Neutrino Event Tagging Based On Nucleon Energy Spectra

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Abstract

Since they were first theorized in 1930 by Wolfgang Pauli, much has been learned about the nature of neutrinos. However, key questions remain about the properties of these particles – questions whose answers might help explain fundamental cosmological questions. It is hoped that the DUSEL Long Baseline Experiment, one of the latest proposed neutrino experiments, will give scientists a reasonable measurement of the amount of CP symmetry violation in neutrino oscillations. This information could help scientists explain the matter/anti-matter asymmetry observed in the universe.

The study presented in this work determines whether neutral current π^0 production can be distinguished from charged current quasi-elastic scattering in a water Cherenkov detector based on the energies of nucleons emitted as a result of neutrino interactions. This work was done as an attempt to find methods of increasing the experiment's overall accuracy.

A simulation of the experiment was run using the Nuance neutrino simulation software. Examination of the simulated data reveals no significant differences in the energies of nucleons emitted as a result of neutrino interaction. This indicates that the proper identification of the neutrino events important to this study might not be possible based on nucleon energies.

A Brief History of Neutrinos

The existence of neutrinos was first postulated by Wolfgang Pauli in 1930 to explain unexpected deficits of energy in the products of beta decay and inconsistencies with the Pauli exclusion principle [1]. Experimental observation of the elusive neutrino came in 1956 when Cowan et al. observed anti-electron neutrinos created in a nuclear reactor participate in the reaction $\bar{\nu}_e + p \rightarrow n + e^+$ [1]. Different types of neutrinos were theorized to exist and confirmation of the existence of the muon neutrino came in 1962 with the work of Lederman et al. [2]. The existence of a third type of neutrino, the tau neutrino, came 25 years after the discovery of a the tau lepton [3]. In studying a problem involving a deficit in the number of neutrinos arriving from the sun, it was discovered through a series of experiments that neutrinos, like neutral kaons, oscillate between flavors [4].

Though much has been learned about neutrinos since they were first theorized, there remain interesting questions regarding the properties of these particles. For example, some scientists believe that the presence of dark matter in the universe can be at least partially explained by neutrinos [5].

The DUSEL Experiment

One of the latest experiments to be devised to advance the field of neutrino physics is the DUSEL Long Baseline Experiment. This experiment, which is currently in the early stages of planning and construction, will involve directing a neutrino beam over a distance of 1300km from Fermi National Accelerator Laboratory (FNAL) to the Deep Underground Science and Engineering Laboratory (DUSEL) located in South Dakota. Along with making improved measurements of certain neutrino properties (such as the difference in the square of neutrino masses), it is hoped that the experiment will be able to give scientists accurate measurements of the degree of CP violation present in neutrino oscillation probabilities. This information would improve the ability of the scientific community to determine the role of neutrinos in the matter/anti-matter asymmetry problem.

The following equation governs the probability that a neutrino of type α traveling in a vacuum will oscillate to type β as a function of the distance traveled and the neutrino's energy [4].

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij}(L/E)]$$
$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[2.54 \Delta m^2_{ij}(L/E)]$$

The constants Δm_{ij}^2 represent the differences in the square of the masses of two different neutrino types. U, referred to as the neutrino mixing matrix, is a unitary matrix that take the following form [4]:

$$U=\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where

$$c_{ij}=\cos(\theta_{ij})$$
$$s_{ij}=\sin(\theta_{ij})$$

The quantities θ_{ij} are constants referred to as neutrino mixing angles. The indices i and j take the values of 1, 2, or 3 representing electron, muon, and tau neutrinos respectively. The quantities α_1, α_2, and δ are measures of CP violation in neutrino oscillation. The constants α_1 and α_2 are only of importance if neutrinos have the characteristic of being their own anti-neutrinos (in this case, they would be termed Majorana particles) [4]. One of the quantities being measure by the DUSEL experiment is the other CP violating phase, δ.

