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L.S.Azhgirey, N.P.Yudin[1]

TENSOR ANALYZING POWER OF NUCLEAR FRAGMENTATION OF RELATIVISTIC DEUTERONS WITH PROTON EMISSION AT NON-ZERO ANGLES

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[1]Moscow State University, Moscow, Russia

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1. Introduction

In the recent years considerable efforts have been undertaken to obtain a reliable information on the deuteron structure at small distances between nucleons. One of the important directions of such a search is the investigation of the spin polarization observables in reactions with relativistic polarized deuterons. Recently the results of the first measurements of the tensor analyzing power T_{20} of the reaction

$$d + p \rightarrow p + X \tag{1}$$

at initial momenta of deuterons 2.5, 3.5 and 9.1 GeV/c and zero angle of proton emission have been described [1, 2]. The complementary restrictions to the high-momentum part of the deuteron wave function outlined in these experiments have given rise to a lively discussions [3,4] and suggestions of new experiments [5].

In the same configuration (the directions of momenta of incident deuterons and detected protons were the same) a proton polarization in a rapidly moving deuteron have been measured [6,7]. A detailed investigation of spin observables in elastic $d-p$ scattering at a deuteron bombarding energy of 1.6 GeV with both polarized deuteron beam and polarized proton target has been described in ref. [8]. An exclusive study of the deuteron break-up with polarized protons and deuterons is now planned at COSY (Jülich) [9].

In this paper a tensor analyzing power of the reaction (1) with proton emission at non-zero angles is considered in the framework of the light front dynamics. The parameters T_{20} and T_{22} are calculated for the 9 GeV/c polarized deuterons with the deuteron wave functions corresponding to the Paris, Reid soft core, Bonn, and Moscow potentials of $N-N$ interactions.

The measurements of these analysing powers seem to be of interest as an independent of [1,2] method of probing the deuteron structure at small distances. A higher sensitivity to the small distances is due in this case to the fact that protons emitted at non-zero angles have large, from 0.5 to 1 GeV/c, transverse momenta.

2. Formulae for describing the tensor analyzing power of the reaction (1)

In our previous papers [10,11] the global features of proton spectra in the region of the transverse momenta of $0.5 - 1$ GeV/c, produced in the reaction (1) by unpolarized deuterons with the initial momentum of 9 GeV/c, were satisfactorily described taking into account only nucleon degrees of freedom by means of interfering sum of the three Feynman diagrams shown in fig. 1.

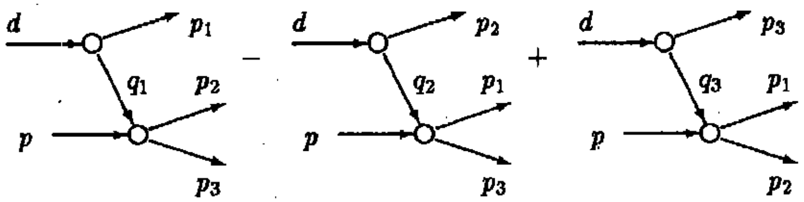

Fig. 1. Impulse approximation diagrams describing the fragmentation of deuterons on protons.

Here d is an incident deuteron, p is a target proton, p_1 is a proton detected, q_1, q_2, q_3 are virtual nucleons, and p_2, p_3 are nucleons. The letter labels also denote the corresponding four-momenta of particles taking part in the reaction, for example, $p_1 = (p_{10}, \mathbf{p}_{1T}, p_{13})$. In addition to the nucleons, one or some pions may produce in low vertex; as it was shown previously,

however, the contribution of such processes to the high-momentum part of the proton spectrum, being of matter of interest to us, is small [11]. The diagram (a) describes the detection of a proton emitted as a result of the deuteron direct fragmentation, and diagrams (b) and (c) correspond to the situation when the detected particle experiences an additional interaction.

