Nuclear Effects on Quasi-Elastic Reconstruction in Low-Energy Neutrino Long-Baseline Experiments.

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Uncertainties in neutrino-nucleus cross sections limit how well we can determine the true parameters of neutrino mixing in long-baseline experiments. Although the K2K experiment is presently limited by statistical error, future experiments like J-PARCnu will need to consider these effects.

1. INTRODUCTION

In the last five years a strong consensus has grown in the neutrino physics community that neutrinos have mass, and that their flavor states mix with each other. Strong evidence now exists from atmospheric neutrinos [1], solar neutrinos [2, 3], and reactor experiments [4]. In addition, the K2K experiment, which is the first of the new generation of long baseline neutrino oscillation experiments has begun [5]. The first results from K2K are consistent with the neutrino oscillation parameters found with atmospheric neutrino experiments [6].

The most compelling explanation for the atmospheric data is that we are observing $\nu_\mu \rightarrow \nu_\tau$ oscillations with a Δm^2 of $\approx 2 \times 10^{-3}$ and a $\sin^2 2\theta$ close to or equal to one. The goal of the long-baseline experiments is first to confirm this effect, and second to measure it to much higher precision including observing sub-dominant oscillations. For $\nu_\mu \rightarrow \nu_\tau$ oscillations in low-energy experiments(where in this context low-energy means $\approx 1GeV$) this is observed through the energy dependent disappearance of a beam ν_μ neutrinos.

The reason that the ν_μ beam seems to disappear and no tau neutrinos are observed to appear, is that low energy beams do not have enough energy to produce tau leptons in charged-current reactions. Greater than 3500 MeV of energy is required in order for the tau lepton to be produced.

2. WATER CHERENKOV DETECTORS AT 1 GEV

Water Cherenkov detectors like Super-Kamiokande [7] have been extremely successful as neutrino detectors. Water is an inexpensive target which also serves as Cherenkov radiator. However, because of the nature of the Cherenkov process not all particles produced in neutrino interactions are visible in a water Cherenkov detector. The momentum threshold for producing Cherenkov light in water is .6 MeV for electrons, 120 MeV for muons, and 1.1 GeV for protons.

So, in a low energy neutrino beam, while all electrons, and most muons are visible, most protons are not. Fortunately, if the reaction is charged current quasi-elastic(QE), the kinematics of the the event, and thus the incoming neutrino energy can be reconstructed using *only the energy and angle with respect to the beam of the produced lepton.* Equation 1 shows the relationship between the incoming neutrino energy and the reconstructed momentum of the produced lepton.

$$E_\nu = \frac{m_N E_\mu - m_u^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}, \tag{1}$$

Where m_N is the mass of the nucleon and θ_μ is the angle of the outgoing lepton with respect to the beam.

Water Cherenkov detectors are quite well suited to use neutrino beams with energies at or below $\approx$ 1 GeV because of this relationship. This is because, at energies less than 1 GeV, the cross-section is dominated by QE interactions. This is

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shown in figure 1 which is taken from [8].

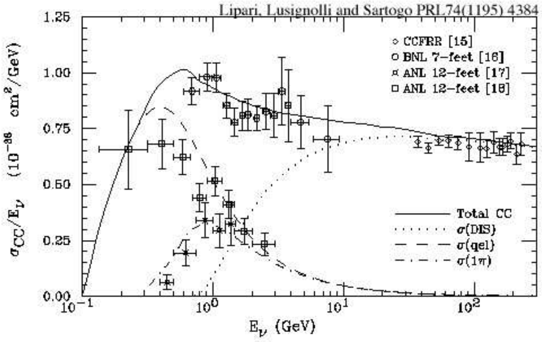

Figure 1. The neutrino-nucleon cross section as a function of neutrino energy. Below 1 GeV the cross section is dominated by QE interactions. For these interactions the neutrino energy can be reconstructed using only the outgoing lepton.

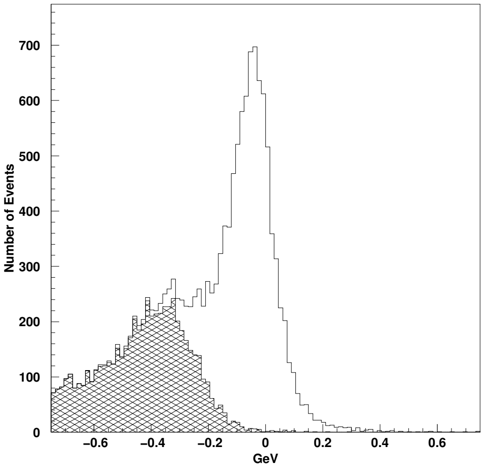

Figure 2. The difference in true and reconstructed energy for Super-K events using the K2K Monte Carlo. QE(open histogram) events are reconstructed properly, while non-QE(hatched histogram) have their energy systematically under underestimated.

