Progress in neutrino-nuclear scattering

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Abstract. Neutrino-nuclear interactions are an integral part of accelerator based measurements of neutrino oscillation. However, the presence of significant nuclear effects complicates our understanding and can be a source of bias in the determination of oscillation parameters. The modeling of nuclear effects can be tested against new measurements made with a range of target materials and incident beams. Answers to outstanding questions in neutrino nuclear scattering are presented based on recent results from T2K, MINERνA, NOνA and ArgoNeuT experiments, alongside new questions and puzzles.

1. Introduction

Current accelerator-based oscillation experiments typically use charged current (CC) interactions, $\nu_l^- + A \rightarrow l^- + A'$, with a nucleus ($A$) to tag the flavor of the (electron or muon) neutrino by observing the corresponding lepton ($l = \mu, e$) in the detector. The charge of the lepton indicates if a neutrino or antineutrino interaction occurred. Significant processes used in current and future experiments on nucleons (N) include:

- Charged-Current Quasi-Elastic (CCQE): $\nu l^- + n(p) \rightarrow l^- + p(n)
- Multinucleon knock-out (2p2h)$\textsuperscript{1}$: $\nu l^- + A(n,p) \rightarrow l^- + A' + p + p$ and $\nu l^- + A(n,p) \rightarrow l^+ + A' + n + n
- Charged-Current Single $\pi^+/0$ (CC1$\pi$): $\nu l^- + N \rightarrow \nu l^- + N' + \pi^+/0
- Charged-Current Coherent $\pi^+$ (CCCoh): $\nu l^- + A \rightarrow \nu l^- + A + \pi^+
- Neutral-Current Single $\pi^+/0$ (NC1$\pi^+/0$): $\nu l^- + N \rightarrow \nu l^- + N' + \pi^+/0

Making precision measurements of neutrino interactions is challenging due to the presence of nuclear effects and the extended nature of neutrino sources. First, neutrino interactions include the vector-axial coupling of the weak interaction, and so are not completely described by information such as electron scattering, where a mono-energetic beam is used to probe the nucleus. Second, neutrino beams are not mono-energetic$^2$. Nuclear effects modify the processes mentioned above, but our source is not narrow enough to resolve multiple, competing effects within a given process, e.g. CCQE interactions modified by the presence of other nucleons near the one where the interaction occurred. In addition, all that is measured in the detector is

$^1$ Note this is an approximation for illustration. There are significant questions about the proton, neutron composition of the final state for 2p2h.
$^2$ An interesting approach to make a pseudo-mono-chromatic neutrino beam can be found in Ref [1]
Figure 1. Neutrino sources, in arbitrary units, shown as a function of neutrino energy for recent experiments

a topology, which is similar for multiple processes. An example of this mixing of processes is the observable topology: CC with no pions, any number of nucleons in the final state (CC0π). CCQE, 2p2h both contribute to this topology, as do CC1π where the pion or \( \Delta \) has been modified by the presence of nuclear matter (final-state interactions). In the last case, the pion does not exit the nucleus and the interaction has no pions in the final state.

Estimators of the neutrino energy, necessary for neutrino oscillation physics, depend critically on neutrino interaction models. The oscillation probability depends on energy and so an estimate is needed of this quantity. A combination of leptonic and/or hadronic information is used. On the T2K experiment, as the neutrino direction is known, and the nucleus is approximately at rest, then assuming QE interactions, the energy is estimated using only outgoing muon or electron momentum and angle. On NO\( \nu \)A, the muon energy and all other charged particles (protons and pions) deposit energy, and this is included in the estimate. But, the estimator will be modified by nuclear effects. One example comes from T2K, where 2p2h processes produce interactions at a higher energy, but have a lower estimated energy, this produces a bias in the relationship between the estimator and the true neutrino energy. The effect on an oscillation analysis is subtle but significant. In principle, a near detector would constrain the presence of 2p2h interactions, but the 2p2h interactions are buried under the peak of QE interactions. At the far detector, where the CC muon flux has undergone oscillation, the 2p2h interactions migrate into “dip” region, and this can create bias on the extraction of \( \theta_{23} \). While the 2p2h case is one example, this can be generalized. Any inference of the far detector energy spectrum depends on the cross section model and oscillation probability. Any nuclear-effect energy dependance therefore couples to the extracted oscillation probability.

To summarize, current and future long and short baseline oscillation rely on modeling of neutrino interaction physics even with near detectors. All experiments require a model to create a signal and background prediction, estimate efficiency and energy for all four flavors (muon, electron, neutrino, antineutrino). But, outstanding puzzles in the QE and 1\( \pi \) interactions, discussed in the next section, indicate our understanding is incomplete.

