Emission of neutron-proton and proton-proton pairs in electron scattering induced by meson-exchange currents

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We use a relativistic model of meson-exchange currents to compute the proton-neutron and proton-proton yields in (e,e') scattering from ^{12}C in the 2p-2h channel. We compute the response functions and cross section with the relativistic Fermi gas model for a range of kinematics from intermediate- to high-momentum transfers. We find a large contribution of neutron-proton configurations in the initial state, as compared to proton-proton pairs. The different emission probabilities of distinct species of nucleon pairs are produced in our model only by meson-exchange currents, mainly by the Δ isobar current. We also analyze the effect of the exchange contribution and show that the direct-exchange interference strongly affects the determination of the np/pp ratio.

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I. INTRODUCTION

The process of two-nucleon knockout reactions in electron scattering is thought to involve short-range correlations (SRCs) in nuclei. In this case one expects an excess of neutron-proton (np) pairs over proton-proton (pp) pairs. Experiments on ^{12}C for high-momentum transfer and missing momentum have reported a number of np pairs 18 ± 5 times larger than their pp counterparts [1–3]. More recently the dependence on the nuclear mass number has been studied in Refs. [4–6], where the aim of this series of recent investigations at Jefferson Lab is to unambiguously determine the short-range properties of light nuclei [7–10]. The analysis of these experiments seems to be in agreement with theoretical predictions of nucleon and nucleon pair momentum distributions in variational Monte Carlo calculations, where the importance of the tensor forces in the ground-state correlations of nuclei has been emphasized [11,12]. Note that in the mentioned electron scattering experiments the kinematics involved high-momentum transfers, $Q^2 > 1.4\,(\mathrm{GeV}/c)^2$, and thus relativistic corrections are likely to be important in the theoretical descriptions employed.

Another source of SRC evidence comes from calculations of the semi-inclusive electron scattering reaction $(e,e'pN)$, which however relies on factorization approximations that have not been fully justified for all the kinematics of interest [13]. While the kinematics of the experiments have been selected to minimize the contribution from other mechanisms that can induce two-particle emission, such as meson-exchange currents (MECs) and isobar excitations [1], the contribution of MECs cannot be ruled out *a priori*.

Similarly to the electron case, observation of events in neutrino scattering with a pair of energetic protons has been reported in the ArgoNeuT experiment [14]. From these events several back-to-back nucleon configurations have been identified and associated with nuclear mechanisms involving short-range correlated np pairs in the nucleus [15]. The SRC explanation of this excess of back-to-back events in ArgoNeuT is still controversial [16,17].

In this work we investigate the relative effects of MECs on the separate pp and np channels in the inclusive 2p-2h cross section, without including NN correlations. It is important to know if the MEC alone can explain, at least partially, the observed enhancement of the ^{12}C$(e,e'np)$ cross section over that of the ^{12}C$(e,e'pp)$ cross section, as observed in the data [2]. This is in lieu of a fully reliable relativistic model for the $(e,e'pN)$ cross section, because such a model is unavailable.

II. THE MODEL

We have recently developed a fully relativistic model of meson-exchange currents in the 2p-2h channel for electron and neutrino scattering [18]. This model is an extension of the relativistic MEC model of Ref. [19] to the weak sector. It has been recently validated by comparing to the ^{12}C(e,e') inclusive cross section data for a wide kinematical range within the superscaling approach [20]. This model describes jointly the quasielastic and inelastic regions using two scaling functions fitted to reproduce the data, while the 2p-2h MEC contribution properly fills the dip region in between, resulting in excellent global agreement with the data.

With this benchmark model we are able to study the separate np and pp channels in the response functions and cross section for the three (e,e'), (ν_l,l^-), and $(\bar{\nu}_l,l^+)$ reactions. Although our 2p-2h model does not explicitly include NN correlations, they are implicitly accounted for in the phenomenological scaling functions, and thus we cannot isolate the 2p-2h contributions coming from SRCs in this approach. However, with this model we are at least able to provide a precise estimation of the size of MECs in the separate channels for high-momentum and energy transfers where relativistic effects are important. In this work we focus on the contributions of pion-in-flight, seagull, and $\Delta(1232)$ excitation diagrams of the MECs.

We write the inclusive (e,e') cross section as the product of the Mott cross section and a linear combination of longitudinal and transverse response functions:

$$\frac{d\sigma}{d\Omega d\omega} = \sigma_{\rm Mott}[v_L R_L(q,\omega) + v_T R_T(q,\omega)]. \qquad (1)$$

The response functions for the momentum transfer q and the energy transfer ω contain the contribution of all of the nuclear excitations with energy ω.

