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Probing the deuteron structure at small N-N distances by cumulative pion production

A.Yu. Illarionov[a], A.G. Litvinenko, and G.I. Lykasov

Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia

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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. 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. 24.70.+s Polarization phenomena in reactions – 25.10.+s Nuclear reactions involving few-nucleon systems

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. These are the so-called cumulative processes.

Cumulative proton production in the collision of polarized deuterons with the target results in information about the deuteron spin structure at small inter-nuclear distances. This can be seen from the experimental and theoretical study of deuteron fragmentation into protons at a zero angle (see [1] and references therein). 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. At present, not a single DWF relativistic form can describe T_{20} measured by $Dp \to pX$ stripping at light-cone variable $x \geq 1.7$. 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 nucleonic degrees of freedom [1]. 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 inter-nuclear 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 $x \geq 1.7$ [1].

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 [2]. These data are presented as a function of the so-called cumulative scaling variable $x_{\mathcal{C}}$ ("cumulative number") [3]. (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 $x_{\mathcal{C}} \sim x$ larger than 1 correspond to cumulative pions.) It was found a very small, approximately constant, value of the tensor analyzing power T_{20} for the deuteron fragmentation into pions $Dp \to \pi X$ at $x_{\mathcal{C}} \geq 1$.

In recent papers [4,5] we have investigated the reaction of deuteron fragmentation into pions within the framework of the relativistic impulse approximation. The mechanism of this reaction is mainly an impulse approximation as the secondary interaction or the final-state interaction is very small and can be neglected [6]. The main goal was to describe this reaction in a consistent relativistic approach using a nucleon model of the deuteron. A fully covariant expression for all quantities was obtained within the Bethe-Salpeter formalism. In this way we have obtained general conclusions about the amplitude of the process, which cannot be drawn in the non-relativistic approach. The main investigation results can be summarized as follows: I) It was evident from the behavior of the inclusive pion spectrum and particularly the tensor analyzing power T_{20} at large $x_{\mathcal{C}}$, that the relativistic effects are sizeable. However, 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

[a] e-mail: `Alexei.Illarionov@jinr.ru`

methods of the relativistic deuteron wave function was found for T_{20} at $x_{\mathcal{C}} \geq 1$. It was shown that the inclusion of the $\mathcal{P}$-wave contribution to the DWF within the Bethe-Salpeter approaches [7,8] results in a better (but not satisfactory) description of the data over the cumulative region. II) It was demonstrated a large sensitivity of the inclusive spectrum of pions to the vertex of the $NN \to \pi X$ subprocess. In contrast to this, a small sensitivity of T_{20} to this vertex was found. This polarization observable is very sensitive to the DWF form, that can be used for systematic investigation of the DWF. III) For the deuteron fragmentation into protons emitted forward, the tensor analyzing power T_{20} is not described by standard nuclear physics using the nucleonic degrees of freedom at $x_{\mathcal{C}} \geq 1.7$ [1]. On the contrary, T_{20} for the fragmentation $Dp \to \pi X$ cannot be described within the same assumptions over the whole region $x_{\mathcal{C}} \geq 1$ [4].

In this paper we try to include the non-nucleonic degrees of freedom within the approach suggested in [1,9], the use of which has reproduced the data for the proton spectrum in the deuteron stripping rather well.

We consider the inclusive reaction of deuteron fragmentation into a pion, $\vec{D} + p \to \pi(0^{\circ}) + X$, for the polarized deuteron and pion emitted forward at initial energies of order few GeV. If the initial deuteron is only tensor aligned due to their p_D^{ZZ} component, the inclusive spectrum of this reaction can be written in the form

$$\rho_{pD}^{\pi}\left(p_D^{ZZ}\right) = \rho_{pD}^{\pi}\left[1 + A_{ZZ}\, p_D^{ZZ}\right], \tag{1}$$

where $\rho_{pD}^{\pi} \equiv \varepsilon_\pi \cdot \mathrm{d}\sigma_{pD}^{\pi}/\mathrm{d}^3 p_\pi$ is the inclusive spectrum for the case of unpolarized deuterons and $A_{ZZ} \equiv \sqrt{2} T_{20}$ ($-\sqrt{2} \leq T_{20} \leq 1/\sqrt{2}$) is the tensor analyzing power. In the relativistic impulse approximation they can be written in a fully covariant manner within the Bethe-Salpeter formalism [4]:

