Detector Efficiency and Potential Background Sources in Double Chooz

August 1, 2008

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Abstract

Double Chooz is a neutrino oscillation experiment set to take place in 2009 in Chooz, France. The town of Chooz is the site of a nuclear power plant which contains two reactors. The experiment aims at detecting anti-electron neutrinos ($\bar{\nu_e}$) produced by the reactors at two different detectors located at different distances from the reactors. By comparing the number of $\bar{\nu_e}$ events at each detector, it is expected that the experiment will find less $\bar{\nu_e}$ events at the far detector than the the Standard Model would predict based on the number of events at the near detector. From this deficiency, the Double Chooz experiment hopes to obtain a more accurate measurement of the θ_{13} parameter, which describes amount of mixing between the ν_e and ν_τ states.

My research focused on the calibration of the detectors. By simulating the placement of AmBe, ^{252}Cf, and $\bar{\nu_e}$ sources at various locations throughout the detector, I was able to find locations where the detection efficiency had a relatively large and small gradient. Also, I was able to find differences in simulated detector response to AmBe and ^{252}Cf sources, versus $\bar{\nu_e}$ sources. These differences are very important to understand, since AmBe and ^{252}Cf will be used to calibrate the detector. My research also focused on investigating potential background sources which could cause false neutrino counts. I simulated the effects of ^{8}He, ^{12}B, neutrons, and photons in the detector. From this, I was able to determine the percentage of background events which caused false $\bar{\nu_e}$ counts and also the deposited energy distributions for each background. From there I attempted to develop an effective way of using maximum likelihood fits to recover the $\bar{\nu_e}$ signal from simulated observed signals.

Introduction

Double Chooz is a neutrino oscillation experiment taking place in Chooz, France and beginning in late 2009. Chooz is the site of a nuclear power plant containing two nuclear reactors which produce copious amounts of $\bar{\nu}_e$ particles. Before going too much more into the experimental setup, it is worthwhile to go over some background concepts of this experiment.

Background Information

Neutrinos are elementary particles and are members of the lepton group. There are three flavors of neutrinos: electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ). They have no charge and were previously thought to be massless. The idea of neutrino oscillations comes up if neutrinos have mass, and if their masses are different. In this situation, neutrinos would have three flavor eigenstates (ν_e, ν_μ, and ν_τ) and three mass eigenstates (ν_1, ν_2, and ν_3). If these two sets of eigenstates don't match, i.e. if the flavor operator doesn't commute with the mass operator, then it would be impossible to have a neutrino in a state of definite flavor and definite mass simultaneously. A consequence of this is that if you measure (or create) a neutrino with a specific flavor and mass and then measure the neutrino again at a later time, the neutrino could be in a different state.

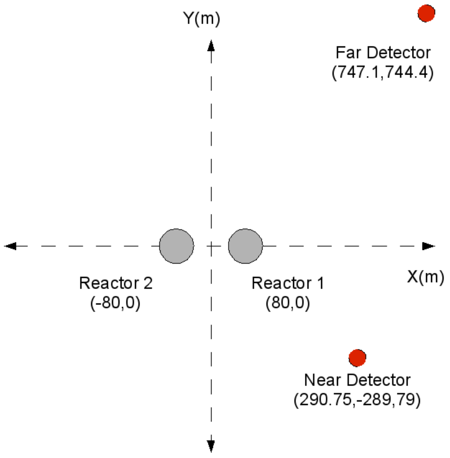

Figure 1: A schematic of the experimental setup.

Experimental Setup

The experiment is set up as shown in Figure 1. There are two reactors which produce $\bar{\nu_e}$ particles and there are two detectors located at different distances from the reactors. By measuring the number of $\bar{\nu_e}$ events detected at the near detector, it is possible to predict how many $\bar{\nu_e}$ should be observed at the far detector in the absence of neutrino oscillations. It is expected that the true number of $\bar{\nu_e}$ events detected at the far detector will be significantly less than the predicted number. From this deficit, the researchers at Double Chooz hope to obtain a value for the θ_{13} parameter, which describes the mixing between the ν_e and ν_τ states.