3. THE EFFECT OF NON-QE INTERACTIONS

As was noted in section 2, QE reactions allow one to reconstruct the energy of the incoming neutrino even if all of the reaction particles aren't visible. It should be noted however that, in a real experiment, one cannot know a priori which events come from QE interactions and which come from non-QE interactions. If one uses equation 1 for all events, those events which are QE will reconstruct with the proper neutrino energy, while non-QE events won't. This is illustrated in figure 2, which is the difference between the reconstructed and true energy for events in Super-K using the K2K Monte Carlo. It is clear from the figure that those events which are not QE have their energies systematically underestimated.

Figure 3 shows the effect on mis-reconstruction on an oscillation experiment. The top panel shows the energy of Super-K events from the K2K beam MC with oscillations applied using the true energy of the MC for the axis. In this figure Δm^2 $= 3.0 \times 10^{-3}$ and $\sin^2 2\theta = 1$. As can be expected for $\sin^2 2\theta$ =1, the effect of oscillations is to suppress the flux of ν_μ neutrinos all the way to zero at about 700 MeV(which is the oscillation maximum at 3×10^{-3} and 250 km.).

The bottom panel shows what happens if the reconstructed energy is used instead. The non-QE events have their energy mis-reconstructed to lower energy. Since almost all of the non-QE events have energies greater than then where the oscillations take place, they are not suppressed, and they "fill in" the region of the oscillation signal. This effect is why, although the neutrino mixing can be maximal, the reconstructed energy spectra can still have many reconstructed events in the region of the oscillation dip.

For this reason, it is quite important to accurately model the fraction and shape of this non-QE "background". The parameter $\sin^2 2\theta$ de-

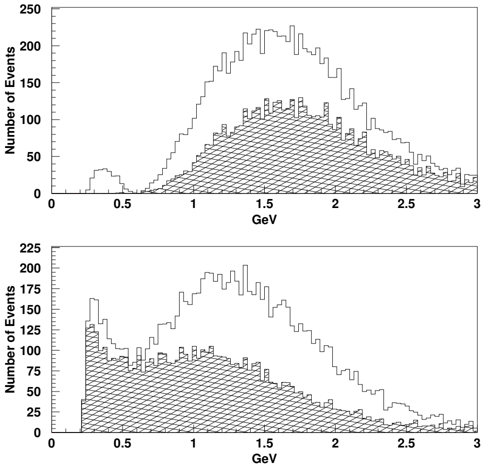

Figure 3. The top panel shows the Monte Carlo K2K spectrum at Super-K with oscillations applied. The oscillation dip at 700 MeV maximally suppresses the flux of ν_μ neutrinos. The non-QE interactions(hatched region) are unaffected by oscillations because their energy is too high. The bottom panel shows the same thing using reconstructed energy. The non-QE interactions "fill in" the oscillation dip.

termines the overall normalization of the oscillation suppression, with $\sin^2 2\theta$ =1 resulting in a complete suppression of the flux. If the amount of non-QE interactions is not-properly modeled, then the overall suppression in the oscillation region will not be modeled properly either, and the less than maximal suppression will be incorrectly interpreted as a $\sin^2 2\theta$ less than unity.

4. MEASURING THE QE FRACTION

For the reasons outlined above, it is important to verify the correctness of the neutrino-nucleus interaction models in the Monte Carlo that is used. Using a detector which is sensitive to all tracks including the produced proton it is possible to compare the MC expectation for the QE/non-QE fraction to data.

Measurements of cross section need to be made close to the source of neutrino production so that the neutrinos do not have a chance to oscillate. In long-baseline experiments this is done in the near detectors which are typically located a few hundred meters from the beam source.

In K2K this comparison has been done using the scintillating fiber(SCIFI) detector [9] which is part of the near detector complex at KEK. To do the comparison with the Monte Carlo expectation events are chosen in the SCIFI where a muon can be tagged and there is a second track which might be associated with a proton.

