

This is the accepted manuscript made available via CHORUS. The article has been published as:

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

I. Ruiz Simo, J. E. Amaro, M. B. Barbaro, A. De Pace, J. A. Caballero, G. D. Megias, and T. W. Donnelly

Phys. Rev. C **94**, 054610 — Published 8 November 2016

DOI: [10.1103/PhysRevC.94.054610](https://doi.org/10.1103/PhysRevC.94.054610)

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

I. Ruiz Simo<sup>a</sup>, J.E. Amaro<sup>a</sup>, M.B. Barbaro<sup>b,c</sup>, A. De Pace<sup>b</sup>, J.A. Caballero<sup>d</sup>, G.D. Megias<sup>d</sup>, T.W. Donnelly<sup>e</sup>

<sup>a</sup>*Departamento de Física Atómica, Molecular y Nuclear,*

*and Instituto de Física Teórica y Computacional Carlos I, Universidad de Granada, Granada 18071, Spain*

<sup>b</sup>*INFN, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy*

<sup>c</sup>*Dipartimento di Fisica, Università di Torino Via P. Giuria 1, 10125 Torino, Italy*

<sup>d</sup>*Departamento de Física Atómica, Molecular y Nuclear,*

*Universidad de Sevilla, Apdo.1065, 41080 Sevilla, Spain and*

<sup>e</sup>*Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics,  
Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

(Dated: June 22, 2016)

We use a relativistic model of meson-exchange currents to compute the proton-neutron and proton-proton yields in  $(e, e')$  scattering from  $^{12}\text{C}$  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  $\Delta$  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.

PACS numbers: 25.30.Fj; 21.65.-f; 24.10.Jv

The process of two-nucleon knockout reactions in electron scattering is thought to involve short-range correlations (SRC) in nuclei. In this case one expects an excess of neutron-proton (np) pairs over proton-proton (pp) pairs. Experiments on  $^{12}\text{C}$  for high momentum transfer and missing momentum, have reported a number of np pairs  $18 \pm 5$  times larger than their pp counterparts [1–3]. More recently the dependence on the nuclear mass number has been studied in [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,  $Q^2 > 1.4 \text{ (GeV/c)}^2$ , 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  $(e, e'pN)$ , that however rely 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 (MEC) and isobar excitations [1], the contribution of MEC 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 to nuclear mechanisms involving short-range correlated neutron-proton (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 MEC 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  $^{12}\text{C}(e, e'np)$  cross section over that of the  $^{12}\text{C}(e, e'pp)$  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, as this is unavailable.

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 [19] to the weak sector. It has been recently validated by comparing to the  $^{12}\text{C}(e, e')$  inclusive cross section data for a wide kinematical range within the SuperScaling approach (SuSA) [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 an 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  $(e, e')$ ,  $(\nu_l, l^-)$  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

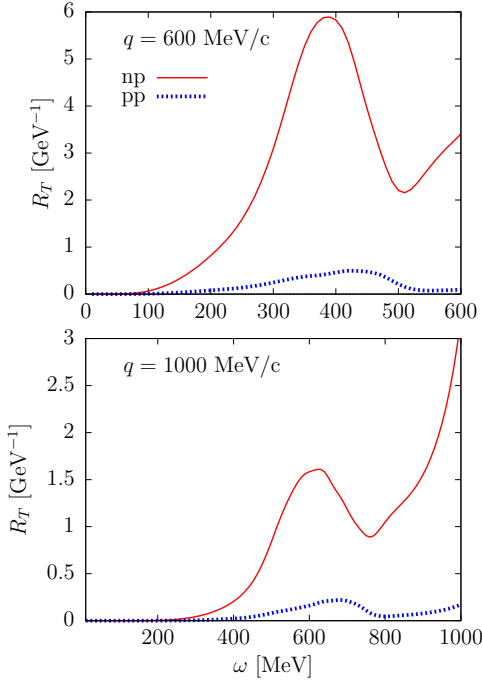


FIG. 1: (color online) Electromagnetic transverse response function for np and pp pair emission off  $^{12}\text{C}$  as a function of  $\omega$  for two values of  $q$ .

SRC in this approach. However, with this model we are at least able to provide a precise estimation of the size of MEC 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 MEC.

