Tensor analyzing power $A_{yy}$ in deuteron inclusive breakup on hydrogen and carbon at 9 GeV/$c$ and large proton transverse momenta

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Abstract

The tensor analyzing power $A_{yy}$ in inclusive breakup of 9.0 GeV/$c$ deuterons on hydrogen and carbon has been measured at different emission angles of protons. The data are compared to calculations within the framework of light-front dynamics by using different deuteron wave functions. The results suggest that the relativistic deuteron structure may depend on more than one independent variable.

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1. Introduction

Deuteron structure investigations are considered to be an important ground to test models of nucleon–nucleon interactions. The static properties of the
deuteron, such as binding energy, radius, quadrupole, magnetic and electric moments, seem to be well studied, but the dynamics of this nucleus is much less understood. The knowledge of the high momentum component of deuteron wave function (DWF) puts a strong constraint on the nucleon–nucleon interaction. One of the central goals of these investigations is to determine when a transition from a traditional meson–nucleon picture to quark–gluon degrees of freedom occurs in the description of a nuclear reaction. In this respect, polarization observables in the high-energy processes are especially reliable because they are sensitive to the details of the deuteron internal structure at short internucleonic distances.

Recent measurements of the tensor polarization $T_{20}$ for the ed elastic scattering [1] performed at JLab can be reproduced quite well at $Q^2 \lesssim 1.7$ (GeV/c)$^2$ by the covariant relativistic model [2] without contribution of non-nucleonic degrees of freedom. The perturbative QCD (pQCD) predictions [3] are not reliable for these momentum transfers. The cross section of high energy two-body photodisintegration of the deuteron, $\gamma d \rightarrow pn$, at large angles in the cms [4] has shown the scaling behavior up to 5.5 GeV predicted by pQCD constituent-counting-rules [5]. On the other hand, recent measurements of the proton polarization [6] at energies up to 2.4 GeV are also consistent with the pQCD hadron helicity conservation prediction [7], but not the polarization transfers obtained in the same experiment.

Breakup of relativistic deuterons on nuclei, $A(d, p)X$, is a traditional tool to investigate the internal deuteron structure at short distances between the constituents. The tensor analyzing power $T_{20}$ in deuteron breakup with proton emission at zero angle, has been measured recently up to internal momenta $k \sim 1$ GeV/c [8–11] defined in the light-cone dynamics [12]. The data have demonstrated their weak dependence on the initial energy and as well as on the $A$-value of the target, i.e., the features of relativistic impulse approximation (RIA). On the other hand, $T_{20}$ does not reach $-\sqrt{2}$ at $k \sim 300$ MeV/c and has a large negative value of $\sim-0.3$ at high internal momenta of the proton [10,11] in contradiction with the calculations performed in the framework of RIA by using DWFs based on reasonable nucleon–nucleon potentials. Including additional mechanisms next to RIA [13] allows one to obtain a better agreement with the $T_{20}$ data, however, it does not describe the data over the whole range of measurements. The model [14] which incorporates Pauli principle at the quark level and multiple scattering, reproduces qualitatively the behavior of $T_{20}$ in deuteron breakup at a zero angle only with the DWF based on the Nijmegen nucleon–nucleon potential [15]. Different relativistic models [16–18] with dependence of the deuteron internal structure on one variable have also failed to reproduce the data on the tensor analyzing power $T_{20}$ [10,11].

On the other hand, pion-free deuteron breakup process $dp \rightarrow ppn$ in the kinematical region close to that of backward elastic $dp$ scattering at a given value of $k$, also depends on the incident momentum of deuteron [19]. This makes one suggest that an additional variable is required to describe such a dependence.