In the relativistic Fermi gas model the excitations can be 1p-1h, 2p-2h, and so on. We describe the particle and hole states as relativistic plane waves with momenta above and below the Fermi momentum k_F, respectively. In this work we compute the 2p-2h contributions to the response functions that are proportional to the volume V of the system, which for symmetric nuclear matter has $Z = N = A/2$, where $V = 3\pi^2 Z/k_F^3$. They are given by

$$R^K_{\text{2p-2h}} = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3h_1 d^3h_2 \frac{m_N^4}{E_1E_2E'_1E'_2} \times r^K(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2)\delta(E'_1+E'_2-E_1-E_2-\omega) \times\theta(p'_2-k_F)\theta(p'_1-k_F)\theta(k_F-h_1)\theta(k_F-h_2), \qquad (2)$$

for $K = L$ and T, where $\mathbf{p}'_2 = \mathbf{h}_1 + \mathbf{h}_2 + \mathbf{q} - \mathbf{p}'_1$ is fixed by momentum conservation, m_N is the nucleon mass, and E_i and E'_i are the on-shell energies of the holes and particles, respectively. The response functions for the elementary 2p-2h excitation, $r^K(\mathbf{p}'_1,\mathbf{p}'_2,\mathbf{h}_1,\mathbf{h}_2)$, for given initial and final momenta, are the sums over spins of the squares of the MEC matrix elements and can be found in Ref. [18] for the separate np, pp and nn, charge channels. The 2p-2h states are antisymmetrized and therefore our MEC matrix elements and response functions contain direct and exchange contributions. The seven-dimensional integral of Eq. (2) is computed numerically without approximations by following the method of Refs. [21,22]. We refer the reader to Ref. [18] for further details on the model.

III. RESULTS

In what follows we show results for the separate np and pp pair emission from ^{12}C. In our model, the nn channel gives the same contribution as the pp one, because both are induced by the Δ-isobar current. In Figs. 1 and 2 we show the transverse and longitudinal response functions. For $q = 600$ MeV/c, the np transverse response is around a factor of 12 times larger than the pp one. For $q = 1000$ MeV/c this factor gets reduced to ~ 6. In the longitudinal responses the np/pp ratio is further reduced. However, the longitudinal MEC contribution to the cross section is almost negligible compared with the transverse one, because the dominant Δ excitation current is mainly transverse.

In Fig. 3 we show the effect of neglecting the direct-exchange interference of the MEC matrix elements. For np pair emission it is negligible. On the other hand, for pp emission

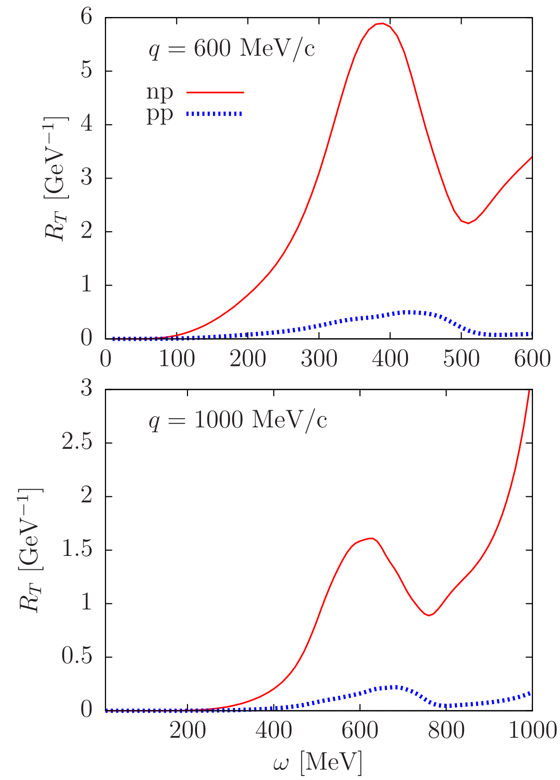

FIG. 1. Electromagnetic transverse response function for np and pp pair emission off ^{12}C as a function of ω for two values of q.

