Review of Current and Future Neutrino Cross-Section Experiments

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Abstract. There has been a surge of progress and published results in neutrino cross-section physics in recent years. In many cases, absolute differential cross-sections are being measured for the first time and can be compared to interaction models first developed decades ago. These measurements are important input for the next generation of accelerator-based neutrino oscillation experiments where precise understanding of both signal and background channels will be critical to the observation of sub-dominant oscillation effects. This paper discusses recent results from several experiments and describes new experiments currently under construction dedicated to making these measurements with unprecedented precision.

Keywords: Neutrino, scattering experiments, cross-sections

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INTRODUCTION

The discovery of neutrino mass and mixing has led to an ambitious worldwide program of long baseline, accelerator-based neutrino oscillation experiments. In particular, next generation experiments such as NOvA [1], T2K [2], and LBNE [3] endeavor to make precision measurements of dominant oscillation channels, search for evidence of sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations, and discover possible CP violation within the lepton sector.

These experiments rely on intense neutrino beams to reduce statistical uncertainties forcing a more careful consideration of sources of systematic errors, many of which may have been negligible in previous long baseline oscillation experiments.

For example, our understanding of basic neutrino-nucleus interactions is incomplete and this directly affects how well one can separate signal from backgrounds and measure oscillation parameters. Further, long baseline experiments use heavier nuclear targets to increase interaction rates but the impacts of nuclear effects within heavy nuclei on final state particle kinematics are significant. This, in turn, impacts one's reconstruction of the incoming neutrino energy. These systematic effects must be well understood to maximize the sensitivity of the next generation of oscillation experiments.

Fortunately, a diverse program of modern experiments aims to make precision measurements of neutrino-nucleus interactions for neutrino energies up to a few GeV. These experiments will measure absolute cross-sections for a variety of inclusive and exclusive final states and for a range of nuclear target materials. This should create the possibility of unfolding neutrino-nucleon scattering rates from complicated nuclear effects.

Neutrino Energies and Target Materials

Figure 1 (top) shows the regions of neutrino energy and target materials relevant for current and future long baseline oscillation experiments. NOvA uses a liquid scintillator detector (carbon) and sits off-axis from the NuMI (Neutrinos at the Main Injector) [4] beam at Fermilab creating a relatively narrow neutrino flux around 2 GeV. The T2K beam is lower energy (0.5-1 GeV) and uses a water target (oxygen). The LBNE (Long Baseline Neutrino Experiment) collaboration is currently planning a low energy wideband beam generated at Fermilab [5] and pointing to either a large water or liquid argon detector at a far site. The MINOS [6] detector, running now at Fermilab and Soudan, is constructed of iron and sits on-axis of the NuMI beam. Finally, the CNGS (CERN to Gran Sasso) [7] beam is significantly higher energy allowing for tau lepton production in lead within the OPERA [8] detector at Gran Sasso.

Figure 1 (bottom) shows the coverage provided by modern experiments which include a program of neutrino cross-section measurements. As defined here, “current” experiments are listed in the left column; “future” experiments are in the right column. By comparing the two panels, one sees that the coverage provided by these experiments relative to the LBL experiments’ needs is nearly complete. This is important given the difficulty that often arises in extrapolation of neutrino interaction models to different energies or nuclei. Further, the overlap within the cross-section experiments can be leveraged to untangle complicated systematics such as flux predictions and detector efficiencies from the underlying physics of the neutrino-nucleus interactions.
Interaction Channels

Figure 2 shows the current cross-section data for $\nu_\mu$ charged current interactions between 100 MeV and 400 GeV. The approximate energy range of the neutrino fluxes for various accelerator-based oscillation experiments is represented by the colored blocks. These experiments are done in a range where quasi-elastic scattering and single pion production dominate the interaction cross-section.

In particular, next generation long baseline experiments, T2K, NOvA, and LBNE/DUSEL, will each rely on charged current quasi-elastic (CCQE) scattering as a signal channel in making precision measurements of muon neutrino disappearance, searching for electron neutrino appearance, or both.

Single pion production channels create important backgrounds for these measurements. Charged current $\pi^+$ production (CC$\pi^+$) can mimic a CCQE interaction if the pion is absorbed within the target nucleus. Reconstructing such an event under a CCQE hypothesis results in a systematic shift to lower reconstructed neutrino energy. This is an irreducible background event-by-event, making the ratio of CCQE to CC$\pi^+$ interaction rates an important input in making a precision measurement of the energy dependence of $\nu_\mu$ disappearance.