If the reaction is truly QE then, except for the nuclear effects, the kinematics is completely described. Momentum conservation allows us to predict the direction of the outgoing proton. In order to test whether the event actually is QE we compare the direction of the measured second track with that of the expected proton direction. In the case where the event was actually a QE event, and the outgoing particle is in fact a proton, the measured second track should have a direction very close to what is expected.

In the case where the reaction is not QE things are quite different. For example, if the reaction is single pion production and the second track is a pion with the proton not tracked, then the second track will not be traveling in the same direction as expected for the proton. Figure 4 illustrates this technique. In this figure the x-axis is the difference in angle between the expected and measured second track direction(delta theta). The QE events peak near zero degrees. The non-QE events peak away from zero degrees.

This technique can be used to test the correctness of the Monte Carlo's QE/nonQE fraction and also to determine how well the fraction has been determined. This systematic error is then directly used in the oscillation analysis as an uncertainty on the fraction of non-QE events.

5. INTERACTIONS IN THE NUCLEUS

When modeling neutrino interactions there are several nuclear effects which must be taken into account since, in water, the interactions mostly take place inside of a O^{16} nucleus.

For example, as is further explained in [10] in

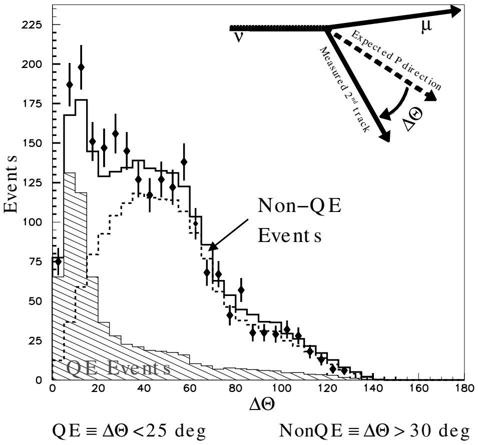

Figure 4. Delta theta distribution for two track events. Delta theta is the difference between the expected direction of the outgoing proton in a QE interaction and the measured direction of the second track. For true QE events the measured second track is a proton and delta theta is close to zero.

order to properly perform the analysis outlined in section 4 the nuclear re-interactions of the proton as it leaves the nucleus must be correctly modeled. As the proton scatters off of other nucleons while moving through the nucleus, it loses energy and changes direction. If this effect is not taken into account, both the number of found second tracks, and their reconstructed directions will not agree with the Monte Carlo.

There are several important effects to consider when calculating the neutrino interactions themselves. First of all there is Pauli blocking. If the produced proton does not have enough momentum to escape the Fermi sea then the interaction is suppressed. This tends to decrease the number of events observed at low Q^2. In this meeting we saw the effect of Pauli blocking for both QE scattering and resonant single pion production [11].

The fact that we are scattering off of nucleons and not point like particles must also be accounted for. The value that is chosen for the axial mass also changes the shape of the observed Q^2 distribution. The results of the K2K experiment are insensitive to these choices since the experiment is limited by statistics [6]. However, for future experiments such as J-PARCnu [12], where one hopes to measure Δm^2 and $\sin^2 2\theta$ at the 1% level, these effects cannot be ignored.

There are additional effects which should be taken into account in future analyses. For example, both previously and at this meeting [13, 14], it has been pointed out the the dipole approximation to the vector form factor is not adequate. New fits to electron scattering data for the vector form factors can change the expected cross section, and axial mass values extracted from scattering data by $\approx 2\%$.

Both the initial momentum distribution of the struck nucleons and the nuclear potential also need to be modeled properly. At this meeting [15] we saw the difference between measured spectral functions and the Fermi gas model used in almost all present neutrino Monte Carlos. Varying the nuclear potential and momentum distribution of the nucleons effects the momentum of the outgoing lepton. One useful technique to test our Monte Carlo models it to compare them with electron scattering data [16] at fixed energies and angles. In this case we are probing a fixed Q^2 transfer and the response should be very similar to neutrino scattering at that Q^2.

If the nuclear potential is not modeled at all there can be errors of $\approx$ 20-30 MeV in the outgoing lepton energy. This is a few percent effect in the oscillation formula. A quantitative study of the effect of this systematic error on oscillation experiments is yet to be done.

