EPJ Web of Conferences **66**, 08004 (2014)
DOI: 10.1051/epjconf/20146608004

Neutrino-nucleus interactions: from nuclear dynamics to neutrino oscillations

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Abstract. We present a theory of neutrino interactions with nuclei aimed at the description of several partial cross sections, namely quasielastic and multinucleon emission, coherent and incoherent single-pion production. We put a special emphasis on the multinucleon emission channel which is related to the two particle-two hole excitations. As we suggested, this channel can account in particular for the unexpected behavior of the quasielastic cross section measured by MiniBooNE. The impact of the multinucleon emission channel on the neutrino energy reconstruction procedure hence on the determination on the neutrino oscillation parameters, is also analyzed in connection with the recent T2K and MiniBooNE results.

1 Introduction

Neutrino physics has undergone a spectacular development in the last decade, following the discovery of neutrino oscillations. In the neutrino oscillation experiments nuclear targets, such as ^{12}C or ^{16}O, are involved, hence the knowledge of neutrino-nucleus scattering is crucial. A number of results have been obtained for quasielastic processes or coherent and incoherent single pion production by several experiments (K2K, MiniBooNE, SciBooNE, T2K). The question is then if our present understanding of neutrino interactions with matter can reproduce the available data. Many works have been devoted to this problem, using various theoretical approaches. In our works [1–4], we explore these interactions in the energy region around 1 GeV using the formalism of the nuclear response functions treated in the Random Phase Approximation (RPA) and incorporating Δ-resonance excitation. This approach has the merit of describing in a unique frame several final state channels. It incorporates the treatement of the multinucleon emission channel which, as we suggested [1], can account in particular for the unexpected behavior of the quasielastic cross section measured by MiniBooNE [5]. The impact of this multinucleon emission channel on the neutrino energy reconstruction procedure (which is based on the quasielastic kinematics in the experimental analysis), hence on the determination on the neutrino oscillation parameters, is also presented by summarizing the main results of Refs. [6, 7] related to the MiniBooNE and T2K oscillation experiments.

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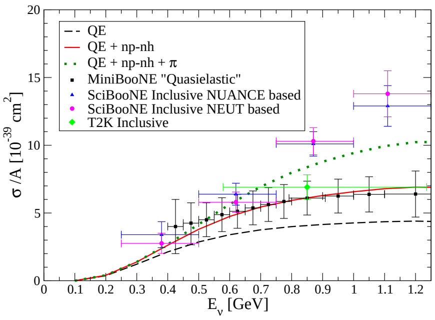

Figure 1. “Quasielastic” and inclusive cross sections measured by MiniBooNE [5], SciBooNE [9] and T2K [10] compared to our calculations.

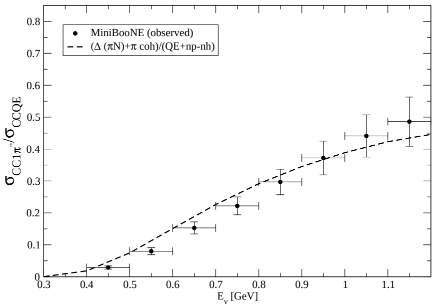

Figure 2. Ratio of the ν_μ-induced charged current one π^+ production to “quasielastic” cross section. The MiniBooNE data are taken from Ref. [11]

2 Neutrino-nucleus cross sections

For a complete description of our model and results we refer to [1–4].

The main feature of our model is the treatment of the multinucleon emission channel in connection with the quasielastic. In fact, as suggested in [1, 2], and illustrated in Fig. 1, the inclusion of this channel in the quasielastic cross section is the possible explanation of the MiniBooNE quasielastic total cross section [5], apparently too large with respect to many theoretical predictions employing the standard value of the axial mass. Since the MiniBooNE experiment, as well as many others 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 [8]. This leads to the excitation of 2 particle-2 hole (2p-2h) states; 3p-3h excitations are also possible. As illustrated in Fig. 1, also the inclusive cross section measured by SciBooNE [9] and T2K [10], which is less sensitive to the background subtraction with respect to exclusive channels, can be reproduced, at lest up to $E_\nu \simeq 1$ GeV once the multinucleon (np-nh) channel is added to the genuine quasielastic and the pion production ones.

