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SHORT-RANGE NN CORRELATIONS AND RESCATTERINGS IN THE $^{12}\mathrm{C} + p \to {}^{10}A + pp + N$ REACTION*

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The exclusive $^{12}\mathrm{C}+p \to {}^{10}A + pp + N$ reaction, where the ^{12}C beam at the energy of 4 GeV/nucleon interacts with the proton target and as a result, one proton is knocked-out from a short-range correlated NN pair in ^{12}C, was measured recently by the BM@N Collaboration. This reaction is considered here by analogy with the theory of quasi-elastic knockout of fast deuterons from nuclei (p, Nd) using the translationally-invariant shell model with short-range NN correlations. The initial- and final-state interaction effects are estimated in the eikonal approximation using the Glauber model for elastic N–^{10}A scattering.

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1. Introduction

The idea of the fluctuation of nuclear density in the ground state of nuclei was suggested by Blokhintsev [1] after observation of the quasi-elastic knockout of fast deuteron from nuclei by protons [2]. The NN pairs at the small relative distances $r_{NN} < 0.5$ fm, *i.e.* with high relative momentum $q_{\mathrm{rel}} > 0.4$ GeV/c and almost zero momentum of the center-of-mass of the pair k_{cm}, were called later on as short-range correlated (SRC) pairs [3]. Properties of the SRC pairs are studied using electron beams in hard exclusive reactions $A(e, e'pN)$, assuming the simplest mechanism of quasi-elastic knockout of the nucleon from the SRC NN pair when the second nucleon is a spectator. The main results obtained from this study are the following. The SRC

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pairs do exist in nuclei. Distribution $n(\boldsymbol{p}_1, \boldsymbol{p}_2)$ over momenta $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ of nucleons in the SRC pair is factorized as $n(\boldsymbol{p}_1, \boldsymbol{p}_2) = C_A\, n_{\rm cm}(\boldsymbol{k}_{\rm cm}) n_{\rm rel}(\boldsymbol{q}_{\rm rel})$, where $n_{\rm cm}(\boldsymbol{k}_{\rm cm})$ is the distribution over the momentum of the center-of-mass NN pair, and $n_{\rm rel}(\boldsymbol{q}_{\rm rel})$ is the distribution over the internal relative momentum $\boldsymbol{q}_{\rm rel}$. The internal distribution $n_{\rm rel}(\boldsymbol{q}_{\rm rel})$ at high $|\boldsymbol{q}_{\rm rel}|$ is a universal function close to that for the momentum distribution of nucleons in the free deuteron. The constant C_A depends on the type of nucleus A. The contribution of the pp SRC pairs is by a factor of about 20 smaller than for the pn pairs. This is caused by the tensor forces which are absent in the spin-zero states and acting only in the spin-1 NN states. A review of this study can be found in Ref. [4].

It is important to confirm these observations by reactions with other probs. For this aim the exclusive $^{12}{\rm C}+p \to {}^{10}A + pp + N$ reaction was studied recently at BM@N in JINR [5] using the ^{12}C beam at the energy of 4 GeV/nucleon interacting with the hydrogen target to probe the SRC pairs in the ^{12}C. In theoretical analysis [6, 7] of the SRC effects, in this reaction a properly modified approach developed earlier was used (see Ref. [8] and references therein) to describe the quasi-elastic knockout of fast deuterons from the light nuclei ^{12}C and ^{7,6}Li by protons in the reactions (p, pd) and (p, nd) at the proton beam energy of 670 MeV [9–11]. As in Ref. [8], the spectroscopic amplitudes for NN pairs in the ground state of the ^{12}C nucleus are calculated here within the translation-invariant shell model (TISM) with mixing configurations. For the internal momentum distribution, the $n_{\rm rel}(q_{\rm rel})$, of the squared deuteron (or singlet deuteron) wave function for the CD Bonn NN-interaction potential was used. Relativistic effects in the sub-process $p\{NN\} \to pNN$ of quasi-elastic knockout of nucleon from the SRC pair are taken into account in the light-front dynamics [12]. We found that the c.m. distribution, $n_{\rm cm}(k_{\rm cm})$, of the NN clusters obtained within the TISM and used in [11, 13] to describe the (p, Nd) data [11] has to be sizable modified [14] to describe the $k_{\rm cm}$ distribution of the SCR NN pairs measured in the electron data [15]. On the other hand, the ratio of the spin-singlet to spin-triplet pairs $\{pp\}_{\rm s}/\{pn\}_{\rm t}$ calculated within this approach [14] is in agreement with the existing data [16].