Recent measurements of the tensor analyzing power $A_{yy}$ in deuteron breakup on nuclear targets at large transverse momenta of protons at 9 GeV/c [20], 4.5 GeV/c [21] and 5.0 GeV/c [22], have shown a significant variation of $A_{yy}$ versus the transverse proton momentum at a fixed value of the longitudinal proton momentum. This finding also indicates that the deuteron structure may depend on two variables. We have also found a significant deviation of the experimental data from the predictions based on a relativistic hard scattering model [23,24], using the standard DWFs. On the other hand, the behavior of $A_{yy}$ data at 5.0 GeV/c [22] has been explained within the light-cone dynamics model of Karmanov’s relativistic DWF depending on two internal variables [2] without invoking degrees of freedom additional to the nucleon ones [25].

In this Letter we present new results on the angular dependence of the tensor analyzing power $A_{yy}$ in the deuteron inclusive breakup reaction on hydrogen and carbon at 9.0 GeV/c initial deuteron momentum, up to transverse momenta of proton $\sim0.9$ GeV/c. These results are compared with the calculations within the framework of light-front dynamics by using different DWFs.

2. Experiment

The experiment has been performed with a polarized deuteron beam at the Dubna Synchrophasotron
and the SPHERE setup described elsewhere [20,21]. The details of the experiment are given in [21]. Below the main features of the experimental procedure are briefly described.

The polarized deuterons were produced by the ion source POLARIS [26]. The sign of the beam polarization was changed cyclically and spill-by-spill as “0”, “−”, “+”, where “0” means the absence of polarization, “+” and “−” correspond to the sign of $p_{zz}$ with the quantization axis perpendicular to the plane containing the mean beam orbit in the accelerator.

The tensor polarization of the beam was periodically measured during the experiment from the $A(d, p)X$ reaction at a zero emission angle and a proton momentum of $p_p \approx \frac{2}{3}p_d$ [27] using the same setup. The tensor polarization corrected for the dead time effect [28] and averaged over the whole duration of the experiment, was $p_{zz}^+ = 0.798 \pm 0.002$ (stat) $\pm 0.040$ (sys) and $p_{zz}^- = -0.803 \pm 0.002$ (stat) $\pm 0.040$ (sys) in “+” and “−” beam spin states, respectively.

The vector polarization of the beam was measured from the asymmetry of quasi-elastic $pp$-scattering on a thin CH$_2$ target placed 20 m upstream the setup [29,30]. The vector polarization was obtained using the results of asymmetry measurements at a momentum of 4.5 GeV/c per nucleon and a 8° proton scattering angle assuming a value of the effective analyzing power of the polarimeter $A(CH_2)$ to be equal to 0.123 $\pm$ 0.006 [30]. The vector polarization of the beam in different spin states was $p_{z}^+ = 0.275 \pm 0.016$ (stat) $\pm 0.014$ (sys) and $p_{z}^- = 0.287 \pm 0.016$ (stat) $\pm 0.014$ (sys), respectively.

A slowly extracted deuteron beam with a typical intensity of $\sim 5 \times 10^8$–$10^9$ d/spill was directed onto a liquid hydrogen target 30 cm long or onto carbon targets with a varying length. The beam intensity was monitored by the ionization chamber placed in front of the target. The beam positions and profiles at certain points of the beam line were monitored 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.

Most of the data were obtained at secondary proton emission angles of 85, 130 and 160 mrad and proton momenta between 4.5 and 7.0 GeV/c on hydrogen and carbon. Separation of the protons and inelastically scattered deuterons was achieved by the measurements of their time-of-flight (TOF) over a base line of $\sim 34$ m. The TOF resolution was better than 0.2 ns (1σ), and allowed one to eliminate the background completely by the requirement that particles would be detected at least in two prompt TOF windows.

The acceptance of the setup was determined via Monte Carlo simulation taking into account the parameters of the incident deuteron beam, nuclear interaction and multiple scattering in the target, in the air, windows and detectors, energy losses of primary and secondary particles, etc. The momentum and polar angle acceptances of the setup were (FWHM) $\Delta p/p \sim \pm 2\%$ and $\pm 8$ mrad, respectively.