Since neutrinos have no charge, they only interact via the Weak force, which makes them very difficult to detect. In fact, in the Double Chooz experiment, the cross section for a neutrino event in the detector is only $\sim 10^{-45}\text{cm}^2$. When neutrinos do interact in the detectors, however, they do so via the process: $\bar{\nu_e} + p \rightarrow n + e^+$. When this occurs, the positron will almost immediately annihilate with a nearby electron, emitting two photons which can be detected by the photomultiplier tubes (PMTs) surrounding the detector. In the meantime, the neutron will thermalize, usually within 100μs, and be captured by a nucleus. This will also result in photon emissions, but their energy will vary depending on the nucleus the neutron was captured on.

When detecting $\bar{\nu_e}$ events, Double Chooz only wants to detect those events which occurred in the target of the detector (a schematic of the detector is given in Figure 2). Since the target is loaded with gadolinium (Gd) and the γ-catcher is not, and since Gd has a relatively large neutron capture cross section, a good requirement for a $\bar{\nu_e}$ event is an energy deposition consistent with e^+e^- annihilation (the primary event), followed within 100μs by an energy deposition consistent with neutron capture on Gd (the secondary event). Since neutron capture also occurs on hydrogen in the target and the γ-catcher, this requirement will not allow all events occurring in the target to be counted, but it will help ensure that all counted events did take place in the target.

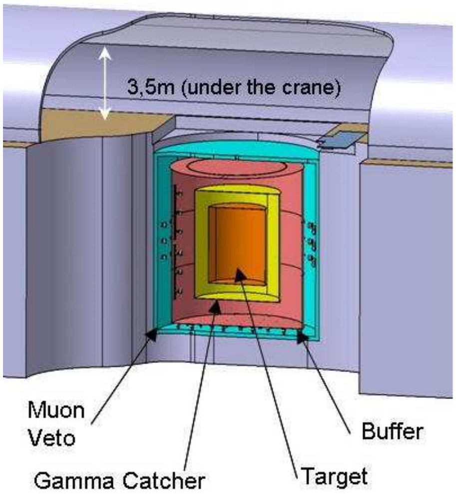

Figure 2: An illustration of the regions of the detector.

Investigation of Detector Efficiency

The first project I took on was to investigate the detector efficiency and how it depends on location in the detector and on which calibration source is used. Since there is no way to physically place $\bar{\nu_e}$ sources in the detector to measure the detection efficiency, calibration sources must be used instead. These sources have energy deposition signatures similar to that of $\bar{\nu_e}$ events and also have very well known decay rates. However, in order to estimate the $\bar{\nu_e}$ detection efficiency accurately, it is very important to understand how the calibration source detection efficiency relates to the $\bar{\nu_e}$ detection efficiency and also how this efficiency varies throughout the detector.

To investigate this, I simulated the placement of ^{252}Cf, AmBe, and $\bar{\nu_e}$ sources, each with about 5000 events, in 53 different locations throughout the detector. I then counted how many events fit the constraint mentioned earlier[1] in order to calculate the detection efficiency. Figure 3 shows the locations in the detector where the sources were simulated.

While the results from all the simulations are too large to be fully displayed here, figures

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[1] More specifically, this constraint is a $>.5$ MeV event, followed within 100μs by an event depositing between 6 MeV and 9 MeV in the detector. Since neutron capture on hydrogen usually deposits $\sim$2 MeV of energy in the detector, those events are ignored.

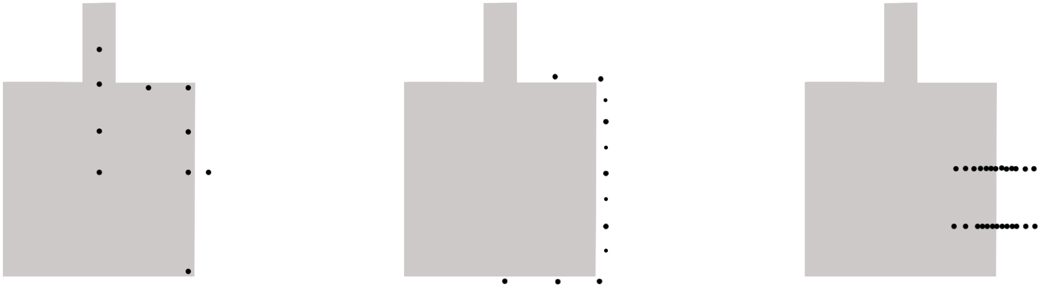

Figure 3: An illustration of where the simulated source locations were. The grey body is the target of the detector.

