Theoretical challenges in neutrino scattering studies

J. Nieves
Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain
E-mail: jmnieves@ific.uv.es

Abstract. New and more precise measurements of neutrino cross sections in the few GeV energy region have renewed interest in a better understanding of electroweak interactions on nucleons and nuclei. This interest comes from neutrino oscillation experiments and their need to reduce systematic errors. Neutrino fluxes used in contemporary long and short baseline experiments (K2K, T2K, MINOS, NOvA, MiniBooNE, MINERvA, ...) are peaked in the 1–5 GeV energy domain. In this context, I will present some details about the theoretical development in the description of (anti)neutrino-induced quasielastic scattering and the role of multi-nucleon mechanisms.

1. Introduction

Knowledge of neutrino interaction cross sections is an important and necessary ingredient in any neutrino measurement, and it is crucial to reduce systematic errors affecting present and future neutrino oscillation experiments, making new discoveries, like the CP violation in the leptonic sector, possible. This is because neutrinos are detected through their interactions with the nuclei that form part of the detectors. For nuclear physics this represents a challenge and an opportunity. A challenge because precise knowledge of neutrino oscillation parameters requires an accurate understanding of the detector responses, and it can only be achieved if nuclear effects are under control. An opportunity because neutrino cross sections incorporate richer information than electron-scattering ones, providing an excellent testing ground for nuclear structure, many-body mechanisms and reaction models. In addition, neutrino cross-section measurements allow us to investigate the axial structure of the nucleon and baryon resonances, enlarging our views of hadron structure beyond what is presently known from experiments with hadronic and electromagnetic probes. Moreover, the nuclear medium effects in these processes can be linked to chiral symmetry restoration in nuclear matter, and shed light to some parts of the QCD phase diagram.

At low energies the neutrino interacts with composite entities such as nucleons or nuclei. Given enough energy, the neutrino can actually begin to resolve the internal structure of the target: the neutrino can scatter off an individual quark inside the nucleon: DIS (deep inelastic scattering) and it manifests in the creation of a hadronic shower. In this talk, however, I will address some aspects of the low energy neutrino interactions, and I refer the reader to the reviews [1, 2, 3] (and references therein) on partonic nuclear effects in DIS relevant for the present and future neutrino long and short baseline experiments.

Some of the recent cross section measurements at low energies raised doubts in areas which seemed to be well understood. Thus, in the last years some questions emerged triggered by
theoretically surprising experimental results. What is the value of the QE (quasielastic) axial mass? How large is the two-body current contribution that can mimic genuine quasielastic interactions, and what it its influence in the reconstruction of the neutrino energy? How large is CC (charged current) coherent pion production at a few GeV neutrino energies? What is behind the large discrepancy between MiniBooNE pion production measurements and theoretical model predictions?, etc..

In this talk, I will concentrate on CC (anti-)neutrino-nucleus QE scattering, paying a special attention to the so called “MiniBooNE $M_A$ puzzle”.

2. MiniBooNE determination of $M_A$ and multinucleon absorption

Neutrino and antineutrino CC scattering on nuclei without pions exiting the nucleus (CCQE-like) is a fundamental detection channel for many neutrino experiments \([4, 5, 6, 7, 8]\) and has been theoretically studied within different approaches \([9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32]\). Experimentally, it has been generally assumed that most of those events, after subtracting the background due to the production of an on-shell pion in the first step followed by its absorption in the nucleus, could be attributed to the QE scattering of the weak probe with a bound nucleon.

In 2010, MiniBooNE published the first measurement of the muon neutrino CCQE double differential cross section \([6]\), based in this assumption. It turned out that the measured cross sections were much larger than the theoretical predictions \([33, 2, 34]\), and an unexpectedly large nucleon axial mass, $M_A = 1.35 \pm 0.17$ GeV, was required to describe these data \([6, 22, 16]\). The MiniBooNE antineutrino CCQE data \([35]\), selected in a similar way and published three years later, reinforced this puzzling situation. The value of $M_A$ determined from these experiments is in clear conflict with $M_A = 1.016 \pm 0.026$ GeV \([36]\) extracted from early CCQE measurements on deuterium and, to a lesser extent, hydrogen targets, which is, however, in excellent agreement with the pion electro-production result, $M_A = 1.014 \pm 0.016$ GeV, obtained from the nucleon axial radius \([34, 37]\) computed within chiral perturbation theory.

