K2K cross section results

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Abstract. This paper contains results from several cross section studies made using the near detectors in the K2K neutrino beam. These include an estimate of neutral current single π^0 production, an upper limit on the cross section for charged current coherent π^+ production, and an analysis of the axial vector form factor for quasi-elastic interactions.

1. Introduction

The neutrino experiments which have been running during the first half of this decade have accumulated hundreds of thousands of neutrino interactions at energies around 1 GeV. The K2K experiment was designed to study neutrino oscillation phenomena, but we have also used our high statistics samples to study neutrino cross sections. For K2K, these neutrino interactions occur on water (H_2O), scintillator (HC), and iron (Fe), and come from a beam that peaks around 1.2 GeV, and averages 1.3 GeV. In these proceedings, we summarize the results of three such cross section studies.

We are challenged to understand neutrino interactions in the region around 1 GeV because this is the energy of the expected oscillation signal for several neutrino oscillation experiments [1,2,3] as well as future neutrino oscillation initiatives. At the same time, it is the most complicated region for neutrino interactions: this is where quasi-elastic, resonance production, and deep inelastic scattering all contribute significantly. Finally, because of the difficulty in designing beams and detectors for these energies, previous experimental measurements have significant uncertainties in the cross sections. By necessity, neutrino oscillation experiments at these energies must make their own measurements and arrange their experiments to minimize these uncertainties.

The K2K near detectors were designed to measure the features of the neutrino beam right after it was produced. The spectrum of neutrinos at the far detector can then be compared to the near detector spectrum to observe the characteristic distortion caused by neutrino oscillations. From upstream to downstream, the near detector system consists of a 1000 ton water Cerenkov detector (1kT), a scintillating fiber detector which uses tanks of water as a target (SciFi), a fully active plastic scintillator detector (SciBar), and a muon range detector (MRD).

The 1kT detector is designed to be a small scale version of Super-Kamiokande, in order to partially cancel systematics due to the Cerenkov technique and uncertainties in the neutrino-water interactions. The SciFi also uses water as the primary neutrino interaction target, but its fine grained design and the use of the MRD to get muon momentum from range give it sensitivity to higher energy neutrino interactions and yields different information about those reactions than the 1kT. The SciBar works on the same principle, but uses a fully active scintillator design, and is even more sensitive to the protons and pions that come out of the interaction.

These detectors took data in several running periods between 1999 and 2004 in the K2K neutrino beam, though, for technical reasons, the analyses below use data from different portions of this run time. This beam is produced when 12 GeV protons are extracted from the proton synchrotron at the KEK accelerator in Tsukuba, Japan, and bent toward the Super Kamiokande detector. A proton spill 1.1 μs wide hits an aluminum target every two seconds. Among the resulting hadrons, the π^+ are focused into a decay region filled with helium where they decay to μ^+ and ν_μ. The muons and undecayed pions are absorbed by earth, while the neutrinos continue to the near detector hall, 300 meters from the target, and eventually to Super Kamiokande, 250 km away. The resulting neutrino beam is 98% pure ν_μ.

More details about the experimental setup, with additional specifications and references, are available in [1].

2. Neutral current single π^0 production in the 1kT detector

This study is described more completely in Ref. [4]. The 1kT detector has excellent ability to observe and reconstruct the π^0 interactions. The neutral pions decay to two gamma rays, each of which initiate an electromagnetic shower. These appear in the detector as two electron-like Cerenkov rings, but no visible muon. In addition, any recoil proton will nearly always be below threshold as well. From the two Cerenkov rings, it is possible to estimate the implied invariant mass and select a sample of candidate π^0 events.

This measurement is of the neutral current single π^0 production. It includes as signal neutral pions from resonance production events, coherent production, as well as from deep inelastic scattering events in which only one neutral pion was produced. In the context of this measurement, it is the outgoing pion, after intranuclear processes such as charge exchange and absorption have occurred. The signal, after selections, is expected to be about 70% of the total sample. The backgrounds to these processes are from charged current interactions in which the muon is not seen, as well as from multi pion production in which the other particles are below detection threshold.

Starting from this sample, we estimate the detection efficiency for the signal, and make the appropriate calculation. Also, we use the Monte Carlo to estimate the background, and subtract it. After these corrections, the measurement for NC single π^0 interactions yields (3.61 $\pm$ 0.07 stat. $\pm$ 0.36 syst.) x 10^3 events in the 25 ton fiducial volume. We form the ratio with all muon-like (i.e. charged current) interactions observed in the same samples: (5.65 $\pm$ 0.03 stat. $\pm$ 0.26 syst.) x 10^4 events.

Thus, the measured neutral current single π^0 ratio at an average neutrino energy of 1.3 GeV is 0.064 $\pm$ 0.001 stat. $\pm$ 0.007 syst. This can be compared to the ratio predicted from our Monte Carlo which is 0.065. Systematic errors dominate; they come from model errors (DIS model 5.6%, NC/CC cross section 3.2%) which affect the background subtraction. The two largest detector uncertainties are in identifying and counting Cerenkov rings (5.4% uncertainty in the ratio) and the separation of electron-like and muon-like Cerenkov rings (4.2%). There is an additional uncertainty in the denominator of the ratio of 4%, which comes from the interplay between vertex reconstruction and the definition of the fiducial volume.

