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Polarization phenomena by deuteron fragmentation into pions

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Abstract. The fragmentation of deuterons into pions emitted forward in the kinematic region forbidden for free nucleon-nucleon collisions is analyzed. The inclusive relativistic invariant spectrum of pions and the tensor analyzing power T_{20} are investigated within the framework of an impulse approximation using various deuteron wave functions. The influence of $\mathcal{P}$-wave inclusion in the deuteron wave function is also studied. The invariant spectrum is shown to be more sensitive to the amplitude of the $NN \to \pi X$ process than the tensor analyzing power T_{20}. It is shown that the inclusion of the non-nucleonic degrees of freedom in a deuteron results in a satisfactory description of the data for the inclusive pion spectrum and improves the description of the data about T_{20}. According to the data, T_{20} has very small positive values, less than 0.2, which contradicts the theoretical calculations ignoring these degrees of freedom.

PACS. 25.10.+s Nuclear reactions involving few-nucleon systems – 24.70.+s Polarization phenomena in reactions – 24.10.Jv Relativistic models

1 Introduction

Important information of the deuteron structure at small distances arises from the study of reactions of hadro-production in proton-deuteron and deuteron-deuteron collisions in the kinematic region forbidden for the free nucleon-nucleon interaction [1,2]. These are the so-called cumulative processes. This kinematic region corresponds to values for the light-cone variable $x = 2(E' + p')/(E_D + p_D) \geq 1$, where E', E_D and p', p_D are the energies and momenta of the final hadron and deuteron, respectively. The nucleon momentum distributions in the deuteron, extracted from the reaction $Dp \to pX$ at forward proton emission and eD-inelastic scattering [3], actually coincide with each other (see, for example, [4]). One can conclude that hadron and lepton probes lead to the same information on the deuteron structure. The so-called Paris [5], Reid [6] and Bonn [7] deuteron wave functions (DWFs) reproduce rather well the data on the $Dp \to pX$ reaction for internal momenta $k = \sqrt{m^2/(4x(1-x)) - m^2}$ up to 0.25 GeV/c within the framework of the impulse approximation (IA) [4]). The inclusion of corrections to the IA related to secondary interactions allows one to describe the data on the deuteron fragmentation $Dp \to pX$ at $k > 0.25$ GeV/c [8].

The investigation of polarization phenomena by deuteron fragmentation at intermediate and high energies in the kinematic region forbidden for hadron emission by free N-N scattering has recently become very topical. Cumulative proton production in the collision of polarized deuterons with the target results in information about the deuteron spin structure at small internuclear distances. This can be seen from the experimental and theoretical study of deuteron fragmentation into protons at a zero angle [8–10]. The theoretical analysis of this reaction has shown that the tensor analyzing power T_{20} and the polarization transfer coefficient κ are more sensitive to the deuteron wave function (DWF), particularly to the reaction mechanism, than the inclusive spectrum [8]. At present, not a single DWF relativistic form can describe T_{20} measured by $Dp \to pX$ stripping at $x \geq 1.7$. On the other hand, the inclusion of the reaction mechanism, namely the impulse approximation and the secondary interaction of the produced hadrons, can describe both the inclusive spectrum and T_{20} at $x \leq 1.7$ using only the nucleon degrees of freedom [8]. Among other things this phenomenon can be due to the fact that the deuteron structure at a high (> 0.20 GeV/c) internal momentum (short internuclear distances < 1 fm) is determined by non-nucleonic degrees of freedom. The inclusion of non-nucleonic degrees of freedom, (it can be a six-quark state, $\Delta\Delta$, $NN^\star$, $NN\pi$ and other states in the deuteron) allowed one to describe the data on the inclusive proton spectrum at $x \geq 1.7$ [8]. A number of papers were dedicated to the theoretical analysis of the deuteron stripping to protons, see for example, references in [2,8]. However, to date there has been no unified theoretical description of T_{20} for the whole kinematic region of protons emitted forward by the $Dp \to pX$ stripping.

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If we try to study the manifestation of non-nucleonic degrees of freedom, it is natural to investigate the cumulative production of different hadrons having different quark contents. Interesting experimental data on T_{20} in the reaction $Dp \to \pi X$, where the pion is emitted forward, have been published recently [11]. They show very small, approximately constant, value of the tensor analyzing power T_{20} for the deuteron fragmentation into pions $Dp \to \pi X$ at $x \geq 1$. The mechanism of this reaction is mainly an impulse approximation as the secondary interaction or the final-state interaction (FSI) is very small and can be neglected [12]. The large yield of high-momentum pions produced by p-D and p-A collisions in the kinematical region forbidden for free N-N scattering was explained by models incorporating few-nucleon correlation [2,13] or multi-quark bags [14,15]. However, the polarization phenomena in the deuteron fragmentation into pions were not explained by these approaches.

In this paper, we present a relativistic invariant analysis of the deuteron tensor analyzing power T_{20} and the unpolarized-pion spectrum in the backward inclusive $p + D \to \pi(180°) + X$ reaction (in the deuteron rest frame). The main goal is to describe this reaction in a consistent relativistic approach using a nucleon model of the deuteron. A fully covariant expression for all quantities is obtained within the Bethe-Salpeter (BS) formalism [16]. In this way, we obtain general conclusions about the amplitude of the process, which can not be drawn in the non-relativistic approach. On the other hand, the non-relativistic limit will be calculated, and some links to non-relativistic corrections can be found. Our analysis of deuteron models can be very important to search for quark nuclear phenomena.

2 Relativistic impulse approximation

Let us consider the inclusive reaction of deuteron fragmentation into a pion:

$$\vec{D} + p \to \pi(0°) + X\,, \tag{1}$$

within the framework of the impulse approximation, fig. 1.

