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MEASUREMENT OF TENSOR ANALYZING POWER OF THE 5-GeV/c DEUTERON BREAKUP ON ^{9}Be WITH THE PROTON EMISSION AT 180 mr

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The tensor analyzing power A_{yy} of the ^{9}Be(d,p)X reaction at an initial deuteron momentum of 5 GeV/c and a proton detection angle of 180 mr has been measured at the JINR Synchrophasotron. The preliminary data obtained are compared with the relativistic calculations made within the framework of the light-front dynamics. With Karmanov's relativistic deuteron wave function we have managed to explain the new data without invoking degrees of freedom additional to nucleon ones.

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1 Introduction

The experiments with the polarized deuteron beams conducted in Saclay [1-4] and Dubna [5-10] have led one to recognize that an usual description of the deuteron by means of a non-relativistic wave function does not work at short distances between nucleons. The discrepancies between theory and experiment are most conspicuous in the following facts.

First, the experimental dependence of the analyzing power T_{20} of the A(d,p)X reaction on k — internal momentum of nucleons in the deuteron — does not change the sign at $k \sim 0.5$ GeV/c. Further, T_{20} data for the pion-free deuteron breakup process dp $\rightarrow$ ppn in the kinematical region close to that of backward elastic dp-scattering depends on the incident momentum in addition to k [10]. This forces one to suggest that description of this quantity requires an additional independent variable, aside from k. At last, the recent measurements of the tensor analyzing power A_{yy} of inclusive breakup of relativistic deuterons on nuclei at large transverse momenta of emitted protons [11, 12] have demonstrated significant dependence of the A_{yy} parameter on the transverse secondary proton momentum p_T being plotted at a fixed value of the longitudinal proton momentum.

Of course, the features mentioned above can be due to several factors. For instance, one of them can be the use of a rather simple pole mechanism to explain the experimental data. However, there are serious reasons to think that this simple mechanism works quite well for

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processes of this kind. For instance, recently it has been shown [13] that the main peculiarities of the experimental data on the tensor analyzing power of the nuclear fragmentation of relativistic deuterons with the emission of protons with large transversal momenta can be explained within the framework of a simple pole mechanism in the light-front dynamics [14] with the use of the relativistic deuteron wave function obtained in ref. [15].

This result, in our opinion, is due to the fact that in Karmanov's approach [15–17] a new relation between the transverse and longitudinal components of the momentum of the internal motion of nucleons in the deuteron is established. This relation differs from that dictated by the superposition of the S and D waves in non-relativistic wave functions of the deuteron. The new function depends on two momenta — longitudinal and transverse ones. In the non-relativistic limit these components are folded into a module of the momentum and a non-relativistic function depends only on one nontrivial variable.

It follows from [13] that in the fragmentation process the relativistic effects become significant very rapidly, and these effects can be taken into account in the most simple way through the use of the light-front dynamics without accounting any additional degrees of freedom. It turns out rather unexpectedly that up to small relative distances corresponding to the internal momenta of nucleons $k \sim 0.5 - 0.8$ GeV/c the deuteron can be considered as a two-nucleon system in the light form of quantum mechanics. A similar conclusion was drawn in connection with the measurements of the momentum spectra of protons emitted as a result of fragmentation of 9 GeV/c deuterons in the region of proton transverse momenta of 0.5 — 1 GeV/c [18].

Thus, investigation of polarization properties of the deuteron fragmentation reaction, (d,p), seems to remain one of currently central problems of relativistic hadron physics. In this paper we present new results on tensor analyzing power A_{yy} of the inclusive deuteron breakup reaction on a beryllium target, ^{9}Be(d,p)X, at an initial deuteron momentum of 5 GeV/c and a secondary proton emission angle of ~ 180 mr in the laboratory system. The results obtained are compared with the calculation within the framework of light-front dynamics using different deuteron wave functions.

2 Experiment

The measurements have been made at a polarized deuteron beam of the JINR Synchrophasotron using the SPHERE setup described elsewhere [12]. A slowly extracted beam of tensor polarized 5-GeV/c deuterons with an intensity of $5 \cdot 10^8$ particles per beam spill with a duration of 0.5 s hit a beryllium target 16 cm thick. The beam intensity was monitored by an ionization chamber and two scintillation counter telescopes.

