

Low Energy Neutrino Cross Sections from K2K, MiniBooNE, SciBooNE, and MINER ν A

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Abstract. The advent of intense accelerator-based sources of neutrinos and the demand of neutrino oscillation experiments to more precisely determine signal and background rates in their detectors has precipitated a resurged interest in low energy neutrino interactions. Such measurements have not been updated for decades, having first been measured in bubble and spark chamber experiments. New measurements are sorely needed and yield important constraints for present and future neutrino oscillation experiments operating in this few-GeV energy range. This paper reviews the status of current and planned low energy neutrino cross section measurements from the K2K, MiniBooNE, SciBooNE, and MINER ν A experiments.

1. Introduction

The recent development of intense accelerator-based neutrino sources for oscillation searches has necessitated and enabled the exploration of low energy neutrino interactions. This few-GeV energy region is particularly interesting both for its richness and complexity. Figure 1 shows a collection of the world's existing charged current (CC) neutrino cross section data.

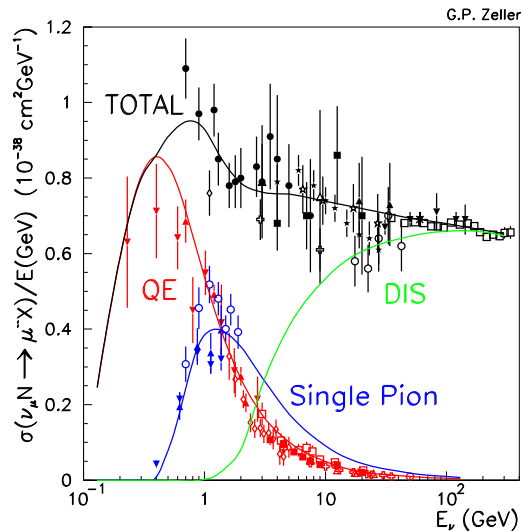


Figure 1. Isoscalar CC neutrino cross sections divided by energy as a function of neutrino energy. QE, resonant single pion, and DIS data is shown from a variety of past experiments [1] along with the prediction from the NUANCE event generator [2].

At energies below a few GeV, neutrino interactions arise from a variety of sources. They are predominantly quasi-elastic (QE) and resonant single-pion production processes, though

deep inelastic scattering (DIS) interactions also begin to contribute at these energies. Present-day atmospheric and accelerator-based neutrino oscillation experiments operate in this complex energy range where they rely on knowledge of the contributing neutrino cross sections. Historically, cross sections in this regime have not been as well measured as the DIS reactions that fully dominate at higher neutrino energies. Our current few-GeV knowledge originates mainly from bubble chamber, spark chamber, and emulsion experiments that collected their data decades ago [1]. Such measurements typically suffer from poor statistics and large neutrino flux uncertainties; nonetheless, they offer an important and necessary constraint on model predictions in present use. The situation is quickly changing with the emergence of new, high statistics neutrino (and antineutrino) data samples from K2K, MiniBooNE, and SciBooNE, along with the anticipation of future data from MINER ν A. These proceedings describe the current programs at all four experiments. Table 1 compares their general attributes, for reference.

Table 1. Comparison of various attributes of the K2K, MiniBooNE, SciBooNE, and MINER ν A experiments.

| experiment | $\langle E_\nu \rangle$ | ν target(s) | detector | run period |
|---------------|-------------------------|--|-------------------------|--------------|
| K2K | 1.3 GeV | C ₈ H ₈ , H ₂ O | Čerenkov & fine-grained | 1999-2004 |
| MiniBooNE | 0.8 GeV | CH ₂ | Čerenkov | 2002-present |
| SciBooNE | 0.8 GeV | C ₈ H ₈ | fine-grained | 2007-2008 |
| MINER ν A | 4.2, 5.7, 6.1, 8.5 GeV | He, CH, C, Fe, Pb | fine-grained | 2009+ |

While outside the scope of this talk, the author acknowledges that both the NOMAD and MINOS experiments will complement the situation by adding neutrino cross section results in the few-GeV range on carbon and iron targets, respectively, in the near future.

2. K2K

The K2K experiment was not only the first experiment to verify the evidence for neutrino oscillations previously observed by the Super-K experiment, but was also the first to publish updated neutrino cross section measurements in the 1 GeV energy range. Operating in a 1.3 GeV ν_μ beam produced by the interaction of 12 GeV protons on an aluminum target at KEK, K2K collected a host of unoscillated neutrino data using a suite of near detectors. These measurements were of immediate utility, serving as important input to the analysis of neutrino oscillation samples at the K2K far detector site [3]. The K2K near detector ensemble consisted of a 1 kton water Čerenkov detector, a scintillating fiber water target tracker (SciFi), a fully active solid scintillator tracker (SciBar), and a muon range detector (MRD). In this way, neutrino interactions on both carbon and oxygen-based targets could be studied. K2K has previously published several results from these detectors. They include the first measurement of neutral current (NC) π^0 production in water [4], the first measurement of the axial mass (M_A) in QE interactions in water [5], and the first search for CC coherent π^+ production at low energy [6]. Despite the fact that K2K completed their neutrino data taking in late 2004, the experiment continues to produce new and valuable neutrino interaction results. Three such results were discussed at this conference.