The agreement of our model with the experimental data in the pion production channels has been proved. For sake of illustration we present in Fig. 2 a comparison between the experimental result, given by MiniBooNE [11], and our model on the ratio beween charged current π^+ production and the quasielastic cross sections.

In Figs. 1 and 2 as well as in Refs. [1, 2] we focus on cross sections as a function of the neutrino energy. Nevertheless these quantities are affected by the energy reconstruction problem (see later). For a comparison between theory and experiment the most significant quantities are the double differential cross sections which are function of two measured variables, the muon energy and the scattering angle.

In Refs. [3] and [4] we have calculated these cross sections for neutrino and antineutrino charged current “quasielatic” scattering on carbon and we have compared with the MiniBooNE experimental data [5, 12]. Some examples of the published results are given in Fig. 3. The agreement of our RPA approach with data is good once the np-nh component is included. We observe also that the antineutrino cross section falls more rapidly with angle than the neutrino one. This also reflects in the Q^2 distribution shown in Fig. 4. These Q^2 distributions establishe the necessity of the multinucleon contribution, independently of the RPA quenching. As discussed in details in [2], in spite of the identity

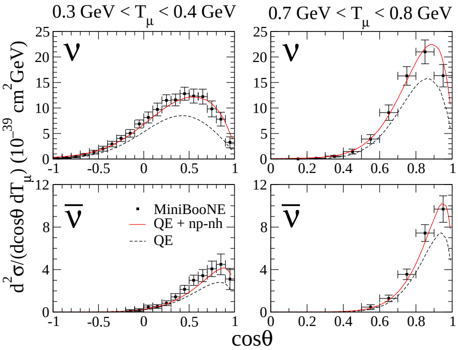

Figure 3. MiniBooNE flux-averaged double differential QE cross section for some values of T_μ. Experimental data are taken from Ref. [5] for neutrino and from Ref. [12] for antineutrino.

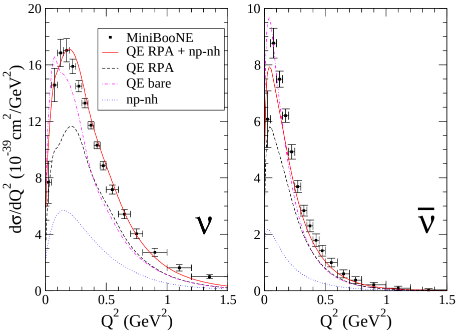

Figure 4. MiniBooNE flux-averaged Q^2 distribution. Experimental data are taken from Ref. [5] for neutrino and from Ref. [12] for antineutrino.

of the inputs, which are the nuclear response functions, for neutrino and antineutrino calculations the various responses weight differently in the respective cross sections, generating an asymmetry of the nuclear effects for neutrinos and antineutrinos which is important for CP violation syudies.

3 Neutrino energy reconstruction problems and neutrino oscillations

Neutrino oscillation experiments require the determination of the neutrino energy which enters the expression of the oscillation probability. This determination is commonly done through the charged current neutrino-nucleus "quasielastic" events. For these events where only the charged lepton is observed, the only measurable quantities are then its direction, i.e., its emission angle θ with respect to the neutrino beam direction and its energy E_l (or kinetic energy T_l and momentum P_l). The neutrino energy E_ν is unknown. The usual reconstruction procedure assumes that we are dealing with a genuine quasielastic event on a nucleon at rest. The quasielastic condition then gives the value $\overline{E_\nu}$ of the reconstructed energy: $\overline{E_\nu} = \frac{E_l - m_l^2/(2M)}{1-(E_l-P_l\cos\theta)/M}$. Several nuclear effects can influence this expression. The most important are the np-nh events which have no reason to fulfill the quasielastic relation. This means that for a given set of lepton variables, E_l and θ, an infinity of neutrino energy values, instead of the unique quasielastic value implemented in the neutrino energy reconstruction formula, is possible.

