INVESTIGATION OF THE ANGULAR DEPENDENCE OF THE TENSOR ANALYZING POWER OF 9 GEV/C DEUTERON BREAKUP


(1) Joint Institute for Nuclear Researches, 141980 Dubna, Russia
(2) St.-Petersburg State University, 198350 St.-Petersburg, Russia
(3) Institute of Nuclear Research and Nuclear Energy, 1784 Sofia, Bulgaria
(4) Russian Scientific Center "Kurchatov Institute", 123182 Moscow, Russia
(5) Moscow State University, 117234 Moscow, Russia

† E-mail: azhgirey@jinr.ru

Abstract

An angular dependence of the tensor analyzing power of the breakup of polarized deuterons at 9 GeV/c has been investigated. The measurements have been made on hydrogen and carbon targets at angles in the range from 85 to 160 mr. The data obtained are analyzed within the framework of the light-front dynamics using the deuteron wave functions for Paris and Bonn CD potentials, and the relativistic deuteron wave function by Karmanov et al. The experimental data are in rough agreement with calculations with the use of Karmanov’s deuteron wave function.

1. Introduction

Investigations of polarization properties of the deuteron fragmentation reaction \((d, p)\) have amassed a convincing body of evidence that the description of the deuteron structure by means of wave functions derived from non-relativistic functions through the kinematical transformation of variables is liable to break down at short distances between nucleons. The main discrepancies between the expected and observed behaviour of data manifest themselves in the following facts.

(i) The expression for the tensor analyzing power \(T_{20}\) of deuteron breakup, \(A(d, p)X\), in the impulse approximation (IA) has the form \(T_{20} \sim w(k)[\sqrt{8}u(k) - w(k)]\), where \(u(k)\) and \(w(k)\) are the deuteron momentum space wave functions for \(S\) and \(D\) states, respectively, and \(k\) is the internal momentum of the nucleons in the deuteron (defined in the light-front system). With standard deuteron wave functions, the \(T_{20}\) dependence on \(k\) can be expected to change the sign at \(k \sim 0.5\) GeV/c, but this expectation lacks support from experiment [1].

(ii) The recent measurements of the tensor analyzing power \(A_{yy}\) of the breakup of relativistic deuterons on nuclei at non-zero angles of emitted protons [2, 3] show that the measured \(A_{yy}\)-values at fixed value of the longitudinal proton momentum have the dependence on the transverse proton momentum that differs from that calculated with standard deuteron wave functions.

(iii) The above-mentioned data show that the values of \(A_{yy}\) being plotted at fixed values of \(k\) tend to decrease as the variable \((\mathbf{n} \cdot \mathbf{k})\) grows (vector \(\mathbf{n}\) is the unit normal to
the surface of the light front).

(iv) The pion-free deuteron breakup process $dp \rightarrow ppm$ in the kinematical region close to that of backward elastic $dp$ scattering at a given value of $k$ depends on the incident momentum of deuteron [4].

The foregoing forces one to suggest that an additional variable is required to depict the deuteron structure function at short distances, where relativistic effects are significant.

One approach that gives a relativistic description of the deuteron is light-front dynamics, one of several forms of Hamiltonian dynamics, first discussed by Dirac [5]. Each form of dynamics is associated with a hypersurface on which the commutation relations for the generators of the Poincaré group are defined. There are many desirable features of the light-front dynamics [6].

(i) High-energy experiments are naturally described using light-front coordinates: the fraction of the longitudinal momentum of the bound state taken away by the constituent particle in the infinite momentum frame is simply the ratio of the the plus momentum of the constituent to the total plus momentum of the bound state.

(ii) There is a clean separation between center-of-momentum (internal) and relative (external) momentum variables in the light-front dynamics.

(iii) The vacuum for a theory with massive particles can be very simple on the light front: the vacuum with $p^+ = 0$ is empty, and diagrams that couple to this vacuum are zero.

(iv) The generators of boosts in one, two, and plus directions are kinematic, meaning they are independent of the interaction. Thus, even when the Hamiltonian is truncated, the wave functions will transform correctly under boosts.

These attractive features have led to the possibility that light-front dynamics is the best approach for calculating the spectrum and wave functions of relativistic composite system from an underlying field theory, such as quantum chromodynamics.