Neutral-current $\pi^0$ production (NC$\pi^0$) is the largest contributor to backgrounds in a search for electron neutrino appearance in a muon neutrino beam. $\pi^0 \rightarrow \gamma\gamma$ decays can be mis-identified as a final state electron from a $\nu_e$ charged current interaction if one of the gammas is improperly identified. This is not an irreducible background and the mis-ID rate will depend on the detector technology employed, but the cross-section for NC$\pi^0$ production is very poorly known. Analysis of data from current oscillation experiments and sensitivity estimates for future experiments would greatly benefit from improved measurements of NC$\pi^0$ production rates.

CURRENT EXPERIMENTS

Next, we discuss recent cross-section results from the MiniBooNE, SciBooNE, and MINOS experiments at Fermilab as well as the NOMAD experiment conducted at CERN. Later, we introduce future cross-section experiments, in particular the MINERvA experiment at Fermilab.

Charged Current Quasi-Elastic Scattering

CCQE event samples are often analyzed using the cross-section formalism of Llewellyn Smith [9]. The relativistic Fermi gas (RFG) model of Smith and Moniz...
A certain parameter in this model is the axial-vector form factor at nucleon cross-section off nucleons bound in a nucleus. The least squares method is typically employed to expand this to include the nucleon cross-section as measured by three experiments, MiniBooNE [13, 14], SciBooNE [13], and NOMAD [15].

\[ F_A(Q^2) = F_A(0) \left( 1 + \frac{Q^2}{M_A^2} \right)^{-2}, \]

where the form factor at \( Q^2 = 0 \), \( F_A(0) = -1.267 \), is well known from neutron beta decay experiments [11]. \( M_A \), however, must be determined from neutrino scattering data and the weighted average from available measurements (excluding any new measurements mentioned here) is \( M_A = 1.03 \text{ GeV} \) [12].

Several experiments have recently presented new measurements of CCQE interaction rates, including MiniBooNE [13, 14], SciBooNE [13], NOMAD [15], and MINOS [16]. Three of the four recent experimental results are compared in Figure 3. The two curves correspond to cross-section models with different values of the axial mass parameter, \( M_A \).

NOMAD measured the absolute charged current quasi-elastic cross-section in the neutrino energy interval 3-100 GeV by normalizing to the total \( v_\mu \) charged current cross-section. As evidenced in Figure 3, their result is consistent with a cross-section model using the average axial mass value of 1.03 GeV. NOMAD extracts this parameter from their absolute cross-section data to be \( M_A = 1.05 \pm 0.02(\text{stat}) \pm 0.06(\text{syst}) \) GeV, and states it is consistent with a pure \( Q^2 \) shape analysis of their \( v_\mu \) quasi-elastic 2-track events.

MiniBooNE and SciBooNE have measured the absolute CCQE cross-section in the neutrino energy range below 2 GeV. Absolute normalization of the results is achieved through “dead-reckoning” of the flux from the Booster Neutrino Beam at Fermilab by incorporating hadron production data from the HARP experiment [17].

FIGURE 3. Charged current quasi-elastic (CCQE) per nucleon cross-section as measured by three experiments, MiniBooNE [13, 14], SciBooNE [13], and NOMAD [15].

A modification to the model.

The MINOS experiment has not released absolute cross-section numbers, but a preliminary neutrino energy and \( Q^2 \) analysis has been presented. MINOS extracts \( M_A = 1.19^{+0.09}_{-0.10}(\text{fit})^{+0.12}_{-0.14}(\text{syst}) \) from a \( Q^2 \) shape only fit to their data [16].

One can see that a potential inconsistency between results of modern experiments is developing and this is not currently understood. This has motivated tremendous recent effort to advance the models describing quasi-elastic scattering in heavier nuclei [19], but additional data will be needed to unravel this mystery.

**Charged Current \( \pi^+ \) Production**

Two experiments, K2K and MiniBooNE, have presented recent measurements of the \( \text{CC}\pi^+ \) to CCQE cross-section ratio at neutrino energies below 3 GeV [20, 21]. Figure 4 shows their results compared to that of the Argonne 12-ft bubble chamber experiment published in 1982 [22].

