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Theoretical aspects of (e, e′NN) reactions

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Abstract. Electromagnetically induced two-nucleon knockout reactions are considered. The theoretical framework is outlined and some results are presented for the exclusive $^{16}O(e,e'pp)^{14}C$ reaction. The possibility of obtaining in comparison with data direct and clear information on short-range correlations is discussed.

PACS. 25.30.-c Lepton-induced reactions – 24.10.-i Nuclear-reaction models and methods

1 Introduction and motivations

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 knockout reactions have been envisaged as a preferential tool for such an investigation.

Only indirect evidence of SRC has been obtained from the exclusive $(e,e'p)$ knockout reaction, where the spectroscopic factors (s.f.) found for the removal of protons from the valence shells are about 60–70% of the values of the independent-particle shell model (IPSM) [1,2]. The s.f. account for the depletion of the quasi-hole states produced by NN correlations and the discrepancy with respect to the predictions of the IPSM can give a measurement of correlation effects. Theoretical investigations within different correlation methods indicate that only a few percent of the depletion is due to SRC [3–6]). When tensor correlations (TC) are added, the depletion amounts to $\sim 10\%$, at most $\sim 15\%$ in heavy nuclei. Further depletion is given by the long-range correlations (LRC) [7–9], which are related to the coupling between the s.p. dynamics and the collective excitation modes of the nucleus.

Thus, SRC account for only a small fraction of the depletion of the quasi-hole states. This depletion is compensated by the admixture of high-momentum components in the nuclear wave function. One might then think to investigate SRC studying the high-momentum components of the s.p. wave functions in exclusive $(e,e'p)$ experiments. Indeed, large differences for the cross-sections calculated with different overlap functions are generally found at high values of the momentum. It is not clear, however, if these differences are due to correlations or to the different methods used in the calculations. Microscopic calculations of the momentum distribution (see, *e.g.*, [10]) indicate that a strong enhancement of the high-momentum components is due to SRC, but it shows up at large values of the excitation energy of the residual nucleus. In exclusive $(e,e'p)$ experiments one does not measure the whole momentum distribution, but only the spectral function at the energy corresponding to the specific final state that is considered. In general, low-lying discrete states of the residual nucleus are considered, corresponding to low values of the excitation energy, while the missing strength due to SRC is found at large values of the excitation energy, where other competing processes are present. This makes a clear-cut identification of SRC in $(e,e'p)$ very difficult.

This identification appears possible in two-nucleon knockout reactions. Here, particular situations can be envisaged where the knockout of the two nucleons is entirely due to correlations. These situations appear very well suited to study SRC.

Two nucleons can be naturally ejected by two-body currents due to meson exchanges and Δ-isobar excitation. More direct insight into SRC can be obtained from the situation where the real or virtual photon hits, through a one-body current, either nucleon of a correlated pair and both nucleons are then ejected from the nucleus. Both these competing processes are included in the experimental cross-sections and cannot be simply singled out. Their role and relevance, however, is different in different reactions and kinematics. It is thus possible, with the help of theoretical predictions, to envisage appropriate situations

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where various specific effects can be disentangled and separately investigated.

Complementary information is available from electron- and photon-induced reactions, but the electron probe is preferable to study SRC. In fact, two-body currents predominantly contribute to the transverse components of the nuclear response. Only these components are present in photon-induced reactions that appear thus generally dominated by two-body currents. Also the longitudinal component, dominated by correlations, is present in electron-induced reactions. The possibility of independently varying the energy and momentum transfer of the exchanged virtual photon allows one to select kinematics, where the longitudinal response and thus SRC are dominant.

A combined study of *pp* and *np* knockout is needed for a complete information. Correlations are different in *pp* and *np* pairs. They are stronger in *np* pairs and thus in *np* knockout due to the tensor force, that is predominantly present in the wave function of a *np* pair. But also two-body currents are much more important in *np* knockout, while they are strongly suppressed in *pp* knockout, where the charge-exchange terms of the two-body current do not contribute. Therefore, the $(e, e'pp)$ reaction was devised as the preferential process for studying SRC. It is however clear that, since different effects can be emphasized in suitable conditions for different reactions, a combined study of *pp* and *np* knockout induced by real and virtual photons is needed to unravel the different contributions and obtain complete information on correlations.

Exclusive reactions 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 [11,12]. 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 light nucleus, which lacks specific final states.

The theoretical framework for cross-section calculations is outlined in sect. 2. Some numerical results for the exclusive $^{16}\mathrm{O}(e, e'pp)^{14}\mathrm{C}$ reaction and the possibility of extracting information on SRC are discussed in sect. 3.

2 Theoretical framework

A detailed description of the theoretical framework can be found in refs. [11,13,14]. Here, only the main features are outlined.

The basic ingredients of the calculations 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

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

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 two-body current includes terms due to the lowest-order diagrams with one-pion exchange, namely seagull, pion-in-flight and diagrams with intermediate Δ-isobar configurations. All these terms contribute to *pn* knockout, while only the non–charge-exchange terms in the Δ current operator contribute to *pp* knockout. The two-nucleon overlap integral ψ_{i} and the two-nucleon scattering state ψ_{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 interaction of each of the outgoing nucleons with the residual nucleus is considered by means of a phenomenological optical potential and the interaction between the two outgoing nucleons is neglected. Some work is in progress to include in the model the interaction between the two outgoing nucleons [15].

