Recent developments in neutrino-nucleus scattering theory*

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Abstract

In the present and future accelerator-based neutrino oscillation experiments nuclear targets (such as C, O, Ar and Fe) are involved. Hence the knowledge of neutrino-nucleus scattering is very important. In particular it is crucial for the determination of the neutrino energy which enters the expression of the oscillation probability. The status of the different theoretical approaches treating the open channels in the few-GeV region, i.e. the quasielastic, the pion production and the multinucleon emission, is reviewed. Special emphasis is devoted to the multinucleon emission channel, which turned to be crucial to explain the unexpected behavior of the charged current quasielastic measurement performed by MiniBooNE. The theoretical and experimental interest towards these multinucleon excitations continues to increase.

INTRODUCTION

Neutrino physics has undergone a spectacular development in the last decade, following the discovery of neutrino oscillations. In the present and future accelerator-based neutrino oscillation experiments nuclear targets, such as ^{12}C, ^{16}O ^{40}Ar or ^{56}Fe, are involved, hence the knowledge of neutrino-nucleus scattering is very important. In particular it is crucial for the determination of the neutrino energy which enters the expression of the oscillation probability. In accelerator-based experiments the neutrino beams (at difference with respect to electron beams, for example) are not monochromatic but they span a wide range of energies, hence the incoming neutrino energy is reconstructed from the final states of the reaction. This determination is typically done through the charged current quasielastic (CCQE) events, commonly defined as those in which the emission product only includes one charged lepton. The reconstructed energy hypothesis used to obtain the neutrino energy from the measured charged lepton variables (energy and scattering angle) via a two-body formula is that the neutrino interaction in the nuclear target takes place on a nucleon at rest. The identification of the reconstructed neutrino energy with the real one is too crude. Several nuclear effects such as Pauli blocking, Fermi motion, collective aspects of the nuclear response and, very important, multinucleon emission, need to be taken into account. Furthermore, the fact that in the accelerator-based experiments the incoming neutrino beam exhibits a wide spectrum of energies implies that not only the quasielastic but also other reaction mechanisms, such as for example the pion production, contribute to the neutrino nucleus cross section. The status of the different theoretical approaches treating the open channels in the few-GeV region, i.e. the quasielastic, the pion production and the multinucleon emission, is here reviewed, devoting special emphasis to the multinucleon emission channel.

QUASIELASTIC AND MULTINUCLEON EMISSION

The multinucleon emission channel in connection with the quasielastic has attracted a lot of attention in these last years. In fact, as illustrated in Fig. 1, the inclusion of this channel in the quasielastic cross section was suggested [1, 2] to be the possible explanation of the MiniBooNE CCQE total cross section on carbon [3], apparently too large with respect to many theoretical predictions employing the standard value of the axial mass. Since the MiniBooNE experiment, as well as other experiments involving Cherenkov detectors, defines a charged current "quasielastic" event as the one in which only a final charged lepton is detected, the ejection of a single nucleon (a genuine quasielastic event) is only one possibility, and one must in addition consider events involving a correlated nucleon pair from which the partner nucleon is also ejected, as discussed first in Ref. [4]. This leads to the excitation of 2 particle-2 hole (2p-2h) states; 3p-3h excitations are also possible. The inclusion in the quasielastic cross section of events in which several nucleons are ejected (np-nh excitations), leads to an excess over the genuine quasielastic value. Martini *et al.* [1, 2] have argued that this is the likely explanation of the MiniBooNE anomaly showing that their evaluation can account for the excess in the cross section without any modification of the axial mass. After this suggestion the interest of the neutrino scattering and oscillation communities on the multinucleon emission channel rapidly increased. Indeed this channel was not included in the generators used for the analyses of the neutrino cross sections and oscillations experiments. Today there is an effort to include this np-nh channel in several Monte Carlo. Concerning the theoretical situation, nowadays several calculations agree on the crucial role of the multinucleon emission in order to explain the MiniBooNE neutrino [3] and antineutrino [5] data. Nevertheless there are some differences on the results obtained for this np-nh channel by the different theoretical approaches. The aim of this section is to review the current theoretical status on this subject.