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

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

where $\lambda(p_1, p_2) \equiv (p_1 p_2)^2 - m_1^2 m_2^2 = \lambda(s_{12}, m_1^2, m_2^2)/4$ is the flux factor; p, n are the four-momenta of the proton-target and intra-deuteron nucleon, respectively; ρ_{pN}^{π} is the relativistic invariant inclusive spectrum of pions arising from the interaction of the intra-deuteron nucleon with the target proton. The functions $\Phi^{(u)}(|\boldsymbol{q}|)$ and $\Phi^{(t)}(|\boldsymbol{q}|)$ depend on the relative momentum $q = n - D/2$ and contain full information about the structure of deuteron with one on-shell nucleon [4].

According to [10], 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 [11,12]. 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 asymptotic at $x \to 2$ [9], and the corresponding parameters can be found from the good description of the inclusive proton spectrum in the deuteron fragmentation $Dp \to pX$ [9]. According to [1,9], one can write the following form for $\widetilde{\Phi}^{(u)}(|\boldsymbol{q}|)$:

$$\Phi^{(u)}(|\boldsymbol{q}|) = \frac{E_{\boldsymbol{k}}/E_{\boldsymbol{q}}}{2(1-x)} \widetilde{\Phi}^{(u)}(|\boldsymbol{k}|), \tag{4}$$

where

$$\begin{aligned}\widetilde{\Phi}^{(u)}(|\boldsymbol{k}|) = N_D^{-1} \frac{M_D^2}{m^2} \Bigg[&(1 - \alpha_{2(3q)}) \left(U^2(|\boldsymbol{k}|) + W^2(|\boldsymbol{k}|)\right) \\ &+ \alpha_{2(3q)} \frac{8\pi x(1-x)}{E_{\boldsymbol{k}}}\, G_{2(3q)}(x, \boldsymbol{k}_\perp)\Bigg],\end{aligned} \tag{5}$$

where $(x, \boldsymbol{k}_\perp)$ are the light-cone variables [10] and $\boldsymbol{k}^2 = (m^2 + \boldsymbol{k}_\perp^2)/(4x(1-x)) - m^2$. The normalization factor $N_D^{-1} = \pi\sqrt{2/M_D}$ is chosen according to the non-relativistic normalization DWF [4]. 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:

$$G_{2(3q)}(x, \boldsymbol{k}_\perp) = \frac{b^2}{2\pi} \frac{\Gamma(A+B+2)}{\Gamma(A+1)\Gamma(B+1)}\, x^A (1-x)^B\, \mathrm{e}^{-b|\boldsymbol{k}_\perp|}. \tag{6}$$

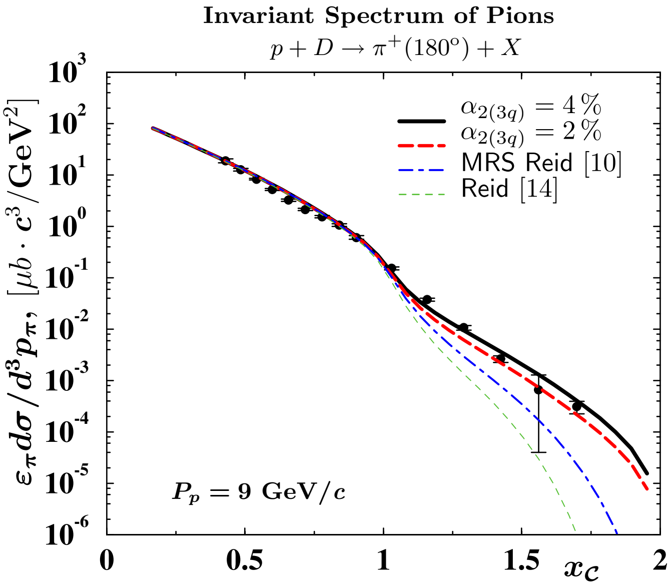

Fig. 1. The invariant pion spectrum calculated within the relativistic impulse approximation where non-nucleonic components in the DWF [1,9] have been included; its probability $\alpha_{2(3q)}$ is 0.02–0.04 (long-dashed and solid curves, respectively). One can have a good description of the data [13] for all $x_{\mathcal{C}}$.