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:

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

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

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

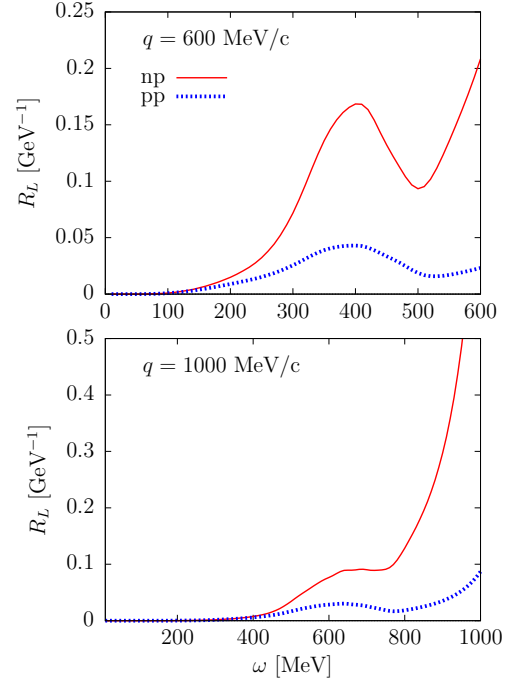


FIG. 2: (color online) As for Fig. 1, but now for the longitudinal response function.

$Z = N = A/2$ , where  $V = 3\pi^2 Z/k_F^3$ . They are given by

$$\begin{aligned} R_{2p-2h}^K &= \frac{V}{(2\pi)^9} \int d^3p'_1 d^3h_1 d^3h_2 \frac{m_N^4}{E_1 E_2 E'_1 E'_2} \\ &\times r^K(\mathbf{p}'_1, \mathbf{p}'_2, \mathbf{h}_1, \mathbf{h}_2) \delta(E'_1 + E'_2 - E_1 - E_2 - \omega) \\ &\times \theta(p'_2 - k_F) \theta(p'_1 - k_F) \\ &\times \theta(k_F - h_1) \theta(k_F - h_2), \end{aligned} \quad (2)$$

for  $K = L, T$ , 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,  $E_i$  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 [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 7D integral of Eq. (2) is computed numerically without approximations by following the method of [21, 22]. We refer the reader to [18] for further details on the model.

In what follows we show results for the separate np and pp pair emission from  $^{12}\text{C}$ . In our model, the nn channel gives the same contribution as the pp one, because both are induced by the  $\Delta$ -isobar current. In Figs. 1, 2 we show the transverse and longitudinal response functions. For  $q = 600$  MeV/c, the np transverse response is around a factor of twelve times larger than the pp one. For  $q = 1000$  MeV/c this factor gets reduced to  $\sim 6$ . In the the

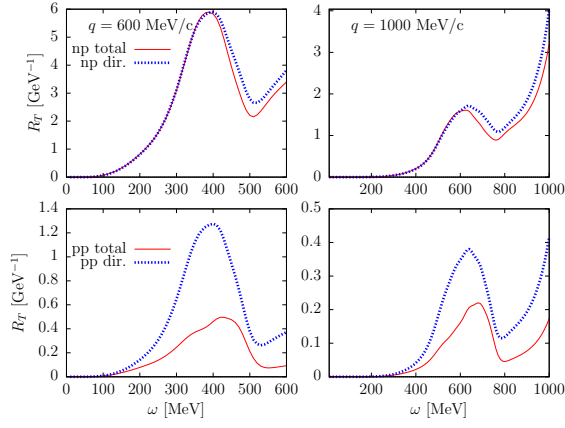


FIG. 3: (color online) Electromagnetic transverse response function showing the contributions of direct-exchange interference terms to the separate np and pp channels.