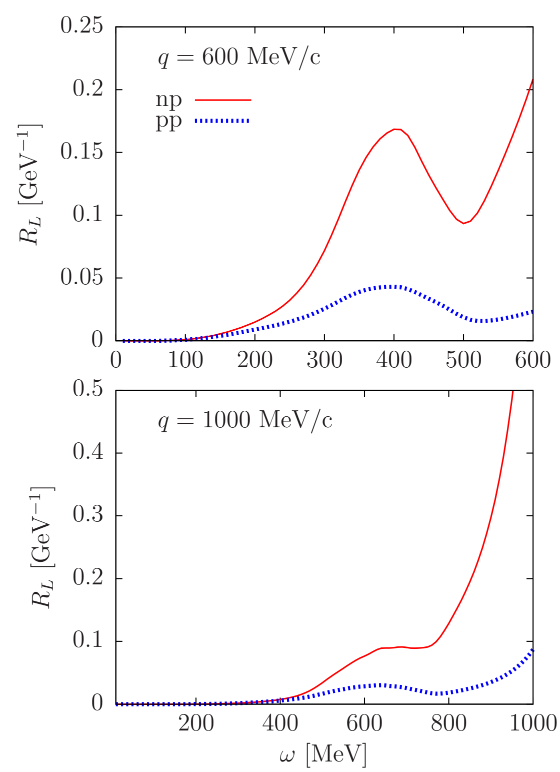

FIG. 2. Same as for Fig. 1, but now for the longitudinal response function.

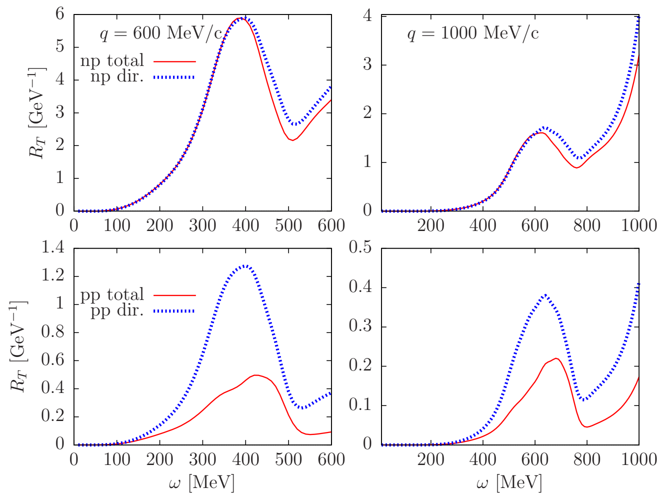

FIG. 3. Electromagnetic transverse response function showing the contributions of direct-exchange interference terms to the separate *np* and *pp* channels.

it is of the same order as the direct contribution. Therefore neglecting this interference would reduce the abovementioned np/pp ratios by a factor of 2. This implies that the interference is crucial for describing this ratio properly. Although the net effect of the interference in the 2p-2h is less than 20% and sometimes it can be safely disregarded [23,24], this is not the case for the *pp* separate contribution. However, up to now there have been no calculations of these ratios.

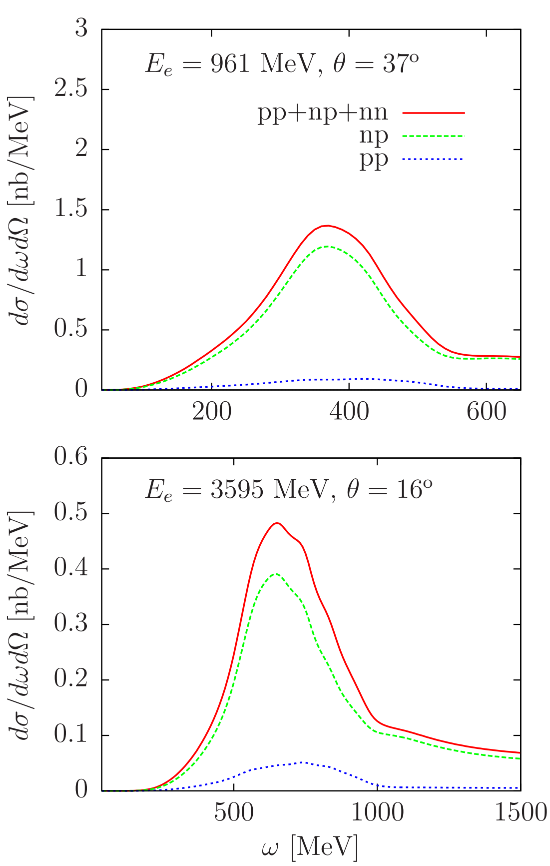

FIG. 4. Electromagnetic differential cross section separated into the different charge contributions.