4 and 5 help to illustrate some of the conclusions from the project. The graph on the left illustrates the very high radial dependence the efficiency has near the wall of the target. This can be explained by a greater proportion of neutrons being captured in the γ-catcher as you get to larger and larger radii. The figure on the right of Figure 4 illustrates the relatively weak dependence on Z for sources deployed at R=1180mm, which is 3cm outside of the target wall. This information could be especially useful for the planned source calibration outside the target wall, since this data implies that there need not be a great amount of accuracy in the Z-position of these source locations.

Both of these graphs also illustrate another important result, which is the difference in detection efficiencies between the ^{252}Cf and AmBe sources and the $\bar{\nu_e}$ source. This difference is very important to understand in order to be able calculate $\bar{\nu_e}$ detection efficiency from the calibration source efficiencies. Figure 5 goes at least some of the way in explaining this difference. This figure shows the $\log_{10}$ of the kinetic energies of the neutrons emitted in ^{252}Cf decay and $\bar{\nu_e}$ events in black and red, respectively. Since neutrons emitted in $\bar{\nu_e}$ events have significantly less kinetic energy, they will take less time to thermalize and will be captured by a nucleus sooner. When the neutrons are emitted deep in the target, this means they will capture on Gd sooner, and therefore less events will be dropped due to the 100μs time cut. However, when the neutron emission happens outside the target wall, the neutrons have less time to diffuse back into the target to capture on Gd, and therefore they have a greater

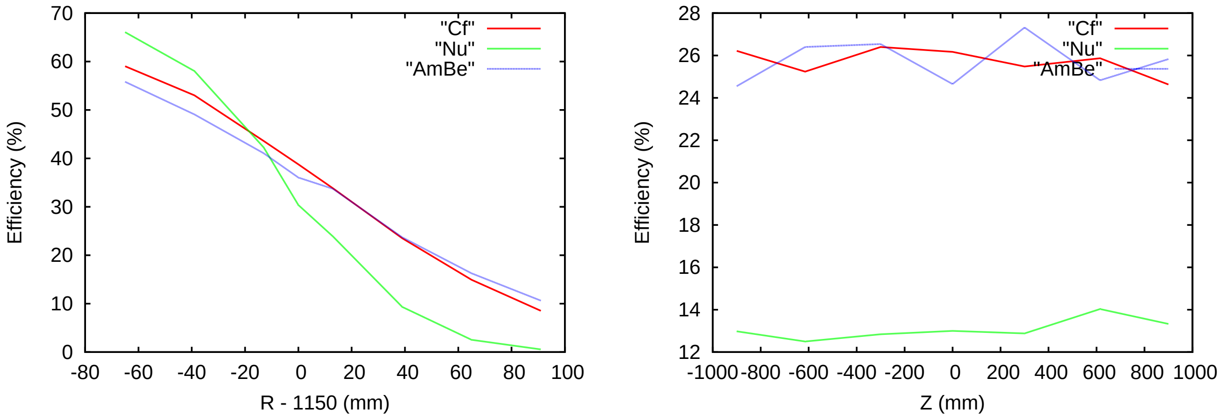

Figure 4: The graph to the left is of the detection efficiency at Z=0 as a function of radius. "R - 1150(mm) = 0" corresponds to the wall of the target. The graph on the right is of detection efficiency for R=1180mm and varying Z.

chance of being dropped due to the energy cut.

Investigating Potential Sources of Background

The second project I worked on involved looking into potential sources of background which could cause false neutrino counts. In doing this, we had to consider two types of background: correlated and uncorrelated. Correlated backgrounds are backgrounds which can cause a neutrino-resembling coincidence all on their own, while uncorrelated background can only cause one primary event or one secondary event at a time.

