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NN Correlations and Final-State Interaction in Electromagnetic Two-Nucleon Knockout Reactions

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Abstract.

The role of correlations in the initial state and of the mutual interaction between the two outgoing nucleons (NN-FSI) in the final state of electromagnetically induced two-nucleon knockout is investigated. The theoretical framework for cross section calculations is outlined and some results are presented for exclusive reactions from ^{16}O. The calculated cross sections indicate that the relative importance of correlation effects as compared to the contributions of two-body currents depends on the final state of the residual nucleus. This opens up good perspectives for the study of short-range correlations. The contribution of NN-FSI, which was neglected in previous investigations, depends on the kinematics and on the type of reaction considered and is in general non negligible.

1 Introduction

It has always been a great challenge of nuclear physics to develop experiments and theoretical models able to investigate the short-range correlations (SRC), which are linked to the short-ranged repulsive core of the NN interaction. The hope is that the comparison between the predictions of different models and data can give detailed information on correlations and can allow one to distinguish the different models of the NN interaction at short distance.

Since a long time electromagnetically induced two-nucleon knockout has been envisaged as a preferential tool for such an investigation, since the probability that a real or a virtual photon is absorbed by a pair of nucleons should be a direct measure for the correlations between these nucleons [1, 2]. This simple picture, however, has to be modified because additional complications have to be taken into account, such as competing mechanisms, like contributions of two-body currents as well as the final-state interaction (FSI) between the two outgoing nucleons and the residual nucleus.

Complementary information is available from electron and photon-induced reactions, but the electron probe seems preferable to explore SRC. In fact, in electron scattering a large sensitivity to correlations has been found in the longitudinal response [3], whereas in photoabsorption the only existing transverse part is dominated, in most of the kinematics studied till now, by medium-range two-body currents [4]. Therefore, photoreactions, besides giving complementary information on correlations, are better suited to investigate two-body currents, whose good understanding is essential to disentangle and investigate short-range effects.

A combined study of pp and pn knockout is needed for a complete information. Correlations are stronger in pn pairs and thus in pn knockout due to the tensor force, that is predominantly present in the wave function of a pn pair. But also two-body currents are much more important in pn knockout [4, 5], while in pp knockout the nonrelativistic seagull- and pion-in-flight meson-exchange currents (MEC) are forbidden, due to isospin selection rules, and only the Δ-excitation and deexcitation mechanisms contribute.

Exclusive reactions, for transitions to specific discrete eigenstates of the residual nucleus, are of particular interest for this study. One of the main results of the theoretical investigation is the selectivity of exclusive reactions involving different final states that can be differently affected by one-body and two-body currents [3, 5]. Thus, the experimental resolution of specific final states may act as a filter to disentangle the two reaction processes. ^{16}O is a suitable target for this study, due to the presence of discrete low-lying states in the experimental spectrum of ^{14}C and ^{14}N well separated in energy. From this point of view, ^{16}O is better than a few-nucleon target like ^{3}He, where the residual "nucleus" consists only of a nucleon without any excitation spectrum.

The existing microscopic model calculations (see, e.g., [2–11]) are able to give a reasonable and in some cases even fair description of the available data [12–15]. The results obtained till now have confirmed the validity of the direct knockout mechanism for low values of the excitation energy of the residual nucleus and have given clear evidence of SRC in the reaction ^{16}O(e,e$'$pp) for the transition to the 0^+ ground state of ^{14}C [15]. This result is a great success of the experimental and theoretical efforts. However, some discrepancies have been found between theory and data. They may be due to the approximations adopted in the models, which are necessary to reduce the complexity of the calculations.

In order to obtain more insight into the two-nucleon knockout process, the models should be improved in the near future as much as possible. This is of specific importance for the interpretation of data.

One of the main ingredients in the cross section of an exclusive two-nucleon knockout reaction is the two-hole spectral function, which contains information on nuclear structure and correlations. The theoretical study of the spectral function must include SRC as well as tensor correlations, but also those processes beyond the mean-field approximation falling under the generic name of long-range correlations (LRC), which are related to the coupling between the single-particle dynamics and the collective excitation modes of the nucleus and which mainly represent the interaction of nucleons at the nuclear surface. These processes are very important in finite nuclear systems. A reliable and consistent evaluation of these different types of correlations in the spectral function requires substantial computational efforts, that are anyhow necessary to solve the existing discrepancies in comparison with data and for the analysis of future data.

Another important aspect of the theoretical model is the treatment of FSI. A crucial assumption adopted in the past was the complete neglect of the mutual interaction between the two outgoing nucleons (NN-FSI). Only the major contribution of FSI, due to the interaction of each of the two outgoing nucleons with the residual nucleus, was taken into account in the different models. The guess was that the effect of NN-FSI should not be large, at least in the kinematics usually considered in the experiments.

