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Two-nucleon emission in neutrino and electron scattering from nuclei: The modified convolution approximation

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ABSTRACT

The theoretical formalism of inclusive lepton–nucleus scattering in the two-nucleon emission channel is discussed in the context of a simplified approach, the modified convolution approximation. This allows one to write the 2p2h responses of the relativistic Fermi gas as a folding integral of two 1p1h responses with the energies and momenta transferred to each nucleon. The idea behind this method is to introduce different average momenta for the two initial nucleons in the matrix elements of the two-body current, with the innovation that they depend on the transferred energies and momenta. This method treats exactly the two-body phase space kinematics, and reduces the formulae of the response functions from seven-dimensional integrals over momenta to much simpler three-dimensional ones. The applicability of the method is checked by comparing with the full results within a model of electroweak meson-exchange currents. The predictions are accurate enough, especially in the low-energy threshold region where the average momentum approximation works the best.

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1. Introduction

The electromagnetic nuclear response for intermediate momentum and energy transfer is dominated by particle–hole excitations in the vicinity of the quasielastic peak, located around the energy transfer $\omega = \sqrt{q^2 + m_N^2} - m_N$ needed to knock-out a nucleon initially at rest with momentum transfer q. But for higher energies other channels open and the 1p1h description becomes insufficient; in particular the two-particle two-hole channel starts to play a role as was first noticed in [1–3].

In the last decade the increasing interest in the role of multi-nucleon emission in the electroweak nuclear responses has revealed once more its importance in describing the kinematical region of the quasielastic peak and above, and it is at present an active focus of research both in neutrino and electron scattering studies [4–9]. In particular, in charged-current (CC) quasielastic neutrino scattering (ν_μ, μ^-), the two-particle two-hole (2p2h) channel is now being considered an essential part in the analysis of the long baseline experiments [10–15].

In electron scattering the $(e, e'p)$ and $(e, e'pp)$ reactions were recently measured [16–19] with the hope of extracting information on high-momentum components of the reaction dynamics involving differences between ejection of np and pp pairs of nucleons. These experiments have also revitalized interest in developing models to describe the inclusive 2p2h response function [20–22]. More evidence of two nucleon emission of correlated nucleon pairs has been thought to be found in the ArgoNeuT neutrino scattering experiment [23]. This has generated theoretical discussions [24,25], and it is still under debate. The most recent theoretical developments of the 2p2h response functions in neutrino and electron scattering with the shell model has been reported in [26,27].

The first model of 2p2h excitations in the nuclear response can be traced back to the works of Van Orden et al., [1,2] who computed the two-body meson-exchange currents (MEC) contribution in the non-relativistic Fermi gas model. Later on, Alberico et al. used the same model, by adding pionic correlation currents [3], obtaining a satisfactory description of the transverse response functions after including the important enhancement produced by 2p2h excitations. The first shell model calculations of the inclusive (e, e') response in the two-nucleon emission channel with MEC were done by Amaro et al. [28,29]. Several other improvements including correlation currents, random-phase approximation and effective interaction were made in [30,31].

All of these models were non-relativistic and therefore cannot be applied to the high energy and momentum transfers of interest for the current experiments, for which a relativistic description is mandatory. The first fully relativistic approach to the MEC 2p2h response function of ^{56}Fe by Dekker et al. [32–34] was followed by the Torino model [35,36], where the relativistic effects and the scaling properties of the transverse electromagnetic response were studied. The effect of pionic correlations was evaluated in [37]. The validation of the relativistic MEC model for (e, e') scattering has been recently made in [38]. These models were extended to the weak sector in [39] to compute the five CC response functions and the neutrino inclusive cross section [40]. In these fully relativistic models the presence of the Δ excitation peak without pion emission is evident, which the non-relativistic models cannot describe in the static limit where the Δ propagator is constant.

The calculation of the inclusive 2p2h response implies the sum over all the 2p2h final states. This involves an integration over all of the momenta of particles and holes and sums over spin and isospin. In general, the complexity of the antisymmetrized two-body current matrix element prevents the reduction of the dimensionality of the integrals involved below seven dimensions. But simplifications can be done in the non-relativistic case, if one neglects the interference terms between direct and exchange current matrix elements [2], where the integrals are reduced to two dimensions to be performed numerically.

In the present applications to the neutrino oscillation experiments the neutrino energy is not fixed and an integral over the neutrino flux has to be done; this complicates the already cumbersome calculation of the 2p2h contribution. Therefore, an important goal in such studies is to find simpler approximations to these response functions in order to reduce the computational time while keeping the accuracy of the results. This is the motivation of the present work.

Recently we have developed an approximation which highly simplifies the calculation of the 2p2h responses, the *frozen nucleon approximation*. It consists in neglecting the momentum of the initial nucleons inside the integrals [41], thus allowing one to perform analytically a six-dimensional integral