The theoretical calculations of np-nh excitations contributions to neutrino-nucleus cross sections are presently performed essentially by three groups. There are the works of Martini

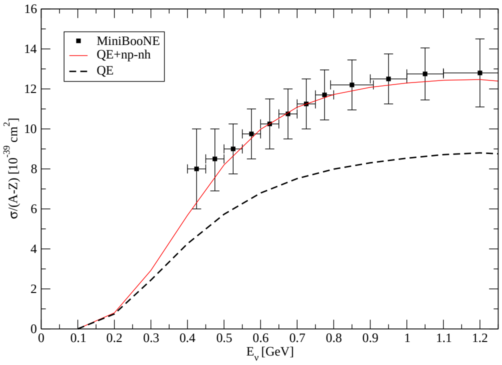

FIG. 1: Charged current "Quasielastic" cross section on carbon measured by MiniBooNE [3] compared to Martini *et al.* calculations. The figure is taken from Ref. [1].

et al. [1, 2, 6–11], the ones of Nieves *et al.* [12–16] and the ones of Amaro *et al.* [17–23]. The np-nh channel is taken into account through more phenomenological approaches in the so called Transverse Enhancement Model (TEM) [24] and in GiBUU [25–27]. In the 2p-2h sector, the three microscopic approaches mentioned above are based on the Fermi gas. We remind that there exist several two-body current contributions. We have first of all the Meson Exchange Currents (MEC), given by the pion-in-flight term, the contact term and the Δ-intermediate state or Δ-MEC term. Furthermore in the independent particle models, such as the Fermi gas, the nucleon-nucleon (NN) correlations must be taken into account. It is possible by including an additional two-body current, the correlation current. Even in the simple Fermi gas model, an exact relativistic calculation of all the two-body current contributions is difficult for several reasons. First of all it involves the computation of 7-dimensional integrals for a huge number of 2p-2h response Feynman diagrams. Second divergences in the NN correlations sector and in the angular distribution of the ejected nucleons [20, 21] may appear and need to be regularized. Furthermore the calculations should be performed for all the kinematics compatible with the experimental neutrino flux. For these reasons an exact relativistic calculation is computationally very demanding and as a consequence different approximations are employed by the different groups in order to reduce the dimension of the integrals and to regularize the divergences. The choice of subset of diagrams and terms to be calculated presents also important differences. In this connection Amaro *et al.* explicitly add to the genuine quasielastic only the MEC contributions and not the NN correlations-MEC interference terms. MEC contributions, NN correlations and NN correlations-MEC interference are present both in Martini *et al.* and Nieves *et al.* even if Martini *et al.* consider only the Δ-MEC. On the other hand the treatment of Amaro *et al.* is fully relativistic as well as the one of Nieves *et al.* while the results of Martini *et al.* are related to a non-relativistic reduction of the two-body currents. The interference between direct and exchange diagrams is neglected by Martini *et al.* and Nieves *et al.* Another important difference is that Amaro *et al.* consider the 2p-2h contribution only in the vector sector while Martini *et al.* and Nieves *et al.* also in the axial one. Fully relativistic calculations of Amaro *et al.* for the axial sector are in progress but not published. In this connection, some preliminary results have been presented for the first time by Megias at this conference [23]. Taking into account the existence of all these differences, is not surprising that these models produce different final results. This point is illustrated in Fig. 2 where the MiniBooNE neutrino and antineutrino flux folded double differential CCQE-like cross sections calculated in the different approaches are displayed. For sake of illustration the results are given for $0.8 < \cos\theta < 0.9$ as function of the muon kinetic energy. The complete theoretical results in the different bins for neutrinos and antineutrinos are given in Refs. [6, 9] for Martini *et al.*, in Refs. [13, 15] for Nieves *et al.* and in Refs. [17, 19] for Amaro *et al.* An updated version of the last results is given by Megias *et al.* in Ref. [22] from which we take the results reported in the last two panels of Fig. 2. As one can observe from Fig. 2 the results of Martini *et al.* are in good agreement with the experimental data. In the case of Nieves *et al.* and Amaro *et al.* there is a tendency to underestimate the MiniBooNE data. The preliminary results shown by Megias [23] including also the axial contributions are in a better agreement with the MiniBooNE data. An important point is that the relative role of the multinucleon contribution is different for neutrino and antineutrino in the different approaches. The nuclear cross-section difference for neutrinos and antineutrinos stands as a potential obstacle in the interpretation of experiments aimed at the measurement of the CP violation angle, hence has to be fully mastered. As discussed in Refs. [2, 11, 19] the difference between the neutrino and antineutrino results is due to the presence in the neutrino-nucleus cross section expression of the vector-axial interference term, which changes sign between neutrino and antineutrino, the basic asymmetry which follows from the weak interaction theory. Due to this vector-axial interference term, the relative weight of the different nuclear responses is different for neutrino and antineutrino. As a consequence also the relative weight of the np-nh contributions is different for neutrino