Assuming that neutrinos are not Majorana particles, then if δ is 0, then there is no CP violation in neutrino oscillation and it follows from the above equation that

$$P(\nu_\alpha\rightarrow\nu_\beta)-P(\bar{\nu}_\alpha\rightarrow\bar{\nu}_\beta)=0$$

where $\bar{\nu}$ represents the anti-neutrino associated with ν [4]. Researchers working on the DUSEL experiment will attempt to determine whether or not the above formula holds. Though there are many complicating details, the basic strategy is fairly straight forward. The neutrino running (as apposed to the anti-neutrino running) of the beam produced at FNAL will be predominantly composed of muon neutrinos (some electron neutrino contamination is inevitable). By the time the neutrinos reach the DUSEL detector located 1300km away, some of these muon neutrinos will have oscillated into electron and tau neutrinos. Measuring the number of electron neutrino events that occur in the detector will allow for measurements of the probability associated with the $\nu_\mu \rightarrow \nu_e$ oscillation. It is worth noting that due to presence of matter, the probabilities measured will not conform with the standard equation for oscillation probability given above [4]. This effect is called the Mikheyev-Smirnov-Wolfenstein (MSW) effect [4]. After appropriate measurements are made, the experiment can be repeated with a beam that is instead comprised predominantly of anti-muon neutrinos. After correcting for matter effects, a discrepancy between the $\nu_\mu\rightarrow\nu_e$ transition and the $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$ would imply a non-zero value of δ. My project was concerned with measuring the number of electron neutrino events occurring in the detector.

Interaction Identification Through Nucleon Emission Energy Spectra

Neutrinos are detected through observation of the particles that are ejected as a result of its interaction with other matter. To measure the number of electron neutrino events, it will be necessary to detect electrons created in charged current (CC) quasi-elastic scattering. These interactions are mediated by W bosons and turn incident neutrinos into their associated leptons.

$$\nu + n \rightarrow l + p$$

We focus on these interactions because they leave behind (in the form of the created lepton) information regarding the flavor of the incident neutrino. In order to detected the electrons of interest, a water Cherenkov similar to those used in other neutrino experiments will be used. These detectors use the phenomenon of Cherenkov radiation to help identify charged particles traveling through a medium—the basic theory of these devices is not hard to understand. When a charged particle moves through a medium at a speed greater than the speed of light in that medium, it emits light (termed Cherenkov radiation or light) that propagates through the medium in a cone shape (the pattern of light is not dissimilar from the pattern of sound waves created in a sonic boom). In a Cherenkov detector, this medium (in our case pure water) is surrounded by arrays of highly sensitive light detectors. The Cherenkov light detected by these arrays is used to create images of rings, the properties of which are useful in the identifying the moving particle and its motion.

Unfortunately, the use of Cherenkov detectors in the DUSEL experiment is complicated by the presence of additional neutrino interaction channels. Though many interactions are possible with a three-flavor neutrino beam incident on water, only one occurs frequently enough to reduce the accuracy of the detector. The reaction of concern is the neutral current (NC) production of π^0 particles.

$$\nu + p \rightarrow \nu + p + \pi^0$$
$$\nu + n \rightarrow \nu + n + \pi^0$$

Shortly after their production, π^0 particles can decay to gamma rays that, in the presence of other matter, pair produce electron-positron pairs. These charged particles can themselves lead to the emission of Cherenkov radiation that resembles the signature light generated by CC scattering events. Because these events leave no information regarding the flavor of the incident neutrinos, it is impossible to tell whether or not an event was caused by an electron neutrino (the focus of this study). Therefore devising a method of differentiating NC π^0 production from CC scattering events involving electron neutrinos would be a good method of increasing detector accuracy. My experiment was an initial study of one method potentially useful in this respect.

Both reaction channels considered in this study result in momentum transfer to nucleons. Due to the high energy of incident neutrinos (for DUSEL, most neutrinos fall between 100 MeV and 5 GeV), the nucleons involved in the neutrino interactions are given enough energy to cause the emission of multiple nucleons from the affected atom. The goal of my investigation was to determine if any significant differences present in the energy spectra of emitted nucleons could be used to properly categorize events. If, for example, one type of interaction were significantly more likely to produce protons with momenta in the range of 1.07 GeV/c to 2 GeV/c, a technique similar to that developed by Fechner et al. could be used to properly categorize neutrino events [6].

