Effects of nucleon correlations in (p,d), $(e,e'p)$ and (γ,p) reactions

M.K. Gaidarov[a], K.A. Pavlova[a], A.N. Antonov[a], M.V. Stoitsov[a], S.S. Dimitrova[a], M.V. Ivanov[a], C. Giusti[b], S.E. Massen[c], Ch.C. Moustakidis[c]

[a] *Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia 1784, Bulgaria*
[b] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, Pavia, Italy*
[c] *Department of Theoretical Physics, Aristotle University of Thessaloniki, GR-54006 Thessaloniki, Greece*

A study of the nucleon correlation effects on the one-nucleon removal reactions in closed- as well as open-shell nuclei is performed. We use correlated quasi-hole overlap functions extracted from the asymptotic behavior of the one-body density matrices containing different types of nucleon correlations. The corresponding spectroscopic factors calculated within this approach are reduced with respect to the shell model predictions in a way that reflects the role of the correlations included in different methods. The resulting bound-state overlap functions are applied to calculate the cross sections of $(e,e'p)$, (γ,p) and (p,d) reactions on the same theoretical footing. The theoretical results are generally successful to reproduce the shape of the experimental cross sections. Thus this study clarifies the importance of various types of correlations, which are accounted for to a different extent in the theoretical methods considered, on the reaction cross sections.

1 Introduction

The strong short-range and tensor components of the nucleon-nucleon (NN) interactions induce correlations in the nuclear wave function which are going beyond the independent-particle approximation. Therefore, it has always been a point of experimental and theoretical interest to find observables which reflect these correlations in a unambiguous way. In this sense both, the overlap functions and single-nucleon spectroscopic factors, have attracted much attention in analyzing the empirical data from one-nucleon removal reactions, such as $(e,e'p)$, (p,d), $(d,^3He)$, and also in other domains of many-body physics, as e.g. atomic and molecular physics [1].

Recently, a general procedure has been adopted [2] to extract the bound-state overlap functions and the associated spectroscopic factors and separation energies on the base of the ground-state (g.s.) one-body density matrix (OBDM). The advantage of the procedure is that it avoids the complicated task for calculating the whole spectral function in nuclei [3]. Of course, the general success of the above procedure depends strongly on the availability of realistic OBDM's.

Initially, the method for extracting bound-state overlap functions (OF) has been applied in [4] to a model OBDM [5] accounting for the short-range nucleon correlations within the Jastrow correlation method. The resulting OF's have been used [6] to study one-nucleon removal processes in contrast to the mean-field approaches which account for the nucleon correlations by modifying the mean-field potentials. The results obtained for the differential cross sections of $^{16}O(p,d)$ and $^{40}Ca(p,d)$ pick-up reactions at various incident energies demonstrated that the OF's can be applied as realistic form factors to evaluate absolute cross sections of such reactions. The analysis of single-particle (s.p.) OF's has been extended to more realistic OBDM's emerging from the correlated basis function (CBF) method [7, 8], the Green function method (GFM) [9] and the generator coordinate method (GCM) [1, 10]. In addition, OBDM's of open-shell nuclei deduced from Jastrow-type calculations have been used [11]. We have chosen the CBF theory since it is particularly suitable for the study of the short-range correlations (SRC) in nuclei. The CBF calculations have recently been extended to medium-heavy doubly-closed shell nuclei [7, 8] using various levels of the Fermi hypernetted chain approximation [7]. The GFM [9, 12] provides detailed information on the spectral functions and nucleon momentum distributions predicting the largest effects of the short-range and tensor correlations at high momentum and energy. The results on the one- and two-body density and momentum distributions, occupation probabilities and natural orbitals obtained within the GCM using various construction potentials [13] have shown that the NN correlations accounted for in this method are different from the short-range ones and are rather related to the collective motion of the nucleons.