The analysis of spin effects of mechanisms shown in fig. 1 will be carried out in the infinite momentum frame (IMF) as it was done in [10,11]. In IMF the vertex function of the break-up of a deuteron on nucleons $\mathcal{M}(d \to pn)$ divided by $l^2 - m_N^2$, where l is the four-momentum of the virtual nucleon, and m_N is the mass of a nucleon on the mass shell, is related to the deuteron wave function $\psi_M(\mathbf{k}, \mu_1, \mu_2)$ (in the same frame) as:

$$\left(\frac{\mathcal{M}(d \to pn)}{l^2 - m_N^2}\right) = \sum_{\mu_1\mu_2} R^\dagger_{m_1\mu_1}(\mathbf{k}_T) R^\dagger_{m_2\mu_2}(-\mathbf{k}_T) \frac{\psi_M(\mathbf{k}, \mu_1, \mu_2)}{1 - x}. \qquad (2)$$

Here $M, \mu_1, \mu_2, m_1, m_2$ are the deuteron and nucleon spin projections on the quantization axis, and $R^\dagger_{m\mu}(\mathbf{k}_T)$ is the Wigner rotation matrix corresponding to the Lorentz boost of nucleons from their rest frame to IMF. This matrix is the same [12] as the familiar Melosh matrix [13] arising in the mathematical apparatus of the light front dynamics,

$$R^\dagger_{m\mu}(\mathbf{k}_T) = \frac{m_N + \epsilon_\mathbf{k} + \mathbf{k}_3 - i\varepsilon_{rs}\mathbf{k}_{Ts}\sigma_r}{\sqrt{2(\epsilon_\mathbf{k} + m_N)(\epsilon_\mathbf{k} + \mathbf{k}_3)}}, \qquad (3)$$

where $\mathbf{k}_T$ is the transverse part of the momentum $\mathbf{k} = (\mathbf{k}_T, \mathbf{k}_3)$ of nucleons in their rest frame, $\epsilon_\mathbf{k} = \sqrt{m_N^2 + \mathbf{k}^2}$, σ_r is the Pauli matrix, ε_{rs} is the antisymmetric tensor ($r, s = 1, 2, \quad \varepsilon_{12} = -\varepsilon_{21} = 1$), $x = (\epsilon_k + \mathrm{k}_3)/(2\epsilon_k)$.

The wave function $\psi_M(\mathbf{k}, \mu_1, \mu_2)$ is normalized by the condition

$$\frac{1}{(2\pi)^3} \sum_{M\mu_1\mu_2} \int |\psi_M(\mathbf{k}, \mu_1, \mu_2)|^2 \frac{d\mathbf{k}}{\epsilon_k} = 1. \qquad (4)$$

In parameterization (2) of vertex $\mathcal{M}(d \to pn)$ in IMF there are isolated the trivial kinematical factors that are presented at the Lorentz boost in

IMF of non-interacting nucleons with momenta $\mathbf{k}$ and $-\mathbf{k}$ in their rest frame. In fact eq. (2) is a definition of the function $\psi_M(\mathbf{k},\mu_1,\mu_2)$.

The question of the form of the wave function $\psi_M(\mathbf{k},\mu_1,\mu_2)$ in IMF is a matter of principle. In the general case of the time instant dynamics the Lorentz boost operators depend on an interaction, and the relation of $\psi_M(\mathbf{k},\mu_1,\mu_2)$ with the usually used wave function of the deuteron at rest is very complicated. In this general case one should independently parameterize the function $\psi_M(\mathbf{k},\mu_1,\mu_2)$ in IMF [14] and, generally speaking, all great work on finding the deuteron wave function in IMF should be done over again. On the other hand, within the both time instant and light front dynamics there are models in which the wave function does not depend on the direction of the boost [12]. In these models

$$\psi_M(\mathbf{k},\mu_1,\mu_2) = \psi_M^{\rm rest}(\mathbf{k},\mu_1,\mu_2), \tag{5}$$

where $\psi_M^{\rm rest}(\mathbf{k},\mu_1,\mu_2)$ is the wave function of the deuteron in its rest frame. In the present paper eq. (5) is assumed to be true.

