Neutrino-nucleus cross-sections: a unified theoretical approach for nucleon knock-out, coherent and incoherent pion production

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Abstract
Neutrino-nucleus cross-sections are needed to interpret neutrino oscillation data, as neutrino detectors involve complex nuclei. We present a theory of neutrino interactions with nuclei aimed at a unified description of the partial cross-sections, namely quasi-elastic and multi-nucleon emission, coherent and incoherent single pion production. We compare our approach to the available neutrino experimental data on carbon. We also discuss the evolution of the neutrino cross-sections with the mass number in view of future precision experiments which will use a liquid argon chamber.

1 Introduction

Neutrino physics has undergone a spectacular development in the last decade, following the discovery of neutrino oscillations. A number of results on the interaction of neutrinos with matter are now available. Neutrino detectors do not usually consist of pure hydrogen but they involve complex nuclei for instance ^{12}C, as in SciBar, where the molecule C_8H_8 is involved, or in MiniBooNE which uses the mineral oil CH_2. Heavier nuclei are also under consideration for instance in the liquid argon chamber planned for T2K. A number of results have been obtained, for neutral or charged current (K2K, MiniBooNE, SciBooNE) on quasi-elastic processes or coherent and incoherent single pion production (*e.g.* [1, 2, 3, 4]). The first 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 work, 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. For a complete description of our model we refer to [5]. Here we just sketch the basic ideas.

Several types of nuclear responses enter the total neutrino-nucleus cross-section: the isovector, the spin-isospin transverse or longitudinal. The bare response, related to the polarization propagator $\mathrm{Im}\Pi^0$, is the sum of quasi-elastic, incoherent one-pion production and two- or three-nucleon knock-out partial components. The RPA response generically writes

$$\mathrm{Im}\Pi = |\Pi|^2 \ \mathrm{Im}V \ + |1 + \Pi\, V|^2 \ \mathrm{Im}\Pi^0 \,. \tag{1}$$

It splits in two terms. The first implies a cut on the pion exchange potential V_π. It represents the coherent pion production where the nucleus is left in the ground state. The second, proportional to the bare polarization propagator $\mathrm{Im}\Pi^0$, reflects the type of final state already mentioned in the bare case, modified by collective effects. In the following we present the results obtained for each of them.

2 Results

Concerning the *coherent pion production*, the response naturally associated to this process is the spin-isospin longitudinal one, since it has the same coupling as the pion. We have tested our description of the coherent responses on the elastic π -^{12}C scattering which is sensitive to collective effects.

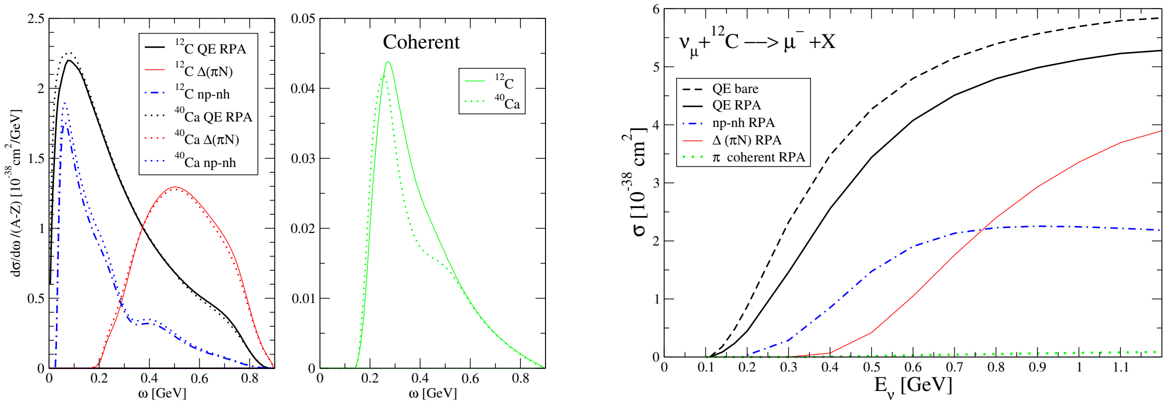

Fig. 1: Left panel: differential ν_μ-^{12}C and ν_μ-^{40}Ca charged current cross-section as a function of transferred energy in the various channels for E_ν=1 GeV. Right panel: total ν_μ-^{12}C CC cross-section in the various channels.

The *quasi-elastic* channel corresponds to a single-nucleon knock-out. This process is dominated by the spin-isospin transverse response. The RPA effects tend to reduce the cross-section, as expected from the repulsive character of the particle-hole interaction which dominates in the transverse channel. A distinct feature of our model is that we can take into account also *multi-nucleon emission*, namely two- and three-nucleon knock-out cross-sections, whose sum represents a sizable fraction of the quasi-elastic channel. Part of multi-nucleon channels arises from the modification of the Δ width in the medium where other decay channels are possible. The remaining contribution is taken from an extrapolation of the calculations on the two-particle - two-hole $(2p-2h)$ absorption of pions at threshold. In neutrino interactions this last part of the cross-section is important but not very well constrained by phenomenology. We tested this channel considering also another parametrization of the $2p-2h$ responses deduced from a microscopic evaluation of the $2p-2h$ contribution to the transverse magnetic response of (e, e') scattering.

Turning now to *incoherent pion emission*, the pion arises from the pionic decay of the Δ leaving the nucleus in a particle-hole excited state. As compared to a free nucleon, the emission probability in the nucleus is already reduced in the bare case by the change in the Δ width. Moreover the RPA effects, which are moderate, also contribute to this reduction. The reduction due to the modification of the Δ width has a counterpart in the presence of the multi-nucleon knock-out component discussed before.