A consistent treatment of FSI would require a genuine three-body approach for the interaction of the two nucleons and the residual nucleus, which represents a challenging task. A first estimate of the role of NN-FSI within an approximated but more feasible approach has been done in [16, 17]. Work is in progress to tackle the full three-body approach.

A review of the present status of the theoretical treatment of two-nucleon knockout is presented in this contribution. The theoretical framework is outlined in Sec. II. Results are presented, for different reactions, devoting particular attention to the role of correlations. In Sec. III different approaches for FSI are discussed and illustrated with some numerical examples for different reactions in selected kinematics.

2 NN Correlations

2.1 The Theoretical Framework

The basic ingredients for the calculation of the cross section of the reaction induced by a real or virtual photon, with momentum $\boldsymbol{q}$, where two nucleons are emitted from a nucleus are the transition matrix elements of the nuclear current operator between initial and final nuclear states. For an exclusive reaction and under the assumption of a direct knockout mechanism the matrix elements can be written as [3, 5, 18]

$$J^{\mu}(\boldsymbol{q}) = \int \psi_{\mathrm{f}}^{*}(\boldsymbol{r}_1, \boldsymbol{r}_2) J^{\mu}(\boldsymbol{r}, \boldsymbol{r}_1, \boldsymbol{r}_2) \psi_{\mathrm{i}}(\boldsymbol{r}_1, \boldsymbol{r}_2) \mathrm{e}^{\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{r}} \mathrm{d}\boldsymbol{r} \mathrm{d}\boldsymbol{r}_1 \mathrm{d}\boldsymbol{r}_2. \tag{1}$$

The nuclear-current operator J^μ is the sum of a one-body and a two-body part, corresponding to the two reaction processes already mentioned. The one-body part consists of the usual charge operator and the convection and spin currents. The two-body current includes the nonrelativistic pionic seagull MEC, the pion-in-flight MEC and the Δ contribution, whose explicit expressions can be found, for example, in [4, 19]. All these terms contribute in pn knockout, while the seagull and the pion-in-flight MEC do not contribute in pp emission, at least in the adopted nonrelativistic limit.

The two-nucleon overlap function (TOF) $\psi_{\rm i}$ and the two-nucleon scattering state $\psi_{\rm f}$ are consistently derived in the model from an energy-dependent non-Hermitian Feshbach-type Hamiltonian for the considered final state of the residual nucleus. In practice, since it would be extremely difficult to achieve this consistency, the treatment of initial and final states proceeds separately with different approximations.

In the scattering state, the two outgoing nucleons, 1 and 2, and the residual nucleus interact via the potential

$$V_{\rm f} = V^{\rm OP}(1) + V^{\rm OP}(2) + V^{\rm NN}(1,2), \tag{2}$$

where $V^{\rm OP}(i)$ denotes the interaction between the nucleon i and the residual nucleus. In our approach we use a complex phenomenological optical potential fitted to nucleon-nucleus scattering data, which contains a central, a Coulomb and a spin-orbit term [20]. Only this contribution of FSI has been included in the past. The role of the NN interaction $V^{\rm NN}(1,2)$ is discussed in the next section.

The TOF requires a calculation of the two-hole spectral function including consistently different types of correlations. So far, different approaches are available in the most refined version of our model for pp and pn knockout [3, 5]. In both cases the TOF for transitions to discrete low-lying states of the residual nucleus are given by a combination of different components of the relative and center-of-mass (CM) motion. SRC and TC are introduced in the radial wave function of the relative motion by means of state dependent defect functions which are added to the uncorrelated partial wave. For the pp case [3,21], the defect functions are obtained by solving the Bethe-Goldstone equation using, for a comparison, different NN interactions: Bonn-A, Bonn-C [22], and Reid Soft Core [23]. The calculations with Bonn-A and Bonn-C do not show significant differences, while those with the Reid Soft Core potential produce lower cross sections which are in worse agreement with the available (e,e′pp) data [3,13–15]. For the pn case [5], SRC and TC correlations are calculated within the framework of the coupled-cluster method [24] with the AV14 potential [25] and using the so-called S_2 approximation, where only 1-particle 1-hole and 2-particle 2-hole excitations are included in the correlation operator. This method is an extension of the Bethe-Goldstone equation and takes into account, among other things and besides particle-particle ladders, also hole-hole ladders. These, however, turn out to be rather small in ^{16}O [24], so that the two approaches are similar in the treatment of SRC. The advantage of the coupled-cluster method is that it provides directly correlated two-body wave functions [5, 24]. TC give an important contribution to pn knockout, while their role is very small in pp knockout.

LRC are included in the expansion coefficients of the TOF. For the pp case, these coefficients are calculated in an extended shell-model basis within a dressed random phase approximation [3, 21]. For the pn case, a simple configuration mixing calculation of the two-hole states in ^{16}O has been done and only $1p$-hole states are considered for transitions to the low-lying states of ^{14}N [5].