Calculations [6, 7, 14] were performed in the plane-wave impulse approximation (PWIA). In Ref. [5], the BM@N data in question are considered as unperturbed by the initial- and final-state interaction. To check this statement, we estimate here the initial- and final-state interaction effects within the eikonal approximation using the Glauber model for the N–^{10}A elastic scattering. Since the effects of the detector acceptance were not eliminated from the data [5], a direct comparison with the presented theory is hardly possible. Therefore, we perform below mainly a comparison between the PWIA and distorted wave impulse approximation.

2. Elements of formalism

Due to the contribution of the rescatterings, the transition matrix element of this reaction is modified as compared to the impulse approximation in such a way that the wave function of relative motion of the c.m. of the NN pair in respect to the c.m. of the residual nucleus B, $\psi_{\nu\Lambda}(\boldsymbol{k}_{\rm cm})$, where ν and Λ are the number of oscillator quanta and orbital momentum, respectively, is modified and takes the following form (see Ref. [8] and references therein):

$$
\begin{aligned}
\Phi_{\nu\Lambda}(\boldsymbol{k}_{\rm cm}) &= \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm}\right) + \frac{i}{4\pi k_{p_0 A}} \int {\rm d}^2\boldsymbol{q}_{p_0} F_{pB}\left(\boldsymbol{q}_{p_0}\right) \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_0}\right) \\
&+ \sum_{j=1,2,3} \frac{i}{4\pi k_{p_j B}} \int {\rm d}^2\boldsymbol{q}_{p_j} F_{pB}\left(\boldsymbol{q}_{p_j}\right) \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_j}\right) \\
&- \sum_{j=1,2,3} \frac{(4\pi)^{-2}}{k_{p_0 A} k_{p_j B}} \int {\rm d}^2\boldsymbol{q}_{p_0} {\rm d}^2\boldsymbol{q}_{p_j} F_{pB}\left(\boldsymbol{q}_{p_0}\right) F_{pB}\left(\boldsymbol{q}_{p_j}\right) \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_0} - \boldsymbol{q}_{p_1}\right) \\
&- \frac{(4\pi)^{-2}}{k_{p_1 B} k_{p_2 B}} \int {\rm d}^2\boldsymbol{q}_{p_1} {\rm d}^2\boldsymbol{q}_{p_2} F_{pB}\left(\boldsymbol{q}_{p_1}\right) F_{pB}\left(\boldsymbol{q}_{p_2}\right) \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_1} - \boldsymbol{q}_{p_2}\right) \\
&- \frac{(4\pi)^{-2}}{k_{p_1 B} k_{p_3 B}} \int {\rm d}^2\boldsymbol{q}_{p_1} {\rm d}^2\boldsymbol{q}_{p_3} F_{pB}\left(\boldsymbol{q}_{p_1}\right) F_{pB}\left(\boldsymbol{q}_{p_3}\right) \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_1} - \boldsymbol{q}_{p_3}\right) \\
&- \frac{(4\pi)^{-2}}{k_{p_2 B} k_{p_3 B}} \int {\rm d}^2\boldsymbol{q}_{p_2} {\rm d}^2\boldsymbol{q}_{p_3} F_{pB}\left(\boldsymbol{q}_{p_2}\right) F_{pB}\left(\boldsymbol{q}_{p_3}\right) \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_2} - \boldsymbol{q}_{p_3}\right) \\
&- \sum_{l,i,j=0,1,2,3} \frac{i(4\pi)^{-3}}{k_{p_l B} k_{p_i B} k_{p_j B}} \int {\rm d}^2\boldsymbol{q}_{p_l} {\rm d}^2\boldsymbol{q}_{p_i} {\rm d}^2\boldsymbol{q}_{p_j} F_{pB}\left(\boldsymbol{q}_{p_l}\right) F_{pB}\left(\boldsymbol{q}_{p_i}\right) F_{pB}\left(\boldsymbol{q}_{p_j}\right) \\
&\times \psi_{\nu\Lambda}\left(\boldsymbol{k}_{\rm cm} - \boldsymbol{q}_{p_l} - \boldsymbol{q}_{p_i} - \boldsymbol{q}_{p_j}\right) .
\end{aligned} \tag{1}
$$