The polarized deuterons were produced by the ion source POLARIS [19]. The spin quantization axis was perpendicular to the plane containing the mean beam orbit in the accelerator. The sign of the beam polarization changed cyclically from spill to spill.

The tensor polarization of the beam was determined from the asymmetry of protons with a momentum of $p_p \sim \frac{2}{3}p_d$ emitted at 0° in the A(d,p)X reaction [20]. The tensor polarization was $p^+_{zz} = 0.716 \pm 0.043$ and $p^-_{zz} = -0.756 \pm 0.027$ for positive and negative polarization directions, respectively. Results of the measurement of the tensor component of the deuteron beam polarization are shown in Fig. 1.

The vector polarization of the beam was monitored during the experiment by measuring the

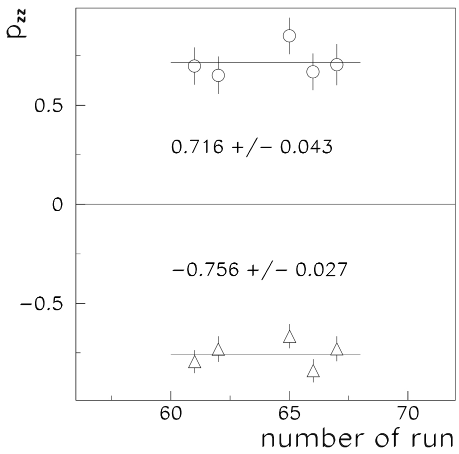

Fig. 1. Tensor polarization of the deuteron beam in the experiment.

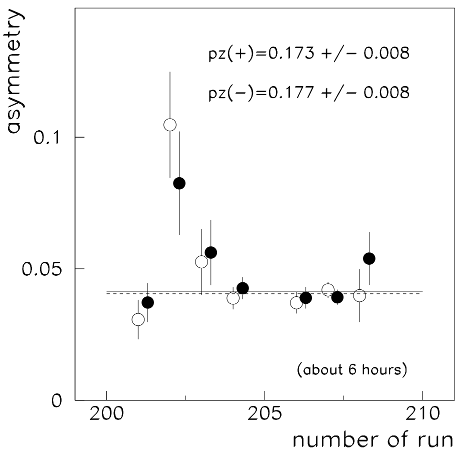

Fig. 2. Vector polarization of the deuteron beam during the experiment.

asymmetry of quasi-elastic pp-scattering on a thin CH_2 target placed in the beam. The values of the vector polarization were determined using the results of the asymmetry measurements at a momentum of 2.5 GeV/c per nucleon and a proton scattering angle of 14°. The corresponding value of the effective analyzing power of the polarimeter $A(CH_2)$ was taken as 0.234 [21]. The vector polarization of the beam in different spin states was $p_z^+ = 0.173 \pm 0.008$ and $p_z^- = 0.177 \pm 0.008$. The results of monitoring vector component of the deuteron beam polarization are shown in Fig. 2. The spread of points about mean values is due to statistical reasons.

The data were obtained for four momenta of secondary particles: 2.7, 3.0, 3.3, and 3.6 GeV/c. This momentum range corresponds to the range of transverse momenta between 0.49 and 0.65 GeV/c. The secondary particles emitted at $\sim$ 180 mr from the target were transported to the detection system by means of magnetic elements of the SPHERE setup.

The particles detected at a given momentum were indentified off-line on the basis of two independent time-of-flight (TOF) measurements with a base line of $\sim$ 28 m. The TOF resolution was better than 0.2 ns (1σ). The background from inelastically scattered deuterons was almost negligible at 2.7 GeV/c and increased with the momentum of secondaries. Useful events were selected as the ones with two measured TOF values correlated. This allowed one to rule out the residual background completely. The correlations of TOF measurements for four momenta are shown in Fig. 3.