3. Charged current coherent pion production in the SciBar detector

Another study we have done is a search for charged current coherent pion production in the SciBar plastic scintillator detector. This study was reported in [5]. In coherent production, the neutrino interacts coherently with the nucleus as a whole, rather than with an individual nucleon. For the charged current reaction on carbon $\nu_\mu + C \rightarrow \mu^- + C + \pi^+$, no recoil nucleon is present, so the only observable products are the charged pion and the muon. This interaction is characterized by very forward going muons, equivalently a small momentum transfer. These final states, with little or no other activity at the vertex of the interaction, combined with the kinematics, give a signature that can be isolated in the SciBar detector data.

One motivation for looking at this reaction is that the K2K experiment, among others, had observed that our Monte Carlo over-predicts the number of events at very low square of the momentum transfer Q^2, which for our beam energies correspond to muons at very forward angles or the lowest energies. In principle this discrepancy could come from any of the relevant interactions, such as quasi-elastic, or resonance production events. It could be something fundamental to the neutrino-nucleon cross section, or to the application of nuclear effects such as Pauli blocking. However, since coherent production always happens at low momentum transfer, this offers a unique probe of this discrepancy.

The first step in isolating coherent pion enhanced samples is to make a subsample of events which have two tracks. This sample can be further divided into quasi-elastic enhanced and non-quasi-elastic enhanced subsubsamples. Because quasi-elastic interactions are a two-body scattering process, it is possible to use the muon angle and momentum to predict the angle at which the recoil proton should be found. If the observed second track matches this prediction, within 25 degrees, it is likely to be QE. If it does not match, then it is likely to be a proton or pion from a resonance, coherent, or DIS interaction.

Because of the fully-active design of the SciBar scintillator detector, it is possible to identify the products of the interaction. For a charged current coherent interaction, there should be a muon and a π^+, but there should be no recoil nucleon. The muon is easy to identify from its long range, and second tracks can be identified as a proton or pion from the dE/dx at the end of the track. In this way, the non-quasi-elastic subsample is further divided into samples where that second track is proton like or pion like.

This latter sample can be further examined. Because nothing comes out of the nucleus in a coherent interaction, there should be little or no vertex activity apart from the two tracks. For ordinary two-track interactions, there is often another particle present: a recoil nucleon or pion. A cut on this feature further purifies the CC coherent sample.

Finally, we estimate the reconstructed Q^2 of this interaction. Actually, this is done using the quasi-elastic kinematic assumptions, so the reconstructed Q^2 does not exactly correspond to the correct momentum transfer, but it gives a method to treat the data and the Monte Carlo the same without knowing the underlying interaction kinematics, so that they data and MC may be compared. We select events with reconstructed $Q^2 < 0.1$ (GeV/c)^2. We again take the ratio to all the CC events and obtain $\sigma_{\mathrm{CCcoh}\pi}/\sigma_{\mathrm{AllCC}} = (0.04 \pm 0.29 stat.^{+0.32}_{-0.35} syst.) \times 10^{-2}$. This is consistent with zero CC Coherent Pion production.

Because the value is consistent with zero, we compute an upper bound on the CC coherent pion cross section. Again, relative to all CC events: $\sigma_{\mathrm{CCcoh}\pi}/\sigma_{\mathrm{AllCC}} < 0.60 \times 10^{-2}$ at 90% C.L. This is approximately 30% of the former Rein and Sehgal prediction [6]. It is important to note that this bound is set by two large systematics: the cross section for resonance pion events (including Pauli blocking effects) and the model for pion reinteractions in carbon. It is possible that the observed Q^2 distribution is a combination of unexpectedly small coherent cross section and an overestimation of resonance production due to one or both of these systematic effects.

Since the original publication of this result, there has been a renewed look at the very low Q^2 cross section calculations. Of principle interest is the inclusion of terms that depend on the muon mass in the calculation, which suppress the cross section below $Q^2 < 0.2$ GeV/c for interactions that produce π^+, including coherent production. In a very recent paper, Rein and Sehgal [7] give a discussion of the size of this effect, not included in their original publication. We have not yet quantified how this recent work impacts the interpretation of these data.

4. Axial vector form factors in the SciFi detector

Our final topic summarized in these proceedings is a study of quasi-elastic interactions measured by the SciFi detector. A full description of the technique and results can be found in [8].

Quasi-elastic interactions, $\nu_\mu + n \rightarrow \mu^- + p$ are the simplest kinematics available. This is a two-body scattering process, which means that the muon momentum and angle are sufficient to reconstruct the details of the interaction. In our analysis we take advantage of this to get an estimate of the incident neutrino energy E_ν, the square of the momentum transfer Q^2 to the nucleon, and a prediction for the angle of the recoil proton.