Here, $k_{p_i B}$ ($k_{p_0 A}$) is the relative momentum in the system of the final nucleon p_i ($i = 1,2,3$) and nucleus B (initial proton p_0 and nucleus A). $F_{NB}(\boldsymbol{q})$ in Eq. (1) is the amplitude of elastic scattering of the nucleon N off the nucleus B. This amplitude is calculated using the Glauber theory and as we checked, well describes the experimental data on a differential cross section of the elastic $p^{10}B$ scattering at energies of 1 GeV in the forward hemisphere. The first term on the right-hand side of Eq. (1) is the PWIA, the next two terms come from the single NB scatterings, other four terms with double two-dimensional integrals over transverse momenta $\boldsymbol{q}_i$ and $\boldsymbol{q}_j$ account for double NB scattering, and the last term accounts for triple re-scatterings. The sum of all terms in Eq. (1) is the distorted wave impulse approximation (DWIA) result. According to arguments given in Ref. [17], the term with four rescatterings has to be zero in the eikonal approximation and we drop this term here. As was noted in Ref. [8], Eq. (1) can be applied for calculation of the ISI@FSI effect in the case of collinear kinematics, for example, for quasi-elastic knockout of fast deuteron clusters by protons (p, pd), when momenta of initial and final particles are directed along the beam. In the $A(p, 2pN)B$ reaction, the kinematics is broader and, therefore, we use this formalism only for a rough estimation of the ISI@FSI effects. On the other hand, the Feynmann diagram formalism with the generalized eikonal approximation (GEA) developed for the $pd \to ppn$ reaction (see Ref. [17] and references therein) allows to account for ISI@FSI effects at realistic kinematics. We made the necessary generalization of the formalism of Ref. [17] to the $^{12}\mathrm{C}(p, 2pN)^{10}A$ reaction under restriction by the single NB-scattering approximation and made numerical estimations on this basis (the detailed results will be published separately).

3. Numerical results

For numerical calculations, we use the harmonic oscillator wave function $\psi_{\nu\Lambda}(p_B)$ with $\nu = \Lambda = 0$ with the oscillator parameter corresponding to the c.m. momentum distribution $n_{\mathrm{cm}}(p_B) = |\psi_{\nu\Lambda}(p_B)|^2$ in the 3D Gaussian form with σ-parameter equal 150 MeV$/c$ that corresponds to the experimental data on the $^{12}\mathrm{C}(e, epp)$ [15] and $^{12}\mathrm{C}(p, 2pN)^{10}A$ [5] reactions. In this case $(\nu = 0)$, the ratio of the PWIA and DWIA cross sections R is equal to $R = |\Phi_{00}(\boldsymbol{p}_B)|^2/|\psi_{00}(\boldsymbol{p}_B)|^2$. The exclusive $^{12}\mathrm{C}(p, 2pN)^{10}B$ reaction is determined by 8 independent kinematic variables, for example, 3-momenta of the residual nucleus $\boldsymbol{p}_B$ and the recoil nucleon–spectator $\boldsymbol{p}_{\mathrm{r}}$ in the $p\langle NN\rangle \to pNN_{\mathrm{r}}$ subprocess and two angles of the 3-momentum of the scattered proton $\theta_{\mathrm{sc}}, \phi_{\mathrm{sc}}$. The results for dependence on the azimuthal angle of the scattered proton ϕ_{sc} are shown in Fig. 1, where the dashed line corresponds to accounting for single NB scattering and the solid line shows the sum of single and double scattering.

One can see from Fig. 1 that in this approach the ISI and FSI effects decrease the cross section by the factor of ~ 2, but this suppression factor does not depend on ϕ_{sc}. We can show that the same result is obtained for the other six independent kinematic variables. The only exception is the dependence on the absolute value of the residual nucleus momentum $p_B = k_{\mathrm{cm}}$ shown in Fig. 2. In this case, one can see that the ratio $R = \mathrm{DWIA}/\mathrm{PWIA}$ decreases with increasing momentum p_B up to 300 MeV$/c$. Further increase of R with increasing p_B at $p_B \geq 300$ MeV$/c$ is non-measurable, since the differential cross section falls quickly with an increase of p_B.