For our correlated sources, we used ^{8}He and neutrons. It is expected that ^{8}He will be produced through muon spallation in the detector. ^{8}He decays via the process:

$$\begin{array}{ll} {}^{8}\mathrm{He} \rightarrow {}^{8}\mathrm{Li} + e^{-} + \bar{\nu}_e & \\ \qquad\qquad\searrow & \\ & {}^{8}\mathrm{Be} + e^{-} + \bar{\nu}_e \end{array}$$

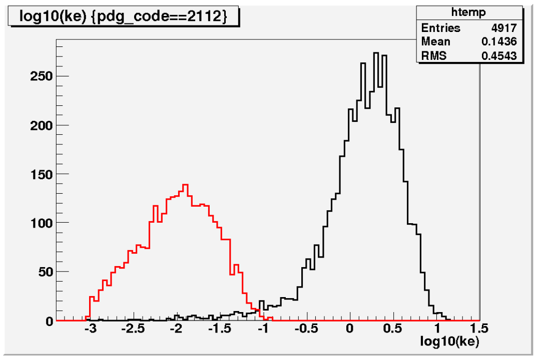

Figure 5: On the right and left are the $\log_{10}$ of the neutron kinetic energy for ^{252}Cf decay and $\bar{\nu}_e$ events, respectively.

In this case, the primary event would be the first β^- decay, and the secondary event would be the second β^- decay. If they occur within 100μs of each other and have appropriate energy, a false neutrino count will be triggered. As it turns out, 16% of the time, ^{8}He decays via β^- decay with a delayed neutron emission. Depending on the energy of the emitted neutron, it is very possible that it will capture on Gd, releasing photons of combined energy between 6 MeV and 9 MeV, and triggering a neutrino count. Because of this, it appears that delayed neutron emission by ^{8}He would be an important background to investigate. However, the simulation did not produce any delayed neutron emissions, so I was unable to look into this.

Neutrons are expected to be emitted from the rock surrounding the detector. In this case, the primary event would be an energetic neutron collision with a proton, which can be picked up by the PMTs, and the secondary event would be neutron capture on Gd.

For uncorrelated background, we used ^{12}B and photons. Due to the presence of ^{12}C in the detector, it is possible for ^{12}B to be made by a free neutron in the detector causing: n + ^{12}C $\rightarrow^{12}$B + p. ^{12}B decays via the processes:

$$^{12}\mathrm{B} \rightarrow^{12} \mathrm{C} + e^- + \bar{\nu}_e \quad \text{and} \quad ^{12}\mathrm{B} \rightarrow^{12} \mathrm{C} + e^- + \bar{\nu}_e + \gamma$$

In either case, if the energy deposited by this decay is of appropriate size, this background can trigger either a primary or secondary event.

The photon sources are meant to represent photons entering the detector as a result of the thorium decay chain in the rock surrounding the detector. Since thorium has a half-life comparable to the age of the universe, a large proportion of it hasn't decayed yet. Because of this, we expect that thorium decay, and the decay of its products, could make up an important part of the background.

From the results of the simulations, we were able to determine that 34.1% of the ^{8}He atoms produced in the detector caused false neutrino counts, while 3.6% of the rock neutrons entering the detector caused false neutrino counts. However, since we don't know the rate at which any of these backgrounds occur (including for photons and ^{12}B), what is especially important is the distribution of energy deposition in the detector for each source. Figures 6, 7, and 8 show the energy deposition distributions acquired from the simulations.

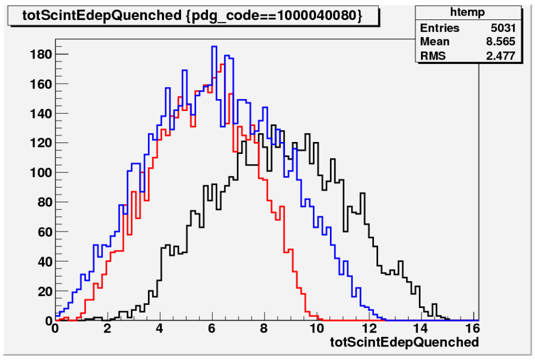

Figure 6: This plot shows the overlap of the deposited energy distributions for ^{8}He and ^{12}B. In red and black are the deposited energy distributions for the early and late β^{-} decays, respectively, for ^{8}He. In blue is the deposited energy distribution for the β^{-} decay for ^{12}B. It is important to note the overlap of the ^{12}B and ^{8}He which occurs until ∼12.5 MeV.

Recovering the Neutrino Signal

Since we do not know the rates at which the background signals occur, it is not possible to simply subtract the expected number of false neutrino counts from the experimental observation. Therefore, we need a more sophisticated method of recovering the neutrino signal.