In previous papers [7] the global features of proton spectra in the region of transverse momenta of $0.5 - 1 \text{ GeV/c}$, produced in the reaction $(d,p)$ by unpolarized deuterons with an initial momentum of $9 \text{ GeV/c}$, were satisfactorily described on the basis of the pole diagrams within the framework of the light-front dynamics. In those calculations the light-front deuteron wave function was connected with the non-relativistic deuteron wave function in a simple way, by the kinematical transition from the equal-time variables to the light-front variables. However, attempts to describe the tensor analyzing power $A_{yy}$ of the reaction $^{12}\text{C}(d,p)X$ at an incident deuteron momentum of $9 \text{ GeV/c}$ and a proton emission angle of $85 \text{ mr}$ within the same approach have not met with the success [3]. The simple kinematical transition from a non-relativistic deuteron wave function to the light-front one [8] presumably does not take into account essential features of the spin structure of a relativistic deuteron.

The relativistic deuteron wave function in the light front dynamics was found in ref. [9]. 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 $z = \cos(\hat{\mathbf{n}} \cdot \mathbf{k})$. The quantities $\mathbf{k}$ (the momentum of nucleons in the deuteron in their rest frame) and $\mathbf{n}$ (the unit normal to the light front surface) are defined by

$$x = \frac{E_p + p_{pl}}{E_d + p_d}, \quad k = \sqrt{\frac{m_p^2 + p_T^2}{4x(1-x)} - m_p^2}, \quad (\mathbf{n} \cdot \mathbf{k}) = \left(1 - x\right) \cdot \sqrt{\frac{m_p^2 + p_T^2}{x(1-x)}}.$$ (1)
where $E_d$ and $p_d$ are the energy and the momentum of the incoming deuteron, respectively, $p_{pl}$ is the longitudinal component of $p_1$, and $m_p$ is the mass of the nucleon. It will be assumed further that $\mathbf{n}$ is directed opposite to the beam direction, i.e. $\mathbf{n} = (0, \ 0, \ -1)$.

The expressions for the tensor analyzing power of the $(d, p)$ reaction using the above function are given in ref. [10].

Within the framework of this approach the following results on the description of the tensor analyzing power of the reaction $A(d, p)X$ have been obtained previously.

(i) It was shown [11] that calculations with Karmanov’s deuteron wave function are in reasonably good agreement with the experimental data on the $T_{20}$ parameter of deuteron breakup on $H$ and $C$ targets with the emission of protons at $0^\circ$ in the $k$ region from $0.4$ to $0.8$ GeV/c.

(ii) A qualitative description of the momentum behaviour of the $A_{yy}$ parameter of the $^9Be(d, p)X$ reaction at a deuteron momentum of $4.5$ GeV/c and a detected proton angle of $80$ mr [2] was obtained [10].

(iii) Rather good description of the $A_{yy}$ data for the $^{12}C(d, p)X$ reaction at $9$ GeV/c and $85$ mr [3] was achieved [10].

(iv) The experimental data on the tensor analyzing power $A_{yy}$ of the reaction $^9Be(d, p)X$ at an initial deuteron momentum of $5$ GeV/c and a proton emission angle of $178$ mr are rather well reproduced with Karmanov’s relativistic deuteron wave function as opposed to the calculations with the standard deuteron wave functions [12].

To get a more comprehensive picture of the angular behaviour of the tensor analyzing power of the deuteron breakup reaction, the $A_{yy}$ parameter in the interactions of polarized deuterons with hydrogen and carbon at $9$ GeV/c has been measured. The measurements have been made on hydrogen and carbon targets at angles in the range from $85$ to $160$ mr.

2. Experiment

The measurements have been made at a polarized deuteron beam of the JINR Synchrophasotron using the SPHERE setup described elsewhere [3]. The polarized deuterons were produced by the ion source POLARIS [13].

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 $0^\circ$ in the $A(d, p)X$ reaction [14], and it was $p_{zz}^+ = 0.798 \pm 0.002(stat) \pm 0.040(syst)$ and $p_{zz}^- = -0.803 \pm 0.002(stat) \pm 0.040(syst)$ for positive and negative polarization directions, respectively. The vector polarization of the beam was monitored during the experiment by measuring the asymmetry of quasi-elastic $pp$-scattering on a thin $CH_2$ target placed in the beam [15], and it values in different spin states were $p_z^+ = 0.231 \pm 0.014(stat) \pm 0.012(syst)$ and $p_z^- = 0.242 \pm 0.014(stat) \pm 0.012(syst)$.

A slowly extracted beam of tensor polarized $9$-GeV/c deuterons with an intensity of $\sim 5 \cdot 10^8 \div 10^9$ particles per beam spill with a duration of $0.5$ s fell on a liquid hydrogen target of $30$ cm length or on carbon targets with varied length. The beam intensity was monitored by an ionization chamber. The beam positions and profiles at certain points of the beam line were monitored by the control system of the accelerator during each spill. The beam size at the target point was $\sigma_x \sim 0.4$ cm and $\sigma_y \sim 0.9$ cm in the horizontal and vertical directions, respectively.

