \rightarrow n + e^- + \nu_e.$$  

A proton has never been observed to freely decay and does not undergo this process outside of the nucleus.

Notably, for heavy nuclei and even values of $A_\circ$, there can often be more than one stable nucleus. This occurs when a nucleus on the even-even parabola is more stable than any on the higher odd-odd parabola. Upon decay, a nucleus converts one of its nucleons to the other type (protons to neutrons and vice versa), so an even-even nucleus becomes an odd-odd nucleus and switches parabolas. If the even-even nucleus is not at the lowest point on its parabola, but is still more stable than any on the odd-odd parabola, it will be stable. In truth, this nucleus can still decay to the lowest point on the even-even parabola via double beta decay, $2\nu\beta\beta$, but the half-life for this interaction is so large that the nucleus is considered to be stable. Thus there can be more than one stable nucleus.

The nuclei must meet conditions in order for a $\beta$ decay to occur. The condition for $\beta^-$ decay is given by equation 5 and the condition for $\beta^+$ decay is equation 6.

$$M(A, Z) > M(A, Z + 1)$$ (5)

$$M(A, Z) > M(A, Z - 1) + 2m_e$$ (6)

Electron capture can also occur in the nucleus. This happens because there is some nonzero probability of finding an inner-shell electron inside the nucleus. This electron can interact as described by

$$p + e^- \rightarrow n + \nu_e.$$  

This interaction occurs mainly in heavy nuclei, where there is a larger nuclei and a more closely bound electron cloud. After the inner shell electron is taken into the nucleus, a cascade of electrons from higher energy levels fills the place of the missing electron. This cascade emits X-rays which indicate that electron capture has occurred.

Electron capture is another way that a nucleus might convert a proton to a neutron. Any nucleus that can $\beta^+$ decay can, in principle, electron capture. The energy threshold for electron capture is lower than the $\beta^+$ decay threshold, so sometimes a nucleus cannot $\beta^+$ decay but can still undergo electron capture.

Sometimes a nucleus will beta decay into the excited state of another nucleus. This excited nucleus can de-excite by emitting gamma rays with energy on the order of MeV. Alternatively, it could decay to a new stable nucleus by emitting a heavy particle like a neutron or an $\alpha$ particle.

4.1.2. Fermi Theory of Beta Decay

Fermi’s theory describes the beta decay of nuclei. The electrons and positrons emerge with an energy spectrum because of the neutrino. The spectrum describes the fraction of the reaction energy, $Q$, that is taken by the beta particle. This spectrum is described by

$$N(E) dE = \left(\frac{g^2}{2\pi^3}\right) F(\pm Z, W) p E (Q - E)^2 |M_{i\rightarrow f}|^2$$ (7)
where $|M_{i\rightarrow f}|^2$ is the matrix element for the interaction. It represents the strength of the coupling between the initial and final nuclear states.

The Fermi Function accounts for the effect of the coulomb field of the nucleus on the electron. In the relativistic approximation it is given by:

$$F(\pm Z', W) = 2(1 + \gamma_0)(2pR/h)^{-2(1-\gamma_0)}\frac{\Gamma(\gamma_0 + i\nu)^2}{\Gamma(2\gamma_0 + 1)}$$

where

$$\gamma_0 = \frac{1}{2}(1-\alpha Z^2)^{1/2}, \quad R = \frac{1}{2}\alpha A^{1/3}, \quad \nu = \pm \frac{\alpha Z W}{c\beta}$$

In the next section I will describe the generator that I wrote to simulate unstable isotope decays. In my generator I used a similar formulation to the one described by the Fermi Function but I include further corrections for electron screening and forbidden decays.

4.2. Generating Decays In Double Chooz

Now that we have explored a bit of how nuclear decays work, I will explain the generator that I made for Double Chooz. I developed a class in C++ called DCGenSpec to simulate the decay of any unstable isotope in the detector. In my class I used some code from Greg Keefer and Lindley Winslow(KamLAND) to generate the proper beta spectrum, as described in the previous section.