The tensor $A_{yy}$ and vector $A_y$ analyzing powers were 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 [28]. The calculations were carried out by using the following expressions:

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

$$A_y = -\frac{2}{3} \frac{p_{zz}^-(n^+/n^0 - 1) - p_{zz}^+(n^-/n^0 - 1)}{p_{zz}^- p_{zz}^+ - p_{zz}^- p_{zz}^+}.$$  (1)

These expressions take into account different values of polarization in different beam spin states, and are simplified significantly when $p_{zz}^\pm = p_{zz}$ and $p_{zz}^\pm = -p_{zz}^\pm$. The systematic errors due to uncertainty of the beam polarization measurements, were $\sim 5\%$, both—for the tensor and vector analyzing powers.

3. Results

The results for the tensor analyzing power $A_{yy}$ in deuteron breakup obtained at 9 GeV/c and 85, 130 and 160 mrad proton emission angles at the laboratory, are plotted in Fig. 1(a), (b) and (c), respectively, as a function of the proton momentum. The data obtained on the hydrogen and carbon targets are shown by the filled and open circles, respectively. The data for the both targets agree within the experimental accuracy. Hence, the multiple scattering is small and carbon is also appropriate to obtain information on the deuteron spin structure at short distances. This confirms earlier findings for the
Fig. 1. Tensor analyzing power $A_{yy}$ in deuteron inclusive breakup obtained at 9 GeV/$c$ and 85, 130 and 160 mr of the proton emission angle at the laboratory are plotted (a), (b) and (c) panels, respectively, as a function of the proton momentum. The data from the present experiment obtained on the hydrogen and carbon targets are shown by the filled and open circles, respectively. The previous data on carbon [20] are shown by the open squares. The solid, dashed and dash-dotted curves are the results of the calculations [24,25] using Karmanov’s [2], CD-Bonn [31] and Paris [32] DWFs, respectively.

Data on the tensor analyzing power at $0^\circ$ [8,10,11], that the systematic difference on hydrogen and carbon targets does not exceed $\sim 20\%$. New data at 85 mr are in a good agreement with the data from the previous experiment [20] shown by the open squares.

The curves in Fig. 1 are the predictions made in the framework of the relativistic hard scattering model [23,24] based on the light-front dynamics mechanism, using different DWFs. In this model the main contribution to deuteron breakup comes from the direct fragmentation and hard scattering of the deuteron nucleon on the target nucleon.

In the light-cone dynamics [12] the internal nucleon momentum $k$ in the deuteron is related to the transverse and longitudinal momenta of protons as follows:

\begin{equation}
    k^2 = \frac{m_p^2 + P_T^2}{4\alpha(1-\alpha)} - m_p^2.
\end{equation}

Here $m_p$ and $P_T$ are the mass and transverse momentum of the detected proton. The variable $\alpha$ is the longitudinal momentum fraction taken away by the proton [12]

\begin{equation}
    \alpha = \frac{E_p + p_\parallel}{E_d + P_\parallel},
\end{equation}

where $E_p$ and $p_\parallel$ are the energy and longitudinal momentum of the detected proton; $E_d$ and $P_\parallel$ are the energy and momentum of the incident deuteron, respectively.

The dashed and dash-dotted curves in Fig. 2 are the results obtained using DWFs based on the Charge Dependent (CD)-Bonn [31] and Paris [32] nucleon–

