EXPERIMENTAL IMPLICATIONS ON NEUTRINO CROSS-SECTIONS AROUND 1 GeV*

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The next generation of oscillation neutrino experiments require more and more precise measurements of the properties of neutrino interactions with matter. This article summarizes the challenges of the new frontier experiments.

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1. Introduction

The next generation of neutrino oscillation experiments aims at the appearance of neutrinos of different flavor, or at an improved precision, $\approx 1\%$, of the disappearance parameters [1, 2]. In both cases, measurements will be most likely limited by systematic errors or by the understanding of the backgrounds. This new generation utilizes neutrino beams of the order of 2 GeV or below. This region is dominated by four poorly known cross-sections: charged and neutral current quasielastic and single pion production. Additional challenges are the nuclear effects contributing to the cross-section and the reconstruction of the kinematics of the neutrino interactions. Near detectors of the new generation of experiments play an important role in controlling systematics errors. Recent results [3] point also to the need of a more precise modelling of the cross-sections on the neutrino interaction Monte Carlos. Most of these contributions have been already studied at electron scattering experiments.

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The understanding of neutrino cross-sections is relevant for the appearance experiments where a ν_e is detected from the oscillation of an almost pure ν_μ beam. The main background to this detection are misidentified π^0 produced both in neutral and charged current neutrino interactions. Nuclear matter and detector interactions further modify the production of π^0 at the final state.

For the ν_μ disappearance, the knowledge of the relative yield of charged current quasielastic *versus* charged current single pions together with the systematic error the neutrino energy reconstruction will dominate the accuracy of the measurement.

A review of neutrino–nucleus interaction measurements are presented emphasizing those aspects that will be critical for the next generation of experiments.

2. Neutrino–nucleus interactions

Existing measurements cover the high-energy regime, above 2 GeV, but very sparsely the low-energy, where many of the new oscillation experiments will operate. The knowledge of the cross-section in this regime is very limited, see [4] for a recent compilation. The picture is more complex since the cross-sections cross several reaction thresholds of ν interactions types between few hundred MeV/c and 2 GeV/c. On the other hand, future experiments have more stringent requirements in the understanding the topology and kinematical properties of the neutrino interactions.

The final state interactions change the momentum and nature of nucleons and pions produced in the ν interactions. Both charged and neutral pions contribute to the background in disappearance (charged pions faking a muon) and appearance (neutral pion faking an electron) experiments and should be understood to better than 10% level for the next generation of experiments [1]. Running and future experiments measure these backgrounds at neutrino detectors close to the production point [1, 2, 5], more extensive set of measurements will be needed to understand the results and include them consistently in the neutrino interaction Monte Carlos.

The nuclear effects also alter the kinematics of the final state muon in charged current interactions by inhibiting the reaction (Pauli blocking) or changing the center of mass energy where the reaction takes place (Fermi Motion). These two phenomena change basic kinematic properties of the interaction like the q^2 or the threshold of the reaction. Variation of the q^2 might change the efficiency calculation and will increase the systematic errors when comparing detectors with different acceptances and performances as the near and far detector of the oscillation experiments.

2.1. Charged Current Quasi-Elastic

The Charged Current Quasi-Elastic (CCQE) neutrino–nucleus interaction is fundamental since it provides a method to reconstruct the neutrino energy. Theory is based on Conserved Vector Current (CVC), Partially Conserved Axial Current (PCAC) and form factors measured in electron–nucleus scattering. The axial form factor is not known and it is normally parameterized as a dipolar form factor with the axial mass (M_A) as a free parameter. It should be noticed that this parameter changes both the total cross-section and the q^2 distribution of the interactions. Both methods had been used to measure the parameter coming to contradicting results as it was noted in [6]. From the experimental point of view the axial mass changes the strength of the cross-section and so the ratio of quasielastic to single pion production modifying the neutrino energy reconstruction. M_A also changes the cross-section dependency as a function of the q^2 of the reaction. Different q^2 distributions alter the calculation of detection efficiency when comparing detectors with different acceptances.

2.2. Charged and Neutral Current pion production

The Charged Current and Neutral Current pion production (CC1π, NC1π) are the second and third dominant cross-sections for neutrinos below 2 GeV/c. The knowledge of the pion production is even more difficult to model. In addition to the axial form factor value and nuclear contributions that are very similar to that of the CCQE interaction, the presence of several resonant and non-resonant contributions makes the description and measurement of this interaction very complicated. The transition to the Deep Inelastic interaction is also not very well known and it is usually described with theoretical approaches. Nuclear re-interaction of hadrons leaving the nucleus makes the full description more challenging adding the final state pions to the nucleons produced in the CCQE reaction.

