Eur. Phys. J. A **17**, 7–10 (2003)
DOI 10.1140/epja/i2002-10148-y

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

On the NN final-state interaction in the $^{16}\mathrm{O}(\mathrm{e},\mathrm{e}'\mathrm{pp})$ reaction

M. Schwamb[1,a], S. Boffi[2], C. Giusti[2], and F.D. Pacati[2]

[1] Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
[2] Dipartimento di Fisica Nucleare e Teorica dell'Università, Pavia and Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, I-27100 Pavia, Italy

Received: 19 December 2002 /
Published online: 15 April 2003 –
Communicated by A. Molinari

Abstract. The influence of the mutual interaction between the two outgoing nucleons (NN-FSI) in the $^{16}\mathrm{O}(e,e'pp)$ reaction has been investigated. Results for various kinematics are discussed. In general, the effect of NN-FSI depends on kinematics and the chosen final state in the excitation spectrum of $^{14}\mathrm{C}$.

PACS. 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.) – 21.60.-n Nuclear-structure models and methods – 25.30.Fj Inelastic electron scattering to continuum

1 Introduction

The independent particle shell model, describing a nucleus as a system of nucleons moving in a mean field, reproduces many basic features of nuclear structure. It is, however, well known that the repulsive components of the NN-interaction induce additional short-range correlations (SRC) which are beyond a mean-field description and whose investigation can provide additional insight into the nuclear structure. A powerful tool for the investigation of SRC are electromagnetic two-nucleon knockout reactions like (γ,NN) or $(e,e'\mathrm{NN})$, 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 (for an overview, see [1]). However, this simple picture has to be modified because additional complications have to be taken into account. In particular, competing mechanisms like contributions of two-body currents as well as final-state interactions (FSI) between the two outgoing nucleons and the residual nucleus have to be considered. However, it turned out in previous studies [2–4] that it is —at least in principle— possible to determine specific kinematical situations where the reaction cross-section is particularly sensitive to SRC.

Due to the complexity of the subject, several approximations have been performed in the past, which restrict the reliability of the existing models (consider [1–9] and references therein) with respect to the interpretation of the existing experimental data. In this context, one crucial assumption is the fact that the mutual interaction between the two outgoing nucleons, denoted as NN-FSI, can be neglected. At the moment no reliable estimate of this approximation exists for two-nucleon knockout on finite nuclei. Indeed, recent calculations on nuclear matter [10] clearly indicate that NN-FSI are non-negligible even if the two detected nucleons are ejected back to back in the so-called superparallel kinematics, where NN-FSI are expected to be minimal. However, a study in nuclear matter does not provide results for cross-sections which can directly be compared with experimental data produced for a specific target nucleus.

A consistent treatment of FSI would require in general a genuine three-body approach for the mutual interaction of the two protons and the residual nucleus (see fig. 1). Presumably due to the enormous computational challenges, this has never been tackled in the past. Before starting such an ambitious project, it may be recommendable to estimate first within an approximative, but more feasible treatment the qualitative role of NN-FSI. This has been done in the present work using as underlying framework the unfactorized approach for two-nucleon knockout on complex, but finite nuclei presented in [2]. If NN-FSI in these studies turned out to be small, a complete three-body calculation would not be necessary and the previous treatment of neglecting NN-FSI completely could be justified.

The paper is organized as follows. The theoretical framework and the adopted approximations are outlined in sect. 2. Numerical results for some selected kinematical