The analyzing power T_{kq} for the reaction (1) is defined by the usual relation [15] (the definition of the spin of a relativistic particle is given, for instance, in ref. [16]):

$$T_{kq} = \frac{\sum\int Sp\left(\mathcal{M}t_{kq}\mathcal{M}^\dagger\right)d\tau}{\sum\int Sp\left(\mathcal{M}\mathcal{M}^\dagger\right)d\tau}. \tag{6}$$

Here $\mathcal{M}$ is the total amplitude of the mechanisms shown in fig. 1, $d\tau$ is the phase space element over that the summation is taken (in the case of an inclusive description of the reaction), and t_{kq} are the k-rank spin-tensor operators for the initial state. These operators are related to the deuteron spin operator $\mathbf{S}$ by the standard relations, for instance,

$$t_{20} = \sqrt{\frac{1}{2}}\left(3S_z^2-2\right).$$

The calculation of T_{kq} will be carried out in the framework of mathematical techniques used in refs. [10,11] for finding the invariant inclusive momentum spectrum of protons emitted in the reaction (1); in fact it is the denominator of eq. (6). If one neglects the dependence of the $N-N$ interaction amplitude on the nucleon spins (this approximation seems to be reasonable in the momentum region under consideration, nearly $\sim 5\ GeV/c$), then from the formal point of view the numerator of eq. (6) is distinguished from the denominator by the following changes of the wave function combinations entered in the denominator:

$$\begin{aligned}
&\frac{1}{3}\sum_{M\mu_1\mu_2}\left|\psi_M(\mathbf{k},\mu_1,\mu_2)\right|^2 \Longrightarrow \\
&\quad\Longrightarrow \Sigma_{MM'\mu_1\mu_2kq}\,\psi_M(\mathbf{k},\mu_1,\mu_2)\,\rho^d_{kq} < M\left|t^i_{kq}\right|M' > \psi^*_{M'}(\mathbf{k},\mu_1,\mu_2),\\
&\frac{1}{3}\sum_{M\mu_1\mu_2}\psi_M(\mathbf{k},\mu_1,\mu_2)\psi^*_M(\mathbf{k},\mu_1,\mu_2) \Longrightarrow \\
&\quad\Longrightarrow \Sigma_{MM'\mu_1\mu_2kq}\,\psi_M(\mathbf{k},\mu_1,\mu_2)\,\rho_{kq} < M\left|t^i_{kq}\right|M' > \psi^*_{M'}(\mathbf{k},\mu_1,\mu_2),
\end{aligned} \tag{7}$$

where

$$\rho_{kq} = \frac{1}{3}Sp\left(\rho^d t^\dagger_{kq}\right),$$

and ρ^d is the deuteron spin density matrix. As a consequence the expression for the numerator of eq. (6) is obtained from the invariant differential cross section given in [11] by means of changes:

$$\begin{aligned}
&\frac{1}{4\pi}\left(u^2(\mathbf{k})+w^2(\mathbf{k})\right) \Longrightarrow \\
&\quad\Longrightarrow \sqrt{\tfrac{48\pi}{15}}Y_{2q}(\mathbf{k})\rho^d_{2q}\left(u(\mathbf{k})w(\mathbf{k})-\tfrac{1}{2\sqrt{2}}w^2(\mathbf{k})\right),\\
&\frac{1}{4\pi}\left(u(\mathbf{k})u(\mathbf{k}')+P_2(\xi)w(\mathbf{k})w(\mathbf{k}')\right) \Longrightarrow \\
&\quad\Longrightarrow \sqrt{3}\,\Sigma_{L,L'=0,2}\left\{\begin{matrix} L & 1 & 1\\ 1 & L' & 2\end{matrix}\right\}\rho^d_{2q}Y^{L,L'}_{2q}(\mathbf{k},\mathbf{k}')u_L(\mathbf{k})u_{L'}(\mathbf{k}'),
\end{aligned} \tag{8}$$

where

$$Y_{2q}^{L,L'}(\mathbf{k},\mathbf{k}') = \sum_{m,m'} < LmL'm'|\, kq > Y_{LM}(\mathbf{k})\, Y^{*}_{L'M'}(\mathbf{k}'), \qquad (9)$$

$$u_0(\mathbf{k}) = u(\mathbf{k}), \qquad u_2(\mathbf{k}) = w(\mathbf{k}),$$

$< LmL'm'|\, kq >$ are the Clebsh-Gordan coefficients, and $\left\{ \begin{array}{ccc} L & 1 & 1 \\ 1 & L' & 2 \end{array} \right\}$ are the Wigner $6j$-symbols.