Figure 1 presents the invariant pion spectrum calculated within the relativistic impulse approximation including the non-nucleonic component in the DWF [1,9]; its probability $\alpha_{2(3q)}$ is 0.02–0.04 (long-dashed and solid curves, respectively). One can see that the inclusion of the non-nucleonic degrees of freedom within the approach suggested in [1,9], the use of which has reproduced the data for the proton spectrum in the deuteron stripping, allows

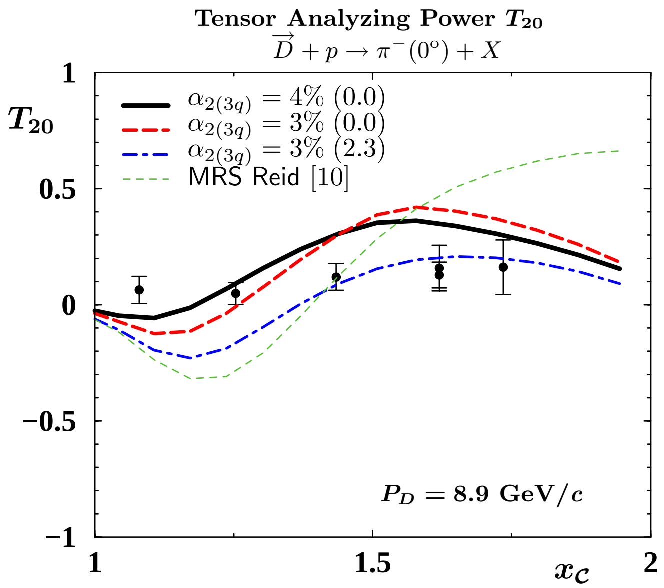

Fig. 2. The tensor analyzing power T_{20} calculated within the relativistic impulse approximation allowing for non-nucleonic components in the DWF. The solid and long-dashed lines represent the calculations with the mixing parameter $a = 0.0$ and the probability $\alpha_{2(3q)} = 4\,\%, 3\,\%$, respectively. 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 [14] obtained by the minimal relativistic scheme (MRS) [10].

us also to describe the inclusive pion spectrum at all values of x_C rather well (fig. 1). 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 impulse approximation. Therefore, the calculation of the tensor analyzing power including the non-nucleonic degrees of freedom in the 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. Actually, in [9] only a form of $\widetilde{\Phi}^{(u)}(|\boldsymbol{k}|)$ 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. (5). Introducing a mixing parameter $\alpha = \pi a/4$ one can find the following forms of new $\mathcal{S}$ and $\mathcal{D}$ waves

$$\widetilde{U}(|\boldsymbol{k}|) = \sqrt{1-\alpha_{2(3q)}}\,U(|\boldsymbol{k}|) + \cos(\alpha)\Delta(|\boldsymbol{k}|)\,, \tag{7}$$

$$\widetilde{W}(|\boldsymbol{k}|) = \sqrt{1-\alpha_{2(3q)}}\,W(|\boldsymbol{k}|) + \sin(\alpha)\Delta(|\boldsymbol{k}|)\,, \tag{8}$$

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

$$\widetilde{\Phi}^{(u)}(|\boldsymbol{k}|) = N_D^{-1}\frac{M_D^2}{m^2}\left[\widetilde{U}^2(|\boldsymbol{k}|) + \widetilde{W}^2(|\boldsymbol{k}|)\right]. \tag{9}$$

Figure 2 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 [1,9]. It is evident from fig. 2 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. (7), (8).

The main results can be summarized as follows. Very interesting experimental data on T_{20} [2] showing approximately zero values at $x_C \geq 1$ are not reproduced by a theoretical calculus using even different kinds of the relativistic DWF [4]. This may indicate the 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.

The inclusion of the non-nucleonic degrees of freedom within the approach suggested in [1,9] allows us to describe experimental data about the inclusive pion spectrum at all the values of x_C rather well, fig. 1, and improve the description of data [2] concerning the analyzing power T_{20} in the fragmentation of the deuteron into pions, fig. 2. 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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