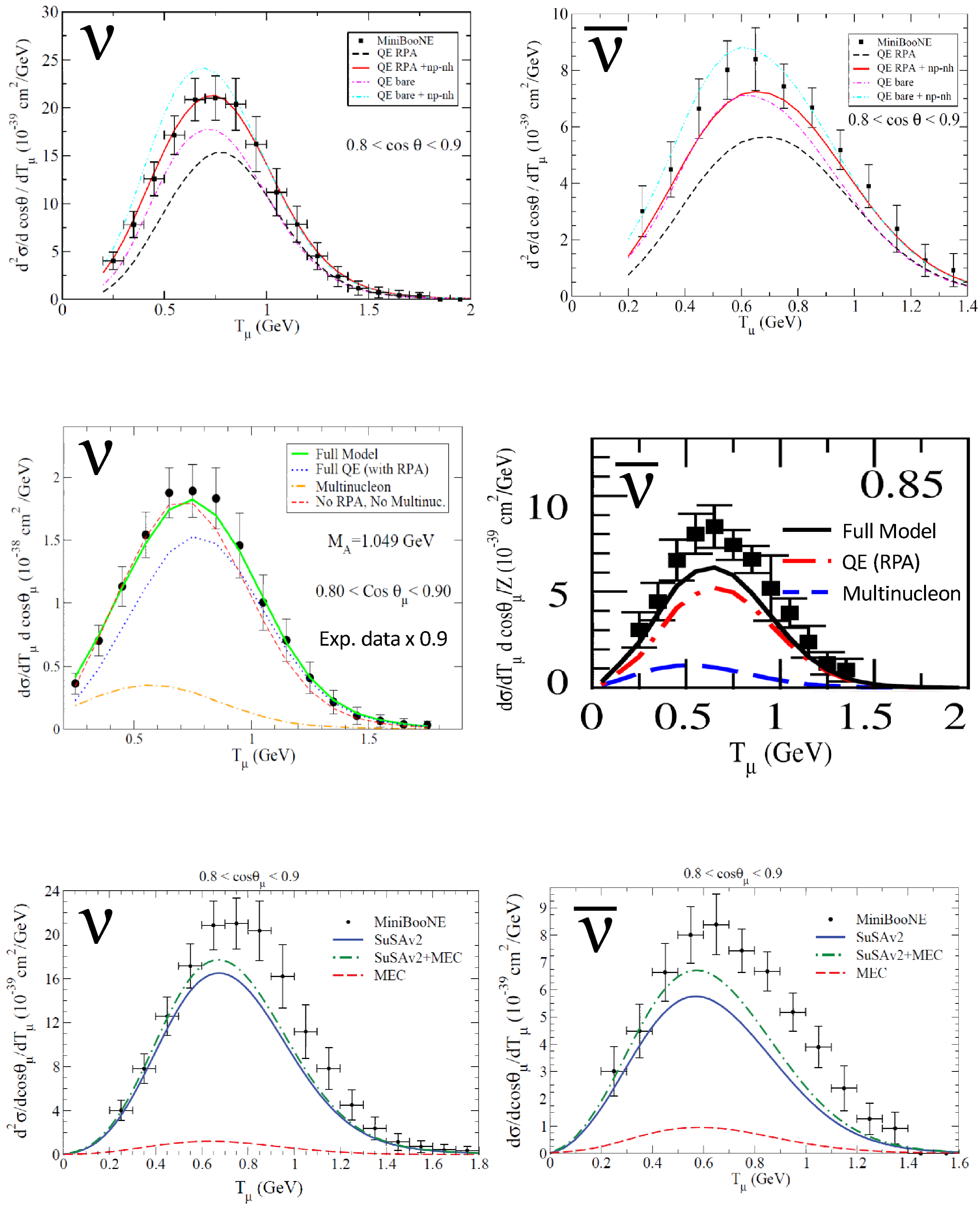

FIG. 2: MiniBooNE flux integrated neutrino (left panels) and antineutrino (right panels) CCQE-like double differential cross section on carbon per active nucleon for $0.8 < \cos\theta < 0.9$ as a function of the muon kinetic energy. Top panels: Martini *et al.* [6, 9] results. Middle panels: Nieves *et al.* [13, 15] results. Bottom panels: Megias *et al.* [22] results representing an update of the Amaro *et al.* [17, 19] results.

and antineutrino. For example the fact that np-nh contributions are larger for antineutrinos with respect to neutrinos in the case of Amaro *et al.* is due to the fact that Amaro *et al.* consider the np-nh contributions only in the vector sector, hence not in the vector-axial interference term. In order to investigate the multinucleon content of the vector-axial interference term, Ericson and Martini have recently considered [11] the difference between the neutrino and antineutrino MiniBooNE quasielastic-like double-differential cross sections. They have shown that the model of Martini *et al.*, which includes the np-nh excitations in the vector-axial interference term, gives a good fit for the difference of the MiniBooNE cross sections reproducing well the data in the full range of muon energy and emission angle. This result represents an important test for the presence of the multinucleon component in the vector-axial interference term. A similar conclusion on a relevant two-body current contribution in the vector-axial interference term has been recently obtained by Lovato *et al.* [28, 29] who calculated the neutral weak current two-body contributions to sum rules and Euclidean responses in ^{12}C.