Fig. 2. $A_{yy}$ data plotted versus transverse momentum $p_T$ at four different fixed longitudinal momentum fractions $\alpha \sim 0.61, 0.67, 0.72$ and 0.78, are shown in (a), (b), (c) and (d) panels, respectively. The filled and open circles are the data of the present experiment obtained on hydrogen and carbon, respectively. The open triangles and squares are the data obtained in the previous experiments on carbon at a zero angle [9–11] and 85 mr [20], respectively. The open crosses and diamonds are the data on beryllium at 4.5 GeV/$c$ [21] and 5 GeV/$c$ [22], respectively. The curves are the same as in Fig. 1.
is determined by six invariant functions $f_1, \ldots, f_6$ in-
stead of the two in the non-relativistic case. In the non-
relativistic limit only two functions remain: $f_1$ and
$f_2$, corresponding to the usual $S$- and $D$-waves in the
deuteron. Each of the invariant functions $f_1, \ldots, f_6$
depends on two variables $k$ and $\cos \chi = (\vec{n} \cdot \vec{k})/|\vec{k}|$, where
the internal momentum $k$ is defined above (2), and

\[
(\vec{n} \cdot \vec{k}) = \sqrt{\frac{m_p^2 + p_T^2}{\alpha(1 - \alpha)}} \left( \frac{1}{2} - \alpha \right).
\]

Here the vector $\vec{n}$ is the unit vector normal to the sur-
face of the light front directed opposite to the beam
direction, i.e., $\vec{n} = (0, 0, -1)$. To obtain the values of function $f_i(k, \cos \chi)$ required for calculations, a
spline-interpolation procedure was used between the
tabulated values given in Ref. [2]. The details of the
calculations can be found in Ref. [25].

It is seen that the experimental data at an angle of
85 mr are rather well reproduced with Karmanov’s
DWF, while the data at angles of 130 and 160 mr
are only in a qualitative agreement with these pre-
dictions. The calculations reproduce the behavior of
$A_{yy}$ at the proton momenta near 4.5 GeV/$c$, however,
these calculations predict the sign of $A_{yy}$ opposite to
the one observed in the experiment at larger momenta.
A significant variation of $A_{yy}$ at a fixed proton mo-
mentum, with the detection angle can be seen in Fig. 1.
Note, that a negative sign of $A_{yy}$ in deuteron inclusive
breakup at large proton momenta is observed for the
first time in this experiment.

The $A_{yy}$ data from the present experiment can be
compared with the results of previous experiments per-
formed at different energies in terms of internal vari-
ables describing the internal structure of the deuteron.
The $A_{yy}$ data plotted versus the transverse momentum
of the proton at values of the longitudinal momentum
fraction $\alpha \sim 0.61, 0.67, 0.72$ and 0.78 are shown in
Fig. 2(a), (b), (c) and (d), respectively. The data from
the present experiment for hydrogen and carbon are
shown by the filled and open circles, respectively. The
open triangles represent the $A_{yy}$ values obtained by
the weighted averaging of the data from different ex-
periments performed at 9 GeV/$c$ and at zero angle of
the proton [9–11], while the open squares, crosses and
diamonds correspond to the data obtained at non-zero
angles at the initial deuteron momenta of 9 GeV/$c$
[20], 4.5 GeV/$c$ [21] and 5 GeV/$c$ [22], respectively.
The good consistency of the data obtained at different
energies has demonstrated that a possible energy de-
pendence of the $A_{yy}$ is weak at the same values of $\alpha$
and $p_T$ due to different contribution of the direct frag-
mentation and hard scattering of the deuteron nucleon
on the target nucleon, as well as the energy depend-
ence of the nucleon–nucleon scattering amplitude.

It is seen that the $A_{yy}$ data for different longitudinal
momentum fractions $\alpha$ are strongly dependent of
the transverse momentum of the protons, $p_T$. Values of
$A_{yy}$ are positive at small $p_T$ and monotonously de-
crease while transverse momentum increasing for all \(\alpha\) values.

This behavior definitely contradicts the predictions of the RHS model [24] using CD-Bonn [31] and Paris
[32] DWFs shown in Fig. 2 by the dashed and dash-
dotted lines, respectively. The RHS calculations pre-
dict positive values of $A_{yy}$ at small $p_T$ and a change of
the $A_{yy}$ sign when the transverse momentum increas-
ing at $\alpha \sim 0.61, 0.67$ and 0.72 (see, Fig. 2(a), (b)
and (c), respectively).