2.2 Results

The differential cross section of the ^{16}O(e,e$'$pp)^{14}C reaction to the 0^+ ground state and to the 1^+ state are displayed in Figure 1 for two kinematic settings considered in the experiments performed at NIKHEF [13, 15] and MAMI [14]. These results represent a nice example of the selectivity of the exclusive reaction involving different final states that can be differently affected by the one-body and the two-body current. The cross sections are obtained from the combined effect of the various ingredients of the model [3], but it is clear that the role of SRC and two-body currents is completely different for the two final states. The transition to the 1^+ state is dominated, in both kinematics, by the Δ current, while the one-body current, and thus SRC, dominate the transition to the ground state. Here, the contribution of the Δ current is important only for large values of the recoil momentum in the super-parallel kinematics.

Thus, the role of SRC can be dominant in (e,e$'$pp). The results are sensitive to the treatment of correlations, of the different types of correlations in the TOF and, in general, to the approach used for the TOF.

An example is shown in Figure 2, for the same final states and kinematics as in Figure 1. Here the cross sections already shown in Figure 1, where the TOF is given by the spectral function of [3, 21], are compared with the results obtained with the simpler approach of [6], where the two-nucleon wave function is given by the product of the pair function of the shell model and of a central and state-independent Jastrow correlation function [26]. In this approach only SRC are included and the ground state of ^{14}C is described as a pure $(1p_{\frac{1}{2}})^{-2}$ hole in ^{16}O. The third result in the figure is obtained from an alternative approach where the TOF's are calculated using their recently established relationship with the two-body density matrix (TDM) [27, 28]. The quality of the results obtained with this method depends strongly on the availability of realistic TDM's. In the present application a simple TDM, calculated within the Jastrow correlation method [29], has been used, which incorporates only SRC. This is at present the only TDM available for this purpose. The main aim of [28] was to check the

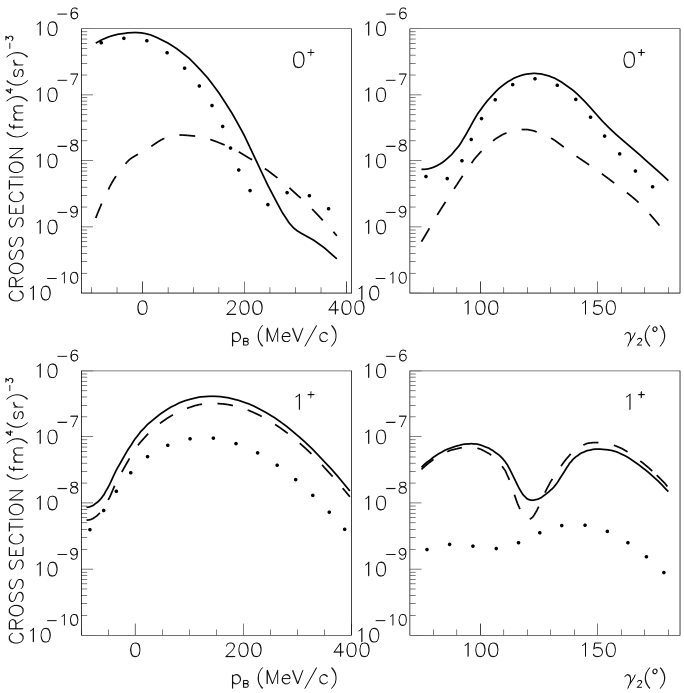

Figure 1. The differential cross section of the reaction ^{16}O(e,e′pp)^{14}C to the 0^+ ground state and the 1^+ state at 11.31 MeV. In the left panels a super-parallel kinematics is considered with incident electron energy $E_0 = 855$ MeV, energy and momentum transfer $\omega = 215$ MeV and $q = 316$ MeV/c. Positive (negative) values of the recoil momentum $p_{\rm B}$ refer to situations where $\boldsymbol{p}_{\rm B}$ is parallel (anti-parallel) to $\boldsymbol{q}$. In the right panels $E_0 = 584$ MeV, $\omega = 212$ MeV, $q = 300$ MeV/c, the kinetic energy of the first outgoing proton is $T_1 = 137$ MeV and its angle with respect to $\boldsymbol{q}$ is $\gamma_1 = -30^{\rm o}$, on the opposite side of the outgoing electron with respect to the momentum transfer. Separate contributions of the one-body and the two-body Δ current are shown by the dotted and dashed lines, respectively. The solid curves give the final result.

practical application of all steps of the method to a given state of the residual nucleus. The results obtained within this simple approach for the TDM, which are able to reproduce the main qualitative features of the cross sections calculated with different treatments of the TOF's, can serve as an indication of the reliability of the method, that can be applied to a wider range of situations and, as an alternative to an explicit calculation of the two-hole spectral function, to more refined approaches of the TDM. The large quantitative differences given by the different treatments in Figure 2 indicate, however, that a refined description of the TOF, involving a consistent evaluation of different types of correlations, is needed to produce reliable predictions.