For the $^{16}\mathrm{O}(e, e'pp)^{14}\mathrm{C}$ reaction the two-nucleon overlap functions are taken from the calculation of the spectral function [11,16], where both LRC and SRC are included. LRC are calculated in a SM space large enough to incorporate the corresponding collective features which influence the pair removal amplitudes. The s.p. propagators used for this dressed Random Phase Approximation (RPA) description of the two-particle propagator also include the effect of both LRC and SRC. In the second step that part of the pair removal amplitudes which describes the relative motion of the pair is supplemented by defect functions obtained from the same G-matrix which is also used as the effective interaction in the RPA calculation.

The two-nucleon OF for a discrete final state of ^{14}C, with angular-momentum quantum numbers JM, is expressed in terms of a combination of relative and c.m. wave functions [11]. SRC are included in the radial wave function ϕ of relative motion through a defect function defined by the difference between ϕ and the uncorrelated relative wave function. These defect wave functions depend on the quantum numbers of the relative motion. Since different components of relative and c.m. motion contribute to each transition, the role of SRC can be different for different final states.

3 Results and discussion

A numerical example is shown in fig. 1. Results are shown for the $^{16}\mathrm{O}(e, e'pp)^{14}\mathrm{C}$ reaction and the transitions to the 0^+ ground state and to the 1^+ state for two kinematical settings considered in the experiments performed at NIKHEF [17,18] and MAMI [19].

Different components of relative and c.m. motion contribute to the two final states [11]: $^1S_0$ and $^3P_1$ relative waves (the notation $^{2S+1}l_j$, for $l = S, P, D$, is used here), which are combined with a c.m. orbital angular momentum $L = 0$ and 1, respectively, for the 0^+ state, and $^3P_0$,

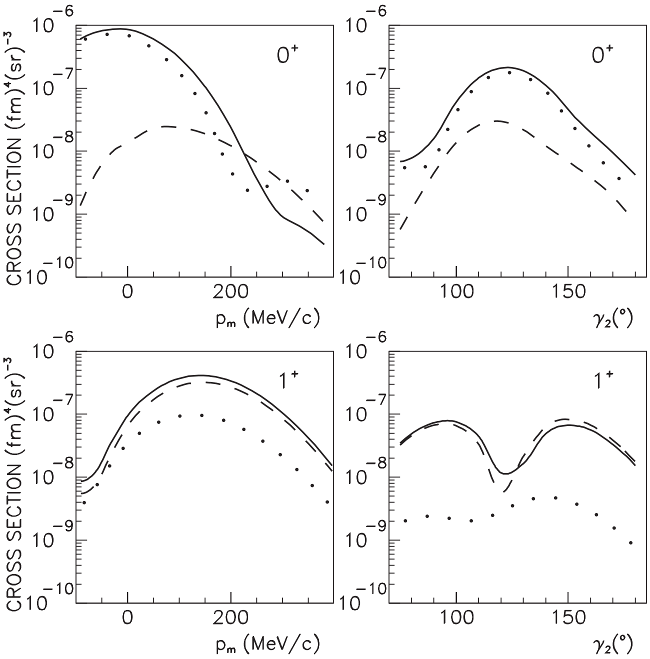

Fig. 1. The differential cross-section of the reaction $^{16}\mathrm{O}(e, e'pp)^{14}\mathrm{C}$ for the transitions to the 0^+ ground state and to the 1^+ state at 11.31 MeV. In the left panels a super-parallel kinematics is considered with incident electron energy $E_0 = 855$ MeV, energy and momentum transfer $\omega = 215$ MeV and $q = 316$ MeV/c. Positive (negative) values of the recoil momentum p_{m} refer to situations where $\boldsymbol{p}_{\mathrm{m}}$ 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 137 MeV and its angle with respect to $\boldsymbol{q}$ is $\gamma_1 = -30^{\circ}$, 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.

$^3P_1$, $^3P_2$, all combined with $L = 1$, for the 1^+ state. The value of L determines the shape of the recoil momentum distribution. Indeed in fig. 1 for the 1^+ state, where only components with $L = 1$ are present, the momentum distributions have a typical p-wave shape, while the s-wave shape obtained for the 0^+ state indicates that in the considered kinematics the cross-section is dominated by the component with $L = 0$ and thus by $^1S_0$ pp knockout. The component with $L = 1$, due to $^3P_1$, becomes meaningful only at large values of p_{m}, where the contribution of the s-wave gets lower.

The comparison between correlated and uncorrelated relative wave functions [11,16] indicates that SRC play a different role in different relative states: they are quite strong for the $^1S_0$ state and much weaker for ^3P states. Moreover, also the role of the isobar current is strongly reduced for $^1S_0$ pp knockout [20,14]. Thus, SRC are emphasized in $^1S_0$ knockout, while the Δ current is much more important in ^3P knockout. This explains the different role of the two reaction processes for the two final states: the transition to the 1^+ state is dominated by the Δ current, while for the 0^+ state the cross-section is dominated by the one-body current and thus by SRC. Thus, the experimental resolution of different states may act as a filter to disentangle and separately investigate the contributions due to SRC and two-body currents.

Data have confirmed the predictions of this model. A reasonable and in some cases an excellent agreement with the available data [17–19] has been obtained. The comparison has clearly shown the validity of the knockout mechanism and has confirmed the predicted selectivity of the exclusive reaction involving discrete final states. In particular, clear evidence for SRC has been obtained for the transition to the ground state [18].

This important result means that two-nucleon knockout reactions can be used to study and hopefully determine SRC. More theoretical and experimental work is however needed for this study.

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