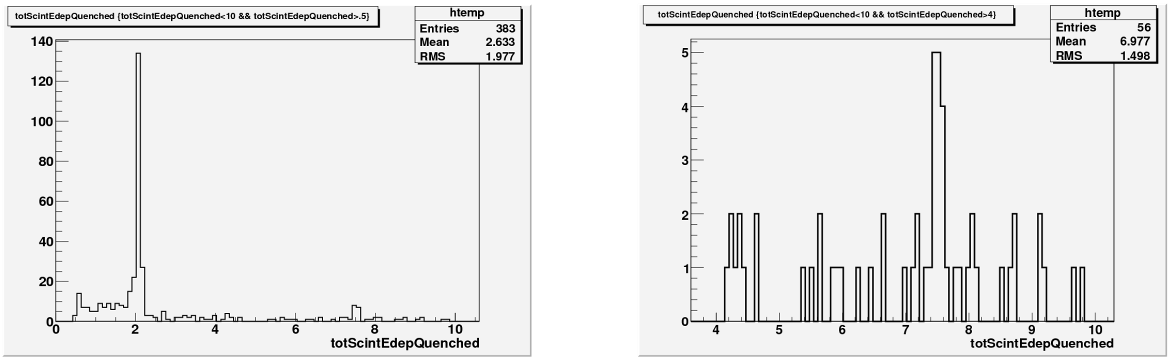

Figure 7: Distribution of energy deposited by the neutrons. The peak at totScintEdepQuenched=2 MeV is from neutron capture on hydrogen. There is a bump that is large relative to its neighbors at ∼7.5 MeV which may be from neutron capture on gadolinium. The figure on the right shows only the 4 MeV to 10 MeV range so the gadolinium capture can be seen more closely.

As part of my last project, I worked on finding an effective way to recover the neutrino signal through the use of maximum likelihood estimators. To use maximum likelihood estimaters, one basically assumes that the signal in question is a linear combination of signals that have a known shape. This is why it is important to know the energy deposition distributions for the background sources. From there, one only has to find the coefficients in the linear combination. In my research, the last thing I was able to accomplish was to produce a way of finding the coefficients if the linear combination is of a small number of signals and if they are all known. However, more difficulty arises if you take into account that the deposited energy distribution for neutrinos depends on θ_{13}[2]. In that case, θ_{13} must also become a parameter in the maximum likelihood fit. Unfortunately, this was something I was not able

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[2] This dependence arises from the fact that if you measure a $\bar{\nu_e}$ and then measure it again a distance L later, the probability of still measuring a $\bar{\nu_e}$ is

$$P(\bar{\nu_e} \rightarrow \bar{\nu_e}) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{1.267\Delta \mathrm{m}^2\mathrm{L}}{\mathrm{E}}\right).$$

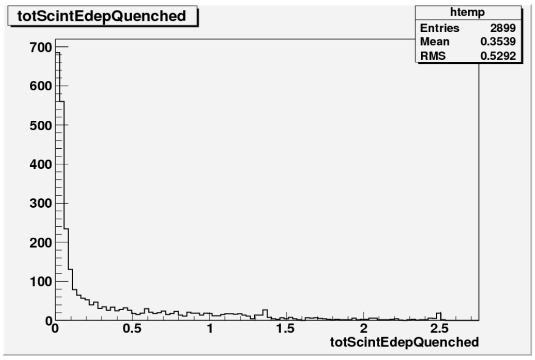

Figure 8: Distribution of energy deposited by the photons.

to consider in my research.

Future Work

Future work that can be done relating to these projects includes updating the nuclear data tables in the Monte Carlo and continued work on separating the background signal from the observed signal. As mentioned earlier, incorporating events such as occasional neutron emission in ^{8}He decay into the Monte Carlo could prove to be valuable in analyzing the background sources in this experiment. Also, with regard to separating the neutrino signal from background, I was not able to do any investigation into potential changes in $\bar{\nu_e}$ event qualifications that could further help isolate the background signals.

Acknowledgements

I would like to thank my adviser John LoSecco for his continued help, even in the face of my often impressive confusion. I also would like to thank the members of Double Chooz who did their best to help me out in the beginning stages of this project. I am also very grateful for the effort that Shari Herman and Umesh Garg put in to make this such a great summer. Thomas Rehagen also deserves thanks, along with the NSF and the University of Notre Dame, who made this opportunity possible.