Quasi-elastic scattering, RPA, 2p2h and neutrino–energy reconstruction

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Abstract. We discuss some nuclear effects, RPA correlations and 2p2h (multinucleon) mechanisms, on charged-current neutrino-nucleus reactions that do not produce a pion in the final state. We study a wide range of neutrino energies, from few hundreds of MeV up to 10 GeV. We also examine the influence of 2p2h mechanisms on the neutrino energy reconstruction.

1. Introduction

Neutrinos cannot be detected directly, because they do not ionize the materials they are passing through, and hence neutrino detectors are based on neutrino-nucleus interactions. Thus, a correct understanding of these interactions is crucial to minimize systematic uncertainties in neutrino oscillation experiments. Current and upcoming neutrino experiments (ScibooNE,MiniBooNE, T2K, MINERνA, MINOS, LBNE, MicroBooNE, . . . ) to measure oscillation effects and neutrino interaction cross sections are/will be mostly sensitive to neutrino energies up to 10 GeV. In this talk, we present results from a microscopic model [1, 2] limited to three-momentum and energy transfers below 1.2 GeV.

2. MiniBooNE $M_A$ puzzle, RPA and 2p2h nuclear effects

Thanks to the MiniBooNE $M_A$ puzzle [3], the theoretical understanding of the so called CCQE-like reactions (CC quasi-elastic neutrino-nucleus processes that do not produce a pion in the final state) at intermediate neutrino energies (∼ 1 GeV) has experienced an enormous boost in the recent years [4]. The absolute values of the CCQE cross section reported in [3] were too large as compared to the consensus of theoretical predictions for the QE contribution [5]. Moreover, the cross section per nucleon on $^{12}$C was clearly larger than for free nucleons, and a fit, using a relativistic Fermi gas model, to the data led to an axial mass, $M_A = 1.35 \pm 0.17$ GeV [3] much larger than the previous world average (∼ 1.03 GeV).

The inclusive cross section for the process $\nu_e + A \rightarrow \ell + X$ is determined by the $W$ gauge boson selfenergy in the nuclear medium [1][2], and in particular for the different modes in which it can be absorbed. In the case of genuine QE events, the gauge boson $W$ is absorbed by just one nucleon, which together with a lepton is emitted (see Figure 1 in Ref. [3]). However, the QE-like sample includes also multinucleon events where the gauge boson is absorbed by two interacting nucleons (in the many body language, this amounts to the excitation of a 2p2h nuclear component). The
Figure 1. Left (Right): Muon angle and energy neutrino (antineutrino) distribution $d\sigma/dT_\mu/d\cos\theta_\mu$ per neutron (proton) on a $^{12}$C target folded with the MiniBooNE $\nu_\mu$ ($\bar{\nu}_\mu$) flux. Different panels correspond to the various angular bins (labeled by the central value of the cosine). Data are taken from Refs. [3, 9], with errors that only account for the shape uncertainties. The green-dashed lines are the full model predictions including QE (relativistic and with RPA) and 2p2h mechanisms from Refs. [7, 10] (calculated with $M_A = 1.05$ GeV). Red-solid lines in the left panels ($\nu$) stand for the best fit ($M_A = 1.32$ GeV) results from the model without RPA and without multinucleon mechanisms. Finally in the right panels ($\bar{\nu}$) the red-dash-dotted curve corresponds to QE and the blue-dashed curve to 2p2h events.

consideration of the 2p2h contributions allows to describe [7, 8] the MiniBooNE CCQE-like flux averaged double differential cross section $d\sigma/dT_\mu/d\cos\theta_\mu$ [3] with values of $M_A$ around 1 GeV. This can be seen in Figure 1 where we also show results for antineutrinos. This is reassuring from the theoretical point of view and more satisfactory than the situation envisaged by some other works that described these CCQE-like data in terms of a larger value of $M_A$ of around 1.3–1.4 GeV (see the discussion in [4]), difficult to accommodate with our current knowledge on the nucleon axial radius. However, not only multinucleon mechanisms, but also RPA corrections turn out to be essential to obtain axial masses consistent with the world average. This can be appreciated in the left panel of Figure 2 where we see that RPA strongly decreases the cross section at low energies, while multinucleon mechanisms accumulate their contribution at low muon energies and compensate for that depletion. 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 (red lines in the neutrino panels of Figure 1).

3. Neutrino–energy reconstruction

Because of the multinucleon mechanisms, the neutrino energy reconstruction based on the QE kinematics is not totally reliable [6, 11, 12, 13]. The energy of the neutrino that has originated a CC event is unknown, and it is common to define a reconstructed neutrino ($E_{\text{rec}}$) energy obtained from the measured angle and three-momentum of the outgoing charged lepton. It corresponds to the energy of a neutrino that emits a lepton and a gauge boson that is being absorbed by a

1 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 strongly interacting nucleons [1].
Figure 2. $\nu_\mu +^{12}$C cross sections. Left: Muon angle and energy distribution per neutron for the $0.80 < \cos \theta_\mu < 0.90$ bin (see Ref. [7]). Right: Theoretical ($\sigma$) and approximate ($\sigma_{\text{appx}}$) CCQE-like integrated cross sections as a function of the $\nu$ energy (see Ref. [6]). The MiniBooNE data [3] and errors (shape) have been re-scaled by a factor 0.9. All theoretical results have been obtained with the model of Refs. [1, 2] and $M_A = 1.05$ GeV, except those corresponding to the $M_A = 1.32$ GeV curve in the left plot, that have been also re-scaled by a factor 0.9.

Figure 3. Double differential 2p2h cross section for neutrino-carbon interactions at energies of 1, 3, and 10 GeV. The black contours show the location of the genuine QE events, while the white ones show lines of constant three-momentum transfer from 0.2 to 1.2 GeV.
from our model, together with the CCQE-like MiniBooNE data are depicted. The unfolding procedure (see Ref. [9]) does not appreciably distort the genuine QE events, however the situation is drastically different for the 2p2h contribution, and as result the MiniBooNE unfolded cross section [3] exhibits an excess (deficit) of low (high) energy neutrinos, which is an artifact of the unfolding process that ignores multinucleon mechanisms. This systematic distortion of the energy spectrum will increase the uncertainty on the extracted oscillation signal.

4. Results above 1 GeV
We have extended to 10 GeV the results from the microscopic model. We find [15], limiting the calculation to three momentum transfers less than 1.2 GeV, the 2p2h mechanisms produce a two dimensional distribution in momentum and energy transfer that is roughly constant as a function of energy (Figure 3). The 2p2h cross section scales approximately with the number of nucleons for isoscalar nuclei, and becomes around 25% (33%) of the QE cross section for 3 GeV neutrinos (antineutrinos). The distortion of the energy and $Q^2$ spectra using the QE kinematic reconstruction, large at 1 GeV and below, steadily decreases as a function of the neutrino energy. When confronted with the MINERνA data [16, 17], the model has the qualitative features and magnitude to provide a reasonable agreement (Figure 4).

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