It should be noted that for the mechanisms under consideration the terms in eq. (7), corresponding to the value of $k = 1$, vanish. Therefore the observation of non-zero values of the vector analyzing power when studying the fragmentation of polarized deuterons may be regarded as an evidence of the presence of other mechanisms.

The contribution of the interference of the amplitudes of the diagrams shown in fig. 1 is found similarly. As a result one can obtain the following expression for the tensor analyzing power T_{2q} taking into account the contributions of the direct fragmentation (diagram of fig. 1a) and hard scattering (diagrams of fig. 1b,c):

$$T_{2q}\left(\frac{p_{10}d\sigma}{d\mathbf{p}_1}\right)_0 = \qquad (10)$$
$$= \frac{2\sqrt{3}}{(2\pi)^3}\Big(F(x,\mathbf{p}_{1T})\frac{I(n,p)}{I(d,p)}\frac{1}{(1-x)^2}\sigma(np\to pX) +$$
$$+ \int F(y,\mathbf{q}_T)\frac{I(N,p)}{yI(d,p)}\frac{1}{y(1-y)}\frac{p_{10}d\sigma(Np\to p_1X)}{d\mathbf{p}_1}\,dy\,d\mathbf{q}_T +$$
$$+ (interference \quad term)\Big),$$

where

$$F(x,\mathbf{p}_{1T}) = \sqrt{\frac{4\pi}{5}}Y_{2q}(\hat{\mathbf{k}})\left(u(\mathbf{k})\,w(\mathbf{k}) - \frac{1}{2\sqrt{2}}w^2(\mathbf{k})\right),$$

$(p_{10}d\sigma/d\mathbf{p}_1)_0$ is the invariant differential cross section for the fragmentation of unpolarized deuterons, $I(n,p), I(d,p)$ are the invariant fluxes of the colliding particles, x and y have the meaning of fractions of the longitudinal deuteron momentum taking away in IMF by a spectator and the second fragment, respectively, and $\hat{\mathbf{k}}$ is the unit vector in the direction of the nucleon momentum $(x,\mathbf{k}_T)$ in the deuteron rest frame. The relation between the momentum $\mathbf{k}$ and the detected proton momentum $\mathbf{p}_1$ in the light front dynamics, where the deuteron is considered as a wave packet of two free nucleons, is determined on the basis of the expressions

$$x = \frac{p_{10}+p_{13}}{d_0+d_3} = \frac{k_0+k_3}{2k_0}, \quad \mathbf{p}_{1T} = \mathbf{k}_T, \quad x+y=1, \qquad (11)$$

with the result that

$$k_0^2 = \mathbf{k}^2 + m_N^2 = \frac{m_N^2+\mathbf{k}_T^2}{4x(1-x)}.$$

The explicit expression for the $(interference \quad term)$ is too cumbersome to be given here; its contribution to the value of T_{2q} does not exceed some percents.

Spin ensembles characteristic of polarized deuteron beams are usually symmetric about the magnetic field axis in an ion source, and after the acceleration of the beam to the necessary energy this symmetry about some quantization axis is retained. To be more definite, we shall carry out the subsequent consideration in the coordinate frame xyz with z axis along the incident deuteron beam $\mathbf{d}$ and y axis along the normal to the reaction plane $[\mathbf{d}\times\mathbf{p}_1]$. Given the symmetry mentioned, the most general expression for the invariant differential cross section of the reaction with the polarized deuteron beam has the form [15]:

$$\frac{p_{10}d\sigma}{d\mathbf{p}_1} = \tag{12}$$

$$= \left(\frac{p_{10}d\sigma}{d\mathbf{p}_1}\right)_0 \Big[1 + \sqrt{2}\rho_{10} iT_{11}(\theta)\sin\beta\sin\phi + \frac{1}{2}\rho_{20}T_{20}(\theta)(3\cos^2\beta - 1) +$$

