Neutrino Cross Sections and Scattering Physics

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Abstract. Large flux uncertainties and small cross sections have made neutrino scattering physics a challenge. However, a worthwhile challenge, as these tiny particle interactions can teach us a lot about neutrinos themselves, the weak interaction, and nucleon structure. As well, knowledge of these cross sections is crucial input to the growing field of neutrino oscillation physics. New, intense, well understood neutrino beams now available, are enhancing both oscillation and neutrino scattering physics measurements. The latest neutrino scattering results from NOMAD, K2K, and MiniBooNE, presented here, take advantage of these new neutrino sources. These results, as well as what to expect in the future, are discussed below.

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Conventional neutrino scattering measurements provide insight into neutrino interactions, nucleon structure, and the Standard Model. However, to address the open questions in this field, neutrino experiments require very intense, well understood beams and fine-grained detectors in order to minimize statistical and systematic errors.

Past experiments from the bubble chamber era (’70s-’80s) measured neutrino interactions with precision detection techniques. However these experiments were limited by low statistics and large flux uncertainties. In the ’80s and ’90s, neutrino scattering measurements moved to higher energies to probe nucleon structure and get higher statistics. In the past decade, as neutrino oscillation measurements pushed beam energies lower, into regions of interest in oscillation space, neutrino scattering physics again has moved into the low energy regime. With a new generation of intense, well understood, low energy neutrino beams interest in neutrino scattering physics has re-kindled. Combining these new neutrino sources with new fine grained detection techniques, we are poised to address the many open questions in this low energy regime.

NEUTRINO INTERACTIONS AT LOW ENERGIES

Neutrino interactions in the 0.1-50 GeV range vary from elastic and quasi-elastic scattering, through single pion production and into deep inelastic scattering. This interesting cross over region, where the different channels are turning on and off, is the region of interest for many present and future oscillation measurements. In addition, precision detectors, high statistics, and well understood beam make conventional neutrino scattering measurements in this region of great interest. In particular, there is growing interest in measurements in the following channels:

• Charged current quasi-elastic scattering (CCQE): Understanding these interactions is necessary to accurately predict signal rates in oscillation experiments, especially
for $\nu_\mu$ disappearance measurements. As well, nucleon form factors, such as $F_A$ and $M_A$, can be extracted from the CCQE cross section.

- Neutral current single pion production: While this channel is the largest background for $\nu_e$ neutrino oscillation appearance searches, it is also the least well understood. Existing data in this channel is minimal to say the least, as shown in Figures 1 and 2. Neutral pions can be produced in these interactions through resonant production or coherent production. So little is understood about the coherent channel that experiments typically assume a 100% uncertainty on this cross section. Unfolding the contributions from coherent and resonant production is crucial to understanding these interactions and to gaining insight into this diffractive scattering process.
• Charged current single pion production: Single pions can also be produced via resonant or coherent scattering in the charged current channel. As such, they provide another handle on the relative contributions of resonant and coherent in neutrino scattering. In addition, these interaction are typically the largest contaminant in the CCQE samples for $\nu_\mu$ disappearance oscillation measurements.

NEW RESULTS

Recent results from the NOMAD, K2K, and MiniBooNE experiments explore CCQE and single pion production channels from higher energies at NOMAD ($E_\nu \sim 24$ GeV), down to lower energies at K2K and MiniBooNE ($E_\nu \sim 0.5-2$ GeV).

Results from NOMAD

The NOMAD experiment, running at CERN from 1995 to 1998, observed more than 1 million neutrino interactions in their detector from primarily 24.3 GeV $\nu_\mu$ interactions [2]. The NOMAD detector consisted of upstream drift chambers which served both as the neutrino target and for momentum measurements. Downstream of these, transition radiation detectors IDed $e^\pm$s. Farther downstream was a lead glass electromagnetic calorimeter, muon chambers, and a hadronic calorimeter. The most recent NOMAD measurement, described here, separates a CCQE sample from their primarily deep inelastic scattering events.

Their CCQE interactions ($\nu_\mu n \rightarrow \mu^- p$) are tagged with the following criteria:

• reconstructed vertex within the fiducial volume
• two tracks emerging from the vertex, one a muon, the other a positive particle with a minimum of 7 hits
• reconstructed neutrino energy of 1-100 GeV
• reconstructed invariant hadronic mass of 1-1.76 GeV$^2$

A likelihood analysis yielded an event sample of 8235 events. The purity in the final CCQE sample is 70.5% and the total efficiency is 23.8%. A cross section measurement is performed with this data, with normalization determined using the deep inelastic scattering sample. This cross section is about 20% below the current world average as shown in Figure 3. An axial mass, $M_A=0.82$ GeV/c$^2$, is extracted from this data [3]. This result also sits below the world average value of $M_A = 1.026 \pm 0.021$ GeV [4]. There is no clear explanation for the discrepancy between these results and past measurements. New measurements of $M_A$ from running experiments, such as results from the K2K experiment presented below, may help to explain these results.
FIGURE 3. NOMAD CCQE new results compared to previous experimental measurements on heavy nuclei. Theoretical bands correspond to both statistical and systematic errors.

Results from K2K

The K2K experiment is a long-baseline oscillation experiment which looked for $\nu_\mu$ disappearance in a 1-2 GeV $\nu_\mu$ beam. The beam was sampled first at the neutrino source (KEK) and then again at the Super-Kamiokande detector, 250 km away [5]. The near detector location at KEK houses a Super-K like water Čerenkov detector as well as fine-grained detectors. New results from their fine-grained “SciBar” and “SciFi” detectors on coherent scattering and $M_A$ are presented here.