The tensor analyzing power A_{yy} was calculated from the numbers of protons $n^+,\ n^-$, and n^0, detected for different states of beam polarization, normalized to the corresponding beam intensities, and corrected for the dead time effect [22], according to the expression

$$A_{yy} = 2 \cdot \frac{p_z^- \cdot (n^+/n^0 - 1) - p_z^+ \cdot (n^-/n^0 - 1)}{p_z^- p_{zz+} - p_z^+ p_{zz}^-}. \tag{1}$$

The values of tensor analyzing power A_{yy} obtained in the experiment are shown in Fig. 4.

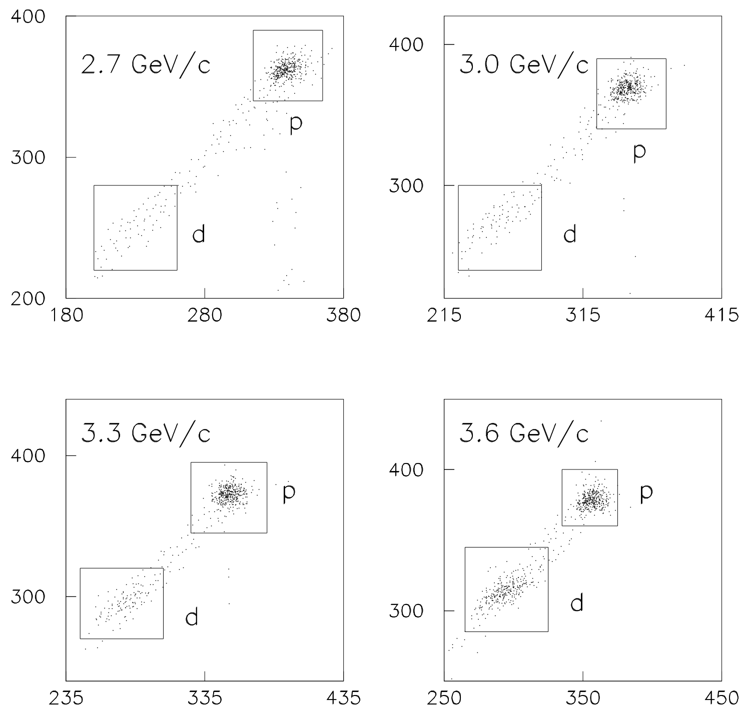

Fig. 3. Correlations between two independent TOF measurements for four momentum values shown in the figure. Relative readings of time-to-digit converters are shown along axes.

3 Elements of theory

The expressions to calculate tensor analyzing power of the A(d,p)X reaction, based on the light-front dynamics formalism, have been derived in [13], and different aspects of this approach are discussed in that paper. However, short consideration of the points related to the analysis of the new data seems to be appropriate here.

The analyzing power $T_{\kappa q}$ of the (d,p) reaction is given by the expression

$$T_{\kappa q} = \frac{\int d\tau \, Sp\{\mathcal{M} \cdot t_{\kappa q} \cdot \mathcal{M}^{\dagger}\}}{\int d\tau \, Sp\{\mathcal{M} \cdot \mathcal{M}^{\dagger}\}}, \tag{2}$$

where $d\tau$ is the phase volume element, $\mathcal{M}$ is the reaction amplitude, and the operator t_{2q} is defined by

$$< m \,|\, t_{\kappa q} \,|\, m' >= (-1)^{1-m} < 1 \, m \, 1 \; - m' \,|\, \kappa \, q >,$$

with the Clebsh-Gordan coefficients $< 1 \, m \, 1 \; - m' \,|\, \kappa \, q >$.