The solution to this puzzle came from the inclusion of long range RPA correlations and multinucleon nuclear effects. It was first pointed out in Refs. \([13, 14]\) that the QE-like sample includes also events where the $W^\pm$ is absorbed by two interacting nucleons (excitation of a 2p2h nuclear component in the quantum many body framework). Neglecting re-scattering processes which could eventually produce secondary pions, 2p2h events will not give rise to emitted pions, and thus they are experimentally misidentified as QE events. The importance of these multinucleon events was confirmed in Refs. \([23, 24]\). This latter approach and that derived in Refs. \([13, 14]\) also account for RPA corrections, and provided a good description of the MiniBooNE double differential (2D) neutrino \([24, 26]\) and antineutrino \([28, 29]\) cross sections, using a value of the order of 1 GeV for $M_A$.

The inclusive cross section for the process $\nu_\ell (k) + A_Z \rightarrow \ell^-(k') + X$ is determined by the $W$ gauge boson selfenergy in the nuclear medium \([10, 23]\), and in particular for the different modes in which it can be absorbed (the discussion is similar for antineutrino or neutral current driven processes). The most relevant ones are: the absorption by one nucleon, or by a pair of correlated nucleons that are exchanging virtual mesons ($\pi$, $\rho$, $\cdots$), or the excitation of a $\Delta$ or a higher energy resonance, etc. (see Fig. 1). The mechanism depicted in Fig. 1a) accounts for what I will call genuine QE events in what follows. There, the gauge boson $W$ is absorbed by just one nucleon, and it does not give rise to pions is the first step. MiniBooNE CCQE cross section includes events in which only one muon is detected, this sample (QE-like) does not include events with pions coming off the nucleus, since they will give rise to additional muons after their decay (see Fig. 1c). However, this event-sample includes multinucleon events, as those displayed in Fig. 1e, where the gauge boson is absorbed by two interacting nucleons. In any of these processes, the virtual pion, that is produced in the first step, will be necessarily
absorbed by a second nucleon, and thus the process should be classified as a two nucleon $W$ absorption mechanism. Hence, events originated by these kind of processes do not contribute to the genuine QE cross section, but they do to the cross section measured in the MiniBooNE experiment, because give rise to only one muon in the final state. Other events like real pion production followed by its absorption should be also included in the QE-like sample, though the MiniBooNE analysis MC (Monte Carlo) corrects for those. A word of caution is needed here. Let us pay attention to processes like the one depicted in the bottom panel of Fig. 1c, the crucial difference with the mechanism in Fig. 1e is that in the latter, the pion is off-shell instead of being on the mass-shell as in Fig. 1c. As a result of the final state interaction, this real pion might be absorbed or its four-momentum be changed, but this unwanted background can be in principle estimated by means of a MC simulation.

![Diagram](image)

**Figure 1.** Diagrammatic representation of some diagrams contributing to the $W$—selfenergy and their connection with different absorption modes of the gauge boson in the nuclear medium.

The existence of 2p2h contributions, in addition to the QE genuine ones, produces an unwanted bias in the measurements carried out in the far detector of long baseline experiments. This has a quantitative impact in the determination of the oscillation parameters, which might even exceed the current $(m_{31}^2 - \theta_{23})$ 95% confident level contours [38, 39].

The relevance of the multinucleon mechanisms has other unwanted consequences. Obviously, the neutrino energy reconstruction, based on the genuine QE kinematics is not so reliable [25, 40, 41, 42], and that implies another source of systematic uncertainties in the analysis of the experiments. Furthermore, if the contribution of multinucleon mechanisms is substantially different in neutrinos and antineutrinos, as predicted for instance in Refs. [14, 18] and this is not properly understood, it could lead to an asymmetry between $\nu$ and $\bar{\nu}$ which could be misinterpreted as a consequence of CP violation.