The expected cross section can be calculated following Llewellyn-Smith [9]. The interesting feature of this calculation is that it involves vector form factors and other constants that are relatively precisely determined from electron scattering data and neutron decay. In this analysis, we assume the axial vector form factor can be approximated with a dipole form which has only one free parameter, and fit to find the value for this parameter, the axial vector mass M_A, that best matches the data.

The parameter M_A has two effects on the cross section. A 10% larger value increases the QE cross section by about 10%. However, uncertainties in absolute normalization of the flux for this experiment are significant. Instead, the fit we will do is a fit to the shape of the Q^2 distribution. In this case, a 10% larger value of M_A produces a shape that is flatter, has relatively more high Q^2, high θ_μ events.

The SciFi detector is made of aluminum tanks filled with water. In between these tanks are scintillating fiber tracker. Thus, the neutrinos are incident primarily on H_2O, but 22% (by mass) of the material is Al, and 8% is plastic. In our interaction model, neutrino quasi-elastic interactions can only occur on neutrons, changing them to protons; there is no allowed final state for the CC interaction on hydrogen. In this sense, we consider our result to be a measurement of the effective M_A for oxygen. Because of the fiber tracker design, this detector has outstanding angle resolution for tracks that go three or more layers.

As with the SciBar samples in the previous section, we separate events into samples with one track, two tracks where the second track matches the QE assumption, and a two-track sample that is non-QE enhanced. The SciFi detector does not have strong capability to differentiate protons from pions via dE/dx, so that additional cut is not used. We further concern ourselves with the low Q^2 discrepancy, as above. Regardless of the source of the discrepancy, resonance production or coherent production cross sections, or Pauli blocking, or another nuclear effect, we disregard all events with reconstructed $Q^2 < 0.2$ $(\mathrm{GeV/c})^2$.

Another feature of the analysis is that we are using the updated vector form factors from electron scattering data [10,11]. Changing this part of the cross section calculation has a significant effect on the shape, and thus affects the M_A parameter extracted from fits to this shape.

We then divide the data into five energy regions and bin it by Q^2. We fit the entire collection of samples. Because this includes the non-QE enhanced sample, the fit will constrain the size of the non-QE background in the one-track and the two-track QE samples. In the end, we obtain a fit value of $M_A = 1.20 \pm 0.12$ GeV, with a $\chi^2 = 261$ for 235 degrees of freedom. Our default MC uses a value of $M_A = 1.1$, so the data prefer a flatter Q^2 spectrum than the MC.

We have investigated several systematic errors, and have a couple interesting conclusions. First, nuclear effects that are understood at this time seem to have a small effect on the shape of the Q^2 distribution. However, the muon momentum scale has a very significant effect on the measurement. Its contribution to this measurement is $M_A \pm 0.07$ GeV. How this is constrained is described in more detail in [8], but can be roughly simplified to an unknown potential bias of $\pm$ 1.5% in the reconstructed muon momentum. A small bias has a large effect on the shape of the Q^2 distribution, stretching or compressing it significantly. The final uncertainty is from the relative flux and normalization of the neutrino beam, which is included in the fit as a sequence of five unconstrained parameters.

Though most of these QE interactions occur on oxygen, it is relevant to compare this result to measurements on deuterium from bubble chamber experiments [12,13,14]. In order to make this comparison, it is easiest to reproduce their assumptions about the vector form factors and other constants. The resulting fit value is higher: $M_A = 1.23 \pm 0.12$. The bubble chamber measurements, which were also primarily shape fits, are usually taken together and give $M_A = 1.03 \pm 0.03$. These two values agree at about the two-sigma level, though there is no expectation that they should be the same. One other comment: because these results were obtained primarily through shape fits, consumers of neutrino interaction generators should be very cautious when assigning an uncertainty in M_A. The small error from a shape fit may hide a larger error in the absolute cross section, and it is the latter that is relevant for most oscillation analyses.

5. Oscillation measurements

At the Neutrino 2006 conference, we are also pleased to present the final oscillation results from the K2K oscillation analysis. Compared to the previous published results [15], these results include small changes to the Super Kamiokande reconstruction and the inclusion of information from the HARP measurement of the hadron production off the K2K target [16]. The K2K best fit result in the physical region is at $\Delta m^2 = 2.8 \times 10^{-3}$ (eV)^2 and maximal $\sin^2 2\theta = 1$. The 90% confidence contour crosses the maximal mixing line at $\Delta m^2 = 1.9 \times 10^{-3}$ and 3.5×10^{-3}. In addition, a full paper with extensive description of the experiment, analysis, and results is now published [1]. Another paper describing the upper limits on ν_μ to ν_e oscillation obtained from an electron neutrino appearance search is also available [17].

6. Conclusion

The K2K experiment has completed a program to measure neutrino oscillations, but also to make measurements of neutrino interactions on nuclei. These measurements, combined with upcoming cross section results from MiniBoone, MINOS, and later SciBoone and MINERvA, will be vital to the continuing program to understand neutrino mixing and its implications for particle physics, astrophysics, and cosmology.

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