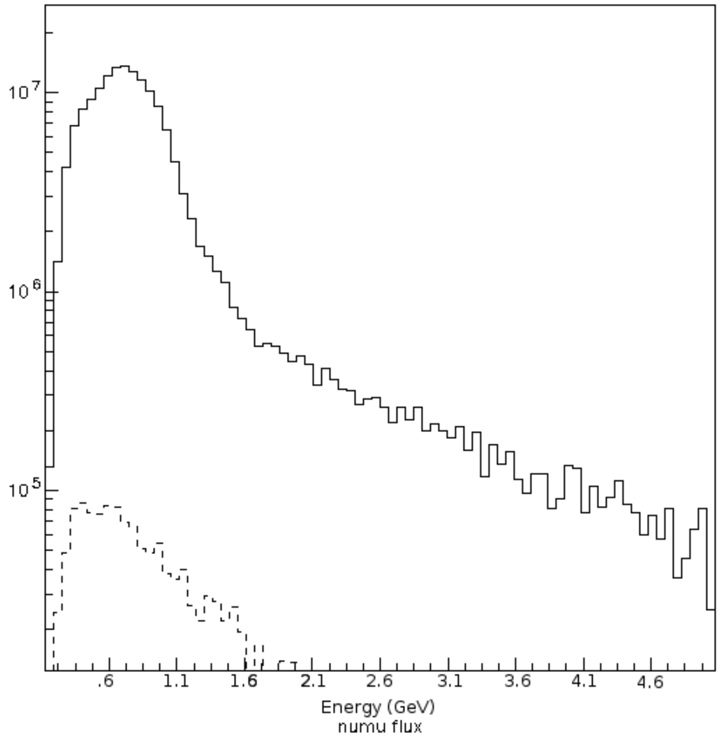

Figure 1: Unoscillated beam fluxes. Solid line corresponds to muon neutrinos. Dotted line corresponds to electron neutrinos

For this investigation, the neutrino interaction simulation software Nuance was used. Though there are newer neutrino simulation tools available, Nuance is the only one that models final state interactions that determine the kinematics of the ejected nucleons.

In order to run the necessary simulation, a description of the DUSEL neutrino beam had to be prepared as input into Nuance. Most importantly, this description required neutrino energy fluxes for the different neutrino flavors present in the beam. The beam fluxes used were generated by a simulation performed at Brookhaven National Laboratory (BNL). Nuance's documentation mentions a built-in feature capable of handling the calculation of neutrino oscillations. Despite our attempts, however, we were unable to make use of this functionality (it appears that neutrino oscillation calculations are only available in Nuance for simulations of atmospheric neutrino). Given the BNL fluxes, which represented the neutrino fluxes at the source of the beam, I had to calculate the corresponding neutrino fluxes after oscillation over the 1300km baseline. To do this, I wrote a program that relies on the software package GloBES (General Long Baseline Experiment Simulator) for the calculation of oscillation probabilities. After the oscillated fluxes were computed, they were converted into the proper units for use by Nuance (neutrinos per bin per cm^2 per unit luminosity) and then put into PAW HBOOK files.