2. Recent progress in neutrino-nuclear scattering

The approach we take to tackle these issues is to test modern models of these processes against a wide variety of experimental probes. Table 1 shows the current cohort of neutrino
Table 1. Table of neutrino experiments with cross section results published in the last two years (2014-2016).

| Experiment | Target | Run Period |
|------------|--------|------------|
| ArgoNeuT   | Ar     | 2009-2010  |
| MicroBooNE| Ar     | 2015-      |
| MINERνA    | He, CH, H2O, Fe, Pb | 2009-     |
| NOνA       | CH     | 2010-      |
| T2K        | CH, H2O, Fe | 2010-    |

and antineutrino scattering (cross-section) experiments. The MINERνA and T2K experiments include data on a range of target materials; changing the target material with the same probe provides a constraint on nuclear effects. The second test of models is through comparisons of neutrino and antineutrino beams on the same target material; with the exception of MicroBooNE, all experiments will or already have neutrino and antineutrino data sets. Finally, a robust model (within its uncertainties and region of validity) should be able to represent data regardless of beam energy which is provided by the current suite of experiments (figure 1). We note a special case—the T2K experiment has two different detectors, one located in the “on-axis” beam and one in the “off-axis” beam position, which offers a unique opportunity to explore processes with shared beam conditions. The remaining sections of these proceedings describe some of the latest results from these experiments.

There are also experiments which perform measurements related to enhancing our understanding of neutrino cross sections or related processes. The DUET experiment [2] has recently made measurements of pion scattering on scintillator targets; this kind of measurement is important to constrain so-called secondary interactions of pions in the detector, which often are a significant source of systematic uncertainty in cross section measurements. The ANNIE experiment [3] will make the first measurements of the abundance of final state neutrons from neutrino-oxygen interactions, using Gd doped water and Large Area Picosecond Photosensor Detectors (LAPPDs); this experiment is currently making background measurements. The CAPTAIN experiment [4] will measure response of LAr detectors to neutrons and rate of neutrons out of neutrino interactions on Ar; that project is currently taking data as Mini-CAPTAIN in a neutron beam.

All modern experiments rely on powerful software programs to predict neutrino interactions in their detectors and there has also been impressive improvements made to the models and their implementation. The GENIE software package, used by all currently operating experiments, has recently released a new version [5], and there have been advances in the tunes and models implemented in NEUT and NuWro. The GiBUU package has also been extensively used in nuclear physics.

Another initiative that has started recently is an alliance between theorists and experiments. The Neutrino Scattering Theory-Experiment Collaboration (NuSTEC) has brought together representatives from all experiments and the major theory groups to try to bridge disagreements in data, theory and the representation of neutrino interactions in software modeling\(^3\). In addition, this group hosts schools to educate students and postdocs in this complex field; the next school will be in October 2017.

\(^3\) Please consider subscribing to nustec-news@fnal.gov if interested, with further details in the backup of the presentation associated to this proceeding.
Figure 2. Measured cross-section with shape uncertainties (error bars: internal systematics, external statistical) and fully correlated normalization uncertainty (gray band). The results from fit to the data are compared to the predictions from Nieves et al (red dashed line), and from Martini et al (red solid line). Figure from [6].

2.1. Measurements of CCQE and 2p2h

The CCQE process is a “golden” channel for long and short baseline experimental programs due to the relatively simple final state and estimator for energy. However, MiniBooNE’s measurement of QE-like interactions were inconsistent with the single-nucleon models available at the time. Subsequent measurements by MINERνA were also at odds with MiniBooNE and single nucleon models. It is now believed the excess is partly due to the presence of 2p2h processes. T2K recently released a new measurement of QE-like interactions [6], and as T2K’s flux is peaked at about the same point as MiniBooNE’s, this is an interesting check of if there was a fundamental issue with the MiniBooNE analysis. The T2K integrated cross section is consistent within the same model framework as MiniBooNE. Furthermore, the T2K result includes detailed kinematical information of the cross section model, which is consistent with recent QE models [7, 8, 9, 10] which include the presence of 2p2h processes. One angular bin is shown as an example of this in figure 2.

While the data supports the presence of 2p2h interactions, there are still outstanding questions. In particular, no single model is able yet to explain all the available datasets, even for just the muon kinematic distributions alone. MINERνA recently released a novel measurement of their inclusive data [11], which shows that the relative strength of 2p2h needs to be adjusted; a similar approach was taken by NOνA, highlighting why different energy probes are valuable to characterize processes. Within QE models, there is also other information in the final state, like the outgoing proton(s). ArgoNeuT sees evidence of back to back protons [12], suggestive of nuclear effects such as 2p2h. Unfortunately, with this new information, we also find that no single model properly represents the muon and proton kinematics consistently, which makes it hard to interpret proton information robustly. Future measurements will add to this complex picture. Antineutrino interactions are another way to characterize 2p2h models and T2K, NOνA, MINERνA, ArgoNEUT all have or will take antineutrino data.

