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In medium dispersion relation effects in nuclear inclusive reactions at intermediate and low energies

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HIGHLIGHTS

- The role of the spectral functions (SFs) in neutrino nucleus reactions is studied.
- Accurate SFs are used to predict intermediate energy CCQE (anti-)neutrino scattering for various targets.
- We compare our SF and RPA results to predictions obtained within other representative approaches.
- We show that uncertainties on the σ_μ/σ_e ratio are much smaller than 5%.

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ABSTRACT

In a well-established many-body framework, successful in modeling a great variety of nuclear processes, we analyze the role of the spectral functions (SFs) accounting for the modifications of the dispersion relation of nucleons embedded in a nuclear medium. We concentrate in processes mostly governed by one-body mechanisms, and study possible approximations to evaluate the particle–hole propagator using SFs. We also investigate how to include together SFs and long-range RPA-correlation corrections in the evaluation of nuclear response functions, discussing the existing interplay between both type of nuclear effects. At low energy transfers ($\lesssim$50 MeV), we compare our predictions for inclusive muon and radiative pion captures in nuclei, and charge–current (CC) neutrino–nucleus cross sections with experimental results. We also present an analysis of intermediate energy quasi-elastic

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neutrino scattering for various targets and both neutrino and antineutrino CC driven processes. In all cases, we pay special attention to estimate the uncertainties affecting the theoretical predictions. In particular, we show that errors on the σ_μ/σ_e ratio are much smaller than 5%, and also much smaller than the size of the SF+RPA nuclear corrections, which produce significant effects, not only in the individual cross sections, but also in their ratio for neutrino energies below 400 MeV. These latter nuclear corrections, beyond Pauli blocking, turn out to be thus essential to achieve a correct theoretical understanding of this ratio of cross sections of interest for appearance neutrino oscillation experiments. We also briefly compare our SF and RPA results to predictions obtained within other representative approaches.

Introduction

The description of inclusive lepton–nucleus processes has attracted a lot of attention in the last years. The topic has become especially important in the context of neutrino physics [1–6], where highly accurate theoretical predictions are essential to conduct the analysis of neutrino properties aiming at making new discoveries possible, like the CP violation in the leptonic sector. For nuclear physics, neutrino cross sections incorporate richer information than electron-scattering ones, providing an excellent testing ground for nuclear structure, many-body mechanisms and reaction models. In addition, neutrino cross-section measurements allow to investigate the axial structure of the nucleon and baryon resonances, enlarging the views of hadron structure beyond what is presently known from experiments with hadronic and electromagnetic probes. Thus and besides the large activity in the last 15 years (see for instance the reviews cited above), a new wave of neutrino–nucleus theoretical works and detailed analysis have recently become available [7–16].

Neutrino and antineutrino scattering on nuclei without pions exiting the nucleus is a fundamental detection channel for long-baseline neutrino experiments, such as T2K, MINOS, NOvA and the future DUNE. At intermediate energies, a microscopical description of the interaction of the neutrinos with the nuclei, that form part of the detectors, should at least account for three distinctive nuclear corrections, in addition to the well-established Pauli-blocking effects. These are long-range collective RPA[1] and in medium nucleon dispersion relation effects, and multinucleon absorption modes. In this work, we will focus in the first two ones, since we will study processes mostly governed by one-body mechanisms. There exists an abundant literature addressing multinucleon contributions to the pion-less quasi-elastic (QE) cross section in the context of the so-called MiniBooNE axial mass puzzle and the problem of the neutrino energy reconstruction [2,4,6,17–29], and we refer the reader to these works for details. We would only like to mention that this topic has become quite relevant in neutrino reactions since the neutrino beams are not monochromatic but wide-band [30,31].

Spectral functions (SFs) account for the modifications of the dispersion relation of nucleons embedded in a nuclear medium, while medium polarization or collective RPA correlations do for the change of the electroweak coupling strengths, from their free nucleon values, due to the presence of strongly interacting nucleons. The latter take into account the absorption of the gauge boson, mediator of the interaction, by the nucleus as a whole instead of by an individual nucleon, and their importance decreases as the gauge boson wave-length becomes much shorter than the nuclear size. In medium dispersion relation effects associated to the hit nucleon are always evaluated for bound nucleons, and thus their impact should be rather independent of the neutrino kinematics. However, one should expect that SF effects become less important in the case of the ejected nucleon, when the energy and momentum transfers are much larger than those accessible close to the Fermi sea level. Both SF [16,32–40] and RPA, [12,17–21,37,38,41–50] corrections have been implemented in

[1] RPA stands for the random phase approximation to compute the effects of long-range nucleon–nucleon correlations.