Polarization observables in $A(d,p)$ breakup and quark degrees of freedom in the deuteron

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Abstract

The differential cross section, the tensor analyzing power, $T_{20}$, and the polarization transfer, $\kappa_0$, in $^{12}C(d,p)$ breakup at relativistic energy are calculated within a model which incorporates multiple scattering and Pauli principle at quark level. It is shown that the rescattering and quark exchange affect drastically the polarization observables for kinematical region corresponding to high internal momentum in the deuteron.

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During last 15 years detailed data on $A(d,p)$ differential cross section (DCS) $[1]$, $[2]$, tensor analyzing power, $T_{20}$ $[3]$, $[4]$–$[8]$, and coefficient of polarization transfer, $\kappa_0$ $[7]$, $[10]$–$[12]$, have been obtained. These data together with data obtained from electromagnetic probe, give important information about the deuteron structure in a wide region, including that of a smooth transition from nucleon–meson to quark–gluon picture.

Although from the very beginning it was evident that multiple scattering (MS) of the deuteron constituents on target nucleons should significantly affect theoretical interpretation of $A(d,p)$ data $[13]$, there were brought up some arguments that it would only renormalize the results of impulse approximation (IA) without strong modification of its shape $[1]$, $[14]$, $[15]$. Following this idea, the MS was often “forgotten” in different theoretical models; for example, in estimations of some reaction mechanisms beyond IA $[16]$, model incorporation of quasi–free channels $[17]$, reduced matrix elements in QCD $[18]$, calculations within the Bethe–Salpeter formalism $[19]$, contribution of quark exchange (QE) in the deuteron $[20]$, etc. Direct calculations of MS effects in the DCS demonstrated that it does not change the universal $A^{2/3}$ dependence of the DCS and cannot explain experimental data without modification of the deuteron wave function (DWF) at short distances $[21]$. From the other hand it should be also mentioned that the recent precise measurements of $T_{20}$ demonstrates that it has a systematic difference for $^1H$ and $^{12}C$ targets, despite the fact that qualitatively it has similar behavior for different target nuclei $[22]$.

Attempts to take into account MS effects $[21]$, as well as those accompanied with a final state interaction $[22]$, in the DCS and $T_{20}$ in the $0^\circ$ inclusive $^1H(d,p)$ breakup were done only in the framework of nonrelativistic calculations. In the present paper we propose the first systematic study of the MS based on relativistic calculations, together with QE effects.

We start with the Bertocchi–Treleani approach $[13]$ based on the Sitenko–Glauber MS theory. It includes elastic rescattering of the deuteron constituents, the proton and neutron, as well as inelastic collision of the constituent neutron. We modify the Bertocchi–Treleani model in the following way:

- the DFW is considered in the framework of “minimal relativization prescription” with dynamics in the infinite momentum frame (IMF) $[14]$, $[15]$;

- it takes into account the Pauli principle at the constituent quark level.
To specify the lab. frame we choose $y$-axis along the quantization one and $z$-axis along the deuteron beam. In turn the IMF is defined as a limiting reference frame moving, with respect to the lab. frame, in the negative $z$-direction with velocity close to the speed of light. In IMF the proton momentum is parametrized by the transversed momentum, $\vec{k}_\perp \equiv (k_1, k_2)$ and the fraction of the deuteron momentum carried by the proton in the longitudinal direction, $\alpha$. These momenta are expressed in the lab. frame as: $\vec{k}_\perp = \vec{p}_\perp$ and $\alpha = (E_p + p_3)/(E_d + d_3)$, where $E_p$ and $E_d$ are lab. energy and $p_3$ and $d_3$ are lab. momenta of the proton and deuteron, respectively. In terms of $\alpha$ and $\vec{k}_\perp$ the invariant mass of virtual proton–neutron system is

$$M^2_{pn} = \frac{m^2_\perp}{\alpha(1 - \alpha)} \neq m^2_d, \quad m^2_\perp = m^2_N + k^2_\perp, \quad (1)$$

where $m_d$ and $m_N$ are the deuteron and nucleon masses. In IMF the argument of the relativistic DWF (usually called internal momentum in the deuteron) is $\vec{k} = (\vec{k}_\perp, k_3)$, where

$$k_3 = \pm \sqrt{\varepsilon^2 - m^2_\perp} = m_\perp(\alpha - \frac{1}{2})/\sqrt{\alpha(1 - \alpha)}, \quad \varepsilon = \frac{1}{2} M^2_{pn} \quad (2)$$

and the relativistic DWF is

$$\psi^{'mm'\mu\nu}_{\mathrm{pn}} = \sqrt{\frac{\varepsilon}{m}} \chi^\dagger_m \hat{U}(\vec{k}) \mathcal{M}^{(M)} \hat{U}(\vec{k}) \sigma_2 \chi_{m'},$$

$$\mathcal{M}^{(M)} = \varepsilon^{(M)} \frac{i}{\sqrt{8\pi}} \left\{ \hat{\sigma} u(k) + \frac{1}{2} \left( \hat{\sigma} \cdot 3 \frac{\vec{k} (\hat{\sigma} \vec{k})}{k^2} \right) w(k) \right\}. \quad (3)$$