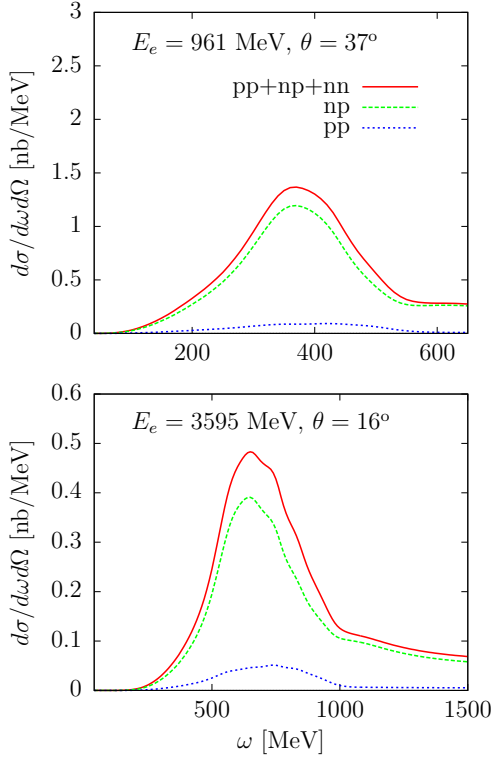


FIG. 4: (color online) Electromagnetic differential cross section separated into the different charge contributions.

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  $\Delta$  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

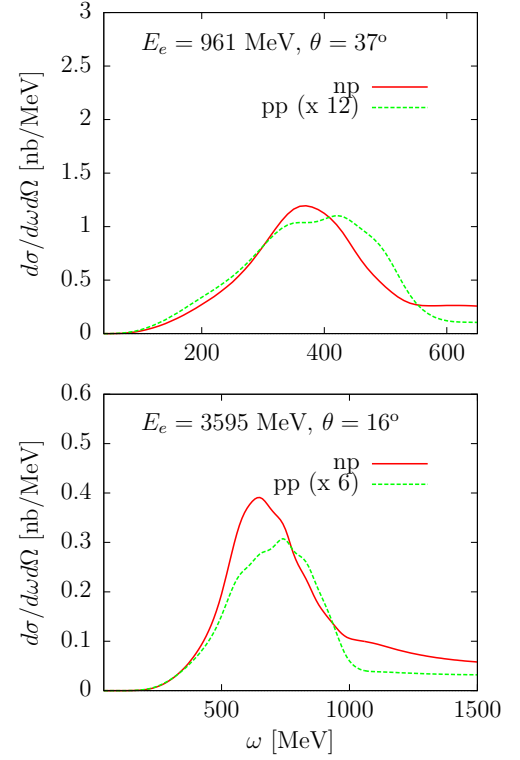


FIG. 5: (color online) As for Fig. 4, but now the pp contribution has been scaled by a constant factor, as shown in the two panels.

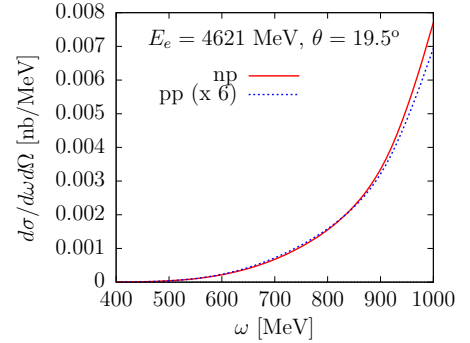


FIG. 6: (color online) As for Fig. 5, but now for the electron kinematics of the experimental setup of [1].

pp emission it is of the same order as the direct contribution. Therefore neglecting this interference would reduce the above mentioned np/pp ratios by a factor of two. 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.

In Fig. 4 we show the semi-inclusive double-differential cross section for pair emission from  $^{12}\text{C}$  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 pp. The ratio of np over pp depends on the kinematics. It is roughly between twelve and six, 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  $\omega$ , 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 [1, 2]. In this experiment the energy transfer was chosen  $\omega = 865$  MeV, well below the  $\Delta$  excitation maximum which 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  $\omega$ . These kinematics were chosen to minimize the MEC contribution that we are showing here. In fact, for this value of  $\omega$  the MEC are small, since we are far from the maximum of the  $\Delta$  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  $18 \pm 5$  found in the experiment and attributed to SRC, coming mainly from 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 [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 SRC, while the np cross section should be considerably increased.

In summary, we have computed the semi-inclusive

$^{12}\text{C}(e, e'np)$  and  $^{12}\text{C}(e, e'pp)$  cross sections in the RFG including a fully relativistic model of MEC. 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 MEC 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 related flavor dependence in charge-changing neutrino reactions. Said another way: while missing contributions in our model (like SRC) could be important at least for the kinematics of existing experiment, our results indicate that, in order 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.