The amplitude of this process $\mathcal{T}^{\pi}_{pD}$ can be written in the following relativistic invariant form:

$$\mathcal{T}^{\pi}_{pD} \equiv \mathcal{T}(Dp \to \pi X) = \left(\bar{\mathcal{U}}_Y \Gamma_{NN}\right)_{\alpha\beta} \bar{u}^{(\sigma_{p'})}_{\gamma}(p') \times \left(\frac{\hat{n}+m}{n^2-m^2}\right)_{\beta\delta} u^{(\sigma_p)}_{\alpha}(p) \left(\Gamma_\mu(D,q)\mathcal{C}\right)_{\delta\gamma} \xi^{\mu}_{M}(D)\,, \tag{2}$$

where $(\bar{\mathcal{U}}_Y \Gamma_{NN})$ is the truncated $NN \to \pi Y$ vertex; α, β, γ and δ are the Dirac indices (with summation over repeated indices); μ is the Lorentz index; $\mathcal{C} = i\gamma_2\gamma_0$ is the charge conjugation Dirac matrix and M is the deuteron spin projection. Here, the deuteron vertex $(\Gamma_\mu(D,q)\mathcal{C})$ satisfies the BS equation and depends on the relative momentum $q = (n - p')/2$ and total momentum $D = n + p'$ of deuteron, $\xi^{\mu}_{M}(D)$ is the four-vector of the deuteron polarization. It satisfies the following equations:

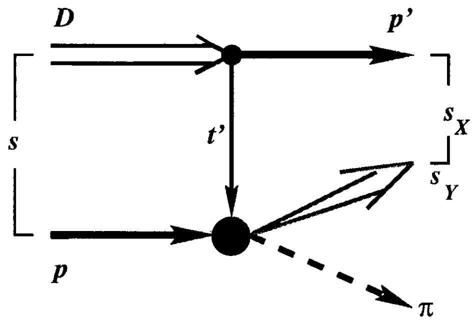

Fig. 1. Diagram representing the relativistic impulse approximation discussed in the text.

$$\xi^{\mu M}(D)D_\mu = 0\,,\quad \xi^{\mu M}(D)\xi_{\mu M'}(D) = -\delta^{M}_{M'}\,,$$
$$\sum_M \left(\xi_{\mu M}(D)\right)^{\star} \xi_{\nu M}(D) = -g_{\mu\nu} + \frac{D_\mu D_\nu}{M_D^2}\,. \tag{3}$$

Squaring this amplitude, one can write the relativistic invariant inclusive pion spectrum of the reaction $Dp \to \pi X$ in the following form:

$$\rho^{\pi}_{pD} = \varepsilon_\pi \frac{\mathrm{d}\sigma}{\mathrm{d}^3 p_\pi} = \frac{1}{(2\pi)^3} \int \frac{\sqrt{\lambda(p,n)}}{\sqrt{\lambda(p,D)}} \times \rho_{\mu\nu}(D) \left[\rho^{\pi}_{pN} \cdot \Phi^{\mu\nu}(D,q)\right] \frac{m^2 \mathrm{d}^3 p'}{E'}\,, \tag{4}$$

where $\lambda(p_1,p_2) \equiv (p_1p_2)^2 - m_1^2 m_2^2 = \lambda(s_{12}, m_1^2, m_2^2)/4$ is the flux factor; p, n are the four-momenta of the target proton and intra-deuteron nucleon, respectively; $\rho^{\pi}_{pN} \equiv \varepsilon_\pi \mathrm{d}\sigma/\mathrm{d}^3 p_\pi$ is the relativistic invariant inclusive spectrum of pions arising from interaction of the intra-deuteron nucleon with the target proton. In the general case, this spectrum can be written as a three-variable function $\rho^{\pi}_{pN} = \rho(x_{\mathrm{F}}, \pi_\perp, s_{NN})$. The Feynman variable, x_{F}, is defined as $x_{\mathrm{F}} = 2\pi_{||}/\sqrt{s_{NN}}$, where π is the pion momentum in the center of mass of two interacting nucleons and $s_{NN} = (p+N)^2$.

$\rho_{\mu\nu}(D)$ is the density matrix of the deuteron [17]:

$$\begin{aligned}\rho_{\mu\nu}(D) = {} & \left(\xi_{\mu M}(D)\right)^{\star} \xi_{\nu M}(D) = \\ & \frac{1}{3}\left(-g_{\mu\nu} + \frac{D_\mu D_\nu}{M_D^2}\right) + \frac{1}{2}(W_\lambda)_{\mu\nu} s^{\lambda}_{D} \\ & -\left[\frac{1}{2}\left((W_{\lambda_1})_{\mu\rho}(W_{\lambda_2})^{\rho}_{\nu} + (W_{\lambda_2})_{\mu\rho}(W_{\lambda_1})^{\rho}_{\nu}\right)\right. \\ & \left. +\frac{2}{3}\left(-g_{\lambda_1\lambda_2} + \frac{D_{\lambda_1}D_{\lambda_2}}{M_D^2}\right)\left(-g_{\mu\nu} + \frac{D_\mu D_\nu}{M_D^2}\right)\right] p^{\lambda_1\lambda_2}_{D}\end{aligned} \tag{5}$$

with $(W_\lambda)_{\mu\nu} = i\varepsilon_{\mu\nu\gamma\lambda} D^{\gamma}/M_D$; s_D the spin vector and p_D the alignment tensor of the deuteron.