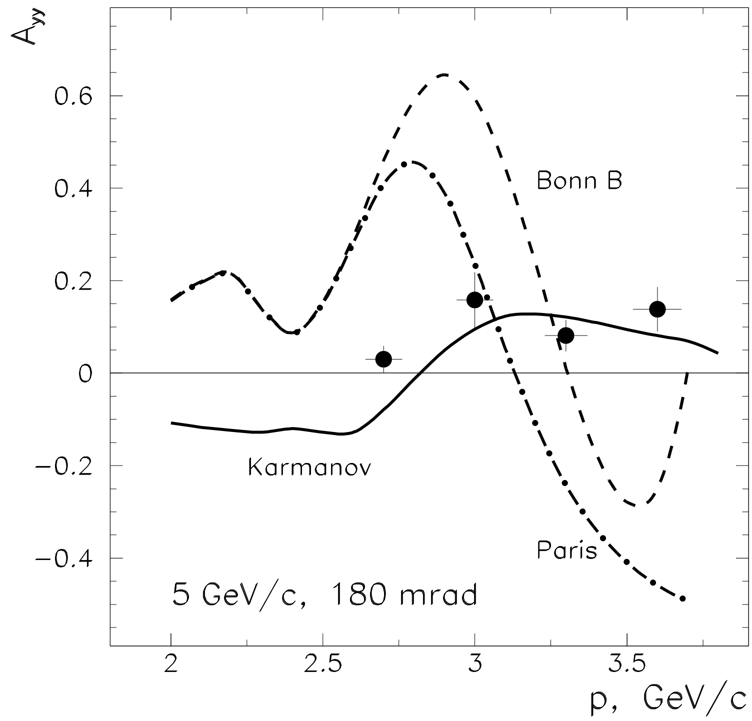

Fig. 4. Parameter A_{yy} of the reaction ^{9}Be(d,p)X at an initial deuteron momentum of 5 GeV/c and a proton emission angle of 180 mr as a function of the detected proton momentum. The calculations were made with the deuteron wave functions for the Bonn B [25] (dashed curve) and Paris [24] (dash-dotted curve) potentials. The solid curve was calculated with Karmanov's relativistic deuteron wave function [15].

The amplitude for the reaction ^{1}H(d,p)X in the light-front dynamics is

$$\mathcal{M}_a = \frac{\mathcal{M}(d \to p_1 b)}{(1-x)(M_d^2 - M^2(k))}\mathcal{M}(bp \to p_2 X), \tag{3}$$

where $\mathcal{M}(d \to p_1 b)$ is the amplitude of the deuteron breakup on a proton-spectator p_1 and an off-shell particle b, and $\mathcal{M}(bp \to p_2 X)$ is the amplitude of the reaction bp $\to$ p_2X. The ratio

$$\psi(x, p_{1T}) = \frac{\mathcal{M}(d \to p_1 b)}{(M_d^2 - M^2(k))} \tag{4}$$

is nothing but the wave function in the channel $(b,\, N)$; here p_{1T} is the component of the momentum p_1 transverse to the z axis, and $M^2(k)$ is given by

$$M^2(k) = \frac{m^2 + p_{1T}^2}{x} + \frac{b^2 + p_{1T}^2}{1-x}, \tag{5}$$

where b^2 is the four-momentum squared of the off-shell particle b.

The relativistic deuteron wave function in the light-front dynamics was found in ref. [15]. It is determined by six invariant functions $f_1, ..., f_6$ instead of two ones in the non-relativistic case, each of them depending on two scalar variables k and $z = cos(\widehat{\mathbf{kn}})$ and has the following form:

$$\begin{aligned} \psi(\mathbf{k},\,\mathbf{n}) \quad &= \quad \frac{1}{\sqrt{2}}\sigma f_1 + \frac{1}{2}\left[\frac{3}{k^2}\mathbf{k}(\mathbf{k}\cdot\sigma) - \sigma\right] f_2 + \frac{1}{2}\left[3\mathbf{n}(\mathbf{n}\cdot\sigma) - \sigma\right] f_3 + \frac{1}{2k}[3\mathbf{k}(\mathbf{n}\cdot\sigma) \\ &+ \quad 3\mathbf{n}(\mathbf{k}\cdot\sigma) - 2\sigma(\mathbf{k}\cdot\mathbf{n})]f_4 + \sqrt{\frac{3}{2}}\frac{i}{k}[\mathbf{k}\times\mathbf{n}]f_5 + \frac{\sqrt{3}}{2k}[[\mathbf{k}\times\mathbf{n}]\times\sigma]f_6, \end{aligned} \tag{6}$$

where $\mathbf{k}$ is the momentum of nucleons in deuteron in their rest frame, $\mathbf{n}$ is the unit normal to the light front surface, and σ are the Pauli matrices. Here

$$k = \sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{4x(1-x)} - m_p^2}, \quad (\mathbf{n}\cdot\mathbf{k}) = (\frac{1}{2} - x)\cdot\sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{x(1-x)}}, \tag{7}$$

where x is the fraction of the deuteron longitudinal momentum taken away by the proton in the infinite momentum frame. We assume that $\mathbf{n}$ is directed opposite to the beam direction, i.e. $\mathbf{n} = (0,\ 0,\ -1)$.