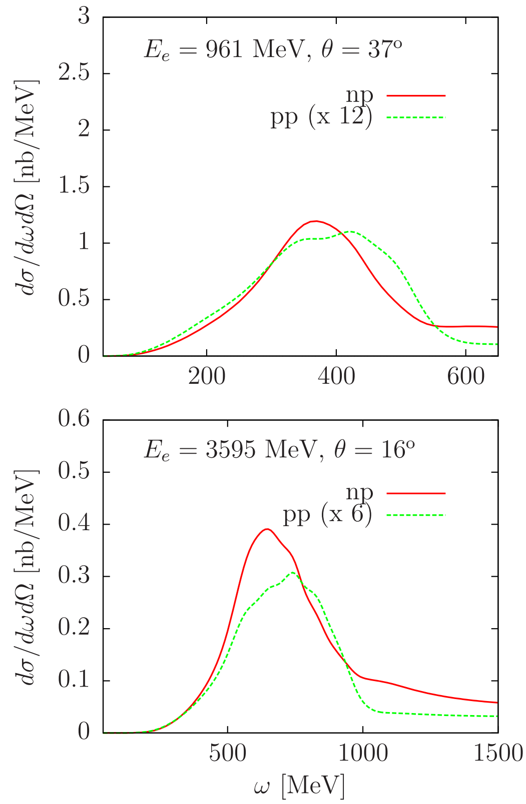

FIG. 5. Same as for Fig. 4, but now the *pp* contribution has been scaled by a constant factor, as shown in the two panels.

In Fig. 4 we show the semi-inclusive double-differential cross section for pair emission from ^{12}C for two incident energies and electron scattering angles. The separate *np* and *pp* pair emission channels are also displayed. As in the case of the transverse response, the *np* pair emission clearly dominates over the *pp* pair emission. The ratio of *np* over *pp* depends on the kinematics. It is roughly between 12 and 6, as can be seen in Fig. 5, where we have multiplied the *pp* cross section by a constant factor. It is worth mentioning that the np/pp ratio also depends on ω, although a constant scaling factor does a reasonable job at inter-relating the different channels.

In Fig. 6 we show the separate *np* and *pp* emission cross sections for the kinematics of the measurement of Refs. [1,2]. In this experiment the energy transfer was chosen to be $\omega = 865$ MeV, well below the Δ excitation maximum that occurs at about 1.12 GeV. For this reason we only show in Fig. 6 the low-energy tail of the cross section below this value of ω. These kinematics were chosen to minimize the MEC contribution that we are showing here. In fact, for this value of ω the MECs are small, because we are far from the maximum of the Δ peak. The results of Fig. 6 are the expected MEC contributions to the semi-inclusive $(e,e'pN)$ cross section in an uncorrelated system. In this case the np/pp ratio is a factor 6. This is not sufficient to explain the factor 18 ± 5 found in the experiment and attributed to SRCs, coming mainly from

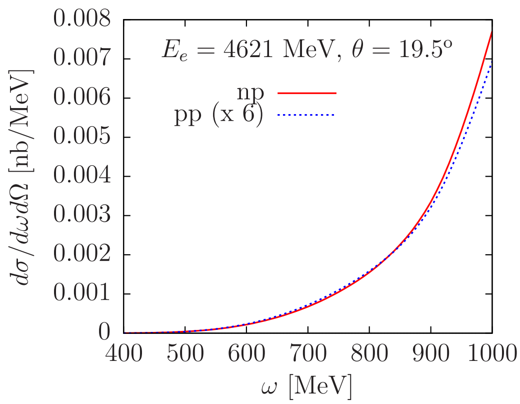

FIG. 6. Same as for Fig. 5, but now for the electron kinematics of the experimental setup of Ref. [1].

the tensor nuclear force. However, it does suggest that any analysis where MEC effects are not included must be viewed with caution. In the MEC case this factor comes roughly from isospin considerations, but the effect of the direct-exchange interference is q dependent and can modify it by a large extent depending on the kinematics. Note that the kinematics of the experiment [1] is relativistic, with $Q^2 = 2$ (GeV/c)^2 and $q = 1.65$ GeV/c. Thus the relativistic calculation of the 2p-2h MEC responses is mandatory. One of the findings of Refs. [1,2] was that there are very few correlated *pp* pairs. Therefore we expect that our result for the *pp* cross section will not change significantly when including SRCs, while the *np* cross section should be considerably increased.

IV. CONCLUSIONS

In summary, we have computed the semi-inclusive ^{12}C($e,e'np$) and ^{12}C($e,e'pp$) cross sections in the relativistic Fermi gas including a fully relativistic model of MECs. The np/pp ratio has been quantified and analyzed for several kinematics. The direct-exchange interference terms are found to be important, especially in the *pp* channel. The MECs alone are not able to explain completely the data for this ratio, which is found to be larger than our findings, although they clearly should be expected to play an important role in determining the np/pp ratio in two-nucleon emission electron scattering as well as the related flavor dependence in charge-changing neutrino reactions. Said another way: while missing contributions in our model (like SRCs) could be important at least for the kinematics of the existing experiment, our results indicate that, to understand in depth the size of such effects, the MEC contributions should also be included. In the future the relativistic modeling used for the latter could be extended to include correlation currents of the pionic type [25], effective interactions, or, alternatively, correlation operators in the wave functions.

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