[a] e-mail: schwamb@kph.uni-mainz.de

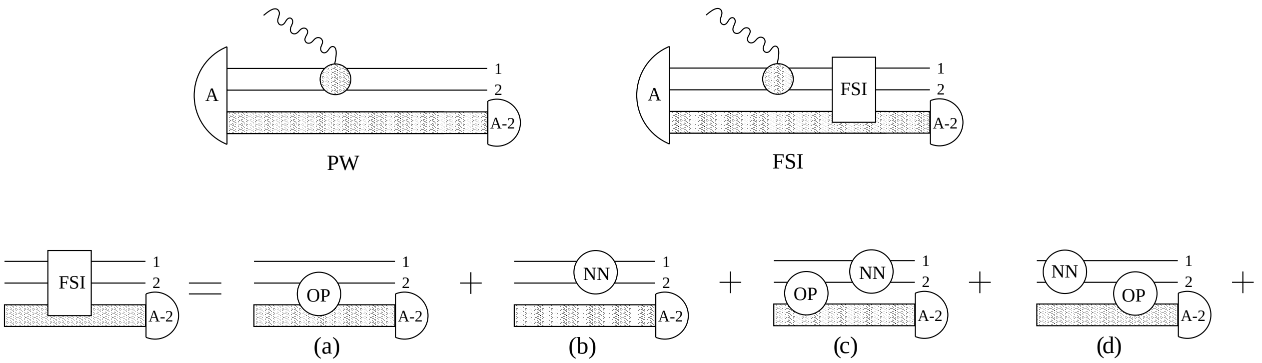

Fig. 1. The relevant diagrams for electromagnetic two-nucleon knockout on a complex nucleus A. The two diagrams on top depict the plane-wave approximation (PW) and the distortion of the two outgoing proton wave functions by final-state interactions (FSI). Below, the relevant mechanisms of FSI are depicted in detail, where the open circle denotes either a nucleon-nucleus interaction given by a phenomenological optical potential (OP) or the mutual interaction between the two outgoing nucleons (NN). Diagrams which are given by an interchange of nucleon 1 and 2 are not depicted.

situations are presented in sect. 3, where also some perspectives of possible improvements and future developments are given.

2 The model

The cross-section for electromagnetic two-proton knockout is given in general by the square of the scalar product of the relativistic electron current j^μ and of the nuclear current J^μ, where the latter is given by the Fourier transform of the transition matrix element of the charge-current density operator between initial and final nuclear states

$$J^\mu(\boldsymbol{q}) = \int \langle \Psi_f | \hat{J}^\mu(\boldsymbol{r}) | \Psi_i \rangle e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\, \mathrm{d}\boldsymbol{r}\ . \tag{1}$$

Concerning the nuclear current $\hat{J}^\mu(\boldsymbol{r})$ and the initial state $|\Psi_i\rangle$ of the two emitted protons, the general framework described in [2] has been adopted without any modification. Thus, the nuclear current operator $\hat{J}^\mu(\boldsymbol{r})$ is the sum of a one- and a two-body part. The one-body part consists of the usual charge operator and the convection and spin current. In the two-body part the non-relativistic pionic seagull and flight meson-exchange current do not contribute to two-proton emission, so that only intermediate Δ isobar excitation has to be considered [11].

For the $^{16}\mathrm{O}(e,e'pp)$ reaction, the initial state $|\Psi_i\rangle$ is taken from the calculation of the two-proton spectral function of ^{16}O in [12], where long-range and short-range correlations are consistently taken into account. The latter are included in the radial wave functions of relative motion through defect functions, which were obtained by solving the Bethe-Goldstone equation for ^{16}O in momentum space.

As has already been outlined in the introduction, several approximations have been used in the past concerning the final state $|\Psi_f\rangle$. In the simplest approach any interaction between the two protons and the residual nucleus is neglected and a plane-wave approximation (PW) is assumed for the two outgoing protons (see fig. 1). In the more sophisticated approach of [2], the interaction between each of the outgoing protons and the residual nucleus is considered by using a complex phenomenological optical potential V^{OP} for nucleon-nucleus scattering which contains a central, a Coulomb and a spin-orbit term [13] (see diagram (a) in fig. 1). Under the simplifying assumption of an infinite heavy residual nucleus, the corresponding final state can be expressed as the *product* of two uncoupled single-particle distorted-wave functions $\langle \boldsymbol{r}_i | \phi^{\mathrm{OP}}(\boldsymbol{p}_i{}^0)\rangle$ $(i = 1,2)$. The latter are given by the solution of the corresponding Schrödinger equation