The final expressions for the tensor analyzing power of the (d,p) reaction are rather cumbersome, and they are given in ref. [13].

4 Comparison between theory and experiment

To calculate the tensor analyzing power we need know the invariant differential cross sections $p_{10}d\sigma(bp \to p_2X)/d\mathbf{p}_1$ of processes taking place in the low vertex of the pole diagram. Moreover, it should be taken into account that the particle b is off the mass shell. To take this fact into account, the analytic continuations of $d\sigma(s', t')/dt'$ parameterizations to values $s',\ t'$ defined in the low vertex of the pole diagram at $b^2 \neq m^2$ were used in the calculations. The contributions of processes pp $\to$ pp, np $\to$ pn, Np $\to$ pΔ, Np $\to$ pNπ (up to values of the invariant mass of the Nπ system of 1.5 GeV/c^2) in the low vertex of the pole diagram have been taken into account according to the parameterizations given in ref. [23].

The results of the calculations of the tensor analyzing power A_{yy} of the reaction ^{9}Be(d,p)X at an initial deuteron momentum of 5 GeV/c and a proton emission angle of 180 mr are compared with the experimental data in Fig. 4. It is seen that the experimental data are rather well reproduced with Karmanov's relativistic deuteron wave function as opposed to the calculations with the standard deuteron wave functions [24, 25]; in the latter case curves change sign at the proton momentum $\sim$ 3.2 GeV/c.

The major contributions to the breakup mechanism is made by the stripping and elastic pp-scattering processes, the stripping dominating at p larger than 2.8 GeV/c. As to different terms of $f_i(k, z)$, the two first terms f_1 and f_2 of Eq. (6) give the dominating contribution to the $A_{yy}(p)$ dependence in the proton momentum region investigated, the remaining terms give only corrections. The role of these corrections increases with the proton momentum, and measurements of A_{yy} in the momentum region above 3.6 GeV/c would be of considerable interest to clarify the relative role of the different invariant functions f_i.

Finally we touch the question why the difference between the predictions and the data for T_{20} in the elastic ed scattering is much smaller than in the elastic dp and deuteron breakup reactions when they are considered in the impulse approximation. Of course, this difference is concerned with the failure of the impulse approximation for hadron reactions with accelerated deuterons. The key advantage of the approach used by us is, in our opinion, going to the infinite momentum frame with the result that the deuteron wave function depends now on an additional nontrivial variable; this allows complementary mechanisms to be effectively taken into account.

5 Conclusions

The following conclusions may be drawn from this investigation.

New experimental data on the tensor analyzing power A_{yy} of the ^{9}Be(d,p)X reaction at an initial deuteron momentum of 5 GeV/c and a proton emission angle of 180 mr are obtained.

The calculation of the tensor analyzing power of the (d,p) reaction within the framework of light-front dynamics using Karmanov's relativistic deuteron wave function is in good agreement with the new experimental data whereas the calculations with the standard non-relativistic deuteron wave functions are in sharp contradiction with the data.

New data favour the view of ref. [13] that the relation between the k_L and $\mathbf{k}_T$ in the moving deuteron differs essentially from that in the non-relativistic case. The method of relativization proposed by Karmanov et al. [15] appear to reflect correctly this relation, at least up to $p_T \sim 0.7$ GeV/c.

It turns out rather unexpectedly that up to small relative distances corresponding to the internal momenta of nucleons $k \sim 0.5 - 0.8$ GeV/c the deuteron can be considered as a two-nucleon system in the light form of quantum mechanics, as was noted in ref. [18].

In the fragmentation process the relativistic effects become significant very rapidly, and these effects can be taken into account in the most simple way through the use of the light-front dynamics.

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