One should note that within the Feynmann diagram formalism with GEA the obtained here results for the ratio R, which are shown by dash-dotted lines in Figs. 1 and 2, are in qualitative agreement with these observations:

for all kinematic variables, except p_B, the ratio R is constant of ≈ 0.8. The p_B dependence of R is also similar to that obtained within the first approach used here.

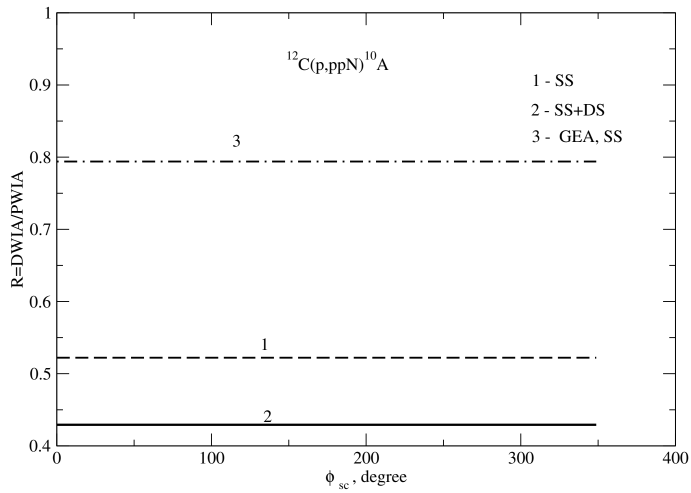

Fig. 1. The PWIA to DWIA ratio for the distribution over the azimuthal angle $\phi_{\rm sc}$ of scattered proton in the ^{12}C$(p,2pN)^{10}A$ reaction at $p_r = 0.65$ GeV$/c$, $p_B = 0.1$ GeV$/c$, $\phi_B = \pi, \theta_B = \phi_r = \theta_r = \theta_{\rm sc} = 0$: 1 — single scattering (SS), 2 — sum of the SS and double scattering (DS); line 3 shows the result for the single scattering obtained within the GEA formalism.

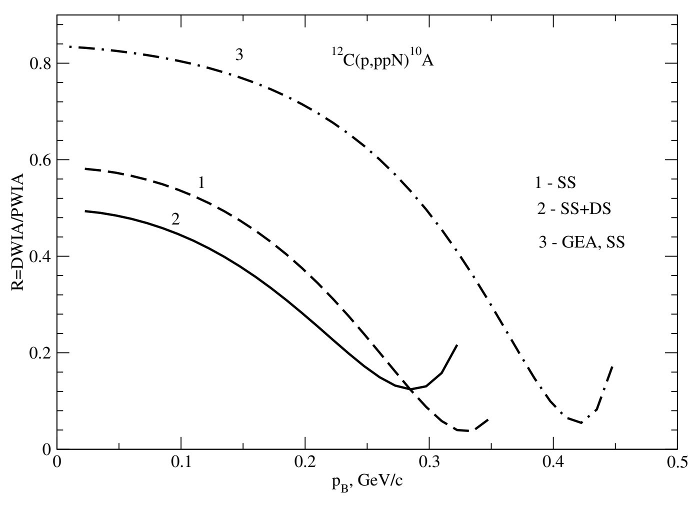

Fig. 2. The same as in Fig. 1, but at $\phi_{\rm sc} = 0$ for distribution over the residual nucleus momentum p_B in the rest frame of the ^{12}C nucleus.

4. Conclusion

As was shown here by our calculations in two different approaches, the rescatterings of the initial proton and final nucleons of the residual nucleus in the ^{12}C$(p, 2pN)^{10}A$ reaction diminish homogeneously the differential cross section and the suppression factor does not depend on kinematic observables if the absolute value of the momentum of residual nucleus is not changing. To some extent, this result confirms and explains the conclusion made in Ref. [5] about non-importance of initial- and final-state interactions in the ^{12}C$(p, 2pN)^{10}A$ reaction studied at BM@N. A similar question about rescatterings in the elementary subprocess $p\langle NN\rangle \to pNN$ will be considered separately.

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