ELECTRONS FOR NEUTRINOS: LEPTON ENERGY RECONSTRUCTION IN THE RESONANCE REGION

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Neutrino oscillation is of particular interest to experiments around the world. The oscillation of the neutrino is measured as a function of the particle's energy divided by propagation distance. This energy (E), however, is not directly measurable and must instead be reconstructed from the momenta of particles knocked out during neutrino-nucleus interactions. In order to test this energy reconstruction, we exploited the similarity between electron-nucleus and neutrino-nucleus interactions using electron-nucleus scattering data collected by the large-acceptance CLAS6 detector at the Thomas Jefferson National Accelerator Facility. This presentation will focus on the resonance-dominated 1p1pi channel and we will present results on pi+ and pi- and compare them to Genie calculations. This data will be used to guide improvements in current event generators which are important to meet the requirements of high-precision experiments currently underway at facilities such as MicroBooNE, MINERvA, DUNE, and T2K.

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1. INTRODUCTION

Neutrinos are small neutral fermions that arise due to the beta decay of free neutrons or the positron decay of protons [1]. Neutrinos are of non-zero mass and exist in three "flavor" eigenstates: ν_τ, ν_μ, ν_e. As they propagate through space they oscillate between these flavors. The mass eigenstate of a neutrino is separate from its flavor eigenstate in that the flavor of a neutrino is a superposition of the three possible mass eigenstates of a neutrino. That is to say that a neutrino of mass eigenstate m_1 does not necessarily mean that it is an electron neutrino ν_e.

The probability of a neutrino oscillating from one flavor eigenstate to the next is given by:

$$P(\nu_\alpha \longrightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(\Delta m^2 \frac{L}{4E}) \tag{1}$$

where $\Delta m^2 = m_1^2 - m_2^2$, and m_1, m_2 are the two mass eigenstates of the neutrino and θ is the mixing angle between the two flavor states [2].

Neutrinos are created during the nuclear decay of nucleons such as protons and neutrons. This decay is governed by the Charged Current Weak Interaction, which is mediated by the exchange of W^- and W^+ bosons. Upon its initial creation, the neutrino is in a pure flavor state. However, during travel, the neutrino becomes a mixture of its three flavor states. The probability of oscillation from one state to another depends on both the energy and the propagation distance of the neutrino [2]. However, since the incident energy of the neutrino cannot be directly measured, it is important for experiments to reconstruct it to determine the mixing angles and mass splitting of the neutrino.

2. BACKGROUND

Neutrinos arise as a product of nucleon decay through the process of the Charged Weak Current Interaction. The simplest reaction illustrating the creation of a neutrino is represented by the following:

$$n_0 \rightarrow p^+ + \beta^- + \nu_- \tag{2}$$

In this reaction, a neutron n_0 decays into a proton p^+, beta particle β^-, and a neutrino - represented by ν_-. The first detection of the neutrino was published by Frederick Reines and Clyde Cowan in 1956. Reines and Cowan detected the neutrino from this beta decay process using a nuclear fission reactor as a neutrino source and large water tanks as neutrino detectors. This experiment determined the neutrino's cross-sectional area to be only $6.3 \times 10^{-44} cm^2$ [1]. This very small cross-section is a reflection of the neutrino being a very weakly interacting particle, which interacts solely through weak nuclear interactions and gravity only.

The neutrino is an elementary particle contained within the Lepton family. It occurs in three flavors: e, τ, and μ. Each flavor of neutrino is a superposition of three mass eigenstates: m_1, m_2, and m_3. Neutrinos oscillate between their three flavor states as a function of their incident energy, E, and their propagation distance, as discussed previously. However, the incident energy cannot be directly measured. To overcome this energy reconstruction methods based on phenomenological models of neutrino-nucleus interactions are used to estimate the incident energy, E. Without the reconstruction of E, the nature of neutrino oscillations cannot be measured or studied [3]. As such, experiments must be designed to reconstruct the incident neutrino energy to determine the mixing angles and mass splittings required for the study of neutrino oscillation.