The microscopical model used in [23, 28] describes the neutrino and antineutrino MiniBooNE CCQE flux averaged cross section $d\sigma/dT_{\mu}/d\cos\theta_{\mu}$ [6, 35] using $M_A = 1.05$ GeV, as can be seen in Fig. 2. We should stress that, not only multinucleon mechanisms, but also RPA corrections turn out to be essential to describe the data. Medium polarization or collective RPA correlations account for the change of the electroweak coupling strengths, from their free nucleon values, due to the presence of strong correlations between the bound nucleons through the whole nucleus [10]. RPA strongly decreases the cross section at low energies, while
multinucleon mechanisms accumulate their contribution at low muon energies and compensate for that depletion [24]. Therefore, the final picture is that of a delicate balance between a dominant single nucleon scattering, corrected by collective effects, and other mechanisms that involve directly two or more nucleons. Both effects can be mimicked by using a large $M_A$ value as done in the original experimental analysis [6]. However, neglecting either of the two effects would lead to a poor description of the data and also lead to incorrect neutrino energy reconstruction.

M. Martini and collaborators find similar results [26, 29], since their model contains the same ingredients: RPA correlation effects and multinucleon mechanisms. Both models provide similar neutrino genuine QE cross sections, with and without RPA corrections, but however, differ in about a factor of two in their estimation of the size of the multinucleon effects. As a consequence of this reduced 2p2h contribution, our predictions in Ref. [24] favor a global normalization scale of about 0.9, which is not required by the model of Refs. [26, 29]. This value of the overall scale is consistent with the MiniBooNE estimate of a total flux normalization error of 10.7%. The evaluation in [23, 24] of multinucleon emission contributions to the cross section is fully microscopical, and it starts from a state-of-the-art model [43, 44, 45, 46] for the $W N \rightarrow \pi N$ reaction at intermediate energies and contains terms, which were either not considered or only approximately taken into account in [13, 14, 26]. Indeed, these latter works rely on the computation of the 2p2h mechanisms for the $(e, e')$ inclusive reaction in [47], which results are used for neutrino-induced processes.

Recent results from T2K [48] and MINERvA [49] show sizable nuclear effects for all muon kinematics, with models including 2p2h+RPA contributions describing better the data. Thus, 2p2h effects result essential for complete modeling of neutrino interactions at low momentum transfer. In Ref. [49] is tested the model of Ref. [23], though it improves the description of the event rate in the region between the QE and the $\Delta(1232)$ peaks, and the rate for multiproton events, it does not go far enough to fully described the data. T2K measurement is not precise enough to disentangle between the models of Refs. [23] and [26].

3. Conclusions

I have addressed the neutrino and antineutrino MiniBooNE CCQE-like double differential cross-section data using the theoretical model of Refs. [10, 23]. The model, that begins with a relativistic local Fermi gas description of the nucleus, includes long range RPA correlations and multinucleon mechanisms. The same model is quite successful in the analysis of nuclear reactions with electron [50, 51, 52], photon [53, 54] and pion [55, 56, 57, 58, 59, 60, 61, 62, 63] probes and contains no additional free parameters. RPA and 2p2h contributions are essential for the description of the data, which in sharp contrast with previous analysis, can be described using previous determinations of the nucleon axial mass, both using neutrino and electron beams, around 1 GeV.

The existence of un-modelled 2p2h contributions, in addition to the QE genuine ones, produces an unwanted bias in the measurements carried out in the far detector of long baseline experiments. This has a quantitative impact in the determination of the oscillation parameters and in the neutrino energy reconstruction.

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Figure 2. Muon angle and energy neutrino (top) and antineutrino (bottom) $d^2\sigma/d\cos\theta\mu dT_\mu$ distributions on a $^{12}$C target folded with the MiniBooNE muon neutrino or antineutrino fluxes. Different panels correspond to the various angular bins labeled by their cosine central value. Data have been taken from Refs. [6] (top) and [35] (bottom). Additional normalization uncertainties are not displayed. The green-dashed (top) and black-solid (bottom) lines show the results from the full model of Refs. [10] and [23] (including multinucleon mechanisms and RPA) with $M_A = 1.05$ GeV. In addition, in the top panels the red-solid line is obtained with a Fermi gas model with $M_A = 1.32$ GeV and without including RPA and multinucleon mechanisms contributions, while the red-dash-dotted and and blue-dashed curves in the bottom panels corresponds to QE-RPA and to 2p2h events, respectively. See Refs. [24] and [28] for further details.

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