In (3) $\hat{U}(\vec{k})$ is the matrix of relativistic spin rotation (the Melosh transformation):

$$\hat{U}(\vec{k}) = \frac{m + \varepsilon + k_3 + i(\hat{\sigma} \times \vec{k})_3}{\sqrt{(m + \varepsilon + k_3)^2 + k^2_\perp}}, \quad (4)$$

$\varepsilon^{(M)}$ is the nonrelativistic polarization vector and $\chi_m$ and $\chi_{m'}$ are Pauli spinors for the proton and neutron, respectively.

The Pauli principle considered at the level of constituent quarks modifies the DWF, which becomes equivalent to the Resonating Group Method (RGM) wave function [23, 24]:

$$\psi^d(1, 2, \ldots, 6) = \hat{A} \{ \varphi_N(1, 2, 3) \varphi_N(4, 5, 6) \chi(\vec{r}) \}, \quad (5)$$
where $\hat{A}$ is the quark antisymmetrizer and $\varphi_N$ are wave functions of the nucleon three quark ($3q$) clusters; $\chi(\vec{r})$ is the RGM distribution function and $\vec{r}$ stands for the relative coordinate between the centers of masses of the $3q$ bags.

Due to the presence of the antisymmetrizer in (5) the DWF, being decomposed into $3q \times 3q$ clusters, includes, apart from the standard $pn$ component, nontrivial $NN_R$, $N_RN$ and $N_RN_R$ components which correspond to all possible nucleon resonance states, $N_R$ (see [24]). Most of the this isobars have negative parity and thus generate effective $P$ waves of the deuteron [20], [24].

Following Refs.[24] we choose $\chi(\vec{r})$ as a conventional $NN$ DWF, $\chi_{NN}(\vec{r})$, modified by the RGM renormalization condition of [25]. Fig.1 displays the renormalization of the $S$ wave for some deuteron wave functions; the corresponding effect for the $D$ wave is less than 1% [20].

The Pauli principle applied to the deuteron at the quark level leads to the following modifications of the relativistic DWF

- in the $d \rightarrow NN$ channel one has to change in (3) $u(k) \rightarrow \tilde{u}(k) = u_{\text{renorm.}}(k) + \varphi(k)$;
- add wave functions of $d \rightarrow N_RN$ channels $\psi_{N_Rp}^{M_{mm'}}(\vec{k})$, which is the Fourier transformation of the overlap

$$\tilde{\psi}_{pN_R}(\vec{r}_p) = \left(\frac{6!}{3!3!2}\right)^{1/2} \langle \varphi_{N_R}(1, 2, 3)\varphi_p(4, 5, 6)|\psi^d(1, 2, \ldots, 6)\rangle \quad (6)$$

(with the appropriate spin projections $M$, $m$, $m'$ on the quantization axis) multiplied by relativistic factor $\sqrt{\varepsilon/m_N}$.

The explicit expressions for $\varphi(k)$ and some of $\psi_{pN_R}(\vec{k}_p)$ can be found in Ref.[21].

With this modifications the Bertocchi-Treleani model for the invariant DCS of the $0^+$ inclusive $(d,p)$ breakup for pure spin states $M$ and $m$ of the deuteron and proton, respectively, becomes:

$$E_p \frac{d^3 \sigma_M^m}{dp^3} \equiv I_M^m = \frac{C_d F(k)}{2(1 - \alpha)^2} \sum_{N_R} \sum_{m'} \left\{ \sigma_{N_RA} \left| \psi_{pN_R}^{M_{mm'}}(\vec{k}_\perp = 0, k_3) \right|^2 - 2 \text{Re} \left( \int d^2 k_\perp \psi_{pN_R}^{M_{mm'}}(\vec{k}_\perp) \frac{d^2 \sigma_{N_RA}}{dk_\perp} \right) \right\} +$$

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\[ + \int d^2k_\perp \left| \psi_{pN_R}^{MMm'}(\vec{k}) \right|^2 \frac{d^2\sigma_{pA}}{d^2k_\perp}, \] (7)

where summation over \( N_R \) includes the neutron and all resonance states generated by QE; \( m' \) is the spin projection of the \( N_R \), \( C_d \) is the renormalization coefficient introduced by Bertocchi and Treleani [13], \( F(k) \) is the ratio of flux factors for \( nA \) and \( dA \) collisions, \( \sigma_{NRA}^T \) is the total and \( d^2\sigma_{NRA}/d^2k_\perp \) and \( d^2\sigma_{pA}/d^2k_\perp \) are differential cross sections of the nucleus \( A \), respectively. In our calculations we use for \( N_R \) the lowest 10 states with effective numbers larger than \( 10^{-4} \).