The first is a recent measurement of CC π^0 production in carbon, the first time this reaction channel has been revisited in over 20 years. Based on a sample of 479 CC π^0 events collected in the SciBar detector, K2K has extracted a preliminary measurement of the ratio of the CC π^0 /QE cross section = 0.306 ± 0.023 (stat) $^{+0.023}_{-0.021}$ (syst), which they also report as a function of

energy [7]. While the K2K measurement agrees well with prediction at low energy, it begins to depart from expectation above $E_\nu \sim 2$ GeV. Because the K2K sample is dominated by multi-pion production processes at these higher energies, a process which has not been well measured historically [1], it offers a rare glimpse into this reaction channel. The results already hint at the inadequacy of multi-pion predictions in present use. This will be important to further investigate utilizing the expanded energy reach of the MINER ν A experiment, which will be able to probe multi-pion production in low energy neutrino interactions in more detail.

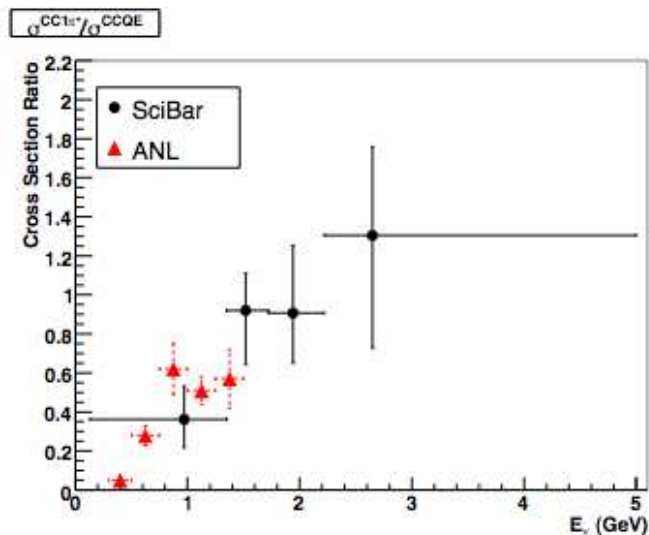


Figure 2. Measurement of the CC π^+ /QE cross section ratio on C_8H_8 from K2K, corrected for final state effects and an isoscalar target, shown plotted with a previous measurement on deuterium from the ANL 12-foot bubble chamber. Plot from [8].

The second K2K result is a new measurement of the CC π^+ /QE cross section ratio in C_8H_8 [8]. Based on a fit to four data samples containing ~ 5600 QE and ~ 2900 CC π^+ events collected in the SciBar detector, K2K reports a flux-integrated CC π^+ /QE cross section ratio of 0.734 ± 0.086 (fit) $^{+0.076}_{-0.103}$ (nucl) $^{+0.079}_{-0.073}$ (syst). K2K also reports the cross section ratio as a function of neutrino energy (Figure 2) and finds the measurement to be consistent with past results from the ANL 12-foot bubble chamber. The K2K result is a 20% measurement and the first published measurement of such a ratio on carbon.

The third result from K2K is a new measurement of the axial mass on carbon from the analysis of QE events collected in the SciBar detector. The result, $M_A = 1.14 \pm 0.11$ GeV [9], is consistent with the previously published result on water from the K2K SciFi detector, $M_A = 1.20 \pm 0.12$ GeV [5]. The overall implications of these findings will be discussed in the next section, in the context of similar results from the MiniBooNE experiment.

3. MiniBooNE

The optimization of MiniBooNE's neutrino beam for the direct search of LSND-like oscillations also makes the experiment particularly well-suited for investigations of low energy neutrino interactions. Starting with an 8 GeV proton beam, MiniBooNE operates both neutrino and antineutrino beams with mean energies of ~ 800 MeV. The experiment boasts record-sized samples of neutrino and antineutrino events in this energy range.