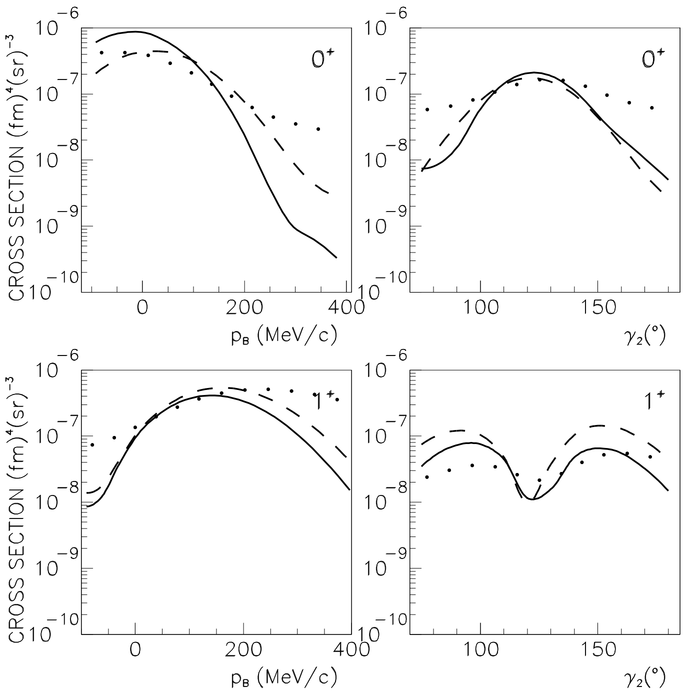

Figure 2. The differential cross section of the reaction ^{16}O(e,e$'$pp)^{14}C to the 0^{+} ground state and the 1^{+} state at 11.31 MeV. Kinematics in the left and right panels as in Figure 1. The curves are obtained with different treatments of the TOF: the product of a pair function of the shell model and the correlation function of [26] (dashed lines), the TOF calculated on the basis of a TDM obtained within the Jastrow correlation method (dotted lines). Solid lines as in Figure 1.

The cross section of the ^{16}O(e,e$'$pn)^{14}N reaction to the 1^{+} ground state is displayed in Figure 3. Calculations have been performed in the same super-parallel kinematics already considered for the reaction ^{16}O(e,e$'$pp)^{14}C. This is the kinematics of the future (e,e$'$pn) experiment at MAMI [30] and appears therefore of particular interest. The results given by the approach of [5] are compared with those given by the simpler prescription where the two-nucleon wave function is given by the product of the pair function of the shell model, described for the 1^{+} ground state as a pure $(1p_{\frac{1}{2}})^{-2}$ hole in ^{16}O, and of the correlation function of [26], which includes only SRC. Separate contributions of the different terms of the nuclear current are shown in the figure and compared with the final result. With the more sophisticated approach the contribution of the one-body current, entirely due to correlations, is larger than in the correspond-

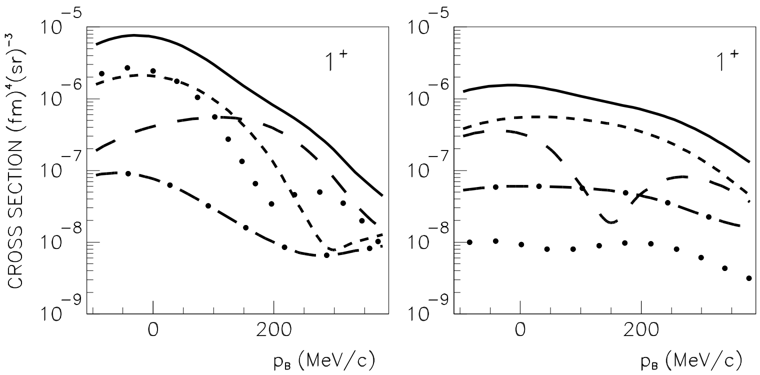

Figure 3. The differential cross section of the reaction ^{16}O(e,e$'$pn)^{14}N to the 1^+ ground state in the same super-parallel kinematics as in the left panel of Figure 1. The proton is ejected parallel and the neutron anti-parallel to $\boldsymbol{q}$. Separate contributions of the one-body, seagull, pion-in-flight and Δ current are shown by the dotted, short-dashed, dot-dashed and long-dashed lines, respectively. Two different treatments of the TOF are compared: the approach of [5] (left panel), and the product of a pair function of the shell model and the correlation function of [26] (right panel).

ing situation for (e,e$'$pp), but also two-body currents are much more important. The final cross section is about one order of magnitude larger than in (e,e$'$pp). In this particular situation the contribution of the one-body current is not dominant, but it is competitive with the one of the two-body current. Also the seagull current is important at low values of the momentum, while the Δ current becomes comparable with the other components only at large values of the momentum. The contribution of the pion-in-flight current is in general very small. Thus, also in this case, correlations are important to determine the size and the shape of the cross section. An important contribution is given by tensor correlations [5]. With the simpler treatment where only SRC are included the contribution of the one-body current is completely negligible. Meaningful differences are produced by the two approaches also on the various terms of the two-body current. These effects are less dramatic than those obtained on the one-body current, but are anyhow large and the two final results are very different, both in size and shape. Thus, also for (e,e$'$pn) a careful description of the TOF involving nuclear structure and correlations is needed to produce reliable predictions.