The main aim of the present work is to study the effects of the NN correlations included in the correlation methods mentioned above on the behavior of the bound-state proton and neutron overlap functions in closed- as well as open-shell nuclei and of the related one-nucleon removal reaction cross sections. Such an investigation allows to examine the relationship between the OBDM and the associated overlap functions within the correlation methods used and also to clarify the importance of the effects of NN correlations on the overlap functions and the reaction cross sections.

2 Overlap functions and their relationship with the one-body density matrix

For a correct calculation of the cross section of nuclear reactions with one-neutron or one-proton removal from the target nucleus, the corresponding OF's for the neutron and proton bound states must be used in the reaction amplitudes. Here we would like to remind that the single-particle OF's are defined by the overlap integrals between eigenstates of the A-particle and the $(A-1)$-particle systems:

$$\phi_\alpha(\mathbf{r}) = \langle \Psi_\alpha^{(A-1)} | a(\mathbf{r}) | \Psi^{(A)} \rangle, \tag{1}$$

where $a(\mathbf{r})$ is the annihilation operator for a nucleon with spatial coordinate $\mathbf{r}$ (spin and isospin operators are implied). In the mean-field approximation $\Psi^{(A)}$ and $\Psi_\alpha^{(A-1)}$ are single Slater determinants, and the overlap functions are identical with the mean-field s.p. wave functions, while in the presence of correlations both $\Psi^{(A)}$ and $\Psi_\alpha^{(A-1)}$ are complicated superpositions of Slater determinants. In general, the overlap functions (1) are not orthogonal. Their norm defines the spectroscopic factor

$$S_\alpha = \langle \phi_\alpha | \phi_\alpha \rangle. \tag{2}$$

The normalized OF associated with the state α then reads

$$\tilde{\phi}_\alpha(\mathbf{r}) = S_\alpha^{-1/2} \phi_\alpha(\mathbf{r}). \tag{3}$$

The OBDM can be expressed in terms of the OF's in the form:

$$\rho(\mathbf{r}, \mathbf{r}') = \sum_\alpha \phi_\alpha^*(\mathbf{r}) \phi_\alpha(\mathbf{r}') = \sum_\alpha S_\alpha \tilde{\phi}_\alpha^*(\mathbf{r}) \tilde{\phi}_\alpha(\mathbf{r}'). \tag{4}$$

The asymptotic behavior of the radial part of the neutron OF for the bound states of the $(A-1)$-system is given by [2]:

$$\phi_{nlj}(r) \to C_{nlj} \exp(-k_{nlj} r)/r, \tag{5}$$

where k_{nlj} is related to the neutron separation energy

$$k_{nlj} = \frac{\sqrt{2m\epsilon_{nlj}}}{\hbar}, \quad \epsilon_{nlj} = E_{nlj}^{(A-1)} - E_0^A. \tag{6}$$

For proton bound states, due to an additional long-range part originating from the Coulomb interaction, the asymptotic behavior of the radial part of the corresponding proton OF's reads

$$\phi_{nlj}(r) \rightarrow C_{nlj} \exp[-k_{nlj}r - \eta \ln(2k_{nlj}r)]/r, \tag{7}$$

where η is the Coulomb (or Sommerfeld) parameter and k_{nlj} in (6) contains in this case the mass of the proton and the proton separation energy.

Taking into account Eqs. (4) and (5), the lowest ($n = n_0$) neutron bound-state lj-overlap function is determined by the asymptotic behavior of the associated partial radial contribution of the OBDM $\rho_{lj}(r, r')$ ($r' = a \rightarrow \infty$) as

$$\phi_{n_0 lj}(r) = \frac{\rho_{lj}(r, a)}{C_{n_0 lj} \; \exp(-k_{n_0 lj}\, a)/a} \;, \tag{8}$$

where the constants $C_{n_0 lj}$ and $k_{n_0 lj}$ are completely determined by $\rho_{lj}(a, a)$. In this way the separation energy $\epsilon_{n_0 lj}$ and the spectroscopic factor $S_{n_0 lj}$ can be determined as well. Similar expression for the lowest proton bound-state OF can be obtained having in mind its proper asymptotic behavior (7).