The main interest in this reaction comes from the fact that it is the main background to both the disappearance and appearance neutrino oscillation experiments in this energy region. In future oscillation experiments, the pion is either the particle that can be misidentified or it is a handle to distinguish background interactions from the dominant CCQE interaction. The presence of higher mass resonances and the transition to the Deep Inelastic region introduces additional unknowns to the prediction of the backgrounds. The approach of running and future experiments is to measure the yield of pions directly, this is by no means a trivial task. The yield of pions might be different in different nuclei, the energy threshold to detect pions has to be very low and the measurement itself is affected by backgrounds such as the re-interaction of produced particles with the detector mass. The existence of a proper Monte Carlo framework to include and control the different levels of measurements seems to be needed to reach systematic errors well below 10% as it will be requested in the next to following series of experiments.

3. Neutrino energy reconstruction

Traditionally the neutrino energy reconstruction at high energies was performed in charged current interaction weighting the energy of all the particles produced in the interaction. At low energies, this is more difficult because the Fermi motion of the target nucleon adds a sizeable momentum, but mainly because the nucleus absorbs and produces new particles during the propagation of the non-leptonic neutrino–nucleon interaction products. Minos [5] still uses this method with very successful results but this seems to be the lowest possible energy to be applied. The large interaction statistics of the next generation of experiments might try to reconstruct the neutrino energy using the kinematics of the lepton and hadrons produced during the interaction. This might be possible selecting specific topologies of events where the information is not distorted by nuclear matter contributions.

Low energy experiments like K2K [7], SciBooNE [8] and MiniBooNE [9] applies a different recipe. The target nucleon is assumed to be at rest, the interaction to be a pure charged-current quasi-elastic (2 body initial and final state) and the neutrino direction is known. Under these assumptions the neutrino energy can be reconstructed from the outgoing lepton kinematics. This has been applied very successfully for the experiments mentioned above but it might be insufficient for the next generation of oscillation experiments. The main reason is the fact that one of the main assumptions, target nucleon at rest is not accurate enough for large nucleus and the corrections to be applied depend on the exact model included in the experiments. Incorrect Fermi momentum and binding energy modelling might introduce bias of the order of 1% to 2% with non-gaussian dispersions. Other contributions such us the two nucleon interactions, long range correlations (RPA) and nuclear dressing (FSI) [10] might shift the energy reconstruction and it has to be consider as a systematic error. Figure 1 shows the prediction of NEUT Monte Carlo to the energy reconstruction dispersion *versus* the Fermi momentum of the target nucleon. As expected, the dispersion is larger for larger Fermi momentum. The predicted resolution of energy reconstruction will be affected by our understanding of the nuclear model.

The same argument apply to the reconstruction of the q^2 of the neutrino interaction and consequently to the acceptance calculation of the detector but also to the measurement of the axial mass based on the shape of q^2 distributions. This might explain the difference of the new M_A measurements that are carried in nuclei, at low energy and based on the q^2 shape with respect to old and recent measurement [11] at higher energies.

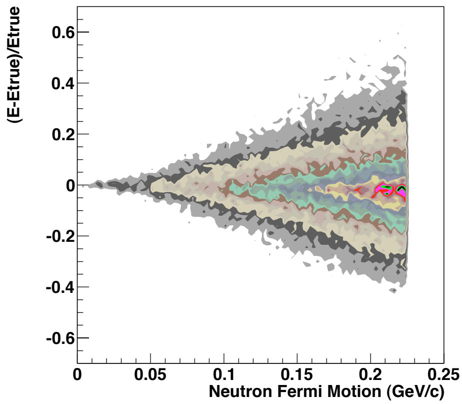

Fig. 1. Reconstructed energy resolution assuming CCQE interaction as a function of the fermi momentum of the target nucleon.

Similar technique for the energy reconstruction can be used for charged current single pion production [12] under the assumption that all pions are produced via a single resonance. CC1π is dominated by the $\Delta^{++}(1232)$ production, but many other higher mass resonances and non-resonance terms also contribute. Despite the lower accuracy of this energy reconstruction, it will help increasing the statistics of the far detector and having and independent measurement for the neutrino spectrum at the near detector in oscillation experiments.