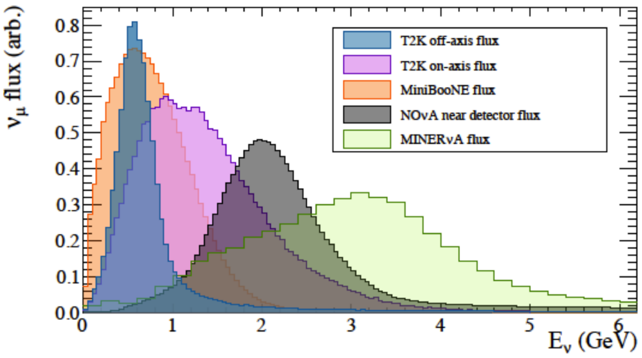

FIG. 1: Energy Distribution of Neutrino Experiments.

3. MOTIVATION

Neutrino oscillation is one of the few phenomena that cannot currently be described by the current standard model of Particle Physics [3]. Because of this, neutrino oscillation is of particular interest to scientists. Specifically, experiments such as the Deep Underground Neutrino Experiment (DUNE, USA) and Hyper-Kamiokanda (HK, Japan) seek to study the oscillation of neutrinos using energy reconstruction methods to determine the incident energy [3].

These experiments produce neutrinos using proton beams. Protons are accelerated to high energies and are allowed to collide with a target, resulting in the production of mesons such as pions and kaons that then decay into neutrino and antilepton or antineutrino and lepton [4]. The DUNE experiment makes use of horns that filter out positive or negative mesons to select particles that will decay into neutrinos or antineutrinos. Thus the beam produced must operate either in neutrino mode or antineutrino mode [5]. The beam passes through a large absorber, such as lead, until charged particles are stopped - leaving a pure neutrino beam [4].

Since neutrino beams do not consist of a single energy and are instead a spread of energies the incident neutrino energy cannot be directly measured. Figure 1 shows the energy spreads for several neutrino experiments.

When the neutrino interacts with a nucleus the resulting emitted particles can be detected and measured. Using the outgoing particles' momenta, identities, and energies the neutrino energy can be reconstructed. Neutrino energy is reconstructed in one of two ways: the calorimetric method and the Cherenkov method.

The first of these two methods, the calorimetric method, use the energies of all of the final state particles to obtain the incident neutrino energy. In this method, all of the energies are summed to give the initial neutrino energy. This method is used for calorimetric experiments. There are two types of calorimetric experiments: ionization-based and scintillator-based. In both types of experiments, the detected energy of all charged final state particles is summed to obtain the final reconstructed energy. The DUNE experiment uses liquid argon in an ionization-type calorimetric experiment to measure the energies of the final state particles (such as knocked-out electrons) [5].

Cherenkov experiments use heavy water, or mineral oil, as the detector. When traveling through a medium such as heavy water, some particles travel faster than the speed of light. This results in the emission of Cherenkov radiation - or rings of light. When a neutrino interacts with a nucleus in this medium, various particles are emitted - which travel faster than the local speed of light. This results in the production of Cherenkov radiation and it is detected by photodetectors inside of the detectors. However, one drawback of this technique is that it is limited to very light particles [6]. This is because only light particles such as electrons, muons, and pions can travel fast enough to emit Charenkov radiation.

For experiments such as DUNE and HK (Hyper Kamiokande), a high level of precision is required. Specifically, oscillation probabilities are required to be measured with an accuracy of 10% or better[7]. However, previous analyses of the energy reconstruction in the one-proton, zero-pion channel of electron scattering experiments show the need to improve current phenomenological models of the neutrino to reach the required precision. Specifically, there is a bias in the energy reconstruction as a result of a discrepancy between data and the phenomenological model. Only a small portion of events reconstruct accurately to the true incident energy[3]. As a result, a more rigorous test of current energy reconstruction methods is required to improve our understanding of neutrino oscillations. Figure 2 shows this large discrepancy between the phenomenological mode: GENIE's prediction and actual data.

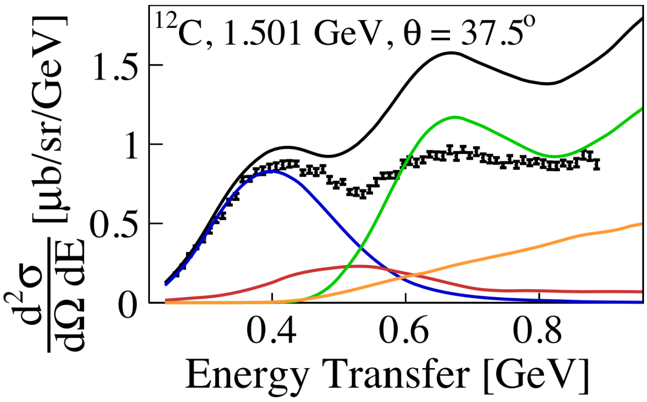

FIG. 2: Comparison of inclusive $C(e, e')$ scattering cross sections for GENIE. Black points are data, the solid black line is GENIE prediction, and colored lines are contributions of different reaction mechanisms: blue - quasielastic scattering, red - meson exchange, green - resonance, and orange - deep inelastic scattering. [8]