3 Results for the cross sections of $(e, e'p)$, (γ, p) and (p, d) reactions on closed-shell (^{16}O,^{40}Ca) and open-shell (^{24}Mg,^{28}Si, ^{32}S) nuclei

Figure 1 shows the ground state angular distribution of the reaction ^{28}Si$(p, d)^{27}$Si representing pickup of $1d_{5/2}$ neutrons induced by 185 MeV protons. In the figure three different theoretical curves are given in respect to deuteron optical potential parameters used in the calculations. Particularly, the effects of changing the radius of the real part of this potential R_d is shown. The best agreement with the experimental data is achieved with the value of R_d=0.8 fm giving also the best fit in [14]. Apart from the shown sensitivity of the calculations to the deuteron optical potential, in general, we should mention that the (p, d) reaction is more sensitive to the reaction mechanism adopted than to the choice of the bound-state wave function. Nevertheless, it is seen from Fig. 1 that our theoretically calculated OF corresponding to the $1d$ bound state is able to reproduce the absolute cross section.

It turned out from the previous analyses of one-nucleon removal reactions [15, 16] that quasifree nucleon knockout is more suitable to investigate the role of overlap functions as bound-state wave functions. An example of electron induced proton knockout from ^{32}S for the transition to the ground $2s_{1/2}$ state of ^{31}P is illustrated in Figure 2. In the figure the result obtained with the proton OF for the $2s$ state of ^{32}S and the optical potential from [17] is compared with the NIKHEF data from [18]. A reasonable agreement with the experimental data for the reduced cross section is obtained. In the analysis of [18] the calculations are performed within the same distorted wave impulse approximation (DWIA) framework and with the same optical potential, but phenomenological s.p. wave function is used with a radius adjusted to the data. We emphasize that in the present work the OF theoretically calculated on the basis of the Jastrow-type OBDM of ^{32}S does not contain free parameters. It can be seen from Fig. 2 that our spectroscopic factor of 0.5648 gives a good agreement with the size of the experimental cross section.

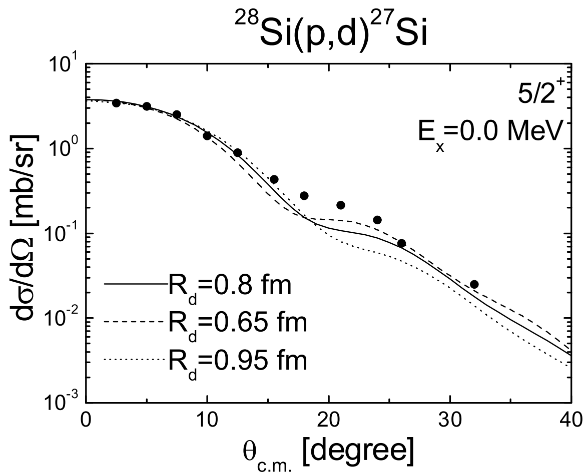

Figure 1: Differential cross-section for the ^{28}Si(p, d) reaction at incident proton energy E_p=185 MeV to the $5/2^+$ ground state in ^{27}Si. Line convention referring to different calculations with neutron OF derived from the OBDM is given (see also the text). The experimental data [14] are given by the full circles.

Apart from the effects of SRC studied in [16, 19] and discussed already in this Section, we looked into the role of correlations caused by the collective nucleon motion. Figure 3 shows the angular distribution of the ^{40}Ca$(\gamma, p)^{39}$K$_{g.s.}$ reaction at E_γ=60 MeV. In the figure the results given by the sum of the one-body and of the two-body seagull currents are compared with the contribution given by the one-body current, which roughly corresponds to the DWIA treatment based on the direct knockout mechanism. The results obtained with the OF from GCM for the ground state transition and with the phenomenological Woods-Saxon (WS) wave function are compared in the figure. In order to check the consistency in the description of different one-proton removal reactions, the calculated cross sections have been multiplied by the same reduction factors obtained from the analysis of corresponding $(e, e'p)$ data, i.e. 0.55 with GCM and 0.6625 with WS. The differences between the two curves are considerable and larger than in the $(e, e'p)$ reaction [15]. A reasonable agreement with the size and the shape of the experimental cross section is obtained when meson-exchange currents (MEC) are added. Although both calculations with the GCM and WS wave functions are able to give a good description of the ^{40}Ca$(e, e'p)$ data for the transition to the $3/2^+$ ground state of ^{39}K [15], the (γ, p) results presented in Fig. 3 for the same transition show that the GCM overlap function leads to a better and more consistent description of data for the $(e, e'p)$ and (γ, p) reactions. This result suggests proper accounting for the nucleon correlation effects in the framework of the GCM.