The Scibar detector [6] is a 2.5 x 1.3 x 300 cm$^2$ stack of extruded scintillator bars with wave length shifting fiber inserted down the center of each bar. Scibar’s granularity allows for detection of tracks as short as 10 cm.

K2K, using the Scibar detector, performed a search for coherent charged pion production in neutrino-carbon interactions [7]. These events have negligible energy transfer to the target and distinct, low $Q^2$, very forward $\pi^+$s produced. As mentioned previously, little is known about coherent production in general. As shown in Figure 4, there is very little existing data in this channel, and model predictions for this process vary by as much as a factor of 20.

For this analysis, K2K tagged an enriched coherent $\pi$ sample in their Scibar detector by selecting events with low vertex activity. This small nuclear recoil is as expected in the coherent channel populating events primarily at low $Q^2$. Figure 5 shows the data compared to expected contributions in the sample. The not-well-understood low $Q^2$ regime below 100 GeV$^2$ is excluded in an initial fit of the data to the prediction. Once the data is fixed with respect to the prediction above 100 GeV$^2$, comparison of the data and the predictions below 100 GeV$^2$ suggests a deficit in the data as compared to the predictions. K2K reports this as no evidence for coherent $\pi^+$ production. Based on this interpretation, K2K reports a limit on coherent pion production, at 1.3 GeV, of less than 0.6% of the total CCQE cross section. This limit is plotted with the other existing data.

*Comparison with previous experimental data*

Nuclear effects are included into calculations according to the standard relativistic Fermi gas model. The theoretical band corresponds to both statistical and systematic uncertainties.
FIGURE 4. Existing data for neutral current coherent pion production. Predictions for coherent contributions vary by as much as a factor of 20 [1].

FIGURE 5. New K2K coherent $\pi^+$ results. No evidence is seen for coherent scattering in the low $Q^2$ regime ($Q^2 < 100 \text{ GeV}^2$).

K2K has also recently reported an extraction of $M_A$ from their CCQE data sample measured using the SciFi (or Scintillating Fiber) fine-grained detector [8]. In total, there are 8814 events from the K2K-I run and 5967 events from the K2K-IIa run included in the data sample. A shape fit to extract $M_A$ to data above $Q^2$ of 0.2 GeV$^2$ is performed, excluding the not well understood low $Q^2$ region. Results from their new coherent cross section analysis are included here. As indicated in Figure 7, a value for $M_A = 1.18 \pm 0.03 \text{ stat} \pm 0.12 \text{ syst}$ is extracted.
FIGURE 6. Based on fit to coherent $\pi^+$ data, limit set on coherent scattering cross section to 0.6% of the CCQE cross section.

FIGURE 7. Picture to fixed height

Results from MiniBooNE

The MiniBooNE experiment is a $\nu_\mu \rightarrow \nu_e$ neutrino oscillation search underway at Fermilab. MiniBooNE observes neutrino interactions from 1 GeV neutrinos, in an open volume oil Čerenkov detector [10]. In addition to the oscillations search, MiniBooNE, taking data now, will measure a suite of cross section measurements from more than 0.5 million events. First cross section results from MiniBooNE examine the charged current single pion production and neutral current single pion production channels.

MiniBooNE tags these events by observing 3 subevents corresponding to the outgoing $\mu$, its delayed decay to a Michel electron, and a Michel electron from the $\pi^+$ decay and the subsequent muon decay. The $\mu$ decay from the $\pi^+$ decay chain, that produces
the so called “Far Michel”, should have a lifetime of $2197 \pm 0.04$ ns. This lifetime is measured in the analysis to be $2242 \pm 17.3$ ns (statistical errors only). The Michel from the outgoing $\mu^-$, the “Near Michel” should have a shorter lifetime, of $2026 \pm 1.5$ ns, as about $8\%$ of $\mu^-$ s capture on $^{12}$C before decaying. The measured Near Michel lifetime is consistent with this at $2070 \pm 15.5$ ns (statistical errors only). With this powerful tag and other simple cuts, a sample of 40 thousand charged current $\pi^+$ events are identified. The sample has an $84\%$ purity with just this first level cuts. Final state identification cuts to improve the sample will be implemented in the future.

Reconstructed neutrino energy is determined assuming 2 body decay kinematics with a Delta 1232 in the final state instead of a proton. Looking at the ratio of these events to CCQE cross section multiplied by the CCQE neutrino prediction, a preliminary CC$\pi^+$ cross section ratio can be determined. Figure 8 shows the existing data for this channel. As suggested by the lack of heavy target data at low energies, this will be the first measurement at low energy on a nuclear target. This sample can also be used to extract coherent vs. resonant fractions like the K2K analysis, however, with significantly larger data sets. MiniBooNE will extract the relative contributions with 2D fits to kinematic distributions

**UPCOMING MEASUREMENTS**

Upcoming precision measurements can help to address the results described here, and more. As well, anti-neutrino running, possible with the MiniBooNE experiment, will make first ever measurements of anti-neutrino cross sections at low energies. These measurements are important for CP violating oscillation searches comparing $\nu$ and $\bar{\nu}$ running, as well as for understanding neutrino interactions. In particular, the angular distribution of resonant and coherent production in the single pion channels differs from $\nu_{\mu}$ to $\bar{\nu}_{\mu}$ running giving a further handle on the not well understood diffractive scattering
component of neutrino scattering.

CONCLUSIONS

Neutrino scattering physics is a rich and growing field. New data from recent and running experiments continue to produce interesting results. Upcoming measurements with well understood beams, high statistics and fine-grained detectors will continue to teach us about neutrino interactions in this rich low energy regime, and likely, surprise us.

REFERENCES

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