4. EXPERIMENT

This study analyzes Jefferson Lab Hall-B e2a experiment data from April 15 to May 27, 1999. This data was collected at several targets and beam energies. A table of the targets are provided below in table I.

Target	Length [cm]	Density [g/cm^3]	Density * Length [g/cm^2]
^{3}He	4.13	0.067	0.277
^{4}He	3.72 - 4.99	0.125	0.465 - 0.624
^{12}C	0.1	1.786	0.179
^{56}Fe	0.015	7.872	0.118
CH$_2$	0.07	1.392	0.097

TABLE I: Target Lengths and Densities

The data was collected at 4.461 GeV and 2.261 GeV with torus current equal to 2250 A. Beam current varied from 3 to 18 nA [9]. The e2a experiment was conducted at Thomas Jefferson National Accelerator Facility (JLab). This is located in Newport News, Virginia. Targets of ^{12}C and ^{56}Fe have been used in this analysis. The experiment used the CEBAF Large Acceptance Spectrometer (CLAS) to measure the momentum and particle type of the final state particles. Figure 3 shows a mock-up of the CEBAF Large Acceptance Spectrometer (CLAS).

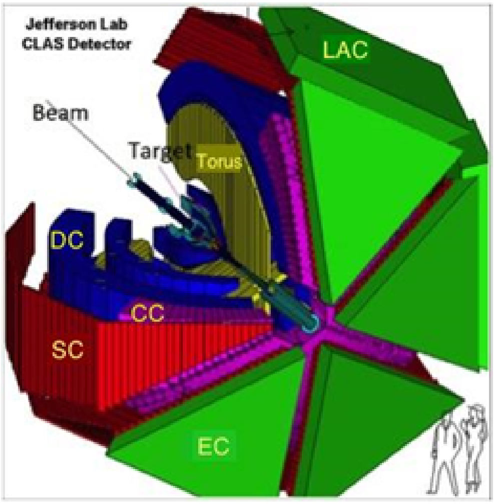

FIG. 3: The CEBAF Large Acceptance Spectrometer

5. RECONSTRUCTION METHODS

Previous analyses focused on events with one proton and zero pions [3]. These events predominantly arise from the quasi-elastic scattering of the nucleus. If the neutrino does scatter quasi-elastically, the energy can be reconstructed as:

$$E_{QE} = \frac{2M_{N\epsilon} + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l \cos\theta_l}) \tag{3}$$

where ϵ is the average nucleon separation energy, M_N is the mass of the nucleon, and $(m_l, E_l, k_l, \theta_l)$ are the lepton mass, energy, momentum, and scattering angle [3].

In the $1p1\pi$ case, the focus of this analysis, there are two energy reconstruction methods used. The first is called the calorimetric method. This is the primary method used for the purposes of this study. In this method, the energy of all final state particles is summed to reconstruct the incident lepton energy. It is given by the equation:

$$E_{cal} = \sum E_i + \epsilon \tag{4}$$

where E_i is the detected particle energies and ϵ is the average binding energy. In the case of the $1p1\pi$ channel, the equation may be rewritten as:

$$E_{cal} = E_l' + E_\pi + T_p + \epsilon \tag{5}$$

where E_l' is the energy of the outgoing lepton, E_π is the energy of the outgoing pion, T_p is the kinetic energy of the outgoing proton, and ϵ is the binding energy. In the case of this research, the outgoing lepton is the electron scattered from the collision.

This method is used in calorimetric-detector-based neutrino experiments. While this is the most straightforward method used, it is limited by the acceptance of the detectors used. Detectors may not be sensitive to certain types of particles and may exclude some of the final state particles.