$$\left(H_0(i) + V^{\mathrm{OP}}(i)\right) |\phi^{\mathrm{OP}}(\boldsymbol{p}_i{}^0)\rangle = E_i |\phi^{\mathrm{OP}}(\boldsymbol{p}_i{}^0)\rangle, \tag{2}$$

with $H_0(i)$ denoting the kinetic energy operator and $\boldsymbol{p}_i{}^0$ the asymptotic free momentum of the outgoing proton i, with kinetic energy E_i in the used laboratory frame. In practice, the finite mass $m_{^{14}\mathrm{C}}$ of the residual nucleus ^{14}C is taken into account by performing in (2) the transformation [14] $(i \neq j \in 1,2)$

$$\boldsymbol{p}_i{}^0 \to \boldsymbol{q}_i{}^0 = \frac{1}{m_{^{16}\mathrm{O}}} \left[(m_p + m_{^{14}\mathrm{C}}) \boldsymbol{p}_i{}^0 - m_p(\boldsymbol{p}_j{}^0 + \boldsymbol{p}_B) \right]\ , \tag{3}$$

where $m_p (m_{^{16}\mathrm{O}})$ denotes the mass of the outgoing proton (^{16}O) and $\boldsymbol{p}_B$ the recoil momentum of the residual nucleus ^{14}C. Moreover, a semirelativistic generalization of (2) has been used as discussed in [13].

In all previous work, the mutual NN-interaction V^{NN} between the two outgoing protons (NN-FSI) was neglected. In the present study, this approximation is dropped by incorporating for the first time the corresponding complete NN-scattering amplitude T^{NN} $\left(z = \frac{(\boldsymbol{p}_1{}^0)^2}{2m_p} + \frac{(\boldsymbol{p}_2{}^0)^2}{2m_p} + i\epsilon\right)$

$$T^{\mathrm{NN}}(z) = V^{\mathrm{NN}} + V^{\mathrm{NN}} G_0(z) T^{\mathrm{NN}}(z), \tag{4}$$

with

$$G_0(z) = \frac{1}{z - H_0(1) - H_0(2)}, \tag{5}$$

up to the first order in the final state, as it has been depicted in diagram (b) of fig. 1. For the sake of simplicity, multiscattering processes like those described by diagrams (c) and (d) of fig. 1 are still neglected. The final state $|\Psi_f\rangle$ in (1) is therefore given in our approach by

$$|\Psi_f\rangle = |\phi^{\rm OP}(\boldsymbol{q}_1{}^0)\rangle\,|\phi^{\rm OP}(\boldsymbol{q}_2{}^0)\rangle + G_0(z)T^{\rm NN}(z)|\boldsymbol{p}_1{}^0\rangle\,|\boldsymbol{p}_2{}^0\rangle, \tag{6}$$

where $|\boldsymbol{p}_i{}^0\rangle$ denotes a plane-wave state of the proton i with momentum $\boldsymbol{p}_i{}^0$. Within this treatment of FSI, we are still far away from having solved the complete three-body problem of the final state. Nevertheless, we are able to obtain a first reliable estimate of the relevance of NN-FSI in various kinematical situations of two-proton knockout.

In our explicit evaluation, we have used in (4) as NN-potential $V^{\rm NN}$ the Bonn OBEPQ-A potential [15] which has also been used for the calculation of the defect functions in the initial state. Due to the non-locality of this potential, the term $G_0(z)T^{\rm NN}(z)|\boldsymbol{p}_1{}^0\rangle\,|\boldsymbol{p}_2{}^0\rangle$ in (6) is explicitly evaluated in momentum space. The initial state $|\Psi_i\rangle$ and the nuclear current $\hat{J}^\mu(\boldsymbol{r})$ in (1) are however calculated in configuration space, so that finally an appropriate Fourier transformation of the NN-FSI from momentum to configuration space had to be performed. Moreover, we would like to mention that a usual partial-wave decomposition [16,17] of the NN-interaction $V^{\rm NN}$ has been adopted taking into account all isospin-1 partial NN-waves up to an orbital angular momentum of 3, *i.e.* the $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^3F_2$, $^3F_3$ and $^3F_4$ contributions. It has been checked numerically that the contribution of G and H NN-waves is negligible, at least for the kinematics considered here.