The invariant DCS, \( I \), the tensor analyzing power, \( T_{20} \), and the polarization transfer coefficient, \( \kappa_0 \), are

\[ I = \frac{1}{3} \sum_{M,m} I_{M}^{m}, \quad T_{20} = -\sqrt{2} \frac{I_{I}^{+} + I_{I}^{-} - 2I_{0}^{+}}{I_{I}^{+} + I_{I}^{-} + I_{0}^{+}}, \quad \kappa_0 = \frac{I_{I}^{+} + I_{I}^{-}}{I_{I}^{+} + I_{I}^{-} + I_{0}^{+}}. \] (8)

In numerical calculations we take for the total cross section \( \sigma_{12C}^{T,n} \) the experimental value for \( \sigma_{12C}^{T,p} = 340 \text{ mb} \). The differential cross sections \( d^2\sigma_{N_{12C}}/d^2k_\perp \) and \( d^2\sigma_{p_{12C}}/d^2k_\perp \) were calculated in the framework of the Sitenko–Glauber model and them approximated by universal curve

\[ A_1 e^{-B_1 k_\perp^2} + A_2 e^{-B_2 k_\perp^2}, \] with \( A_i = 2611.3 \text{ and } 119.3 \text{ mb}/(\text{GeV}/c)^2, \) \( B_i = 69.3 \text{ and } 4.3 (\text{GeV}/c)^{-2} \), respectively. For \( N_R \) we have used similar dependence assuming the \( \sigma_{N_{12C}}^{T,R}, A_{1R}^R, \) and \( B_{1R}^R \) as free parameters.

In Figs.2 and 3 we compare results of our calculations with experimental data for \( I, T_{20}, \) and \( \kappa_0 \). The parameters for average resonance were chosen as \( \sigma_{N_{12C}}^{T,R} = 400 \text{ mb}, A_1^R = 2373.9 \text{ mb}/(\text{GeV}/c)^2, B_1^R = 77.0 \text{ (GeV}/c)^{-2}, A_2^R = A_2 \) and \( B_{2R}^R = B_2 \). One concludes that QE and MS give large contribution in the DCS and polarization observables of the \( 0^\circ \) inclusive \( ^{12}\text{C}(d,p) \) breakup for the kinematical region corresponding to high internal momentum \( k \) and qualitatively reproduce the behavior of this quantities. The Melosh transformation does not affects the final results significantly.

Note that in our calculations we ignore \( NA \rightarrow NA \) spin–flip amplitude. There are some arguments that \( np \) spin–flip is important for \( T_{20} \) in \(^1\text{H}(d,p) \) [21]. This, as well as detailed \( A \)-dependence of the polarization observables in \( A(d,p) \), remains an open question to the theory and we hope to discuss this further in a separate paper.
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Fig. 1.
Fig. 2.

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Fig. 3.
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Fig. 1. Ration \( R = u_{\text{renorm}}(r)/u(r) \) for some deuteron wave functions (PARIS — [26], Nijm-93 and Nijm-I — [27] and see at URL address [http://NN-online.sci.kun.nl/NN/deut.html]) for radius of quark core \( b = 0.8 \) fm.

Fig. 2. The invariant differential cross section (DCS) \( I \equiv E_p \frac{d^3\sigma}{d^3p} \) of the 0\(^{\circ}\) inclusive \(^{12}\)C\((d,p)\) breakup at \( p_d = 9.1 \) GeV/c plotted versus the relativistic internal momentum in the deuteron \( k \) (see text for definition). Curves show results of calculations with the Nijm-I deuteron wave function in the framework of multiple scattering: with (bold solid line) and without quark exchange (short-dashed line); and IA: with (long dashed line) and without quark exchange (dotted line). Contribution of the Melosh transformation in DCS is negligible and not shown. DCS is given in \( \text{mb} \times \text{GeV}/(\text{GeV}/c)^3/\text{srad} \).

Fig. 3. The tensor analyzing power \( T_{20} \) (upper panel) and the polarization transfer \( \kappa_0 \) (down panel) in the 0\(^{\circ}\) inclusive \(^{12}\)C\((d,p)\) breakup as function of the relativistic internal momentum in the deuteron \( k \). Curves are the same as in fig. 2, thin solid lines are the result of multiple scattering with quark exchange omitting relativistic spin rotation (\( U(k) = 1 \)).