Data on neutrino oscillation often involve reconstructed neutrino energies while the analysis implies the real neutrino energy. The corrections corresponding to the transformation from real to reconstructed energy and viceversa are discussed in details in Refs. [6, 7] to which we refer the reader. Here we just summarize some of the main results. Starting from a theoretical distribution expressed with real energies, *i.e.* the product of the neutrino cross section $\sigma(E_\nu)$ by the neutrino energy distribution of the beam $\Phi(E_\nu)$, we performed a smearing procedure to deduce the corresponding distribution of the events, $D_{rec}(\overline{E_\nu})$, in terms of the reconstructed energy. This distribution can be expressed in terms of the double differential neutrino-nucleus cross section and also involves the neutrino flux distribution $\Phi(E_\nu)$, hence the neutrino oscillation parameters.

In Figs. 5 and 6 we show the application of our procedure to the three distributions measured in T2K: muonic distributions in the near detector (ND) and far detector (FD) and electron distribution in the far detector. The influence of the reconstructed energy corrections is such that the events tend

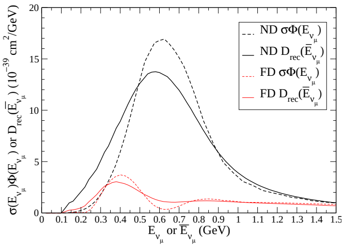

Figure 5. T2K distributions per neutrons of muon events before (dashed lines) and after (continuous lines) reconstruction in the near and far detector

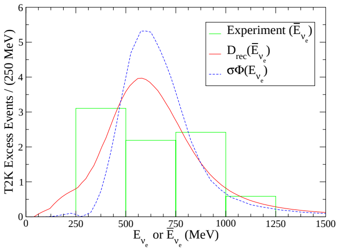

Figure 6. T2K oscillation electron events energy distributions before (dashed lines) and after (continuous lines) smearing. The experimental histogram [13] is shown.

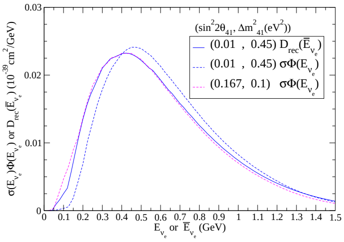

Figure 7. Effect of the smearing procedure for a mass parameter $\Delta m^2_{41} = 0.45$ eV^2 and comparison with the unsmeared case with $\Delta m^2_{41} = 0.1$ eV^2.

to escape from the region of high fluxes with a tendency to concentrate at lower energies. This is an effect of the multinucleon component of the quasielastic cross section. The smeared distribution effect depends on the particular shape of the neutrino energy distribution, the correction being more pronounced for broad distributions. The effects are such that an analysis which takes into account the smearing effect is likely to lead to some increase of the oscillation mass value.

The Fig. 7 is related to the MiniBooNE electron neutrino appearance results where the oscillations, if they exist, imply sterile neutrinos with a much larger mass parameter, in the eV range. The accumulation of electron events observed in the low energy sector favors relatively low values of this mass term which imply large mixing angles, not compatible with existing constraints. This contradiction can be in part solved by the inclusion of the smearing effects. As can be deduced from Fig. 7 taking into account the smearing, a large mass value $\Delta m^2_{41} = 0.45$ eV ^{2} can allow the same quality of fit of the data than is obtained in the unsmeared case with a much smaller mass $\Delta m^2_{41} = 0.1$ eV ^{2}. Obviously there is an important gain for the compatibility with the existing constraints since the angle θ_{41} can be smaller with a larger mass value. Our suggestions have been taken into account in the last analysis of electron neutrino and antineutrino appearance data performed by MiniBooNE [14].

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