4 Conclusions

The s.p. overlap functions calculated on the basis of OBDM for the ground state of closed- and open-shell nuclei emerging from different correlation methods have been used to calculate the cross sections of the (p, d), $(e, e'p)$ and (γ, p) reactions. The theoretical results for the cross sections show that they are sensitive to the shape of the different OF's and are generally able to reproduce the shape of the experimental cross sections. In order to reproduce the size of

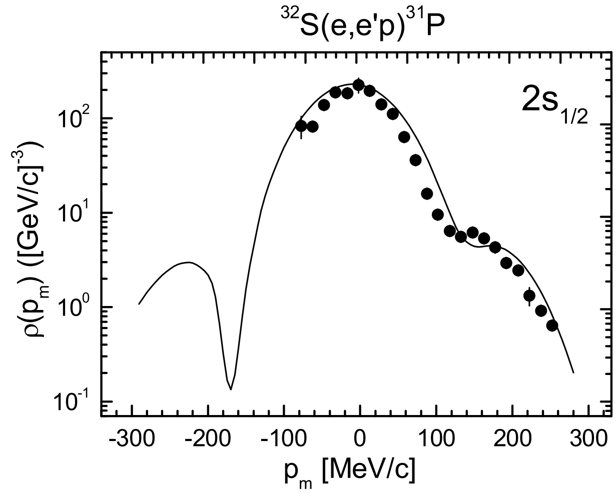

Figure 2: Reduced cross section of the ^{32}S$(e,e'p)$ reaction as a function of the missing momentum $p_{\rm m}$ for the transition to the $1/2^+$ ground state of ^{31}P. The proton OF is derived from the OBDM (solid line). The experimental data (full circles) are taken from Ref. [18].

the experimental data a reduction factor must be applied to the calculated cross sections. The fact that it is consistent in different nucleon removal reactions gives a more profound theoretical meaning to this parameter. The results indicate that the effects of SRC correlations taken into account within CBF and GFM and of correlations accounted for in GCM which are of long-range type are of significant importance for the correct analysis of the processes considered.

The authors thank the Bulgarian National Science Foundation which partly supported this work under the Contract No.Φ–905.

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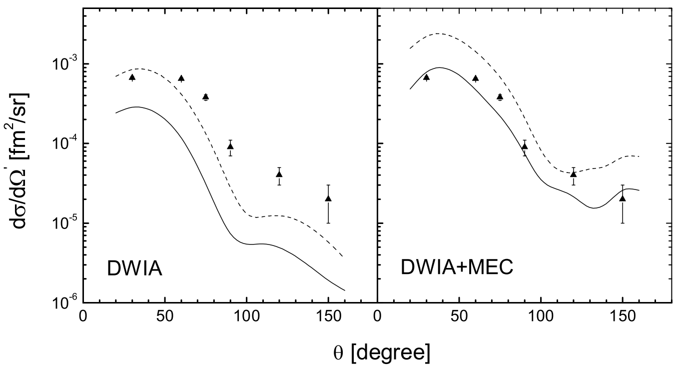

Figure 3: Angular distribution of the ^{40}Ca(γ, p) reaction for the transition to the $3/2^+$ ground state of ^{39}K at $E_\gamma = 60$ MeV. The optical potential is taken from Ref. [17]. The OF is derived from the OBDM of GCM (solid line). The dashed line is calculated with the WS wave function. The experimental data (triangles) are taken from Ref. [20].

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