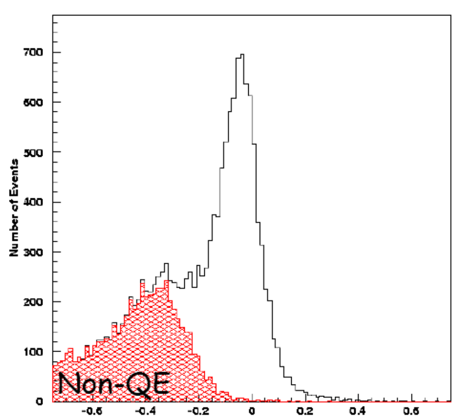

Fig. 2. Reconstructed energy assuming CCQE kinematics minos true energy for an inclusive sample of interactions. Non-QE contribution is shown in the shaded area (red).

The experimental challenge for the neutrino energy reconstruction goes beyond the momentum reconstruction of the outgoing lepton. The assumptions needed for the neutrino energy reconstruction requires an excellent identification of the neutrino interaction. A CC1π interaction comes up always as lower neutrino energy if we assume a CCQE interaction, see Fig. 2. From the other point of view, a low energy CCQE cannot be distinguished from a high energy CC1π. The identification can be carried out only looking at the hadronic part of the interaction that is very much affected by nucleon initial state and nuclear re-interactions.

4. Nuclear effects

K2K [7, 13] and MiniBoone [14] have also reported a deficit in measured events at low $|q^2|$ with respect to existing Monte Carlo models. The disagreement could be due to an incomplete implementation of nuclear effects [10] or to the bad prediction in background determination, in any case more precise measurements including final state particles are needed to fully understand the origin of the low $|q^2|$ deficit.

The other source of nuclear effects are the related to the re-interaction of nucleons and pions as they leave the nucleus. This is relevant to the identification of the interaction channel for the reconstruction of the energy and for the production of pions via neutral currents that are backgrounds for oscillation measurements. Models in MC are rather sophisticated, see

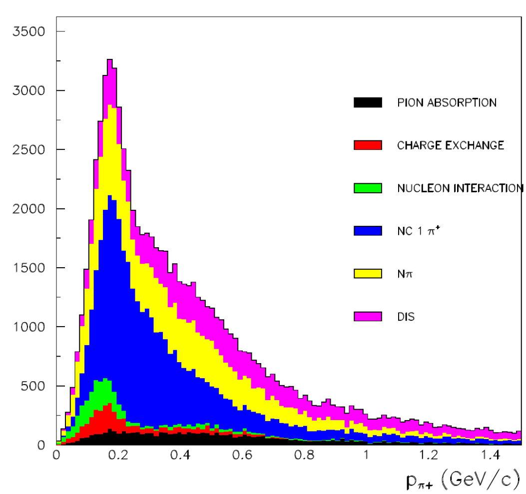

Fig. 3. Pion momentum distribution from 600 GeV/c neutrino beam. The three lower histograms showing small contributions are pions produced by nuclear reinteractions.

Fig. 3 for an example of the predictions of π^+ production in a neutrino beam, but they show discrepancies with observed quantities [15]. The reinteracted particle appear normally as lower momentum objects leaving the nucleus. To access these channels in an exclusive way, the detectors for low energy neutrinos [7–9, 16] are designed to be fully active with low detection thresholds.

5. Neutrino beam spectrum

One of the difficulties of the measurements presented above are the uncertainties in the knowledge of the neutrino beam energy spectrum. This spectrum is relevant not only for the near to far extrapolation at the oscillation experiments but also to de-convolute the cross-section in beams that are not monochromatic.

MINOS [5] experiment has approached the problem with a systematic set of measurements based on the flexibility to produce three distinct neutrino spectra. The accuracy of this prediction has been also checked with indirect measurements using muons from pion decays in the decay volume. In other approach, used at K2K [17] and MiniBooNE [18], stability has to be estimated additionally. The T2K near detector [16] could exploit the fact that the neutrino spectrum shifts across the detector when moving at different off-axis positions. SHIνE [19] experiment will measure for T2K the spectrum of pions produced in the interaction of 30 GeV protons with a replica of the aluminum target.

6. Conclusions

The new generation of neutrino oscillation experiments require increased precision in the understanding of neutrino–nucleus interactions below 2 GeV. The near detectors of oscillation experiments (T2K, Minos, MiniBoone) and some dedicated experiment will improve the understanding of neutrino interactions in the region from 500 MeV to almost 20 GeV. Open questions like the CCQE axial mass, the resonance to deep inelastic transition in charged current reactions, nuclear effects and their dependence with nuclear mass will be addressed with unprecedented precision. This precision will require also advances in the theoretical understanding and implementation in the experiment Monte Carlos. Previous experiences in the description of electron scattering are very valuable to obtain the vector form factors and for the description of initial and final state nuclear contributions.

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