The $p_T$ value at which $A_{yy}$ is zero, depends on the
longitudinal momentum fraction $\alpha$. The corresponding
$p_T$ value decreases while $\alpha$ increasing. For in-
stance, $A_{yy}$ calculated by using Paris DWF [32], over-
laps zero at $p_T \sim 600, 400$ and 200 MeV/$c$ for $\alpha$
values of 0.61, 0.67 and 0.72, respectively. At the highest
value of $\alpha \sim 0.78$ (see Fig. 2(d)) the RHS calculations
produce a negative value of $A_{yy}$, while the experimen-
tal data have positive values.

The results of the calculations within RHS model
[25] by using the Karmanov’s DWF [2] are given in
Fig. 2 by the solid curves. In general, these calcula-
tions have failed to reproduce the $p_T$ dependence of
$A_{yy}$ at $\alpha \lesssim 0.72$. However, they are in a satisfac-
tory agreement with the data obtained at the highest value
of $\alpha \sim 0.78$.

In Fig. 3 the $A_{yy}$ data are plotted at different values
of transverse momenta $p_T$ as a function of the longitu-
dinal momentum fraction $\alpha$. The data shown in panels
(a), (b), (c) and (d) correspond to the averaged values

nucleon potentials, respectively. These functions are
determined by a superposition of $S$- and $D$-waves de-
pending on one internal variable $k$. One can see that
these calculations have failed to reproduce the behav-
or of the experimental data. The solid curves are the
predictions with the Karmanov DWF [2]. This DWF
is determined by six invariant functions $f_1, \ldots, f_6$ in-
stead of the two in the non-relativistic case. In the non-
relativistic limit only two functions remain: $f_1$ and
$f_2$, corresponding to the usual $S$- and $D$-waves in the
deuteron. Each of the invariant functions $f_1, \ldots, f_6$
depends on two variables $k$ and $\cos \chi = (\vec{n} \cdot \vec{k})/|\vec{k}|$, where
the internal momentum $k$ is defined above (2), and

Fig. 3. $A_{yy}$ data plotted as a function of longitudinal momentum fraction $\alpha$ obtained at fixed $p_T$ values of $\sim 550$ MeV/$c$, $\sim 700$ MeV/$c$, $\sim 800$ MeV/$c$ and $\sim 900$ MeV/$c$ and shown in (a), (b), (c) and (d) panels, respectively. The filled and open circles represent the data from this experiment obtained on hydrogen and carbon, respectively. The open diamonds are the previous data on beryllium at 5 GeV/$c$ [22]. The curves are the results of calculation using Karmanov’s DWF [2].

Fig. 4. Tensor analyzing power $A_{yy}$ in deuteron breakup obtained at the fixed $k$ values $\sim 600$ MeV/$c$, $\sim 700$ MeV/$c$, $\sim 800$ MeV/$c$ and $\sim 950$ MeV/$c$, are shown in (a), (b), (c) and (d) panels, respectively, as a function of variable $\cos \chi$. The filled and open circles represent the data from this experiment obtained on hydrogen and carbon, respectively. The open crosses and diamonds are the previous data on beryllium at 4.5 GeV/$c$ [21] and 5 GeV/$c$ [22], respectively. The curves are the results of calculation using Karmanov’s DWF [2].

of $p_T \sim 550$ MeV/$c$, $\sim 700$ MeV/$c$, $\sim 800$ MeV/$c$ and $\sim 900$ MeV/$c$, respectively. The filled and open circles are the data obtained in the present experiment on the hydrogen and carbon targets, respectively, while the open diamonds are the data obtained at 5 GeV/$c$. The solid curves are the results of the calculations [25] by using Karmanov’s DWF [2].