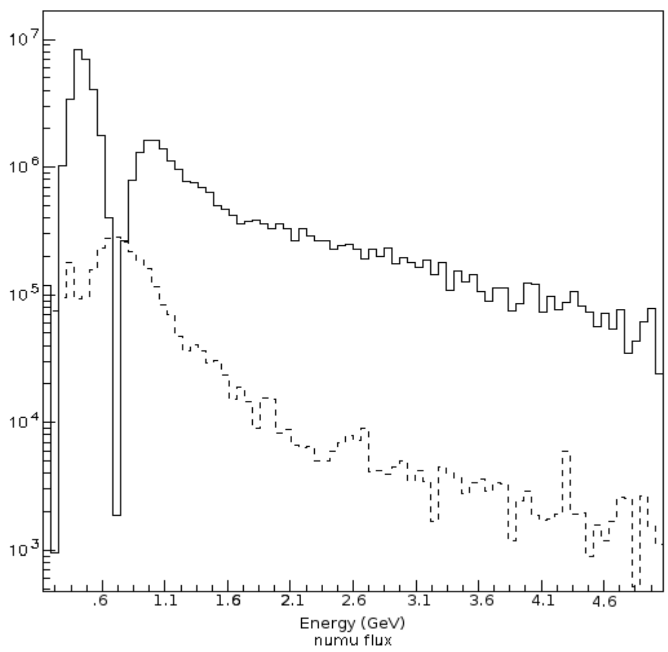

Figure 2: Oscillated beam fluxes. Solid line corresponds to muon neutrinos. Dotted line corresponds to electron neutrinos.

The Nuance simulation was run using 99.985% water and .015% heavy water. The length of simulation can be specified either by providing the time period (in years) over which a simulation takes place or by providing the number of events to be generated. Our simulations were run using the latter method. A total of 100,000 events were generated in 10 runs of 10,000 events each. It is important to note that 100,000 events is an unrealistic number of events to consider for the DUSEL experiment—due to the very low interaction cross-sections between neutrinos and other matter, a few interactions per day are expected at best. However, this many simulated events is useful in determining the overall feasibility of a nucleon-based event tagging approach.

Nuance provides the option of saving output to a text file or to more detailed HBOOK N-tuples. For our study, the text output provides all the necessary information pertaining to neutrino events. After the simulation was run, the data was processes and relevant plots were created using a program written by me that relied on the ROOT visualization library.

Results

The simulated data revealed no significant differences between nucleon energy spectra of NC π^0 production and CC scattering. Figures 3 and 4 contain plots of neutron and proton energy spectra. Based on these results, it would seem distinguishing between NC π^0 production and CC scattering events based differences in emitted nucleon energy spectra is not possible and that different methods of event identification should be sought.