The second method of reconstructing the incident energy is known as the kinematic method. This method only requires knowledge about the outgoing lepton, in this case - the electron. This is given by the equation:

$$E_{kin} = \frac{2(m_p - \epsilon)E_l' + m_\Delta^2 - (m_p - \epsilon)^2 - m_l^2}{2(m_p - \epsilon - E_l' + |k_l'| \cos\theta_l)} \tag{6}$$

where m_Δ^2 is the mass of the delta-resonance state of the lepton, m_p is the mass of the proton, ϵ is the binding energy, E_l' is the energy of the outgoing lepton, $|k + l'|$ is the momentum of the lepton, and θ_l is the scattering angle of the lepton [10].

If the recoil momentum and energy of the nuclear system are reduced to a constant we resolve the quasi-elastic reconstruction of the neutrino:

$$E_{QE} = \frac{2M_\epsilon - m_l^2 + 2ME_l}{2(M - E_l + |k_l| \cos\theta_l)} \tag{7}$$

This method is used in Cherenkov detectors, which cannot detect nucleons. However, if the lepton scatters non-quasi-elastically, the kinematic reconstructed energy will be incorrect. Because of this, and the assumptions asserted in the use of this method, it is much less accurate than the calorimeter method.

This analysis uses a calorimetric reconstruction of the incident lepton energy to rigorously test current interaction models. This analysis exploits the similarities

Resonance	Decay Products
Δ^{++}	$p+\pi^+$
Δ^{+}	$p+\pi^0, n+\pi^+$
Δ^{0}	$p+\pi^-, n+\pi^0$
Δ^{-}	$n+\pi^-$

TABLE II: Decay products of Δ-resonance particles

between electrons and neutrinos and how they interact with nuclei. Electrons and neutrinos are both leptons with spin $\frac{1}{2}$. Electrons interact quasi-elastically via electromagnetic interaction through the exchange of virtual photons. This quasi-elastic scattering of an electron occurs when an electron is incident on a nucleus and a nucleon is knocked out with a final state consisting of the electron and the knock-out nucleon. Neutrinos interact via the Charged Current Weak interaction through the exchange of W bosons. These two interactions are very similar, and when weighted by the mott cross section, σ_{mott} electron scattering can be made very similar to neutrino scattering. This means that nuclear models for neutrinos can be tested using electron scattering data. This is convenient because electrons are more strongly-interacting and the incident energy of an electron is known in electron scattering experiments[2].

Leptons, such as neutrinos or electrons, during scattering, can also excite a nucleon to a delta-resonance state. There are four types of delta-resonance particles - all of which produce pions upon decay. This analysis focuses on the $1p1\pi$ channel and thus only Δ^{++} and Δ^0 particles are considered. Since electrons alone cannot create a Δ^{++} state by interacting with a nucleus, π^+ events are not expected to reconstruct accurately [11].

6. RESULTS AND CONCLUSIONS

Figure 4 show the result of the energy reconstruction for the C12 target and energy and for π^+ and π^-. In the case of π^- events energy, reconstruction is more effective. It should also be noted that energy reconstruction is less effective at higher beam energies and heavier nuclei.

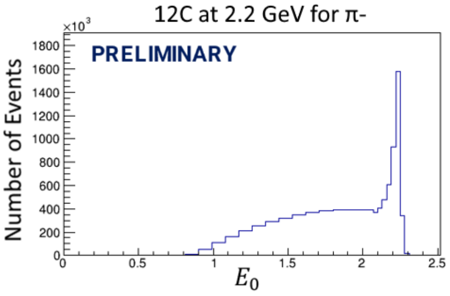

FIG. 4: C12 Target Energy Reconstruction at 2.2 GeV

Figure 5 show the result of subtracting extraneous events from the original $1p1\pi$ sample.

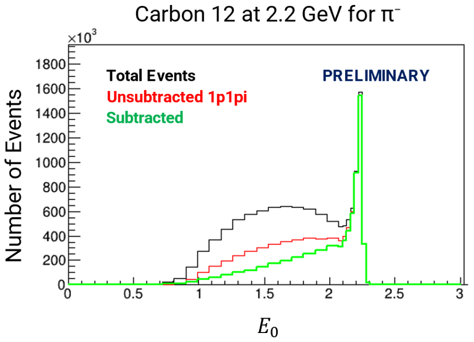

FIG. 5: Subtracting for extra events for C12 Target at 2.2 GeV

This paper demonstrates the use of electron scattering data in order to test energy reconstruction methods for $1p1\pi$ events. It also presents the rigorous testing of subtraction methods for undetected pions and protons to ensure a clean sample.

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