The full symmetric tensor $\Phi_{\mu\nu}(D,q)$ in eq. (4) reads as

$$\Phi_{\mu\nu}(D,q) = \frac{1}{4}\mathrm{Tr}\left[\bar{\Psi}_\mu\left(\frac{\widehat{n}+m}{m}\right)^2\Psi_\nu\frac{\widehat{p'}-m}{m}\right] = -f_0(n^2)g_{\mu\nu} + f_1(n^2)\frac{q_\mu q_\nu}{m^2}\,. \qquad (6)$$

Proving eq. (6), we introduce the modified vertex, $\Psi_\mu(D,q)$:

$$\Psi_\mu(D,q) = \frac{\Gamma_\mu(D,q)}{m^2-n^2-i0} = \varphi_1(n^2)\gamma_\mu + \varphi_2(n^2)\frac{n_\mu}{m} + \frac{\widehat{n}-m}{m}\left(\varphi_3(n^2)\gamma_\mu + \varphi_4(n^2)\frac{n_\mu}{m}\right). \qquad (7)$$

Substituting eq. (7) into eq. (6) and calculating the trace, one finds explicit forms for the invariant functions $f_{0,1}$:

$$\begin{aligned} f_0(n^2) = & \frac{M_D^2}{m^2}\left(\varphi_1 - \frac{m^2-n^2}{m^2}\varphi_3\right)\varphi_1 - \left(\frac{m^2-n^2}{m^2}\right)^2(\varphi_1-\varphi_3)\varphi_3\,;\\ f_1(n^2) = & -4\left[\varphi_1+\varphi_2-\frac{m^2-n^2}{m^2}\left(\frac{\varphi_2}{2}+\varphi_3+\varphi_4\right)\right]\\ & \times(\varphi_1+\varphi_2) + \frac{M_D^2}{m^2}\left(\varphi_2-\frac{m^2-n^2}{m^2}\varphi_4\right)\varphi_2\\ & -\left(\frac{m^2-n^2}{m^2}\right)^2(\varphi_2+2\varphi_3+\varphi_4)\varphi_4\,. \end{aligned} \qquad (8)$$

The corresponding invariant scalar functions $\varphi_i(n^2)$ of the deuteron vertex with one on-shell nucleon can be computed in any reference frame. Let us note that in our case, when one particle is on the mass shell, only four partial amplitudes contribute to the process, namely in the ρ-spin classification, $U = {}^3\mathcal{S}_1^{++}$, $W = {}^3\mathcal{D}_1^{++}$, $V_s = {}^1\mathcal{P}_1^{-+}$ and $V_t = {}^3\mathcal{P}_1^{-+}$. We can write φ_i in the deuteron rest frame in order to relate them to the non-relativistic $\mathcal{S}$- and $\mathcal{D}$-waves of the deuteron. In this case, the invariant functions take the following forms:

$$\begin{aligned} N_D\,\varphi_1 &= U - \frac{W}{\sqrt{2}} - \sqrt{\frac{3}{2}}\frac{m}{|\mathbf{q}|}V_t\,;\\ N_D\,\varphi_2 &= -\frac{m}{(E_\mathbf{q}+m)}U - \frac{m(2E_\mathbf{q}+m)}{|\mathbf{q}|^2}\frac{W}{\sqrt{2}} + \sqrt{\frac{3}{2}}\frac{m}{|\mathbf{q}|}V_t\,;\\ N_D\,\varphi_3 &= -\sqrt{\frac{3}{2}}\frac{mE_\mathbf{q}}{|\mathbf{q}|(2E_\mathbf{q}-M_D)}V_t\,;\\ N_D\,\varphi_4 &= \frac{m^2}{M_D(E_\mathbf{q}+m)}U - \frac{m^2(E_\mathbf{q}+2m)}{M_D|\mathbf{q}|^2}\frac{W}{\sqrt{2}} - \sqrt{3}\frac{m^2}{|\mathbf{q}|(2E_\mathbf{q}-M_D)}V_s\,, \end{aligned} \qquad (9)$$

where all the vertex functions are determined in the deuteron rest frame and all the kinematic variables in eqs. (9) have to be evaluated in this system; $E_\mathbf{q} = \sqrt{|\mathbf{q}|^2+m^2}$. The normalization factor $N_D^{-1} = \pi\sqrt{2/M_D}$ is chosen according to the non-relativistic normalization DWF:

$$\int_0^\infty |\mathbf{q}|^2\mathrm{d}|\mathbf{q}|\left[U^2(|\mathbf{q}|)+W^2(|\mathbf{q}|)\right] = 1\,. \qquad (10)$$

The relativistic invariant functions $f_{0,1}(|\mathbf{q}|)$ (8) can be rewritten in terms of these spin-orbit momentum wave functions as

$$\begin{aligned} f_0(|\mathbf{q}|) &= N_D^{-2}\frac{M_D^2}{m^2}\left[\left(U-\frac{W}{\sqrt{2}}\right)^2 + \sqrt{6}\frac{|\mathbf{q}|}{m}\left(U-\frac{W}{\sqrt{2}}\right)V_t - \frac{3}{2}V_t^2\right];\\ f_1(|\mathbf{q}|) &= N_D^{-2}\frac{3M_D^2}{2|\mathbf{q}|^2}\left[2\sqrt{2}UW + W^2 + V_t^2 - 2V_s^2 - \frac{4}{\sqrt{3}}\frac{|\mathbf{q}|}{m}\left(\left(U-\frac{W}{\sqrt{2}}\right)\frac{V_t}{\sqrt{2}} + \left(U+\sqrt{2}W\right)V_s\right)\right]. \end{aligned} \qquad (11)$$

Then, all the observables can be computed in terms of positive- and negative-energy wave functions U, W and V_s, V_t, respectively. The contribution of the positive-energy waves U, W to the observables results in the non-relativistic limit. The parts containing the negative-energy waves V_s, V_t have a pure relativistic origin, and consequently they manifest genuine relativistic correction effects.