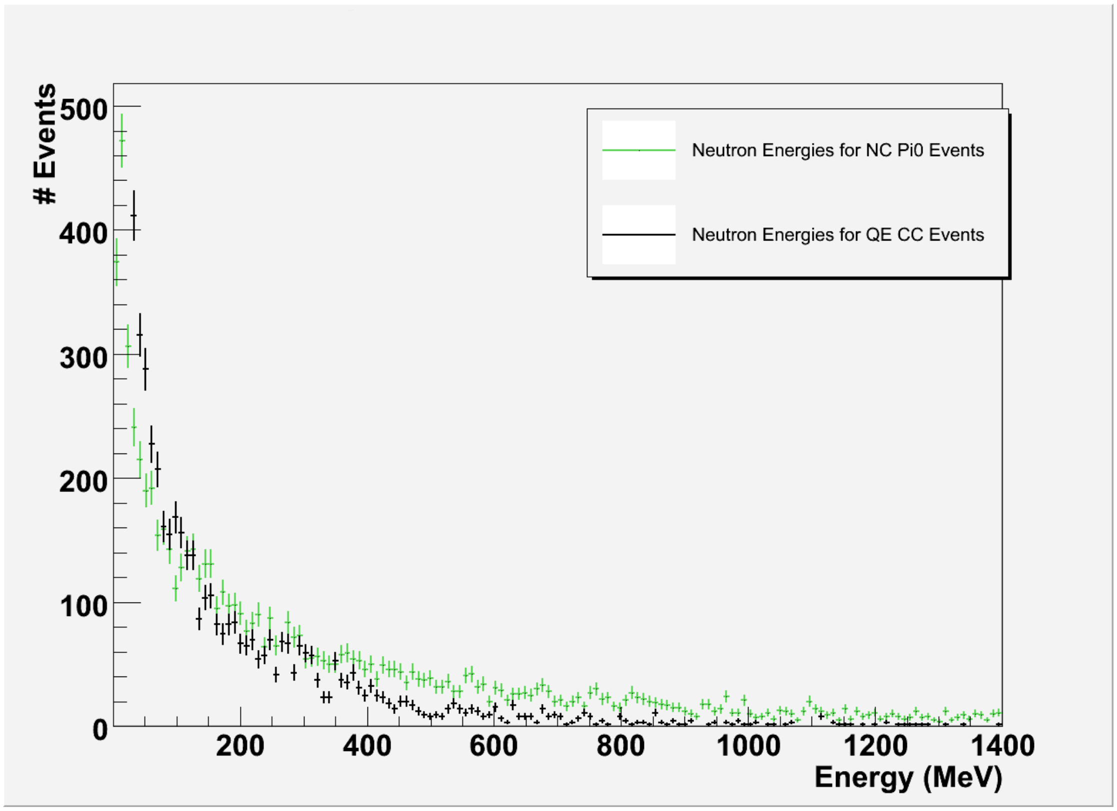

Figure 3: Neutron Energies

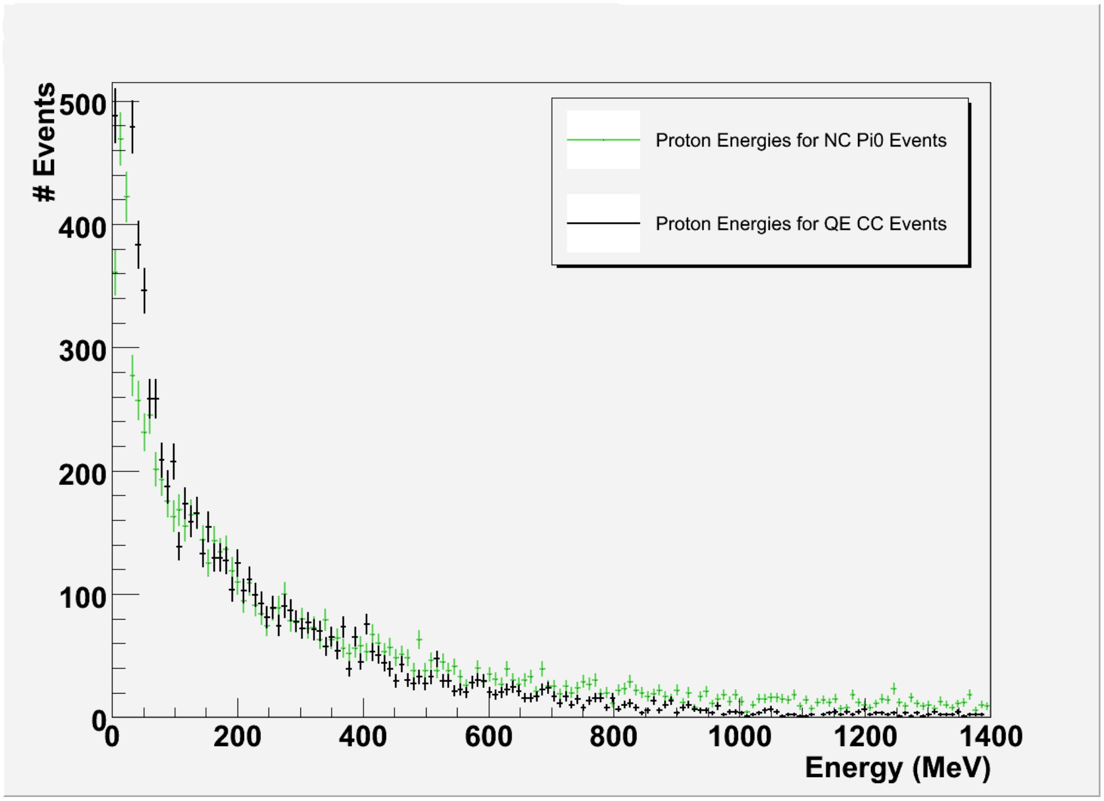

Figure 4: Proton Energies

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