Using over 193,000 ν_μ QE events, MiniBooNE has adjusted the simple but widely-used Fermi-Gas model and found that it can describe the high statistics MiniBooNE QE data on carbon across the entire kinematic phase space. The fact that such a naive model could be tuned to yield such stunning agreement is somewhat surprising. MiniBooNE is also the first experiment to successfully describe QE data on a nuclear target at low Q^2 . This is accomplished with a two

parameter fit, with M_A fixing the agreement between data and prediction at high Q^2 and κ (a parameter used to adjust the level of Pauli blocking in the Fermi Gas model) fixing agreement at low Q^2 . MiniBooNE finds fit values of $M_A = 1.23 \pm 0.20$ GeV and $\kappa = 1.019 \pm 0.011$ best describe the data [10]. The large axial mass value is corroborated by similarly high measurements from both the K2K SciFi [5] and Scibar [9] detectors. Together, all three results are systematically above the value obtained from global fits to past deuterium data, $M_A = 1.014 \pm 0.014$ GeV [11]. Whether this is the result of nuclear effects or the actual axial-vector form factor remains to be seen. Certainly, this is important to resolve as the two have very different impacts on expected QE event rates. This currently remains an open question.

MiniBooNE has also collected the world's largest sample of NC π^0 events, with over 28,000 events collected in neutrino running (and over 2600 NC π^0 events expected in antineutrino running). From two-dimensional fits to the reconstructed pion mass and angle, MiniBooNE obtains a measurement of the NC coherent π^0 fraction, $19.5 \pm 2.7\%$ [12], which is 35% lower than the most commonly used model [13]. While preliminary, clear evidence for NC coherent π^0 production is also seen in the MiniBooNE antineutrino data [14]. These results are intriguing given that K2K sees no evidence for the CC equivalent of this process in their low energy data [6].

4. SciBooNE

Unlike MiniBooNE, SciBooNE is a dedicated neutrino cross section experiment, adding fine-grained detection to more precisely measure the details of neutrino interactions on a nuclear target. Operating in the same beamline as MiniBooNE, but a factor of ~ 5 closer to the proton source, the SciBooNE experiment collected both neutrino and antineutrino data in a period from June 2007 to August 2008. The SciBooNE detector complex specifically consists of three components: the fully active SciBar scintillator tracking detector, an electromagnetic calorimeter (EC), and a muon range detector (MRD). Figure 3 shows a typical event in the SciBooNE detector. True to promise and despite having commissioned the detector less than a year prior, the experiment has already released preliminary neutrino interaction results. A few select SciBooNE measurements were highlighted at this conference.

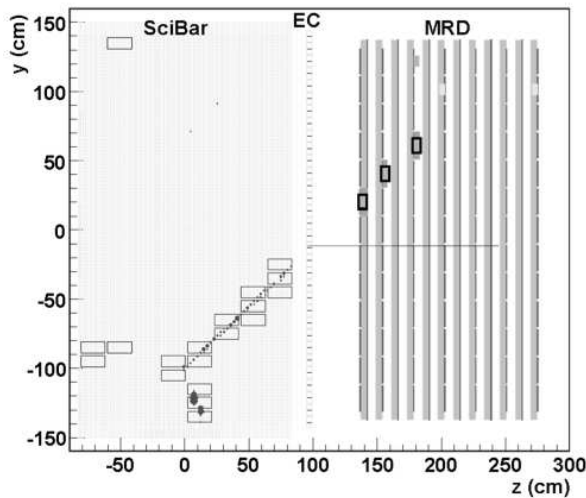


Figure 3. A candidate event in the SciBooNE detector ($\bar{\nu}_\mu p \rightarrow \mu^+ n$). The response in the SciBar detector, EC, and MRD are shown. The small circles (boxes) in the SciBar detector correspond to ADC (TDC) hits, the horizontal bar corresponds to energy deposition in the EC, and the framed boxes indicate TDC hits in the MRD occurring in the beam time window.

Based on a sample of $\sim 24,000$ 96%-pure CC events, SciBooNE finds the ever-present disagreement between the observed angular distribution of muons in CC interactions when compared with expectation. This has been previously noted (as well as in the related quantity, Q^2) by both the K2K and MiniBooNE experiments. The discrepancy is under investigation by SciBooNE and if the previous experimental results are any indication, may likely be a physics

effect (i.e., the axial form factor and/or nuclear effects). Certainly, the consistency between observations in modern experiments is both intriguing and confidence-building.

Further isolating an enhanced sample of CC coherent π^+ interactions based on a collection of $\mu + \pi$ events with low vertex activity, SciBooNE has begun to investigate K2K's earlier (and somewhat surprising) observation of the lack of the CC coherent π^+ production process at low energy [6]. An early glimpse of this data in SciBooNE appears to be consistent with the K2K results, but further analysis is currently underway. Certainly if this observation holds true, it will become quite a challenge for theorists to explain how we can observe this coherent pion production process in NC interactions at low energy but not in CC. Again, another surprise from modern data.