Using the explicit form of the density matrix (5), one can write

$$\Phi \equiv \rho_{\mu\nu}\,\Phi^{\mu\nu} = \Phi^{(u)} + \Phi^{(v)}_\lambda s_D^\lambda + \Phi^{(t)}_{\lambda_1\lambda_2}p_D^{\lambda_1\lambda_2}\,. \qquad (12)$$

The superscripts (u,v,t) denote unpolarized, vector-polarized and tensor-polarized cases, respectively:

$$\begin{aligned} \Phi^{(u)}(\mathbf{q}) &= f_0 + \frac{1}{3}\frac{|\mathbf{q}|^2}{m^2}f_1\,;\\ \Phi^{(v)}_\lambda(\mathbf{q}) &= 0\,;\\ \Phi^{(t)}_{\lambda_1\lambda_2}(\mathbf{q}) &= \left[\frac{1}{3}\frac{|\mathbf{q}|^2}{m^2}\left(-g_{\lambda_1\lambda_2}+\frac{D_{\lambda_1}D_{\lambda_2}}{M_D^2}\right) - \left(-g_{\lambda_1\mu}+\frac{D_{\lambda_1}D_\mu}{M_D^2}\right)\left(-g_{\lambda_2\nu}+\frac{D_{\lambda_2}D_\nu}{M_D^2}\right)\frac{q^\mu q^\nu}{m^2}\right]f_1\,. \end{aligned} \qquad (13)$$

Let us consider now the case when the deuteron has tensor polarization. If the initial deuteron is only aligned due to the p_D^{ZZ} component, the inclusive spectrum of the reaction $\overrightarrow{D}+p\to\pi+X$ (4) can be written in the form

$$\rho^\pi_{pD}\left(p_D^{ZZ}\right) = \rho^\pi_{pD}\left[1+\mathrm{A}_{ZZ}\,p_D^{ZZ}\right], \qquad (14)$$

where ρ^π_{pD} is the inclusive spectrum for the case of unpolarized deuterons and $\mathrm{A}_{ZZ}\equiv\sqrt{2}T_{20}$ $(-\sqrt{2}\le T_{20}\le 1/\sqrt{2})$

is the tensor analyzing power. One can write:

$$\rho^{\pi}_{pD} = \frac{1}{(2\pi)^3}\int \frac{\sqrt{\lambda(p,n)}}{\sqrt{\lambda(p,D)}} \left[\rho^{\pi}_{pN}\cdot\Phi^{(u)}(|\mathbf{q}|)\right] \frac{m^2 \mathrm{d}^3 q}{E_{\mathbf{q}}}\,; \tag{15}$$

$$\rho^{\pi}_{pD}\,\mathrm{A}_{ZZ} = -\frac{1}{(2\pi)^3}\int \frac{\sqrt{\lambda(p,n)}}{\sqrt{\lambda(p,D)}} \times \left[\rho^{\pi}_{pN}\cdot\Phi^{(t)}(|\mathbf{q}|)\right]\left(\frac{3\cos^2\vartheta_{\mathbf{q}}-1}{2}\right)\frac{m^2\mathrm{d}^3 q}{E_{\mathbf{q}}}\,, \tag{16}$$

where

$$\Phi^{(u)}(|\mathbf{q}|) = N_D^{-2}\frac{M_D^2}{m^2}\Bigg[U^2+W^2-V_t^2-V_s^2 + \frac{2}{\sqrt{3}}\frac{|\mathbf{q}|}{m}\left(\left(\sqrt{2}V_t-V_s\right)U-\left(V_t+\sqrt{2}V_s\right)W\right)\Bigg]; \tag{17}$$

$$\Phi^{(t)}(|\mathbf{q}|) = N_D^{-2}\frac{M_D^2}{m^2}\Bigg[2\sqrt{2}UW+W^2+V_t^2-2V_s^2 - \frac{4}{\sqrt{3}}\frac{|\mathbf{q}|}{m}\left(\left(U-\frac{W}{\sqrt{2}}\right)\frac{V_t}{\sqrt{2}}+\left(U+\sqrt{2}W\right)V_s\right)\Bigg]. \tag{18}$$

It is intuitively clear that the nucleons in the deuteron are mainly in the states with angular momenta $L=0,2$ (see also the numerical analysis of the solutions of the BS equation in terms of amplitudes within the ρ-spin basis [18]), the probability of states with $L=1$ ($V_{s,t}$) in eqs. (17),(18) is much smaller than the probability for the U,W configurations. Moreover, it can be shown that the U- and W-waves directly correspond to the non-relativistic $\mathcal{S}$ and $\mathcal{D}$ ones. Therefore, eqs. (17),(18) with only U,W waves can be identified as the main contributions to the corresponding observables, and they can be compared with their non-relativistic analogs. Other terms possessing contributions from $\mathcal{P}$-waves are proportional to $\mathbf{q}/m$ (the diagonal terms in $V_{s,t}$ are negligible). Due to their pure relativistic origin, one can refer to them as relativistic corrections.

Let us consider a minimal relativistic scheme which describes rather well the differential cross-section for such a process as deuteron break-up $A(D,p)X$. The minimal relativistic procedure [19,2] consists in i) replacing the argument of the non-relativistic wave functions by the light-cone variable $\mathbf{k}=(\mathbf{k}_\perp,\mathbf{k}_{||})$,

$$\mathbf{k}^2=\frac{m^2+\mathbf{k}_\perp^2}{4x(1-x)}-m^2; \qquad k_{||}=\sqrt{\frac{m^2+\mathbf{k}_\perp^2}{x(1-x)}}\left(\frac{1}{2}-x\right), \tag{19}$$

where $x=(E_{\mathbf{q}}+|\mathbf{q}|\cos\vartheta_{\mathbf{q}})/M_D=(\varepsilon'-p'_{||})/M_D$; $|\mathbf{k}_\perp|=p'_\perp$ in the deuteron rest frame, and ii) multiplying the wave functions by the factor $\sim 1/(1-x)$. This procedure results in a shift of the argument towards larger values, and the wave function itself decreases more rapidly. This effect of suppressing the wave function is compensated by the kinematic factor $1/(1-x)$.

In the BS approach the relativistic effects are of dynamic nature [20] and are not reduced to a simple shift in the arguments. In addition to the $\mathcal{S}$- and $\mathcal{D}$-waves, the deuteron contains negative-energy components, *i.e.*, $\mathcal{P}$-waves. One can see that they play a more important role in the polarization case and lead to an improvement in the description of the data.