Charged current charged pion production is often reported as a ratio to the CCQE event rate, reducing uncertainties arising from knowledge of the neutrino flux. As stated above, this ratio is an important component to understanding the level of background in a CCQE signal channel of an oscillation experiment. To properly test models of CC\( \pi^+ \) production, however, requires differential cross-section data describing the kinematic distributions of the final state muon and pion. The ANL data were used to study pion angular distributions and, more recently, MiniBooNE has measured absolute cross-section values as a function of both muon and pion angle and momentum [23].

**Neutral Current \( \pi^0 \) Production**

Few measurements of absolute NC\( \pi^0 \) production are available in the literature [25, 26]. The MiniBooNE collaboration has very recently completed the first absolute cross-section measurement of NC\( \pi^0 \) production for both neutrino and antineutrino scattering. Since the neutrino...
FIGURE 4. CCπ⁺ to CCQE cross-section ratio as measured by three experiments, MiniBooNE [21], K2K [20], and ANL [22].

FIGURE 5. Flux averaged differential cross-sections for νµ and νµ induced NC single π⁰ production on CH₂ measured by MiniBooNE [24].

energy cannot be reconstructed in NC π⁰ events, the results are averaged over the incident neutrino flux, but cross-sections as a function of the π⁰ momentum and π⁰ angle with respect to the interacting neutrino are presented. These results are shown in Figure 5 and compared to their default Monte Carlo simulation which is based on the model of Rein and Sehgal [27, 28].

The way the data have been presented in MiniBooNE’s publication illustrates an important point in how neutrino cross-section data will be used by future neutrino oscillation experiments or to improve theoretical models of neutrino-nucleus scattering. NC π⁰ production creates the single largest misidentification background in νµ → νe oscillation searches. These experiments, performed on heavier nuclear targets, are concerned only with the inclusive rate for π⁰’s leaving the nucleus and entering the detector medium. Charge exchange and absorption within the nucleus are complicated effects and can alter the bare neutrino-nucleon event rates. These nuclear effects are a part of this challenging theoretical problem, so providing experimental data to the community as rates of inclusive final states, as MiniBooNE has done, is important.

FUTURE EXPERIMENTS

As MiniBooNE and the K2K experiment have extensively demonstrated, neutrino detectors constructed to make oscillation measurements are often used to make important cross-section measurements as well. Future experiments, such as T2K [29] and MicroBooNE [30], are similar in that their primary physics motivation come from elsewhere, but each experiment will include significant programs in neutrino cross-section physics. One future experiment, MINERvA at Fermilab, is designed specifically for a cross-section physics program aimed at precision measurements of neutrino interactions in nuclei for energies up to a few GeV.

MINERvA makes use of a fine-grained, fully active detector design and a range of nuclear target materials (helium, carbon, iron, and lead). The presence of multiple nuclear targets in the same detector medium and placed in the same neutrino beam provides a significant advantage for unraveling the effects of heavier nuclei on neutrino interactions. Figure 6 shows a schematic diagram of the MINERvA detector which is comprised of multiple nuclear target modules and a fully active scintillator tracking region surrounded by hadronic and electromagnetic calorimeters. The experiment is described in much greater detail elsewhere in these proceedings [31].

MINERvA collected first neutrino data in the NuMI beam with a prototype detector from April-June, 2009. The prototype was built from full-scale detector modules but was ~20% of the full length of MINERvA, being comprised of 24 total modules. Figure 7 shows two sample events from the prototype run. The first is a candidate quasi-elastic event. The top track (actually to the left in the horizontal plane of the detector) appears to be a muon exiting the back of the detector which can be matched to a track in the MINOS detector which is located 2 meters downstream from MINERvA (not shown). The lower track ranges out but the increase in the energy deposited per plane (dE/dx) as it loses energy is clear. This is consistent with the track being a proton. The right panel shows a charged current π⁰ production candidate, where again there is an exiting muon track and two electromagnetic showers which appear consistent with photon conversions and which point back to the primary vertex.

Since this paper was presented, the MINERvA prototype detector has been removed and installation of the final MINERvA detector has begun. As of November, 2009, 55% of the full detector modules are in place and collecting data. The NuMI neutrino beam is running in
antineutrino mode (reversed focusing horn currents). The full MINERvA detector is on schedule to be installed by March, 2010.

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