The data were obtained at secondary particle emission angles of $85$, $130$ and $160$ mr (two measurements were made at $115$ and $145$ mr), and secondary momenta between $4.5$
and 9 GeV/c. Along with the secondary protons, the apparatus detected the deuterons from inelastic scattering. The particles detected at given momentum were identified off-line on the basis of two independent time-of-flight (TOF) measurements with a base line of $\sim 34$ m. The TOF resolution was better than 0.2 ns (1$\sigma$). Useful events were selected as the ones with two measured TOF values correlated. This allowed one to rule out the residual background completely. The values of the tensor analyzing power $A_{yy}$ obtained in the experiment are shown in Figs. 2, 3. The reported error bars are statistical only; possible systematic errors are estimated to be $\sim 5\%$.

The acceptance of the setup was determined by means of Monte Carlo simulation; the momentum and polar angle acceptances were $\Delta p/p \sim \pm 2\%$ and $\pm 8$ mr, respectively.

3. Formalism

The mechanism of the deuteron fragmentation $(d, p)$ can be represented by the Feynman diagrams shown in Fig. 1. Here $d$ is the incoming deuteron, $p$ is the target proton, $p_1$ is the detected proton, $b$ is the virtual (off-shell) nucleon, and $p_2, p_3$ are nucleons. In addition to nucleons, one or more pions may be produced at low vertices. Diagram (a) corresponds to the case where the detected proton results from deuteron stripping, and at the low vertex elastic $np$ scattering takes place. In diagrams (b) and (c) the low vertices correspond to the charge exchange $np$ and elastic $pp$ scatterings, respectively.

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

$$T_{eq} = \frac{\int d\tau Sp\{M \cdot t_{eq} \cdot M^\dagger\}}{\int d\tau Sp\{M \cdot M^\dagger\}},$$

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

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

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

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

$$M_a = \frac{M(d \rightarrow p_1b)}{(1 - x)(M_2^2 - M^2(k))} M(bp \rightarrow p_2p_3),$$

where $M(d \rightarrow p_1b)$ is the amplitude of the deuteron breakup on a proton-spectator $p_1$ and an off-shell particle $b$, and $M(bp \rightarrow p_2p_3)$ is the amplitude of the reaction $bp \rightarrow p_2p_3$ (in the case of diagram (a), and with evident replacements of indices for diagrams (b) and (c)).

![Feynman diagrams](image-url)

Fig. 1. Feynman diagrams describing fragmentation of deuterons on protons.
The ratio
\[ \psi(x, p_{1T}) = \frac{M(d \rightarrow p_1 b)}{M_2^2 - M_2^2(k)} \]
is the wave function in the channel \((b, N)\) given in [9]; here \(p_{1T}\) is the component of the momentum \(p_1\) transverse to the \(z\) axis. The light-front variables \(p_T \equiv p_{1T}\) and \(x\) (the fraction of the deuteron longitudinal momentum taken away by the proton in the infinite momentum frame) are given above. The quantity \(M_2^2(k)\) is given by
\[ M_2^2(k) = m^2 + p_{1T}^2 + b^2 + p_{1T}^2 \frac{x}{1-x}, \]
where \(b^2\) is the four-momentum squared of the off-shell particle \(b\).

The final expressions for the tensor analyzing power of the \((d, p)\) reaction are given in ref. [10].

4. Results and discussion
It should be emphasized that the problem has no adjusted parameters. The invariant differential cross sections of processes taking place in the low vertices of the pole diagrams of Fig. 1, on the one hand, and the values of the invariant functions \(f_1, \ldots, f_6\) taken from ref. [9], on the other, were taken as input data. The contributions of the elastic and inelastic processes in the low vertex of the pole diagram were taken into account according to the parameterizations given in ref. [18]. To account for the off-shell nature of particle \(b\), the analytic continuations of the cross section parameterizations to the values of invariant variables \(s' = (b + p)^2, \quad t' = (b - p_1)^2\) defined in the low vertex of the pole diagram at \(b^2 \neq m^2\) were used in the calculations. To obtain the values of functions \(f_i(k, z)\) required for calculations, the spline-interpolation procedure between the table values given in ref. [9] was used.