3 Results and discussion

Below, the calculated results for the inclusive relativistic invariant pion spectrum and the tensor analyzing power in the fragmentation process $Dp\to\pi X$ are presented and compared with the available data [1,11]. These data are presented as a function of the so-called cumulative scaling variable $x_{\mathcal{C}}$ ("cumulative number") [21]. For our reaction, this variable is defined as

$$x_{\mathcal{C}} = 2\frac{(p\pi)-\mu^2/2}{(Dp)-M_D m-(D\pi)} = 2\frac{t-m^2}{(t-m^2)+(M_D+m)^2-s_X}\le 2\,. \tag{20}$$

In the rest frame of the deuteron $D=(M_D,\mathbf{0})$, it can be rewritten in the form

$$x_{\mathcal{C}} = 2\frac{EE_\pi - pp_\pi\cos\vartheta_\pi-\mu^2/2}{M_D(E-E_\pi-m)} \to 2\frac{E}{T_p}\frac{\alpha}{1-E_\pi/T_p}, \tag{21}$$

where $\alpha=(E_\pi-p_\pi\cos\vartheta_\pi)/M_D$ is the light-cone variable. The value of $x_{\mathcal{C}}$ corresponds to the minimum mass (in nucleon mass units) of the part of the projectile nucleus (deuteron) involved in the reaction. Values of $x_{\mathcal{C}}$ larger than 1 correspond to cumulative pions.

Deuteron (polarized and unpolarized) fragmentation into the proton $D+A\to p(0^\circ)+X$ is one of the most intensively studied reactions with hadronic probes. The reason for this interest lies in the facts that the cross-section is large, and also that a simple relation exists between the inclusive spectrum and the polarization observables, and the $\mathcal{S}$- and $\mathcal{D}$-waves of the DWF obtained within the IA. For example, the tensor analyzing power T_{20} within the IA can be written in the following simple form:

$$T_{20}=-\frac{1}{\sqrt{2}}\,\frac{2\sqrt{2}\,UW+W^2}{U^2+W^2}\,. \tag{22}$$

This relation does not depend on the amplitude of the elementary reaction $pn\to pX$ which is taken off the mass shell in the IA. As is shown in [8], both the differential cross-section and T_{20} for fragmentation $D+p\to p(0^\circ)+X$ can be described within the IA at $k\le 0.2$ GeV/c only. At larger momentum k, secondary interactions, in particular the triangle graphs with a virtual pion, have to be taken into account in order to describe these observables most satisfactorily.

However, as is shown in [22], for the pion production $D+p\to\pi(0^\circ)+X$ over the cumulative region the rescattering mechanism is kinematically suppressed. Therefore, one can use the IA only for theoretical calculation of the differential cross-section and tensor analyzing power T_{20}

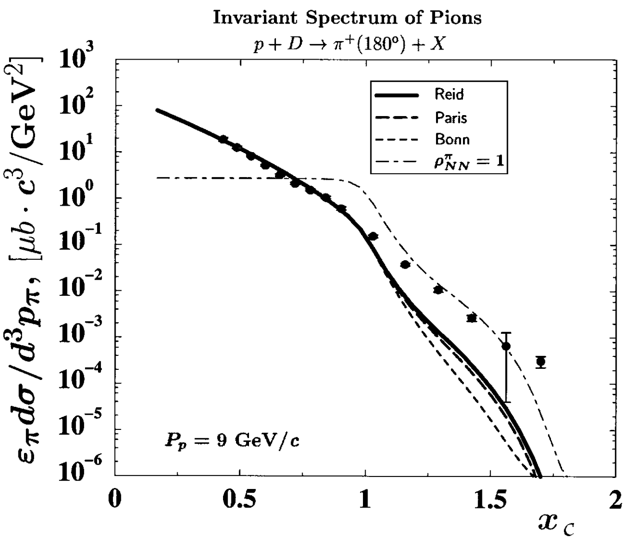

Fig. 2. The invariant spectrum of the backward pions in the deuteron fragmentation reaction calculated in the relativistic impulse approximation using various types of non-relativistic DWF. The calculated results are compared with the data from [1] for a projectile proton momentum $P_p = 9$ GeV/c. The dot-dashed curve corresponds to the calculation where the dependence of the elementary vertex $NN \to \pi Y$ on the relativistic invariant variables has been neglected.

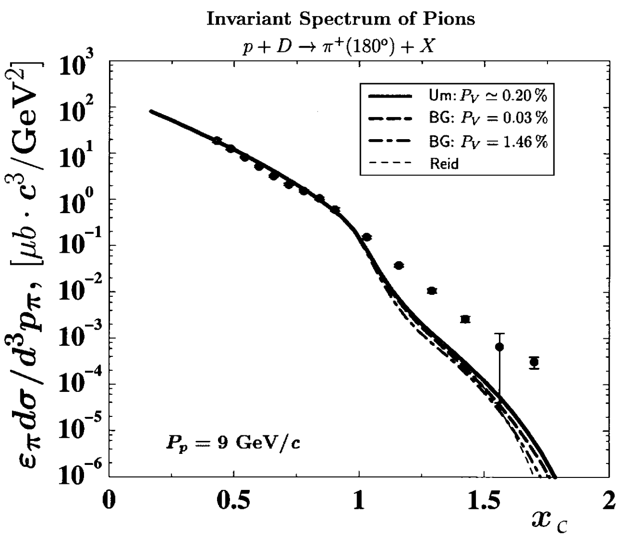

Fig. 3. The invariant spectrum calculated using two forms of the relativistic DWFs, [23] and [24]. The data are taken from [1]. The thick solid line corresponds to the DWF [23], where the total probability of small components is $P_V = \int_0^\infty p^2 \mathrm{d}p\,[V_t^2 + V_s^2] \simeq 0.2\,\%$. The long-dashed and dot-dashed lines represent the calculations with the Gross DWF using the mixing parameter $\lambda = 0.0$ and 1.0, respectively [25]. This corresponds to the probabilities $P_V = 0.03\,\%$ and $1.46\,\%$ obtained for the small component. The thin dashed line corresponds to the non-relativistic Reid DWF.