Up to now we have discussed the theoretical models in connection with the MiniBooNE cross sections. For the moment the theoretical calculations for the np-nh excitations are restricted to the relatively small energy and momentum transfer, prevalent in the MiniBooNE and T2K experiments. Concerning T2K, the measurement performed by this collaboration of charged-current double differential cross sections on carbon with zero pions in the final state (CC0π) has been presented for the first time at this conference [30]. These experimental results have also been compared with the theoretical predictions of Martini *et al.* and Nieves *et al.* Also in this case a good agreement with data is obtained adding to the genuine quasielastic cross section calculated in RPA the multinucleon contributions.

How the np-nh processes behave at large energy and momentum transfer is still an open question. Nevertheless, Megias *et al.* in Ref. [22] applied the model of Amaro *et al.*, which includes only vector MEC contributions, to neutrino energies of up to 100 GeV and compared their predictions also with NOMAD [31] and MINERνA neutrino [32] and antineutrino [33] CCQE data. Preliminary comparison with NOMAD total CCQE cross sections including in the theoretical calculations also axial two-body current contributions have been presented for the first time by Megias at this conference [23]. Gran *et al.* [16] applied the model of Nieves *et al.* to neutrino energies of up to 10 GeV. However they placed a cut on the three-momentum transfer of 1.2 GeV. They compared their results with the MINERνA neutrino and antineutrino CCQE Q^2 distribution. A similar comparison has been performed also by Mosel *et al.* [27] using GiBUU. As a general remark, by comparing the results of Refs. [16, 22, 27] with MINERνA data, one can observe that the MINERνA Q^2 distributions can be reproduced also without the inclusion of np-nh excitations. This is not the case of the MiniBooNE Q^2 distributions [6, 9, 22]. A reasonable simultaneous agreement with the MiniBooNE and MINERνA Q^2 distributions is obtained by Meucci and Giusti [34] using the relativistic Green's function model with a complex optical potential.

PION PRODUCTION AND INCLUSIVE CROSS SECTIONS

In this section we rapidly discuss the present situation for the pion production and inclusive cross sections. In the one pion production channel some questions are still open. For instance, theoretical calculations [10, 35, 36] of CC $1\pi^+$ single and double differential cross sections as a function of muon variables are in agreement with the MiniBooNE data [37]. On the contrary theoretical works [36, 38] on the MiniBooNE differential cross sections function of the final pion variables display a reshaping of the differential cross section due to the inclusion of pion final state interaction which suppresses the agreement with the MiniBooNE data. More recently the MINERνA experimental results appear [39]. Nowadays there is a general tendency of theoretical calculations and Monte Carlo results to underestimate the MiniBooNE data [37, 40] and to overestimate the MINERνA ones [39]. This is discussed for example in Refs. [41, 42]. Further investigations are needed. We remind the different energies of MiniBooNE and MINERνA neutrino beams.

The inclusive ν_μ CC double differential cross section on carbon has been published by T2K in Ref. [43]. The inclusive measurements are important because they are less affected by background subtraction with respect to exclusive channels measurements. Martini and Ericson have compared their predictions with the T2K experimental results in Ref. [10]. In this paper they have shown that in order to obtain an agreement with the T2K inclusive data one needs to consider not only the genuine quasielastic and the one pion production channels but also the multinucleon excitations. These results represent the first successful test of the necessity of the multinucleon emission channel in an experiment with another neutrino flux with respect to the one of MiniBooNE. This conclusion, using the same theoretical model, has been recently reached also in connection with the T2K CC0π results mentioned above and the ν_e charged-current inclusive differential cross sections on carbon [44]. This agreement with both ν_μ and ν_e CC inclusive T2K flux folded differential cross sections is not systematically obtained in other approaches. For instance the SuSAv2 model by Ivanov et al *et al.* [45] reproduces well the CC inclusive T2K flux folded ν_μ double differential cross section but underestimates the CC inclusive T2K flux folded ν_e single differential cross section. A comparison with these quantities has also been performed by Meucci and Giusti using the Relativistic Green's function model which turned to underestimate the ν_μ and ν_e CC inclusive T2K data [46]. Finally, interesting differences between the T2K flux folded ν_μ results obtained by the various theoretical approaches appear in particular in the forward direction where low-lying giant resonance contributions can be non-negligible, as pointed out in Ref. [10], and explicitly shown in Ref. [47].

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