$$+\sqrt{6}\rho_{20}T_{21}(\theta)\sin\beta\cos\beta\sin\phi - \sqrt{\frac{3}{2}}\rho_{20}T_{22}(\theta)\sin^2\beta\cos 2\phi\Big],$$

where the direction of the quantization axis $\hat{\mathbf{s}}$ is specified by the angle β which it makes with the z axis and by the azimuthal angle ϕ measured between x axis and the vector $[\hat{\mathbf{s}} \times \mathbf{d}]$. The parameters ρ_{10} and ρ_{20} define respectively the vector and tensor polarizations of the beam in the coordinate frame where the quantization axis coincides with the symmetry axis. As it has been already noted, $iT_{11} = 0$ for the considered here mechanisms of the reaction (1). If furthermore one assumes the quantization axis to coincide with the y axis, then $\beta = \pi/2$, and

$$\frac{p_{10}d\sigma}{d\mathbf{p}_1} = \left(\frac{p_{10}d\sigma}{d\mathbf{p}_1}\right)_0 \left[1 - \rho_{20}\left(\frac{1}{2}T_{20} + \sqrt{\frac{3}{2}}T_{22}\right)\right]. \tag{13}$$

The combination of the entering in eq. (13) analyzing powers T_{20} and T_{22} is denoted sometimes with

$$A_{yy} = -\sqrt{2}\left[\frac{1}{2}T_{20} + \sqrt{\frac{3}{2}}T_{22}\right].$$

If the quantization axis is directed along x axis then the differential cross section of the interaction of the polarized deuterons depends only on T_{20}.

3. Calculation results

The dependences of the tensor analyzing powers T_{20} and T_{22} for the reaction (1) on the detected proton momenta, calculated for the initial deuteron momentum of 9 GeV/c and proton emission angle of 139 $mrad$,

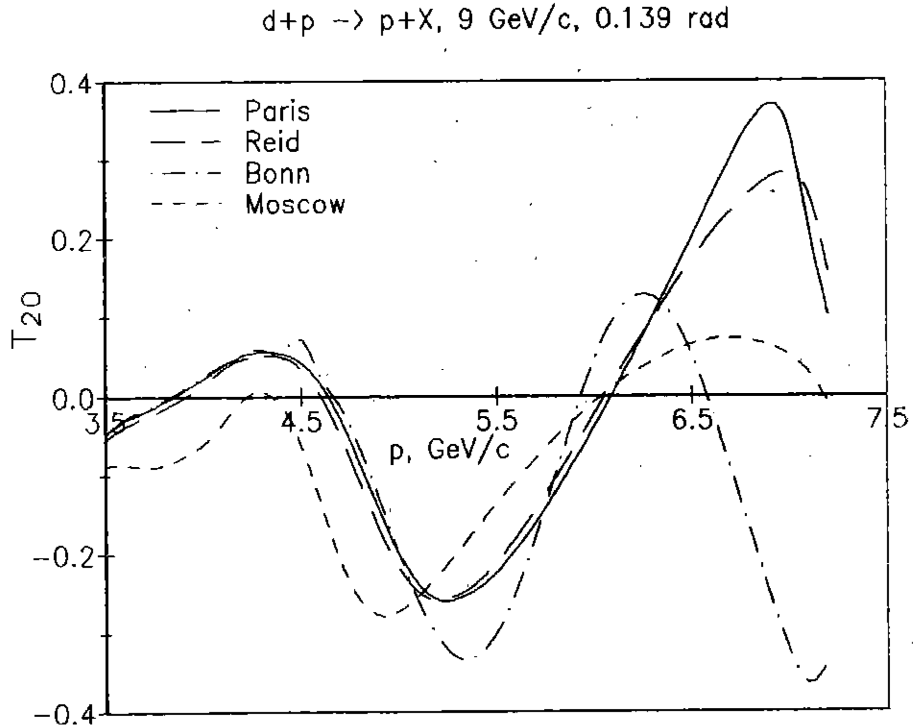

Fig. 2. Tensor analyzing power T_{20} of the reaction $dp \rightarrow pX$ for the 9 GeV/c polarized deuterons and proton emission angle of 139 $mrad$ versus momentum of the detected proton, calculated for the deuteron wave functions corresponding to the Paris [17] (solid curve), Reid soft core [18] (long dash curve), Bonn [19] (dot dash curve), and Moscow [20] (short dash curve) potentials of $N-N$ scattering.