3 Results

In this section, we discuss the influence of NN-FSI for two different types of kinematics which have already been under experimental investigation [18–20]. We call E_0 the incident electron energy and θ_e the electron scattering angle in the laboratory frame. The energy and momentum transfer is denoted, as usual, as ω and q, respectively. The angles between the momentum transfer $\boldsymbol{q}$ and the momenta $\boldsymbol{p}_1{}^0$ and $\boldsymbol{p}_2{}^0$ of the outgoing protons are called γ_1 and γ_2.

Concerning the different approximations for the final state, we denote as PW the plane-wave approximation, where FSI are completely neglected, and as DW the treatment of [2], where only the optical potential $V^{\rm OP}$ is taken into account. In the approach PW-NN we consider the alternative case where only $V^{\rm NN}$, but not $V^{\rm OP}$, is included. The corresponding final states in these different approximations are given by

$$|\Psi_f\rangle^{\rm PW} = |\boldsymbol{q}_1{}^0\rangle\,|\boldsymbol{q}_2{}^0\rangle\ , \tag{7}$$

$$|\Psi_f\rangle^{\rm DW} = |\phi^{\rm OP}(\boldsymbol{q}_1{}^0)\rangle\,|\phi^{\rm OP}(\boldsymbol{q}_2{}^0)\rangle\ , \tag{8}$$

$$|\Psi_f\rangle^{\rm PW\text{-}NN} = |\boldsymbol{q}_1{}^0\rangle\,|\boldsymbol{q}_2{}^0\rangle + G_0(z)T^{\rm NN}(z)|\boldsymbol{p}_1{}^0\rangle\,|\boldsymbol{p}_2{}^0\rangle\,. \tag{9}$$

Our full approach in (6) is denoted as DW-NN.

The results of these different approaches on the cross-section of the ^{16}O$(e, e'pp)$ reaction for the transition to the 0^+ ground state of ^{14}C are shown in fig. 2. In the left panel the superparallel kinematics of a Mainz experiment [18] is considered, with $E_0 = 855$ MeV, $\theta_e = 18°$, $\omega = 215$ MeV, $q = 316$ MeV/c, $\gamma_1 = 0°$, and $\gamma_2 = 180°$. In the right panel an alternative kinematical setup, which has been included in a NIKHEF experiment [19,20], is investigated, with $E_0 = 584$ MeV, $\theta_e = 26.5°$, $\omega = 210$ MeV and $q = 300$ MeV/c. The angle γ_1 is 30°, on the opposite side of the outgoing electron with respect to $\boldsymbol{q}$. The kinetic energy of proton 1 is fixed to $T_1 = 137$ MeV.

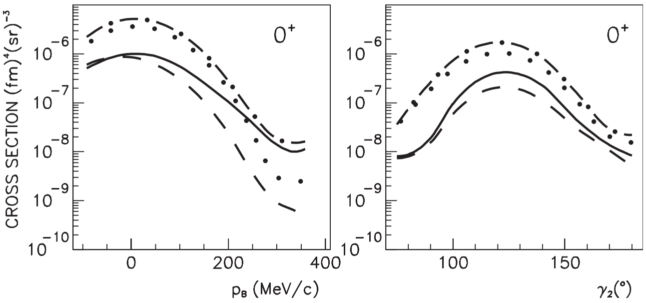

Fig. 2. The differential cross-section in the ^{16}O$(e, e'pp)$ reaction to the 0^+ ground state of ^{14}C for the two kinematics discussed in the text. Used notation for the different calculations: PW (dotted), PW-NN (dash-dotted), DW (dashed), DW-NN (solid).