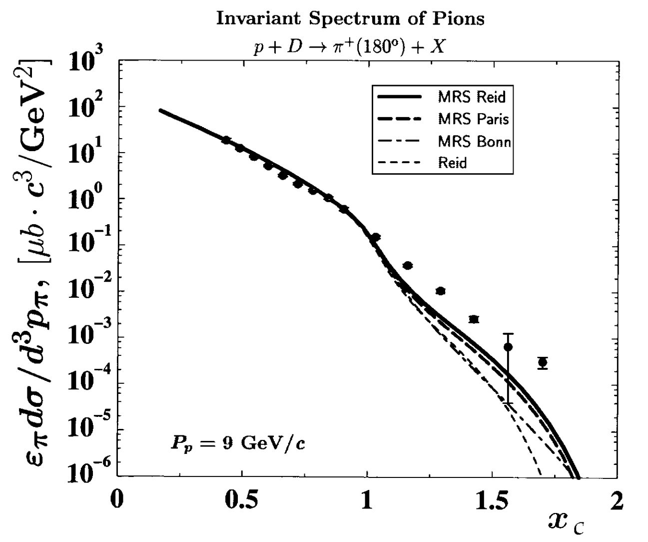

Fig. 4. The invariant pion spectrum calculated using the non-relativistic DWFs obtained by the minimal relativistic scheme (MRS) [2,19]. The solid, dashed and dot-dashed lines correspond to various DWF forms: RSC, Paris and Bonn. The data are taken from [1].

for this reaction. The calculated invariant spectrum of pions produced by the $D + p \to \pi(0^\circ) + X$ reaction is presented in figs. 2-3. The vertex $NN \to \pi Y$ is taken on the mass shell and the corresponding differential cross-section proposed in [26] is used.

A large sensitivity of the inclusive spectrum to this vertex and its small sensitivity to the type of non-relativistic DWF used can be seen in fig. 2. Figure 3 shows that the inclusion of the $\mathcal{P}$-wave contribution to the DWF within the Bethe-Salpeter or Gross approaches results in a better (but not satisfactory) description of the data over the cumulative region. From fig. 4 one can see the effects of the calculation using the minimal relativistic scheme [2]. It should be noted that this simpler relativistic scheme gives better (but not satisfactory) agreement with experiment for the pion spectrum in the relativistic IA.

The calculated T_{20} for the reaction of polarized deuteron fragmentation into cumulative pions is shown in figs. 5-7. From these figures one can see a small sensitivity of T_{20} to the vertex corresponding to the $NN \to \pi Y$ process. It is also seen that T_{20} is more sensitive to the DWF form than the invariant spectrum. The data on T_{20} are not described by any DWF used in this paper. Note that there may be an alternative approach to study the deuteron structure at small distances which assumes a possible existence of non-nucleonic or quark degrees of freedom [8, 27–30] in the deuteron and the nucleus. For example, according to [2], large momenta of nucleons are due to few-nucleon correlations in the nucleus. Then the deuteron structure can be described by assuming quark degrees of freedom [14,15]. On the other hand, the shape of the high-momentum tail of the nucleon distribution in the deuteron can be constructed on the basis of its true Regge asymptotics [13], and the corresponding parameters can be found

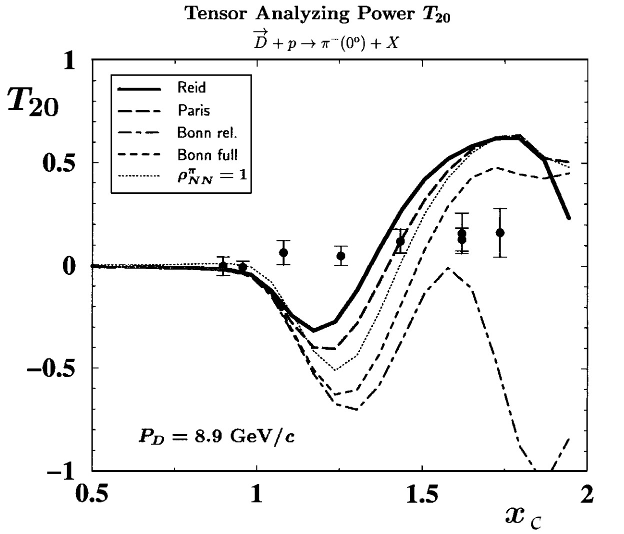

Fig. 5. The tensor analyzing power T_{20} of deuterons. The calculated results are compared with the data from [11] at the projectile proton momentum $P_p = 4.46$ GeV$/c$. The dotted curve corresponds to the calculation where the internal structure of the elementary vertex $NN \to \pi Y$ has been neglected. The solid, long-dashed, dot-dashed and dashed lines correspond to calculations with various types of non-relativistic DWF: RSC, Paris, relativistic Bonn, and full Bonn, respectively.