are shown in figs. 2 and 3, respectively. The calculations have been carried out with the deuteron wave functions corresponding to the Paris [17], (solid curves), Reid soft core [18] (long dash curves), Bonn with relativistic momentum space [19] (dot dash curves), and Moscow [20] (short dash curves) potentials of $N-N$ interactions.

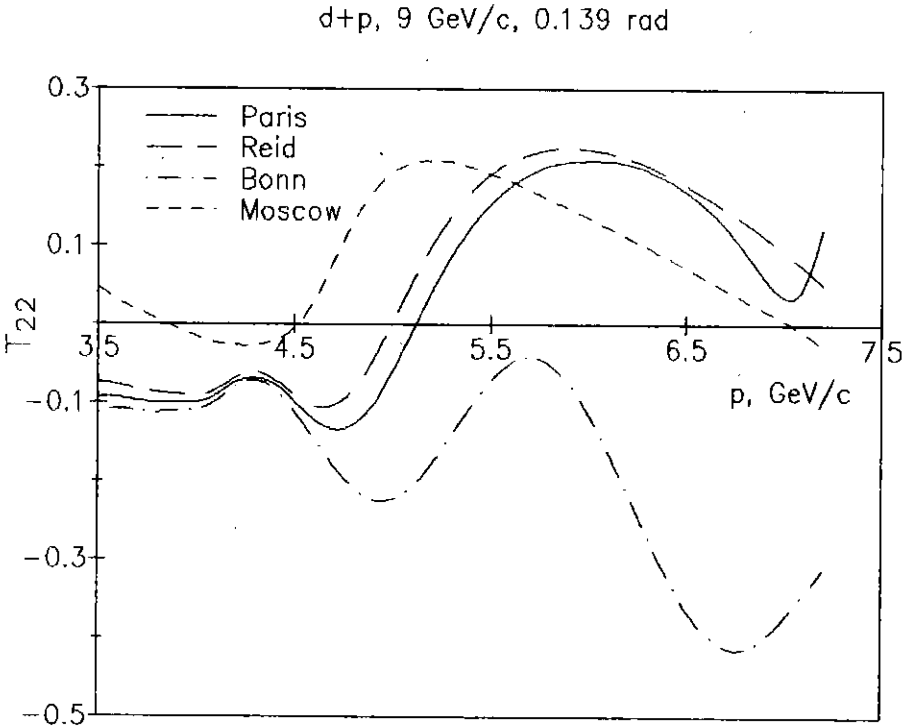

Fig. 3. Same as in fig. 2, but for the tensor analyzing power T_{22}.

As it is the case, when protons emitted at 0°, the dependences of the tensor analyzing powers on the emitted proton momentum are oscillating in behaviour. First it attracts attention that the predictions for the Paris and Reid soft core potentials are close, but they considerably distinguish from results for the Bonn and Moscow potentials that, in their turn, distinguish between themselves. The second observation is that the measurement of the parameter T_{22} seems to be more preferable than the measurement of parameter T_{20} for a choice between different wave functions because in this

case the predictions for the different wave functions begin already to differ at comparatively small detected proton momenta where the differential cross section of the deuteron fragmentation is yet comparatively large.

For the tensor analysing power T_{20} the region of negative values is contained between approximately 4.5 and 6 GeV/c; the minimal value calculated is ~ -0.3. At proton momenta exceeding 6 GeV/c the value of T_{20} turns positive. In this region there are considerable distinctions between the calculation results with the wave functions for the different potentials: for the Bonn potential the value of T_{20} again changes the sign quickly and turns negative whereas for the other potentials it remains positive over a region of approximately 1 GeV/c.