In general, two-body currents give the major contribution to (γ,NN) reactions. In the (γ,pp) reaction, however, suitable kinematics can be envisaged where the role of SRC is important or even dominant. Two examples are shown in Figure 4 for the ^{16}O(γ,pp) reaction to the 0^+ ground state of ^{14}C. The kinematics in the left panel, which appears within reach of available experimental facilities, was already envisaged in [8] as promising to study SRC. At the con-

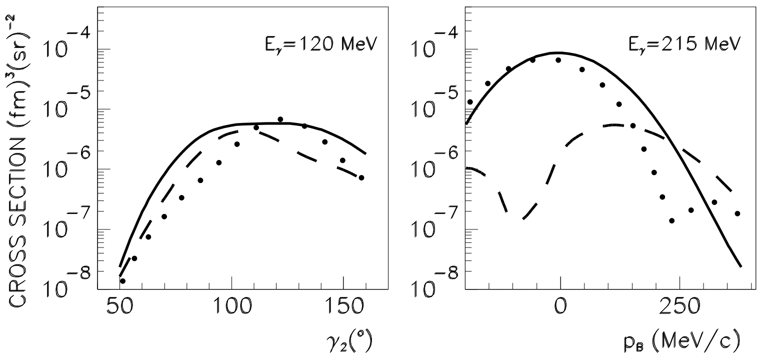

Figure 4. The differential cross section of the reaction ^{16}O(γ, pp) to the 0^+ ground state of ^{14}C. In the left panel a coplanar kinematics is considered, with an incident photon energy E_γ =120 MeV, $T_1 = 45$ MeV and $\gamma_1 = 45°$; in the right panel a super-parallel kinematics at E_γ =215 MeV. Line convention as Figure 1.

sidered value of the photon energy, $E_\gamma = 120$ MeV, where the Δ current is relatively much less important, the contribution of the one-body current is large and competitive with the one of the two-body current: the Δ current plays the main role at lower values of γ_2, while for $\gamma_2 \geq 110°$ the one-body current gives the major contribution. In the right panel a super-parallel kinematics is considered where the incident photon energy has the same value, $E_\gamma = 215$ MeV, as the energy transfer in the (e,e′pp) calculation of Figure 1. In this kinematics, which is however not very well suited for (γ,pp) experiments, the cross section is dominated by the one-body current for recoil-momentum values up to about 150 MeV/c. For larger values the Δ current plays the main role. This is the same behavior as in the corresponding situation for (e,e′pp).

Therefore, two-nucleon knockout is a promising tool to explore NN correlations. A combined study of different reactions in suitable kinematics must be performed to achieve this goal. More data are needed. For the analysis of data the theoretical model must be improved as much as possible. The sensitivity of the results to the treatment of correlations in the TOF indicates that an accurate determination of the two-hole spectral function is most desirable to disentangle the effects of two-body currents from those of correlations. A crucial ingredient of the model is represented by FSI, whose treatment is discussed in the next section.

3 Final-State Interaction

3.1 The Theoretical Framework

In general, a consistent treatment of the final state would require a genuine three-body approach, for the two nucleons and the residual nucleus interacting through the potential $V_{\rm f}$ in Eq. (2), that, due to the complexity of the problem, has never been realized till now for complex nuclei. Different approximations have been used in the past.

In the simplest picture, any interaction between the two nucleons and the residual nucleus is neglected, i.e., $V_{\rm f} \equiv 0$, and a plane-wave approximation (PW) is assumed for the outgoing nucleon wave functions. If $\boldsymbol{p}_i^0$, $i \in \{1,2\}$, denotes the asymptotic momentum of the outgoing nucleon i, the corresponding state is given by

$$|\psi_{\rm f}^{\rm PW}\rangle = |\boldsymbol{p}_1^0\rangle \, |\boldsymbol{p}_2^0\rangle \ , \tag{3}$$

where $|\boldsymbol{p}_i^0\rangle$ describes the plane-wave state of the nucleon i with momentum $\boldsymbol{p}_i^0$.