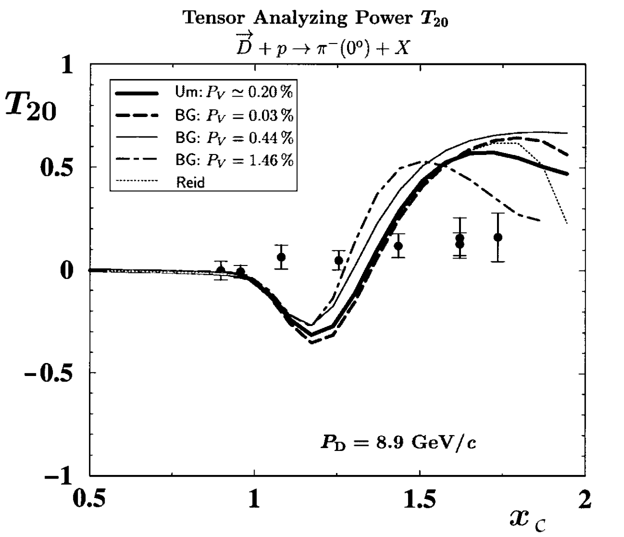

Fig. 6. T_{20} calculated using two forms of relativistic DWFs, [23] and [24]. Notation as in fig. 3. The data are taken from [11].

from the good description of the inclusive proton spectrum in the deuteron fragmentation $Dp \to pX$ [13,8]. According to [13,8], one can write the following form for $\widetilde{\Phi}^{(u)}(|\mathbf{q}|)$ (see eq. (17)):

$$\Phi^{(u)}(|\mathbf{q}|) = \frac{E_{\mathbf{k}}/E_{\mathbf{q}}}{2(1-x)} \widetilde{\Phi}^{(u)}(|\mathbf{k}|)\,, \tag{23}$$

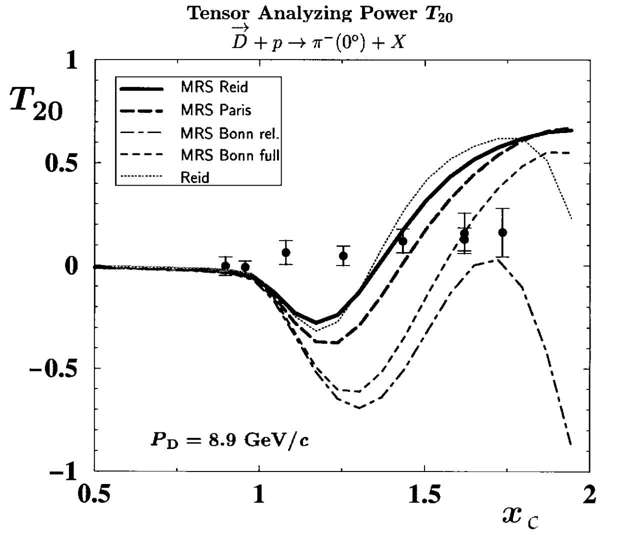

Fig. 7. T_{20} calculated with the non-relativistic DWFs using the minimal relativistic scheme (MRS) [2,19]. The solid, long-dashed, dashed and dot-dashed lines correspond to the various DWF forms: RSC, Paris, full and relativistic Bonn. The data are taken from [11].

where

$$\widetilde{\Phi}^{(u)}(|\mathbf{k}|) = N_D^{-1} \frac{M_D^2}{m^2} \Bigg[(1-\alpha_{2(3q)}) \Big(U^2(|\mathbf{k}|) + W^2(|\mathbf{k}|) \Big) + \alpha_{2(3q)} \frac{8\pi x(1-x)}{E_{\mathbf{k}}}\, G_{2(3q)}(x, \mathbf{k}_\perp) \Bigg]\,. \tag{24}$$

The parameter $\alpha_{2(3q)}$ is the probability for a non-nucleonic component in the deuteron which is a state of two colorless $(3q)$ systems:

$$G_{2(3q)}(x, \mathbf{k}_\perp) = \frac{b^2}{2\pi} \frac{\Gamma(A+B+2)}{\Gamma(A+1)\Gamma(B+1)}\, x^A (1-x)^B\, \mathrm{e}^{-b|\mathbf{k}_\perp|}. \tag{25}$$

Figure 8 presents the invariant pion spectrum calculated within the relativistic impulse approximation including the non-nucleonic component in the DWF [8,13]; its probability $\alpha_{2(3q)}$ is 0.2–0.4 (long-dashed and solid curves, respectively). One can see a good description of the data [1] at all x_C. According to [13,8], analogous results including non-nucleonic degrees of freedom, can be obtained for the tensor analyzing power T_{20}. Actually, in [13] only a form of $\widetilde{\Phi}^{(u)}(|\mathbf{k}|)$ has been constructed. However, to calculate T_{20} it is not enough, the corresponding orbital waves have to be known. Let us assume that non-nucleonic degrees of freedom result in the main contribution to the $\mathcal{S}$- and $\mathcal{D}$-waves of the deuteron wave function. Constructing new forms of these waves by including the non-nucleonic degrees of freedom we have to require that the square of the new DWF be equal to the one determined by eq. (24). Introducing a mixing parameter $\alpha = \pi a/4$ one can find the following forms of new $\mathcal{S}$- and $\mathcal{D}$- waves:

$$\widetilde{U}(|\mathbf{k}|) = \sqrt{1-\alpha_{2(3q)}}\, U(|\mathbf{k}|) + \cos(\alpha)\Delta(|\mathbf{k}|)\,; \tag{26}$$

$$\widetilde{W}(|\mathbf{k}|) = \sqrt{1-\alpha_{2(3q)}}\, W(|\mathbf{k}|) + \sin(\alpha)\Delta(|\mathbf{k}|)\,, \tag{27}$$

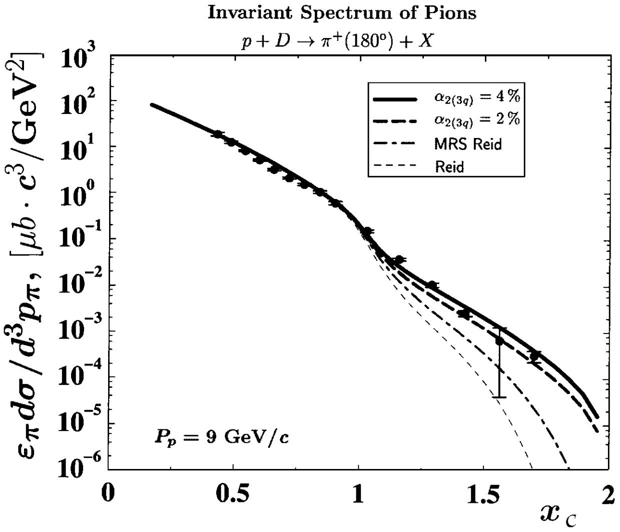

Fig. 8. The invariant pion spectrum calculated within the relativistic impulse approximation where non-nucleonic components in the DWF [13,8] have been included; its probability $\alpha_{2(3q)}$ is 0.02–0.04 (long-dashed and solid curves, respectively). One can have a good description of the data [1] for all x_C.