By changing the kinetic energy of the outgoing protons in the superparallel kinematics and the angle γ_2 in the NIKHEF setup, we are able to explore different values of the recoil momentum of the residual nucleus $p_B \equiv |\boldsymbol{p}_B|$. Positive (negative) values of p_B in the left panel refer to situations where $\boldsymbol{p}_B$ is parallel (antiparallel) to the momentum transfer. It is well known and can be clearly seen in fig. 2 that the inclusion of the optical potential leads to an overall and substantial reduction of the cross-section in both kinematical setups (consider the difference between the PW and DW results). On the other hand, our calculations give a considerable enhancement for medium and large recoil momenta in the superparallel kinematics if NN-FSI are taken into account (see the difference between PW and PW-NN, and between DW and DW-NN). The effect of NN-FSI amounts to about one order of magnitude enhancement at $p_B = 300$ MeV/c. Thus even at back-to-back kinematics the mutual interaction of the two outgoing protons cannot be neglected. In the NIKHEF kinematics, the effect of NN-FSI is also sizeable, although not as strong as in the superparallel kinematics. Moreover, whereas in the superparallel kinematics the relative effect of NN-FSI increases for decreasing cross-section, in the NIKHEF kinematics NN-FSI is maximal when also the cross-section is maximal, *i.e.* for $\gamma_2 \approx 120°$, which corresponds to $\boldsymbol{p}_B \approx 0$ MeV/c. This result clearly shows that the role of NN-FSI is strongly dependent on the kinematics and no general statement can be drawn with respect to its relevance.

As is known from previous work [2], in the ^{16}O$(e, e'pp)$ reaction the transition to the 0^+ ground state of ^{14}C is governed dominantly by the $^1S_0$ partial wave in the initial

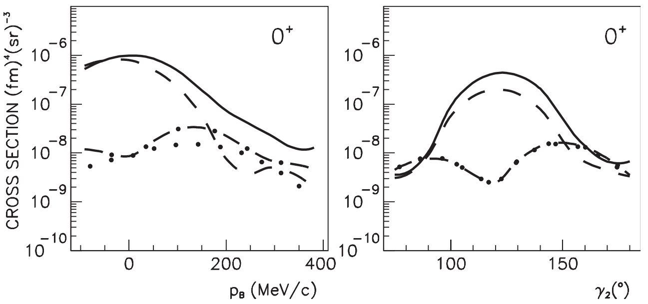

Fig. 3. The differential cross-section in the $^{16}O(e, e'pp)$ reaction to the 0^+ ground state of ^{14}C in the same two kinematics as in fig. 2. The dashed (solid) curve shows the separate contribution of the $^1S_0$ relative partial wave in a DW (DW-NN) calculation. The dotted (dash-dotted) curve shows the separate contribution of the $^3P_1$ relative partial wave in a DW (DW-NN) calculation.

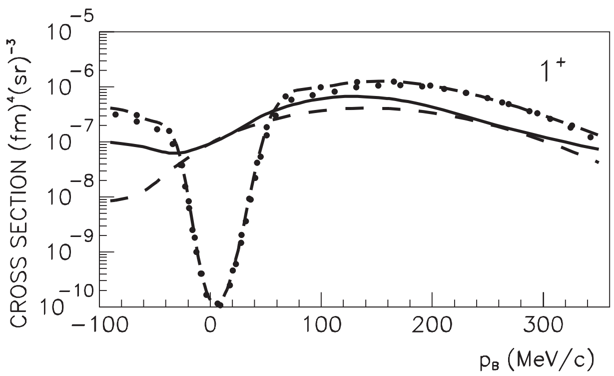

Fig. 4. The differential cross-section in the $^{16}O(e, e'pp)$ reaction to the 1^+ state of ^{14}C for the superparallel kinematics discussed in the text. Line notation as in fig. 2.

relative state of the two protons. A sizeable contribution arises moreover from the $^3P_1$ state. The relative importance of NN-FSI on these two partial waves is presented in fig. 3 for the kinematical setups already considered in fig. 2. In both kinematics the effect of NN-FSI is more important on the $^1S_0$ initial state. The effect on this single state gives in practice almost the full contribution of NN-FSI. For the $^3P_1$ initial state only a negligible effect is given in the NIKHEF kinematics. The effect is somewhat larger in the superparallel kinematics, but also here it is completely overwhelmed in the final result by the dominant contribution of the $^1S_0$ state.