The code accesses decay schemes which describe how each nucleus should decay. L. Winslow compiled these schemes and I verified the ones that I have used in studies thus far. The decay schemes are text files that contain information about all of the different ways the nucleus can decay. These different channels are called decay branches and each branch has an associated probability to occur. For every branch, the data files contain the branching ratio, the endpoint energy of the associated beta spectrum (ie, the Q value for the interaction), and any information about other particles like neutrons and alphas that might also be emitted. These data files are formulated using decay schemes found in the TUNL nuclear data evaluation database.

The decay of $^{12}\text{B}$ is a well known allowed decay, shown in figure 11. It will be useful for calibrating Double Chooz. Because it has a short half-life and is frequently produced by muon spallation (see table II), $^{12}\text{B}$ decay is easy to identify. Since the Q value for the main decay branch is about 13 MeV, the observed beta spectrum can be used to calibrate the detector at relatively high energies.

Figure 11 gives a visual representation of $^{12}\text{B}$ decay. The arrows from the parent nucleus, $^{12}\text{B}$, are the different branches, their branching ratios are shown in red. The figure shows that more than 97% of the time, $^{12}\text{B}$ decays directly into the stable $^{12}\text{C}$ nucleus. In the second and third decay branches, it decays into an excited state of $^{12}\text{C}$, and de-excites by emitting photons. In the fourth and very improbable decay branch $^{12}\text{B}$ decays to a very excited state of $^{12}\text{C}$, which de-excites by emitting an alpha particle and produces $^{8}\text{Be}$ in its ground state.

Figure 12 gives a visual representation of the more complicated $^9\text{Li}$ decay. The first decay branch goes directly into the stable nucleus $^{9}\text{Be}$. The second and third branches on the other hand decay to excited states of $^{9}\text{Be}$ and de-excite by emitting a neutron, leading to the production of $^{8}\text{Be}$. The final three branches emit alpha particles to form $^5\text{He}$, which then de-excite by emitting a neutron and settles on the stable $^4\text{He}$ nucleus. This is a very complicated decay because there are many neutrons and alpha particles involved.

The DCGenSpec generator is run as part of DCGLG4Sim, a Geant 4 simulation that contains information about the specifics of the Double Chooz detector. DCGenSpec requires input: the number of events to generate, the chemical symbol of the element and the A and Z for the isotope. It then accesses the decay schemes that...
contain information like that displayed in figures 11 and 12. It loads all of the decay information and generates the full theoretical beta spectrum for each branch. For each event DCGenSpec randomly generates a number to determine which branch to use. It then randomly generates a beta particle within the theoretical spectrum, and also simulates the emission of any heavy particles associated with that branch. The flow chart for the class can be found in figure 13.

In the flow chart, each box represents an instance of a DCGS program. DCGSGenRandom is the main class, which calls the others as needed. It first makes an instance of DCGSBranchBuilder, which compiles all of the information for each branch. DCGSBranchBuilder makes instances of the three classes that contain particle information for the different decay branches. DCGSCalcBetaSpec takes the endpoint energy of the beta spectrum from the decay schemes and calculates the theoretical beta spectrum. The other two simply store gamma and heavy particle (like neutron and alpha) information. The branch builder then uses that information and constructs branches, which contain all of the information for the decay branches they represent.

After loading the data, DCGenRandom generates the events. It first generates a random number to select which branch to use. It accesses the information in that branch and generates a random beta particle within the beta spectrum, as well as any gammas or heavies that might also be in the branch. It prints all of this information to Geant4, which simulates what Double Chooz would detect if these particles appeared.

4.3. Results: Decay Spectra in Double Chooz

The output of the simulation was verified with the simple $^{12}$B decay. The spectrum of deposited energy in the Double Chooz detector from $^{12}$B decay is shown in figure 14. This decay appears to be appropriate for a beta decay, with an endpoint of 13.37 MeV.

I then tested the simulation of $^{9}$Li decay, verifying that neutron capture was activated and working. The results are shown in figure 15. The plot on the left shows the energy deposited in the prompt event, which I defined as within the first 256 nanoseconds. This represents the deposited energy of the electrons and neutron thermalization energy. The plot on the right shows the energy deposited by neutron capture. There are two peaks, the 8 MeV peak is the signature of neutron capture on Gadolinium, whereas the smaller peak at 2.2 MeV is from neutron capture on Hydrogen. The output of this simulation agrees with expectations of a $^{9}$Li decay spectrum.