All the previous results are summarized in Fig. 1 which displays the muon-neutrino differential cross-section per neutron in the various channels as a function of the energy transfer for the case of ^{12}C and ^{40}Ca and a neutrino energy of 1 GeV. One can see that the evolution of this quantity with the mass number is quite weak. Only the coherent cross-section presents a significant variation. The total neutrino-^{12}C cross-section is also displayed.

3 Comparison with data

Experimental data concern ratios between different cross-sections. For charged current, the SciBooNE collaboration has established a 90% confidence-level upper limit on the ratio of coherent pion production to the total cross-section, giving a value of $0.67\ 10^{-2}$ at neutrino energy of 1.1 GeV [1]. Our prediction for this quantity is $0.71\ 10^{-2}$ just compatible with the experimental limit.

Another experimental result, given by MiniBooNE [2], concerns the ratio for charged currents π^+ production to the quasi-elastic cross-section, as illustrated in Fig. 2. In one set of data (left panel) a correction is applied to obtain a genuine quasi-elastic cross-section and it is corrected as well for pion loss by final state interaction, which is not incorporated in our description. In another set of results (central panel) a generalized quasi-elastic is introduced, defined as events with only one lepton. In this

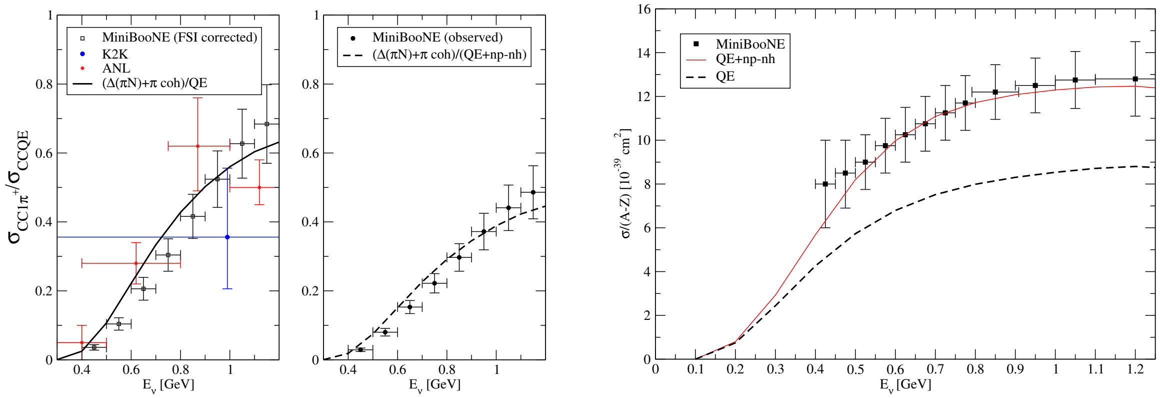

Fig. 2: Left and central panels: ratio of the ν_μ-induced charged current one pion production to quasi-elastic cross-section. Right panel: "Quasi-elastic" $\nu_\mu$$-$^{12}C cross-section per neutron as a function of neutrino energy.

case our $2p-2h$ and $3p-3h$ should be added to the quasi-elastic component. We obtain a successful comparisons between our results and the two sets of experimental data.

Further data involve a ratio of neutral current π^0 production to the total neutrino cross-section for charged currents at the mean neutrino energy of 1.16 GeV. The SciBooNE collaboration obtain the preliminary value $(7.7 \pm 0.5(\mathrm{stat.})^{+0.4}_{-0.5}(\mathrm{sys.})) \cdot 10^{-2}$. Our prediction for this quantity is $7.9 \cdot 10^{-2}$ Here again our evaluation agrees with data.

A new preliminary result on absolute cross-sections has been presented by the MiniBooNE collaboration [4]. This group gives in particular the absolute value of the cross-section for "quasi-elastic" events, averaged over the neutrino flux and as a function of neutrino energy. The comparison of these results with a prediction based on the relativistic Fermi gas model using the standard value of the axial cut-off mass $M_A = 1.03$ GeV$/c^2$ reveals a substantial discrepancy. In the same model a modification of the axial cut-off mass from the standard value to the larger value $M_A = 1.35$ GeV$/c^2$ is needed to account for data. As a possible interpretation we question here the real definition of quasi-elastic events. The nuclear medium is not a gas of independent nucleons, correlated only by the Pauli principle, but there are additional correlations. The ejection of a single nucleon (denoted as a genuine quasi-elastic 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. This leads to the excitation of $2p-2h$ states. At present, in neutrino reactions, such events cannot be experimentally distinguished from the genuine quasi-elastic events and must be considered simultaneously. Our sum of the combined ^{12}C quasi-elastic cross-section and the $np-nh$ $(n=2,3)$ one is displayed in right panel of Fig.2. This prediction fits the experimental data excellently, better than expected in view of the uncertainties of our $np-nh$ cross-section. As for the flux averaged "quasi-elastic" cross-section per neutron the experimental value is 9.4 10^{-39} cm^2 (with a normalization error of 11%). Our prediction for this quantity is 6.3 10^{-39} cm^2 without $np-nh$ contribution and 9.0 10^{-39} cm^2 including it, a value more in touch with the experimental one.

The successful comparison with present experimental data is an indication of the role of the nucleon-nucleon correlations in neutrino interactions.

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