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QE-like scattering and neutrino energy reconstruction

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We address some nuclear effects, collective (long range) RPA correlations and 2p2h mechanisms (absorption of the weak gauge boson by a pair of interacting nucleons), on charged-current neutrino-nucleus reactions that do not produce a pion in the final state. We discuss results from a microscopical model, that includes these corrections, for MiniBooNE muon neutrino and antineutrino CCQE-like $d\sigma/dT_\mu d\cos\theta_\mu$ data. We also argue that the algorithm used to reconstruct the neutrino energy is not adequate when dealing with quasielastic-like events, and analyze the MiniBooNE neutrino CCQE unfolded cross section. We find that this cross section exhibits an excess (deficit) of low (high) energy neutrinos, which is an artifact of the unfolding process that ignores 2p2h mechanisms.

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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. In this talk, we will concentrate on charged-current (CC) antineutrino and neutrino-nucleus quasi-elastic scattering without emitted pions (QE-like), which is a fundamental detection channel for many neutrino experiments [1, 2].

2. CCQE-like cross section and RPA and 2p2h nuclear effects

The absolute values of the CCQE cross section reported by MiniBooNE in [3] were too large as compared to the consensus of theoretical predictions for the QE contribution [4]. 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 world average (~ 1.02 GeV) [5].

A theoretically sound solution to this MiniBooNE puzzled was obtained thanks to the inclusion of some standard nuclear effects produced by RPA correlations and multinucleon mechanisms. The importance of these effects in the non mesonic neutrino nucleus scattering was first pointed out in Refs. [6, 7] and later confirmed in Refs. [8, 9, 10, 11]. The inclusive $\nu_\ell + A_Z \to \ell + X$ cross section is determined by the W gauge boson selfenergy in the nuclear medium [8, 12], 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(a) in Ref. [13]). However, the QE-like sample includes also multinucleon events where the gauge boson is absorbed by two interacting nucleons as shown in Figure 1(b) of Ref. [13]. This latter mechanism involves a two-particle-two-hole (2p2h) nuclear excitation. Up to re-scattering processes which could produce secondary pions, 2p2h events should be part of the MiniBooNE data-set since they will not give rise to pions in the final state. The traditional meson exchange current contributions [8, 14] are part of the 2p2h ones, which in addition also include many-body diagrams that can be cast as a nucleon selfenergy and, are thus related to the nucleon spectral function [8, 12][1]. Besides nucleon knock-out mechanisms, the calculations of Refs. [7, 9, 10, 11] also account for collective (long-range) RPA nuclear correlations, which provide corrections to cross sections due to the response of the whole nucleus to the weak probe, instead of considering only the sum of the responses of the individual nucleons [12]. These effects are important at low energies, as long as the gauge boson wave-length is comparable to the size of the nucleus. Thanks to the combined RPA and 2p2h effects, it is achieved a quite good description of the CCQE MiniBooNE double differential neutrino [3] and antineutrino [15] cross sections, while using standard values for all parameters in the calculations (including M_A), as can be seen in Refs. [7, 9, 10, 11]. As it is discussed in [9], the final picture is that of a delicate balance between a dominant single nucleon scattering, corrected by collective RPA 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 [3]. However, neglecting either of the two effects would lead to a poor description of the data.

[1] This is because, such contributions modify the nucleon dispersion relation inside of the nuclear medium.

In any case, the conclusion is that a substantial part of the CCQE cross section measured in Refs. [3, 15] corresponds to events in which at least two nucleons are emitted. This produces an unwanted bias in the measurements carried out in the far detector of long baseline experiments, and has a quantitative impact in the determination of the oscillation parameters, which might even exceed the current $(m^2_{31} - \theta_{23})$ 95% confident level contours [16, 17]. Furthermore, if the contribution of multinucleon mechanisms is substantially different in neutrinos and antineutrinos, as predicted for instance in Refs. [7, 18] and this is not properly understood, it could lead to an asymmetry between ν and $\bar{\nu}$ which could be misinterpreted as a consequence of CP violation.

3. Neutrino–energy reconstruction

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 [13, 19, 20, 21], and that implies another source of systematic uncertainties in the analysis of the oscillation experiments. The energy of the neutrino that has originated a CC event is unknown, and it is common to define a reconstructed neutrino ($E_{\rm rec}$) 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 nucleon at rest. Each event contributing to the flux averaged cross section defines unambiguously a value of $E_{\rm rec}$, however the actual energy of the neutrino that has produced the event will not be exactly $E_{\rm rec}$. Thus, for each $E_{\rm rec}$, there exists a distribution of true neutrino energies that could give rise to events whose outgoing charge lepton kinematics would lead to the given value of $E_{\rm rec}$. For genuine QE events, this distribution is sufficiently peaked around the true neutrino energy to make the used algorithm accurate enough to study the neutrino oscillation phenomenon or to extract neutrino flux unfolded CCQE cross sections from data [13, 19]. However, for 2p2h events included in the CCQE-like sample, there appears a long tail in the distribution of true energies associated to each $E_{\rm rec}$ that makes less reliable the QE based energy reconstruction procedure, which produces a redistribution of strength from high to low neutrino energies [13]. As a 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. The conclusion should be then that the unfolded CCQE-like cross section is not a clean observable, since the unfolding procedure itself is model dependent and assumes that the events are purely QE [13].

4. Conclusions

Nuclear effects lead to sizable corrections on neutrino nucleus cross sections at low $Q^2 < 1{\rm GeV}^2$, which should be incorporated in neutrino event generators.

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