6. A TOY EXAMPLE

For this meeting, I performed a toy calculation to try to understand if differences in non-QE spectrum shape could effect the results of a oscillation analysis in a high statistics experiment like J-PARCnu. For this purpose I re-weighted the K2K Monte Carlo to be peaked around 700 MeV, with a shape reminiscent of that J-PARCnu beam [12]. This spectrum is show in figure 5. I generated MC with $\Delta m^2 = 3 \times 10^{-3}$ and performed an oscillation analysis on the shape of 1-ring muon-like events at Super-K using the K2K oscillation analysis tools.

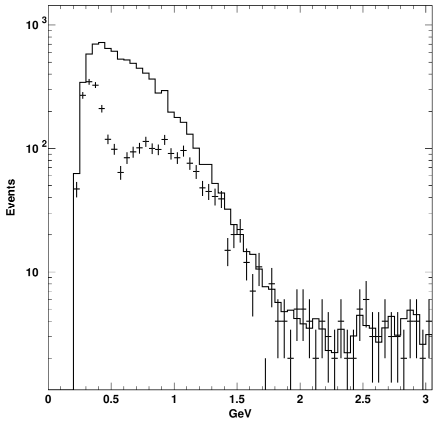

Figure 5. The neutrino spectrum used for the toy calculation. The solid line is the expectation without oscillation, and the data points are taken from the oscillated Monte Carlo.

As expected, the resulting allowed regions were on the order of 1%-2% in both Δm^2 and $\sin^2 2\theta$. I repeated the analysis, but this time used a different set of physical parameters for the oscillated Monte Carlo "data" then the Monte Carlo it was compared against in the oscillation analysis. Specifically, while the "data" had an axial mass of 1.1 and 1.2 for QE, and single pion production respectively the expectation had a axial mass of 1.0. The result of this 10 - 20 % shift in the true vs. presumed axial mass was a 1 - 2 % shift in the reconstructed $\sin^2 2\theta$. This shift is on the same order as the error on the parameter we expected without this effect.

The explanation for this effect is similar to that of section 3, where the normalization of the numbers of non-QE interactions was considered. In this case, only the shapes are being considered, but the differences in shape between the "data" and Monte Carlo in the region of the oscillation dip causes the fit to find a lower value of $\sin^2 2\theta$. This is demonstrated in figure 6.

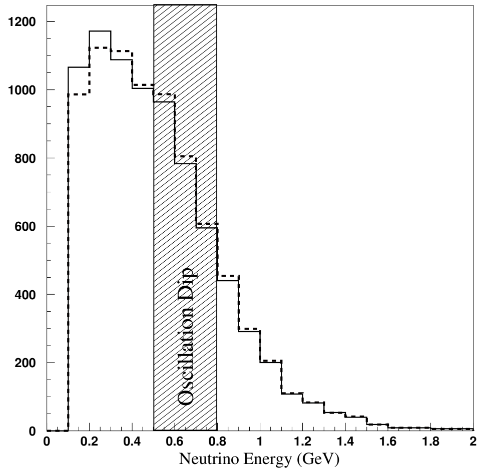

Figure 6. The shape of the non-QE part of the spectrum. The dashed line is the spectrum for the larger axial mass. In the oscillation dip region there are 2% more events than what we would expect if we had the correct axial mass. At higher energy there is no difference.

In this figure the non-QE part of the event spectrum is plotted both for the "data" (dashed-line) and Monte Carlo (solid line). In the region of the oscillation dip there are 2% more events in the "data" then what we expect for our Monte Carlo. In the region where no oscillation takes place there is no difference in the spectrum. Therefore, in order to fit the "data" a smaller $\sin^2 2\theta$ is found, since the non-oscillated spectrum does not need to be reduced as much to match the data.

This shows that varying nuclear parameters within their current errors can induce parameter shifts on the order of the sensitivity we are hoping to achieve. There are other analyses where shape of backgrounds will be potentially important. For example, the subtraction of the wrong sign background in the CP violation search at the second phase of J-PARCnu [17].

7. CONCLUSIONS

In the next generation long-baseline experiments we will no longer be dominated by statistical errors and will have to examine systematic errors in more detail. In particular, for experiments designed to work below 1 GeV, uncertainties involving the energy spectrum shape and size of non-QE interactions need to be studied further. Current uncertainties on the value of some quantities such as the axial mass may introduce errors as larger than hoped for sensitivity.

Fortunately, reducing the errors on these quantities to the necessary size seems well within our reach. New experiments to measure neutrino cross sections along with properly designed near and intermediate detectors at the long-baseline experiments themselves should assure us the sensitivity we all hope for.

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