The tensor analysing power T_{22} calculated with the deuteron wave function for the Bonn potential is negative over all the momentum interval considered. For the other potentials the value of T_{22} turns positive at 4.5–5 GeV/c and does not change the sign further reaching the maximal value of ~ 0.2 at 5.2 GeV/c for the Moscow potential, and approximately at 6 GeV/c for the Reid and Paris potential.

Thus, the measurements of the tensor analyzing powers T_{20} and T_{22}, or their combination A_{yy}, for the reaction (1) with the proton emission at non-zero angles are of great interest since, first, they would serve as an independent check of the somewhat unexpected behaviour of T_{20} at 0° [1,2], second, they may give new information on the deuteron wave function at the small distances.

In connection with the design of an experiment on measuring the tensor analysing power of the reaction (1) with 9 GeV/c polarized deuteron beam and secondary protons emitted with large transverse momenta, the calculations on the basis of the techniques developed have been carried out

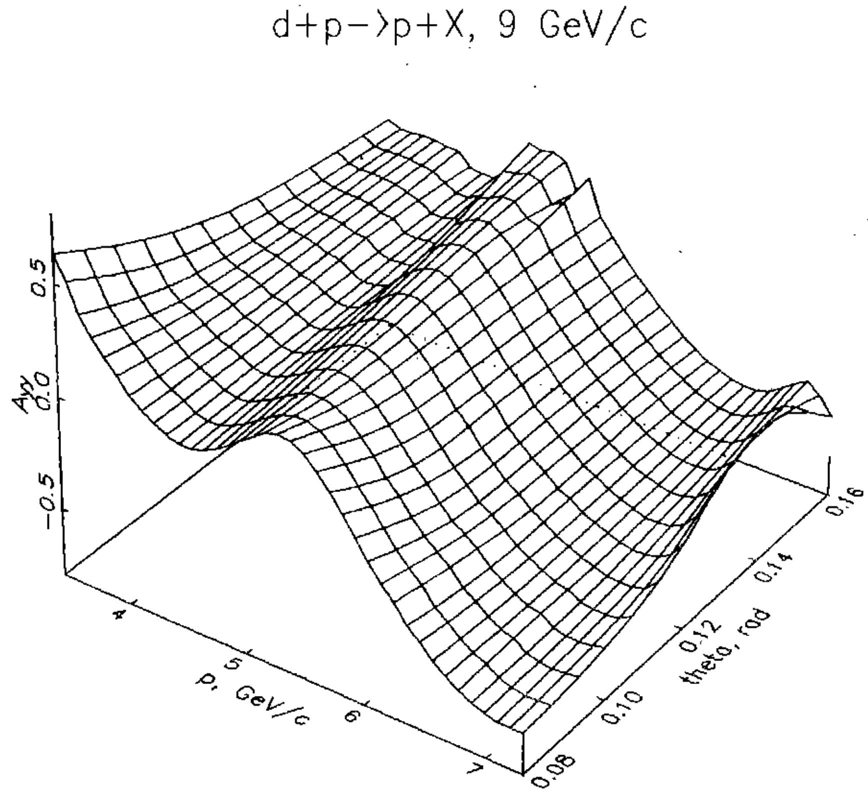

Fig. 4. Tensor analyzing power A_{yy} of the reaction $dp \rightarrow pX$ for the 9 GeV/c polarized deuterons versus momentum p and emission angle θ of detected protons. The deuteron wave function for the Paris potential was used.

for the proton detection angles in the region from 80 to 160 *mrad*. The results of calculations of the parameter A_{yy} with the deuteron wave function for the Paris potential are shown in fig. 4. It is seen that over the all angular interval considered the behaviour of A_{yy} on the detected proton momentum p changes inessential, mainly on kinematical grounds.