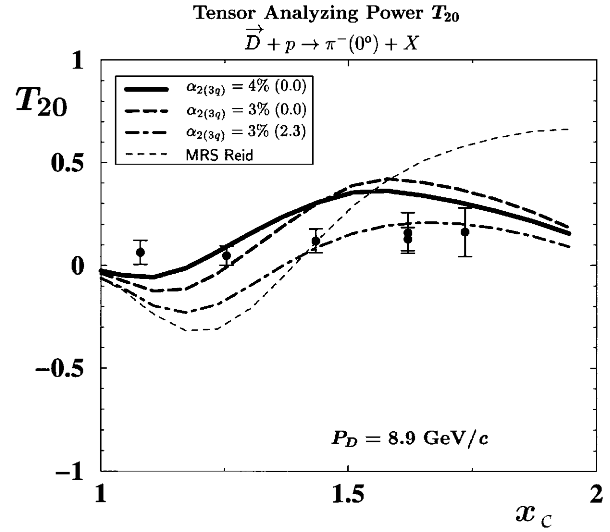

Fig. 9. The tensor analyzing power T_{20} calculated within the relativistic impulse approximation allowing for non-nucleonic components in the DWF, eqs. (26),(27). The solid and long-dashed lines represent the calculations with the mixing parameter $a = 0.0$ and the probability $\alpha_{2(3q)} = 4\,\%, 3\,\%$, respectively. The dot-dashed line corresponds to the calculation with the mixing parameter $a = 2.3$, which gives the curve closest to the data at $x_C \geq 1.5$. The thin dashed curve corresponds to the Reid DWF obtained by the minimal relativistic scheme (MRS).

where the function $\Delta(|\mathbf{k}|)$ has been obtained from the equation

$$\widetilde{\Phi}^{(u)}(|\mathbf{k}|) \;=\; N_D^{-1}\frac{M_D^2}{m^2}\left[\widetilde{U}^2(|\mathbf{k}|)+\widetilde{W}^2(|\mathbf{k}|)\right]. \qquad (28)$$

Figure 9 presents the analyzing power T_{20} calculated by using the functions $\widetilde{U}, \widetilde{W}$ including the non-nucleonic components in the DWF, according to [8,13]. It is evident from fig. 9 that the inclusion of non-nucleonic components in the DWF improves the description of the data for T_{20} at $x_C > 1$. The best description of the observable is obtained for the value $a = 2.3$ of the parameter a entering into eqs. (26),(27).

4 Summary

The main goal of this paper is to study the reaction of deuteron fragmentation into pions within the framework of the nucleon model of the deuteron and to find the role of the non-nucleonic degrees of freedom in a deuteron in this process. The main results can be summarized as follows.

1. It is quite incorrect to use the non-relativistic deuteron wave function for the analysis of D-N fragmentation into hadrons, in particular pions. Relativistic effects are sizeable, especially in the kinematic region corresponding to short intra-deuteron distances or large x. It is evident from the behavior of the inclusive pion spectrum and particularly the tensor analyzing power T_{20} at large x.
2. At the present time, the state of theory is such that the unique procedure to include relativistic effects in the deuteron has not been found yet. An extreme sensitivity to different methods of the relativistic deuteron wave function is found for T_{20} at $x \geq 1$.
3. A large sensitivity of the inclusive spectrum of pions to the vertex of the $NN \to \pi X$ process can be seen from fig. 2. In contrast to this, small sensitivity of T_{20} to this vertex is found, as seen from fig. 5. This polarization observable is very sensitive to the DWF form (figs. 5-7).
4. Very interesting data on T_{20} showing approximately zero values at $x_C \geq 1$ are not reproduced by the theoretical calculation using even different kinds of relativistic DWF. This may indicate a possible existence of non-nucleonic degrees of freedom or a basically new mechanism of pion production in the kinematic region forbidden for free N-N scattering.
5. For the deuteron fragmentation into protons emitted forward, the tensor analyzing power T_{20} is not described by standard nuclear physics using the nucleon degrees of freedom at $x_C \geq 1.7$ [8]. On the contrary, T_{20} for the fragmentation $Dp \to \pi X$ cannot be described within the same assumptions over all region $x_C \geq 1$. The inclusion of the non-nucleonic degrees of freedom within the approach suggested in [13,8], the use of which has reproduced the data for the proton spectrum in the deuteron stripping, allows us also to describe the inclusive pion spectrum at all values of x_C rather well (fig. 8). However, the information contained in both observables is redundant, since it is the same deuteron properties that are the main ingredient in the analysis of both $Dp \to pX$ and $Dp \to \pi X$ reactions in the IA. Therefore, the calculation of the tensor analyzing power including the non-nucleonic degrees of freedom in fragmentation of the deuteron into pions can give

us new independent information about the deuteron structure at small N-N distances and its comparison with the data can be considered as a test of the modified DWF model used. These results are presented in fig. 9 and show some improvement of the description of the data for T_{20} [11], especially at $x_{\mathcal{C}} > 1.3$, if we assume that the non-nucleonic degrees of freedom contribute mainly to the $\mathcal{S}$- and $\mathcal{D}$-waves of the DWF. Of course, the inclusion of the non-nucleonic degrees of freedom in the analysis of T_{20} is approximate, but can be considered as the indication of an important role of these degrees of freedom in studying polarization phenomena in the type of reactions considered.

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