The experimental data on the tensor analyzing power \(A_{yy}\) of the reactions \(^1\)\(H(d, p)X\) and \(^{12}\)\(C(d, p)X\) at an initial deuteron momentum of 9 GeV/\(c\) and proton emission angles of 85, 130 and 160 mr are compared with the calculation results in Fig. 2. The data obtained on hydrogen and carbon targets are shown with empty and full circles, respectively. Above all it should be pointed out that data for both targets agree. By this is meant that nuclear targets are also appropriate to obtain information on the deuteron structure, as indicated before [7]. The previous data obtained at 9 GeV/\(c\) on carbon at a proton emission angle of 85 mr [3] are shown with full triangles.

It is seen that the experimental data at an angle of 85 mr are rather well reproduced with Karmanov’s relativistic deuteron wave function as opposed to the calculations with the standard deuteron wave functions [16, 17]. The data at angles of 130 and 160 mr are only in rough agreement with calculations using Karmanov’s deuteron wave function, and, as before, they are in contradiction with calculations using standard deuteron wave functions.

The dependences of the analyzing power \(A_{yy}\) on the transverse momentum of the protons \(p_T\) at fixed values of total proton momenta \(p\) close to 4.5, 5.0, 5.5, 6.0, 6.5, and 7.0 GeV/\(c\) are shown in Fig. 3. These values of the total momentum of protons correspond to their longitudinal momentum fractions \(x = 0.503, 0.558, 0.614, 0.670, 0.724, \) and 0.791. It may be noted that the dependence of \(A_{yy}\) on \(p_T\) in the range of \(p_T\) between 0.4 and 0.9 GeV/\(c\) investigated in the present experiment is considerably more flat than
in the range of $p_T$ from 0 to 0.6 GeV/c as it was found in ref. [2]. It is seen as well that $p_T$-behaviour of $A_{yy}$ counts in favour of Karmanov’s relativistic deuteron wave function and definitely contradicts the predictions based on Paris and Bonn CD deuteron wave functions particularly at $p = 4.5, 5.0, 6.5,$ and $7.0$ GeV/c.

Fig.2. Parameter $A_{yy}$ of the reactions $^1H(d,p)X$ (empty circles) $^{12}C(d,p)X$ (full circles) at an initial deuteron momentum of 9 GeV/c and proton emission angles of 85, 130 and 160 mr as a function of the detected proton momentum. The data obtained in ref. [3] are shown with full triangles. The calculations were made with the deuteron wave functions for the Paris [16] (dashed curves) and Bonn CD [17] (dash-dotted curves) potentials. The solid curves were calculated with Karmanov’s relativistic deuteron wave function [9].

5. Conclusion
The results of this work can be summarized as follows.

(i) The tensor analyzing power $A_{yy}$ of the reactions $^1H(d,p)X$ and $^{12}C(d,p)X$ has been measured at an initial deuteron momentum of 9 GeV/c and proton emission angles of 85, 115, 130, 145 and 160 mr in the laboratory. The range of measurements corresponds to transverse proton momenta between 0.4 and 0.9 GeV/c.

(ii) The $A_{yy}$ data from the present experiment at 85 mr are in good agreement with the data obtained earlier [3].

(iii) The $A_{yy}$ data demonstrate an approximate independence on the A-value of the target, as it was pointed previously [12].

(iv) The proton momentum dependences of $A_{yy}$ at the fixed values of proton emission angles and the transverse proton momentum dependences of $A_{yy}$ at the fixed values of longitudinal proton momentum fractions are in a better agreement with calculations using Karmanov’s relativistic deuteron wave function instead of standard non-relativistic deuteron wave functions. While a quantitative description is not always achieved, the results obtained favours the description of the relativistic deuteron structure with a function depending on more than one variable.

(v) Additional measurements of $A_{yy}$ and other polarization observables at different initial deuteron momenta and various $p_T$ and $x$ are strongly desirable to provide the necessary
Fig. 3. Parameter $A_y$ of the reactions $^1H(d, p)X$ (empty circles) $^{12}C(d, p)X$ (full circles) at an initial deuteron momentum of 9 GeV/c and proton emission momenta of 4.5, 5.0, 5.5 (left panel) and 6.0, 6.5, 7.0 GeV/c (right panel) as a function of the transverse proton momentum $p_T$. The data obtained in ref. [3] are shown with full triangles. The calculations were made with the deuteron wave functions for the Paris [16] (dashed curves) and Bonn CD [17] (dash-dotted curves) potentials, and with the relativistic deuteron wave function [9] (solid curves).

experimental base to develop relativistic models describing the short-range structure of deuteron.

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