### Acknowledgments

This work was supported by Spanish Dirección General de Investigación Científica y Técnica and FEDER funds (grants No. FIS2014-59386-P and No. FIS2014-53448-C2-1), by the Agencia de Innovación y Desarrollo de Andalucía (grants No. FQM225, FQM160), by INFN under project MANYBODY, and part (TWD) by U.S. Department of Energy under cooperative agreement DE-FC02-94ER40818. IRS acknowledges support from a Juan de la Cierva-incorporación fellowship from Spanish MINECO. GDM acknowledges support from a Junta de Andalucía fellowship (FQM7632, Proyectos de Excelencia 2011). The authors also acknowledge support from “Espace de Structure et de réactions Nucléaire Théorique” (ESNT, <http://esnt.cea.fr>) at CEA-Saclay, where this work was partially carried out.

- 
- [1] R. Shneor, *et al.*, (JLab Hall A Collaboration), Phys. Rev. Lett. 99, 072501 (2007).
  - [2] R. Subedi, *et al.*, Science 320 (2008), 1476.
  - [3] J. Ryckebusch, M. Vanhalst, W. Cosyn, J. Phys. G: Nucl. Part. Phys. 42 (2015) 055104.
  - [4] O. Hen *et al.* [CLAS Collaboration], Phys. Lett. B **722** (2013) 63
  - [5] O. Hen *et al.* [CLAS Collaboration], Science, 346, 614 (2014).
  - [6] C. Colle, O. Hen, W. Cosyn, I. Korover, E. Piasetzky, J. Ryckebusch, and L. B. Weinstein, Phys. Rev. C 92, 024604 (2015).
  - [7] N. Fomin *et al.*, Phys. Rev. Lett. 108, 092502 (2012).
  - [8] P. Monaghan *et al.*, J. Phys. G: Nucl. Part. Phys. 41 (2014) 105109.
  - [9] I. Korover, *et al.*, Phys. Rev. Lett. 113, 022501 (2014).
  - [10] K. S. Egiyan, *et al.*, Phys. Rev. Lett. 96, 082501 (2006).
  - [11] R. Schiavilla, R.B. Wiringa, S.C. Pieper, J. Carlson, Phys. Rev. Lett. 98, 132501 (2007).
  - [12] R.B. Wiringa, R. Schiavilla, S.C. Pieper, J. Carlson, Phys. Rev. C 89, 024305 (2014).
  - [13] C. Colle, W. Cosyn, J. Ryckebusch, Phys. Rev. C 93, 034608 (2016)
  - [14] R. Acciarri, *et al.*, Phys. Rev. D 90, 012008 (2014).
  - [15] F. Cavanna, O. Palamara, R. Schiavilla, M. Soderberg and R. B. Wiringa, arXiv:1501.01983 [nucl-ex].
  - [16] L.B. Weinstein, O. Hen, E. Piasetzky, arXiv:1604.02482 [hep-ex].
  - [17] K. Niewczas, J. T. Sobczyk, Phys. Rev. C 93, 035502 (2016).
  - [18] I. R. Simo, J. E. Amaro, M. B. Barbaro, A. De Pace, J. A. Caballero and T. W. Donnelly, arXiv:1604.08423

- [nucl-th].
- [19] A. De Pace, M. Nardi, W.M. Alberico, T.W. Donnelly and A. Molinari, Nucl. Phys. **A726** (2003) 303.
  - [20] G. D. Megias, J. E. Amaro, M. B. Barbaro, J. A. Caballero and T. W. Donnelly, arXiv:1603.08396 [nucl-th].
  - [21] I. Ruiz Simo, C. Albertus, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, Phys. Rev. **D90** (2014) 033012.
  - [22] I. Ruiz Simo, C. Albertus, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, Phys. Rev. **D90** (2014) 053010.
  - [23] R.C. Carrasco, M.J. Vicente Vacas, and E. Oset, Nucl. Phys. A 570 (1994) 701.
  - [24] A. Gil, J. Nieves, and E. Oset, Nucl. Phys. A 627 (1997) 599.
  - [25] J. E. Amaro, C. Maieron, M. B. Barbaro, J. A. Caballero and T. W. Donnelly, Phys. Rev. C **82** (2010) 044601.