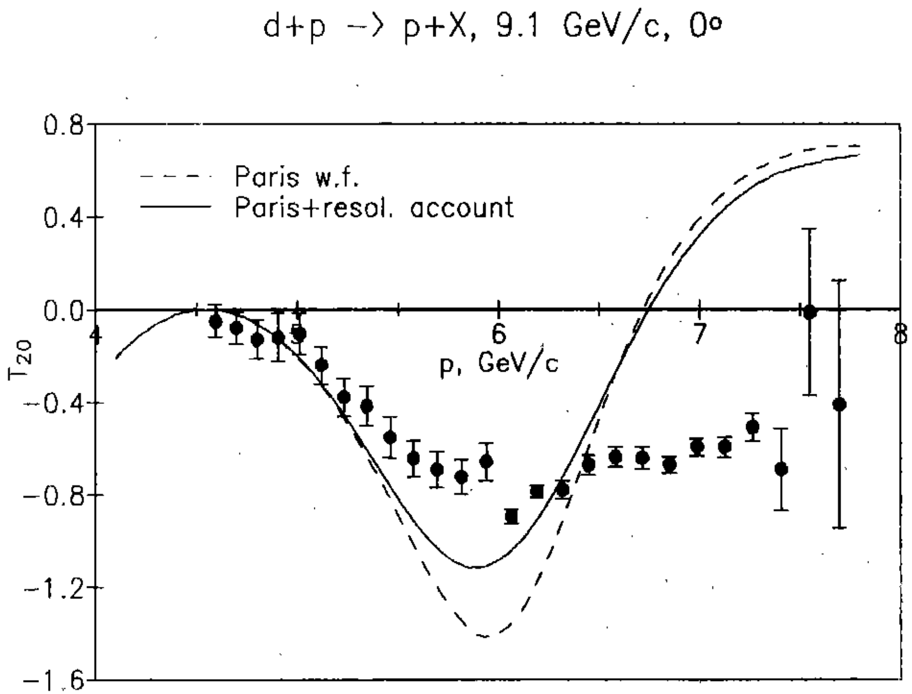

Fig. 5. Tensor analyzing power T_{20} of the reaction $dp \rightarrow pX$ for the 9.1 GeV/c polarized deuterons and proton emission angle of 0° versus momentum of detected proton. The experimental data are taken from ref. [2]. The curves are calculated for the Paris deuteron wave function without reference to (dash curve) and with allowance for (solid curve) the angular and momentum acceptances of the experimental setup.

In the conclusion of this item a methodical property of experiments on measuring the analyzing power should be noted. The differential cross section of the reaction (1) decreases quickly as the momentum of the proton detected grows. To make up for this decrease, the momentum and angular acceptances of an experimental setup have to be increased. This results in that the extremal values of a tensor analyzing power can not be reached in real measurements with finite angular and momentum resolutions. This effect is illustrated for the parameter T_{20} in fig. 5.

In this figure the experimental data on the parameter T_{20} for the reaction (1) at initial deuteron momentum of 9.1 GeV/c and zero angle of proton emission [2] are compared with the calculations made without reference to (dash curve) and with allowance for (solid curve) the angular and momentum acceptances of the experimental setup. In the calculations the deuteron wave function for the Paris potential was used. As the angular and momentum resolutions were used the values $\Delta\theta = 0,017$ and $\Delta p/p = 0,07$ given in ref. [2]. It is seen that the account of the finite setup resolution allowed the experimental data to be better described in the region of the minimum of the dependence $T_{20}(p)$. At proton momenta more than 6.5 GeV/c, however, there remains the substantial discrepancy that should still be explained.

4. Conclusion

In this paper the formulae for calculating the tensor analyzing powers T_{20} and T_{22} of the reaction of fragmentation of relativistic deuterons on protons with the proton emission at non-zero angles have been derived in the framework of the light front dynamics in the relativistic momentum approximation. The wave function of a moving deuteron (in fact in the infinite momentum frame) has been supposed to be connected to the wave function of a resting deuteron purely kinematically. The calculations of the parameters T_{20} and T_{22} for the fragmentation of the polarized deuterons with the momentum of 9 GeV/c have been carried out with the deuteron wave functions corresponding to the Paris, Reid soft core, Bonn,

and Moscow potentials of $N-N$ scattering. The regions of the momenta of secondary protons are indicated where the predictions for these potentials are substantially different. An experimental investigation of the tensor analyzing powers of the deuteron fragmentation with the emission of protons with large transverse momenta can serve, first, as a test of the approach developed, second, to obtain new information about the deuteron structure at small distances.

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