The decays that will emulate inverse beta decays are those that emit a neutron, but figure 15 includes events with and without neutron captures associated with them. The decay scheme in figure 12 shows, a neutron is emitted only about 51% of the time that $^{9}$Li decays. When $^{9}$Li decays directly to the ground state of $^{9}$Be and doesn’t emit a neutron, it will not be considered an inverse beta decay candidate. Thus the energy deposition of those
FIG. 16: The energy deposited by electrons and neutron thermalization from $^9$Li neutron emitting decay branches.

FIG. 17: The energy deposited by capturing neutrons from $^9$Li neutron emitting decay branches.

These events should not be considered when comparing $^9$Li decay to antineutrino events.

I generated $^9$Li decay again, this time turning off the first decay branch so that all events printed to Geant 4 would be those including a neutron emission. The results of this test are shown in figures 16 and 17. The beta spectrum in figure 16 appears shifted, as the endpoint energy for beta spectrum is now 11.2MeV. I verified that the injected energy spectrum was correct and that electrons rather than positrons were being emitted. This shift may be due to neutron kinetic energy deposition, which is included in the plot.

These events can be compared to inverse beta decay events in the detector. The results from antineutrino simulations are also shown. The beta spectra differ, so the energy deposited in the prompt events (figures 16 and 18) differ. As expected, the neutron capture energies are the same (figures 17 and 19). All of these simulations have low statistics and should be redone with more events.

Now with samples of inverse beta decay and $^9$Li decay, I compare pulse information from the two events. A difference in pulse time distributions could be caused by the positron annihilation from inverse beta decay that produces 2 gammas. They might also differ because of the neutron kinetic energies, the neutron from 9 Li decay has kinetic energy on the order of MeV, compared to the negligible kinetic energy of the inverse beta decay neutron. The more energetic neutron should deposit more energy as it thermalizes.

FIG. 18: The energy deposited by electrons and neutron thermalization from inverse beta decay.

FIG. 19: The energy deposited by capturing neutrons from inverse beta decay.

FIG. 20: Pulse time distributions for $^9$Li neutron emitting branches and IBD.
Figure 20 shows a plot of the pulse time distributions for both decays. This plot compares decays that deposit between 4 and 5 MeV in the detector. The histograms are properly normalized. The pulse timing distributions appear very different. Further testing and more statistics are needed, but these results are very promising.

5. WHATS NEXT?

I am continuing in this work for my senior thesis. Now that I have completed my summer project of building the generator and simulating $^9$Li decay in the detector, it is time to develop an algorithm for distinguishing the two decays.

The pulse timing distributions for the two decays appear to differ. To quantify the difference I will use a late light analysis similar to that used on the positron v. electron data described in section 3. I will use a late light variable to assign a probability that the signal was from $^9$Li decay, rather than inverse beta decay. I will then run more simulations and quantify how well this analysis can distinguish the two decays within error. Ultimately, I will develop software that uses algorithm and assigns level of certainty to results.

6. CONCLUSIONS

Muon spallation serves as a major concern for background in Double Chooz. Muons and their shower particles can interact with the scintillator to produce radioactive isotopes like $^9$Li, whose decay emulates inverse beta decay. It would be very useful to be able to distinguish the background $^9$Li decay from the signal. I attempted to distinguish the two decays this summer. My study to differentiate between the signals of positrons and electrons in the detector proved inconclusive. I then wrote a generator that simulates radioactive decay in the Double Chooz detector. The generator appears to work well, and promises to be broadly useful. It will be useful in further studies to distinguish the two decays. Furthermore, it can generate the decay of isotopes like $^{12}$B, which can be used to calibrate the Double Chooz detector.

I plan to use the generator to compare the full signal from $^9$Li decay to that of inverse beta decay and develop an algorithm to distinguish them. I expect to use pulse timing information, since the more energetic neutron from $^9$Li decay should deposit more light in the prompt event, as compared to the neutron from inverse beta decay.

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8. REFERENCES