While this is only a small representation of the analyses currently underway, many upcoming results are expected from SciBooNE soon.

5. MINER ν A

Scheduled to start data-taking in 2009, MINER ν A is a dedicated neutrino cross section experiment planned and approved to run in the 120 GeV NuMI beamline at Fermilab [15]. Making use of the capabilities of the NuMI beam, MINER ν A will measure neutrino interactions across a wide range of neutrino energies (1-20 GeV) accumulating unprecedented statistics. In addition to a fully active fine-grained detector, the experiment will house a wide spectrum of nuclear targets (He to Pb). Using these various targets, MINER ν A will be the first to comprehensively study nuclear effects in low energy neutrino interactions. Completion of this experimental program will finally elevate neutrino measurements to the level seen in the electron sector for many years - a situation long overdue. Two examples of the results we can anticipate from MINER ν A were highlighted in this presentation.

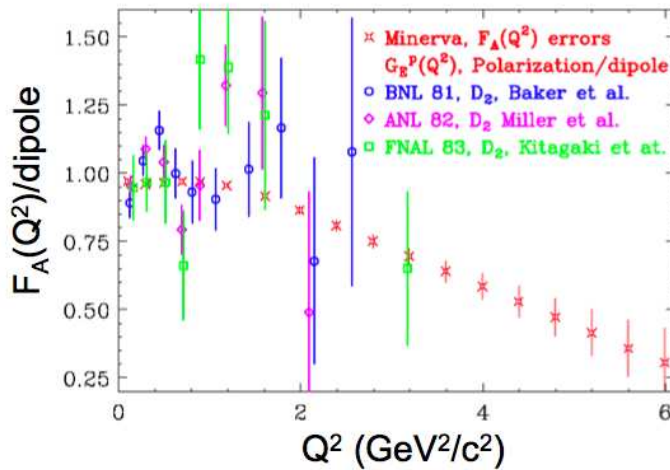


Figure 4. Anticipated axial form factor results from MINER ν A compared to prior measurements from deuterium bubble chamber experiments [15]. Plotted is the deviation of the axial form factor from its expected dipole form.

Both K2K and MiniBooNE have revealed systematically higher values of the axial mass from QE data on nuclear targets assuming a dipole approximation. Equally important are verifications of the form of the axial form factor itself: is it dipole? Experiments such as K2K, MiniBooNE, and SciBooNE are only able to study the axial form factor up to Q^2 values of $\sim 2 \text{ GeV}^2$, given their incoming neutrino fluxes. In contrast, MINER ν A can uniquely access the high Q^2 region; of import because, if electron scattering is any guide, this is the region where deviations from the expected dipole form would be found. Figure 4 shows MINER ν A's projected measurement of the axial form factor as a function of Q^2 after a four year run. The experiment will probe the axial form factor with a precision comparable to vector form factor measurements performed in electron scattering.

Recent MiniBooNE, K2K, and SciBooNE results have fueled renewed interest in neutrino-induced coherent pion production. With record-sized samples on a variety of nuclear targets, MINER ν A will make a precision measurement of the CC coherent π^+ cross section as a function of neutrino energy and be the first to trace out the target dependence of this process in a single experiment [15]. The results will shed light on the lingering question of whether both NC and CC coherent pion production processes contribute at the expected level at low neutrino energies.

While this talk focused specifically on the anticipated axial form factor and coherent pion cross section results from MINER ν A, the experiment boasts an impressive list of planned physics measurements. This includes measurements of exclusive strange particle production near threshold, detailed studies of the transition region between elastic and inelastic scattering, direct measurements of nuclear effects in neutrino deep inelastic scattering, and improved measurements of parton distribution functions at high x , to name a few. From this, it is clear that MINER ν A is poised to propel the field to the next level in precision low energy neutrino interaction physics.

6. Conclusions

We are now in a long-awaited and exciting period in which detailed measurements of low energy neutrino interactions are possible. New measurements from K2K, MiniBooNE, and SciBooNE are filling the gap in our understanding of few-GeV neutrino interactions, while future results from the MINER ν A experiment will launch the field to the next level in precision. These new results are interesting for the surprises they unveil and the questions they raise. Is the higher axial mass in modern neutrino QE samples the result of nuclear effects or the axial form factor itself? Are current multi-pion production predictions accurate? What is the reason behind the event deficits observed in both QE and single pion production data at low Q^2 ? Is there really room for NC but not CC coherent pion production in the low energy data? Future results and planned experiments are on a clear path to answer these questions in the coming years. At the same time, these improved measurements will serve an important role in defining signal and background predictions for current and future generation neutrino oscillation experiments, as they aim for their next leap in precision.

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