In a more sophisticated approach, only the optical potential $V^{\rm OP}(i)$ is considered while the mutual NN interaction $V^{\rm NN}(1,2)$ is neglected. In this so-called "distorted-wave" (DW) approximation, which has commonly been used in our previous work and also in Sec. II, the final state is in general given by

$$|\psi_{\rm f}\rangle^{\rm DW} = \big(1 + G_0(z)T^{\rm OP}(z)\big) \, |\boldsymbol{p}_1^0\rangle \, |\boldsymbol{p}_2^0\rangle \ , \tag{4}$$

with

$$z = \frac{(\boldsymbol{p}_1^0)^2}{2m_1} + \frac{(\boldsymbol{p}_2^0)^2}{2m_2} + \frac{(\boldsymbol{p}_B)^2}{2m_B} - i\epsilon \tag{5}$$

where m_i is the mass of the nucleon i and $G_0(z)$ the free three-body propagator. The scattering amplitude $T^{\rm OP}$ is in general given by the Lippmann-Schwinger equation, i.e.,

$$T^{\rm OP}(z) \quad = \quad \big(V^{\rm OP}(1) + V^{\rm OP}(2)\big) + \big(V^{\rm OP}(1) + V^{\rm OP}(2)\big) \, G_0(z)T^{\rm OP}(z) \tag{6}$$

The residual nucleus has a rather large mass in comparison with the nucleon and can thus be considered as infinitely heavy. In this limit, the scattering state can be expressed as the product of two uncoupled single-particle distorted wave functions, eigenfunctions of the optical potential, i.e.,

$$|\psi_{\rm f}^{\rm DW}\rangle = |\phi^{\rm OP}(\boldsymbol{p}_1^0)\rangle \, |\phi^{\rm OP}(\boldsymbol{p}_2^0)\rangle, \tag{7}$$

If we want to incorporate the interaction $V^{\rm NN}$ in a fully consistent frame, an infinite series of contributions has to be taken into account in $T^{\rm OP}$ and in the NN-scattering amplitude

$$t^{\rm NN}(z_{12}) = V^{\rm NN} + V^{\rm NN} g_0^{12}(z_{12}) t^{\rm NN}(z_{12}), \tag{8}$$

where $g_0^{12}(z_{12})$ is the free propagator for the two nucleons and $z_{12} = z_1 + z_2$.

In the limit $m_B \to \infty$, the leading order terms in the scattering amplitudes are given by [17]

$$
\begin{aligned}
|\psi_{\rm f}\rangle = \big(1 &+ g_0^{12}(z_{12})t^{\rm OP,12}(z_{12}) + g_0^{12}(z_{12})t^{\rm NN}(z_{12}) \\
&+ g_0^{12}(z_{12})t^{\rm OP,12}(z_{12})g_0^{12}(z_{12})t^{\rm NN}(z_{12}) \\
&+ g_0^{12}(z_{12})t^{\rm NN}(z_{12})g_0^{12}(z_{12})t^{\rm OP,12}(z_{12}) + ...\big)\,|\boldsymbol{p}_1^0\rangle\,|\boldsymbol{p}_2^0\rangle \;,
\end{aligned} \tag{9}
$$

where $t^{\rm OP,12}(z_{12})$ follows from Eq. (6) with the substitution of $G_0(z)$ by the free two-body propagator $g_0^{12}(z_{12})$.

A consistent treatment of FSI would require a genuine three-body approach by summing up the infinite series in Eq. (9). This project will be tackled in the near future. In [16, 17] a perturbative treatment has been used by taking into account only the first three terms in Eq. (9). Formally, this corresponds to a perturbative treatment of $t^{\rm OP,12}$ and $t^{\rm NN}$ up to first order and where multiscattering processes, like the fourth and fifth terms, are neglected. Such an approximated but much more feasible treatment should allow one to study the main features of NN-FSI. The present treatment of incorporating NN-FSI is denoted as DW-NN

$$
|\psi_{\rm f}\rangle^{\rm DW-NN} = |\phi^{\rm OP}(\boldsymbol{p}_1^0)\rangle\,|\phi^{\rm OP}(\boldsymbol{p}_2^0)\rangle + g_0^{12}(z_{12})t^{\rm NN}(z_{12})|\boldsymbol{p}_1^0\rangle\,|\boldsymbol{p}_2^0\rangle. \tag{10}
$$

We denote as PW-NN the treatment where only $V^{\rm NN}$ is considered and $V^{\rm OP}$ is switched off, i.e.,

$$
|\psi_{\rm f}\rangle^{\rm PW-NN} = |\boldsymbol{p}_1^0\rangle\,|\boldsymbol{p}_2^0\rangle + g_0^{12}(z_{12})t^{\rm NN}(z_{12})|\boldsymbol{p}_1^0\rangle\,|\boldsymbol{p}_2^0\rangle. \tag{11}
$$

3.2 Results

The results of the different approaches in Eqs. (3), (7), (10), and (11) have been compared for different reactions in selected kinematics. In order to ensure some consistency in the treatment of the NN interaction in the initial and final states, the same NN potential $V^{\rm NN}$ has been used as in the calculation of the TOF, i.e., the Bonn-A potential for pp and the AV14 potential for pn emission. The sensitivity of NN-FSI effects to the choice of the potential is, however, small in the calculations.