The role of NN-FSI on the ^3P initial relative states is of specifical relevance for the transition to the 1^+ excited state of ^{14}C, where only ^3P components are present and the $^1S_0$ relative partial wave cannot contribute. The results for this transition in the superparallel kinematics are depicted in fig. 4. A negligible effect is due to NN-FSI in the PW-NN approach. A significant enhancement is obtained in the DW-NN calculation, especially for negative values of p_B, where the cross-section has a minimum.

Summarizing, we have studied the importance of the mutual final-state interaction of the two emitted protons in the $^{16}O(e, e'pp)$ reaction within a perturbative treatment. Our results indicate that NN-FSI can be important in particular situations and in general cannot be neglected. It has been clearly shown that the role of NN-FSI depends on kinematics and on the final state in the excitation spectrum of ^{14}C. Therefore, one may hope that it is possible to find specific kinematical situations where the effects of FSI are as small as possible, in order to achieve the most direct access to SRC in complex nuclei. This requires a systematic study of the role of FSI for different kinematics which is presently under consideration. Moreover, due to our numerical results, the full three-body problem of the final state has to be tackled in forthcoming studies. In that context, special emphasis has to be devoted to a more consistent treatment of the initial and the final state in our approach.

This work has been supported by the the Istituto Nazionale di Fisica Nucleare and by the Deutsche Forschungsgemeinschaft (SFB 443). M. Schwamb would like to thank the Dipartimento di Fisica Nucleare e Teorica of the University of Pavia for the warm hospitality during his stays in Pavia. Fruitful discussions with H. Arenhövel are gratefully acknowledged.

References

1. S. Boffi, C. Giusti, F.D. Pacati, M. Radici, *Electromagnetic Response of Atomic Nuclei*, in Oxford Studies in Nuclear Physics (Clarendon Press, Oxford, 1996).
2. C. Giusti, F.D. Pacati, K. Allaart, W.J.W. Geurts, W.H. Dickhoff, H. Müther, Phys. Rev. C **57**, 1691 (1998).
3. C. Giusti, F.D. Pacati, Nucl. Phys. A **641**, 297 (1998).
4. C. Giusti, H. Müther, F.D. Pacati, M. Stauf, Phys. Rev. C **60**, 054608 (1999).
5. C. Giusti, F.D. Pacati, Phys. Rev. C **61**, 054617 (2000).
6. C. Giusti, F.D. Pacati, Eur. Phys. J. A **12**, 69 (2001).
7. J. Ryckebusch, V. Van der Sluys, K. Heyde, H. Holvoet, W. Van Nespen, M. Waroquier, M. Vanderhaeghen, Nucl. Phys. A **624**, 581 (1997).
8. J. Ryckebusch, W. van Nespen, D. Debruyne, Phys. Lett. B **441**, 1 (1998).
9. J. Ryckebusch, D. Debruyne, W. van Nespen, Phys. Rev. C **57**, 1319 (1998).
10. D. Knödler, H. Müther, Phys. Rev. C **63**, 044602 (2001).
11. P. Wilhelm, H. Arenhövel, C. Giusti, F.D. Pacati, Z. Phys. A **359**, 467 (1997).
12. W.J.W. Geurts, K. Allaart, W.H. Dickhoff, H. Müther, Phys. Rev. C **54**, 114 (1996).
13. A. Nadasen *et al.*, Phys. Rev. C **23**, 1023 (1981).
14. C. Giusti, F.D. Pacati, Nucl. Phys. A **535**, 573 (1991).
15. R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).
16. R. Machleidt, K. Holinde, C. Elster, Phys. Rep. **149**, 1 (1987).
17. M. Schwamb, H. Arenhövel, Nucl. Phys. A **690**, 647 (2001).
18. G. Rosner, Prog. Part. Nucl. Phys. **44**, 99 (2000).
19. C.J.G. Onderwater *et al.*, Phys. Rev. Lett. **78**, 4893 (1997).
20. C.J.G. Onderwater *et al.*, Phys. Rev. Lett. **81**, 2213 (1998).