2.2. Measurements of CC1π

CC1π is another important process, as both a background to CCQE measurements and as a signal mode for some oscillation physics channels. For cross section physics, CC1π populates some of the same region of phase space as 2p2h processes, which links our understanding of the QE sector to CC1π. Unfortunately, like QE, we have a rift between our understanding of CC1π from lower energy measurements, like MiniBooNE, and higher energy
MINERνA data [13]; it is not possible to reproduce MiniBooNE distribution without making extreme, arguably unphysical, changes to current software implementations of CC1π, and it has also not been possible to create a complete model that represents the outgoing muon and pion kinematic distributions.

T2K is an important experiment in single pion production as the majority of pion production for T2K’s beam is from excitation of the Δ. T2K recently produced a world’s first measurement of the cross section for CC1π interactions on water [14]. While GENIE and NEUT simulations both reproduce the shape reasonably well, we see the same trend as MINERνA that the GENIE prediction over predicts the CC1π signal. In addition to the water measurements, T2K also has produced a result on scintillator, which is consistent with the water result.

In addition to progress with resonant pion production, there has been new progress on coherent production of pions. In coherent production, the nuclear recoil is negligibly small, so it is straightforward to actually measure the neutrino energy with coherent scattering through a combination of muon and the pion kinematic information only. This makes this channel quite valuable for future experiments performing oscillation physics. MINERνA made the first observation of this process recently [15], and T2K now has two new results [16, 17] using the off-axis energy beam and (higher energy) on-axis beam. Both see an excess of data events over prediction; the higher energy measurement sees some of the same trends as the MINERνA measurement, where the coherent production is suppressed at higher angles of the outgoing pion relative to the beam direction. The off-axis result is consistent with a new model, so there potential that this process will be theoretically understood well in the future.

2.3. Measurements of electron neutrino interactions

Appearance experiments, measure electron neutrinos and antineutrinos, but the majority of neutrino interactions are measured with muon neutrinos, so an understanding of how these two cross sections is important for appearance searches. There are two new measurements recently, from NOνA [18] and MINERνA, both on scintillator. The MINERνA result [19] has a nice comparison of the ratio of the νe to νμ interactions to current simulations, which demonstrates consistency between the model and the data at the level of 15-30%.

2.4. Measurements of neutral current interactions

NC1π0 is an important process as the photons can mimic appearance search signal interactions. The open problem here is that we do not have a model which accommodates both NC and CC1π measurements from MiniBooNE. While this is still an outstanding problem, there are new measurements by ArgoNeuT and MINERνA. MINERνA found evidence for diffractive NC π0 production i.e. NC production off of the hydrogen in the scintillator [20]. While this isn’t a large background, it is substantially underestimated. ArgoNeuT has also produced some of the first proof of concept measurements of NC1π0 in a liquid Argon detector [21], the same detector technology used for future oscillation experiments; the measurements were done with both neutrino and antineutrino beams.

2.5. Flux-based determination of CC inclusive cross section

Experiments are also developing new approaches for measuring cross sections, including approaches which use the flux to infer the neutrino energy dependence of the cross section. The T2K on-axis near detector sits in a beam which covers a range of one off-axis degree. By comparing identical modules which see a slightly different flux with slightly different peak energy values, we can infer the energy dependence of the cross section. Unlike conventional cross section measurements which rely on separation of backgrounds from signal with models which do not represent either especially well, this relies on the well characterized production of neutrinos from the decay of pions. A measurement of the CC inclusive cross section was done using energy bins
inferred from the flux on an iron target [22], and is consistent with previous measurements by MINOS.

3. Outlook
A complete and robust understanding of nuclear effects in neutrino interactions is critical for the current and future oscillation physics program. Put simply, all measurements rely on a model, so models need to be tested against different target materials, and a range of neutrino and antineutrino sources. In the last two years, there have been new measurements from multiple experiments (ArgoNeuT, MINERνA, NOνA, and T2K) facing current puzzles in QE, $1\pi$ physics through novel experimental techniques and different beam configurations. While a coherent picture is emerging for CC coherent scattering, for CC resonant production questions still remain for reconciling the muon and pion state and reconciling MiniBooNE and T2K, MINERνA data. New measurements have been made of $\nu_e$ (NOνA, MINERνA) and NC interactions (ArgoNeuT) experiments. The future holds more measurements from currently operating experiments with antineutrino beams and MicroBooNE, and new information from neutrons out of neutrino interactions from ANNIE and CAPTAIN.

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