One can see that the $A_{yy}$ data for different values of $p_T$ demonstrate a weak dependence on $\alpha$. The data from this experiment obtained at $p_T \sim 550$ MeV/$c$ are in a good agreement with the data obtained at 5 GeV/$c$ of deuteron initial momentum [22], as well as with the calculations by using Karmanov’s DWF [2]. At higher $p_T$ $A_{yy}$ data have negative values, while the theory predicts a positive sign in the range of measurements.

The data on $A_{yy}$ corresponding to internal nucleon momenta $k \sim 600$ MeV/$c$, 700 MeV/$c$, 800 MeV/$c$ and 950 MeV/$c$ are plotted in Fig. 4(a), (b), (c) and (d), respectively, as a function of the variable $\cos \chi = (\hat{n} \cdot \hat{k})/|\hat{k}|$. The symbols are the same as in Fig. 2. The solid curves are the results of calculation by using Karmanov’s DWF [2]. Although the data have large errors, it is seen that the values of $A_{yy}$ tend to decrease as the variable $\cos \chi$ grows. The calculations [25] with Karmanov’s DWF are in a satisfactory agreement with the data obtained in the present experiment at $k \sim 600$ MeV/$c$ and $\sim 700$ MeV/$c$ (see Fig. 4(a) and (b), however, they cannot reproduce the behavior of $A_{yy}$ at $\cos \chi \leq -0.7$. Data on $A_{yy}$ at large internal nucleon momenta of $\sim 800$ MeV/$c$ and $\sim 950$ MeV/$c$ shown in Fig. 4(c) and (d), respectively, are in disagreement with the calculations.

The observed features of the $A_{yy}$ data: either the marked dependence of $A_{yy}$ plotted at fixed values of
the longitudinal momentum fraction $\alpha$ on the transverse momentum $p_T$, or different $\cos \chi$-behavior of $A_{yy}$ at fixed values of internal nucleon momentum $k$, clearly demonstrate that an adequate description of the data may be achieved by using a deuteron structure function that depends on more than one variable for $\alpha \gtrsim 0.6$. The relativistic DWF derived by Karmanov and coworkers [2] provides such a possibility. However, further development of this model is required to achieve a quantitative agreement with the experimental data, especially at large internal momenta.

The values of the vector analyzing power $A_y$ are compatible with zero.

4. Conclusions

The results of this work can be summarized as follows.

New data have been obtained on the tensor analyzing power $A_{yy}$ in deuteron inclusive breakup on hydrogen and carbon at 9 GeV/c deuteron initial momentum and transverse proton momenta up to $\sim 0.9$ GeV/c. The data for the both targets agree within the experimental accuracy. Hence, multiple scattering is small and the nuclear targets are appropriate to obtain information on the deuteron spin structure at short distances. The new data at 85 mr are in a good agreement with the data from the previous experiment [20].

The proton momentum dependences of $A_{yy}$ at fixed values of the proton emission angle are in a better agreement with calculations using Karmanov’s relativistic deuteron wave function instead of the standard non-relativistic deuteron wave functions.

The observed feature of $A_{yy}$, namely, the significant variation of $A_{yy}$ at fixed values of the longitudinal momentum fraction versus the transverse proton momentum, or dependence of $A_{yy}$ at fixed internal nucleon momentum versus variable $(\vec{n} \cdot \vec{k})$, favors a description of the relativistic deuteron structure with a function depending on more than one variable.

However, a quantitative description of $A_{yy}$ with the existing model of the deuteron structure depending on two variables [2], is not always achieved. This model requires further improvement, especially at large internal momenta.

The observed features and high precision of the $A_{yy}$ data from the present experiment put serious constraints on the models of the deuteron. However, additional measurements of $A_{yy}$ and other polarization observables at different initial deuteron momenta and various transverse momenta and longitudinal momentum fractions are required to provide the necessary experimental base to develop further the relativistic models describing the short-range structure of deuteron.

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