The results for the ^{16}O(e,e′pp)^{14}C reaction to the 0^+ ground state in the same two kinematics already considered in Figure 1 are displayed in Figure 5. It can be clearly seen in the figure that the inclusion of the optical potential leads, in both cases, to an overall and substantial reduction of the calculated cross sections (see the difference between the PW and DW results). This effect is well known and it is mainly due to the imaginary part of the optical potential, that accounts for the flux lost to inelastic channels in the nucleon-residual nucleus elastic scattering. The optical potential gives in general the main contribution of FSI. The NN-FSI produces in general an enhancement of the calculated cross

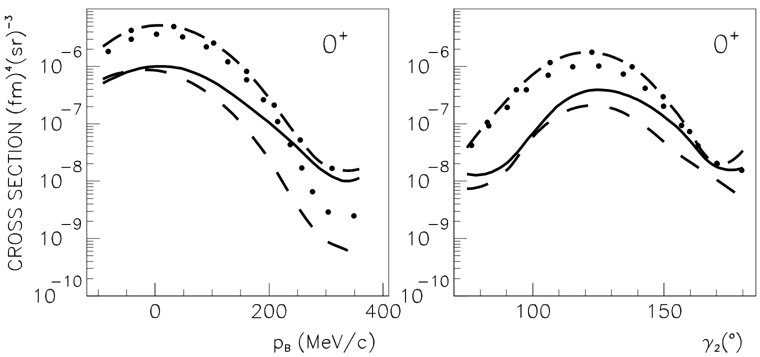

Figure 5. The differential cross section of the reaction ^{16}O(e,e$'$pp)^{14}C to the 0^+ ground state. Kinematics in left and right panels as in Figure 1. The results of different approximations of FSI are compared: PW (dotted), PW-NN (dash-dotted), DW (dashed), DW-NN (solid). The dashed lines correspond the solid lines in Figure 1.

section that depends on kinematics and is larger in the DW-NN than in the PW-NN approach. This effect is particularly relevant for large values of the recoil momentum in the super-parallel kinematics, where the enhancement in the DW-NN approach goes beyond the PW result and amounts to roughly an order of magnitude for $p_{\rm B} \simeq 300$ MeV/c. In the other kinematical setting the effect is less important than in the super-parallel kinematics, but it is anyhow non negligible and, also in this case, it increases with the recoil momentum.

The effect of NN-FSI is different on the different terms of the nuclear cur-

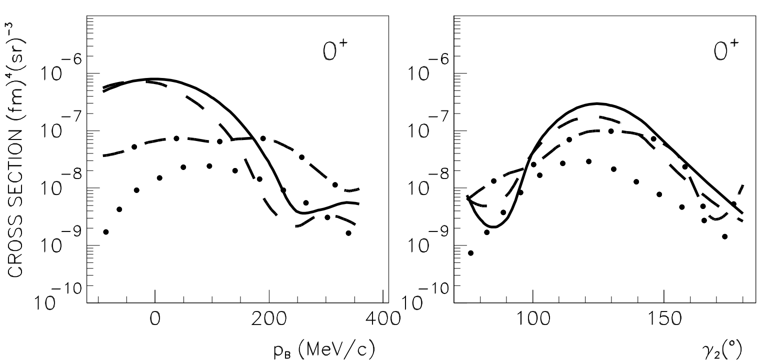

Figure 6. The differential cross section of the reaction ^{16}O(e,e$'$pp)^{14}C to the 0^+ ground state. Kinematics in left and right panels as in Figure 1. Line convention: DW with the Δ current (dotted), DW-NN with the Δ current (dash-dotted), DW with the one-body current (dashed), DW-NN with the one-body current (solid).

rent. This can be seen in Figure 6, where the results of the DW and DW-NN approaches are compared on the separated contributions of the one-body and the two-body Δ current in the two kinematics. In both cases NN-FSI produces a strong enhancement of the Δ-current contribution over the whole angular and momentum distributions. For low values of the recoil momentum, up to about 100-150 MeV/c, this large effect on the Δ current is completely overwhelmed in the final result by the dominant contribution of the one-body current. The effect of NN-FSI on the one-body current is much weaker but anyhow sizable and it is responsible for the final effect in Figure 5 at lower momenta, i.e., in the region where the cross section has the maximum. For larger values of $p_{\rm B}$, where the one-body current is less important in the cross section, the enhancement produced by NN-FSI on the Δ current is responsible for the substantial enhancement in the final result.

The ^{16}O(e,e$'$pp)^{14}C cross sections to the 1^+ state shown in Figure 1 are dominated by the Δ current. In this case, however, the effect of NN-FSI is much weaker than for the ground state [16]. Thus, NN-FSI effects depend on the final state of the residual nucleus and are sensitive to details of the theoretical ingredients of the model.

The results for the ^{16}O(e,e$'$pn)^{14}N reaction to the 1^+ ground state in the super-parallel kinematics are shown in Figure 7. Also in this case the most important effect of FSI is the substantial reduction produced by the optical potential. NN-FSI gives an enhancement of the cross section that is anyhow much weaker than in (e,e$'$pp). This effect is not very important but sizable in DW-NN and very small in PW-NN. It has been shown in [17] that also in (e,e$'$pn) NN-FSI affects more the two-body than the one-body current. In particular, a sizable enhancement is produced on the Δ current, at all the values of $p_{\rm B}$, and a huge enhancement on the seagull current at large momenta. The sum of the two terms, however, produces a destructive interference that leads to a partial cancellation in the final cross section of Figure 7.

Figure 8 shows the results for the ^{16}O(γ,pp)^{14}C reaction in the same kinematics as in Figure 4. At $E_\gamma = 120$ MeV NN-FSI has almost no effect. In contrast, a very large contribution is given by the optical potential, which produces a substantial reduction of the calculated cross sections. The reduction given by the optical potential is the main effect of FSI also in the super-parallel kinematics, where NN-FSI produces a significant enhancement of the Δ-current contribution and a negligible effect on the one-body current. In the corresponding situation for (e,e$'$pp) the enhancement produced by NN-FSI on the one-body current is on the longitudinal component, that does not contribute in reactions induced by a real photon, while the enhancement of the Δ-current contribution is larger than in (γ,pp).

In conclusion, the numerical results confirm that the main contribution of FSI is given by the optical potential, which produces an overall and substan-

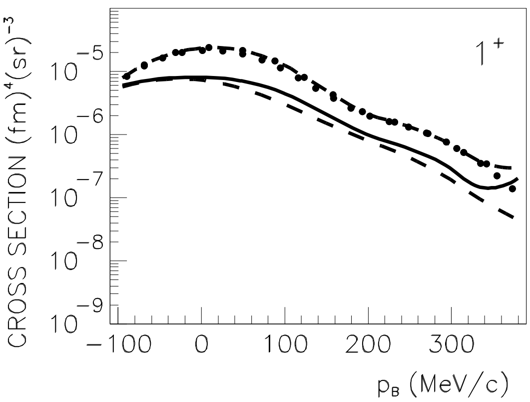

Figure 7. The differential cross section of the reaction ^{16}O(e,e′pn)^{14}N to the 1^+ ground state in the same kinematics as in Figure 3. Line convention as in Figure 6.

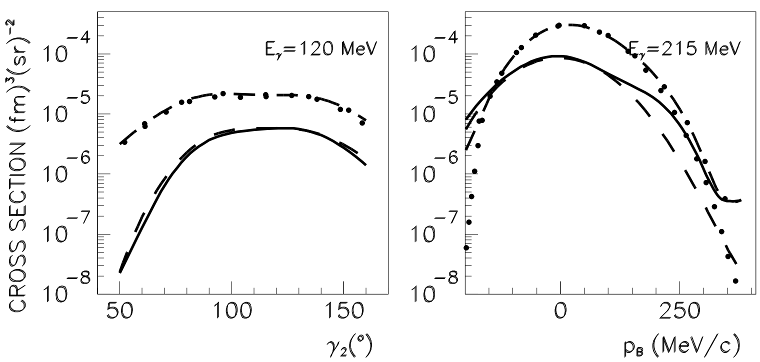

Figure 8. The differential cross section of the reaction ^{16}O(γ, pp) to the 0^+ ground state of ^{14}C. Kinematics in left and right panels as in Figure 4. Line convention as in Figure 6.

tial reduction of the calculated cross sections. This effect is important and can never be neglected. In most of the situations considered here, NN-FSI gives an enhancement of the cross section. This effect is in general non negligible, it depends strongly on the kinematics, on the type of reaction, and on the final state of the residual nucleus. NN-FSI is in general larger in pp than in pn knockout and in electron than in photon-induced reactions. It affects in a different way the various terms of the nuclear current, usually more the two-body than the one-body terms, and is sensitive to the various theoretical ingredients of the calculation. This makes it difficult to make predictions about the role of NN-FSI: each specific situation should be individually investigated.

NN-FSI effects are in general non negligible. In spite of that, the original guess, that justified its neglect in the past, i.e., that its contribution does not significantly change the main qualitative features of the theoretical results, is basically correct. But in order to obtain more reliable quantitative results and to get more insight into the two-nucleon knockout process, for a more careful comparison with available as well as future data, NN-FSI must be included in the model.

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