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MEASUREMENT OF THE TENSOR ANALYZING POWER A_{yy} IN INCLUSIVE BREAKUP OF 9 GeV/c DEUTERONS ON CARBON AT LARGE TRANSVERSE MOMENTA OF PROTONS

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The investigation of nuclear interactions of relativistic deuterons is the subject of extensive work during the last years. In particular, new experimental results on the polarization observables in deuteron inclusive breakup on hydrogen and nuclei with the emission of the proton at zero angle [1]-[7] and deuteron-proton backward elastic scattering [8, 9] have been recently obtained at Dubna and Saclay. These results demonstrate the failure of the traditional picture of the deuteron as bound state of a neutron and a proton at short distances between them.

The tensor analyzing power T_{20} in the deuteron breakup with proton emission at 0^o has been measured up to $k \sim 1$ GeV/c [1]-[4], the internal momentum of a nucleon in the deuteron defined in light-cone dynamics [10]-[12]. Significant deviation of the experimental data from the calculations performed in the framework of the relativistic Impulse Approximation (IA), using conventional deuteron wave functions, occurs even at $k \sim 200$ MeV/c. Various attempts were carried out to restore the deviation: some of them to take account of the mechanisms in addition to IA [13], others to include additional components in the deuteron wave function (DWF) due to relativistic effects [14, 15, 16]. However none of them allow the experimental data to be described. The data on T_{20} in dp backward elastic scattering [8]-[9] are not reproduced either by the one-nucleon exchange mechanism [17] or the calculations performed within Bethe-Salpeter formalism [18]. The spin transfer coefficient from the deuteron to the proton, κ_0, measured in both reactions up to $k \sim 0.55$ GeV/c [5]-[8] is also in definitive disagreement with any calculations using conventional DWFs.

The most intriguing feature of the experimental data is that T_{20} in both reactions give negative values, ~ -0.3 to -0.5, at high internal momenta of the proton [3, 4, 9]. These values are incompatible with the predictions using DWFs from any reasonable nucleon-nucleon potential. On the other hand, attempts to take account of the non-nucleon degrees of freedom in the deuteron seem to be successful. An asymptotic negative value of T_{20} has been obtained in the framework of the QCD motivated approach [19] based on the reduced nuclear amplitude method [20]. Recently, the data on T_{20} and κ_0 in the $^{12}C(d,p)X$ reaction at 0^o have reasonably been reproduced within the model which incorporates multiple scattering and Pauli principle at the quark level [21]. An additional account of exchanges by nucleon resonances with negative parity improves an accordance of the calculations with the experimental data on T_{20} in backward elastic dp scattering [22].

All the above-mentioned experimental data have been obtained under the kinematic condition of the proton with no transverse momentum. While, in the present experiment, the tensor analyzing power A_{yy} has been measured for the deuteron inclusive breakup under the condition of the protons emitted at an angle of about 90° in the rest frame of the deuteron. In this case, one can probe nucleons with higher internal momenta than that in the deuteron stripping at 0°. The measurements of the cross section under these kinematic conditions [23] on different targets have shown that the shapes of the high-momentum parts of the proton spectra depend only weakly on the atomic number of the target, A. Therefore the data reflect the deuteron structure and the mechanism of deuteron-nucleon interaction. The calculations performed within the framework of the hard scattering model [24] based on light-cone dynamics [10]-[12] show that the main contribution to the reaction comes from stripping and scattering of the deuteron nucleon on the target nucleon. Since the contribution of the double rescattering diagrams and the diagrams with virtual pion production is expected to be small from the IA, the reaction mechanism is essentially simplified. Therefore, it is hoped that new polarization measurements will give valuable information on the short range deuteron structure [25, 26].

In this paper we present new results on the tensor analyzing power A_{yy} in the deuteron inclusive breakup reaction on carbon target, $^{12}C(d,p)X$, at a 9 GeV/c initial deuteron momentum and a 85 mr secondary proton emission angle in the laboratory. This corresponds to the range of transverse momenta between 390 and 600 MeV/c.

The experiment has been performed at the Synchrophasotron of the Laboratory for High Energies of JINR. The polarized deuterons were produced by the ion source POLARIS [27]. The deuteron beam polarization was changed spill by spill, with the order of (0,–,+), where "0" means the absence of polarization, "–" and "+" correspond to the sign of the tensor polarization. The polarization was measured using the 2-arm polarimeter ALPHA [28] based on dp elastic scattering. The tensor and vector polarizations, p_{zz} and p_z, were $p_{zz}^+ = 0.624 \pm 0.029(stat) \pm 0.025(sys)$, $p_{zz}^- = -0.722 \pm 0.022(stat) \pm 0.029(sys)$, $p_z^+ = 0.162 \pm 0.017(stat) \pm 0.003(sys)$ and $p_z^- = 0.209 \pm 0.013(stat) \pm 0.004(sys)$, respectively. The systematic errors are due to the uncertainties in the analyzing powers A_{yy} and A_y for dp elastic scattering. The vector admixture of deuteron beam polarization was controlled during data taking by an on-line polarimeter [29]. The tensor polarization of the beam was measured during the run several times from the reaction $A(d,p)X$ at $k \sim 330$ MeV/c and

a zero degree, where the tensor analyzing power T_{20} is well known. The results of these measurements were in agreement with the available world data [1, 2, 3, 4].

The slowly extracted 9 GeV/c deuteron beam with a typical intensity of $\sim 2\cdot10^9$ $\vec{d}$/spill was directed onto a carbon target placed at the focus F5 of the beam line VP1 (see Fig.1). Thickness of the target was either 6.5 or 27.2 g/cm^2. The intensity of the beam was monitored by the ionization chamber IC placed in front of the target.

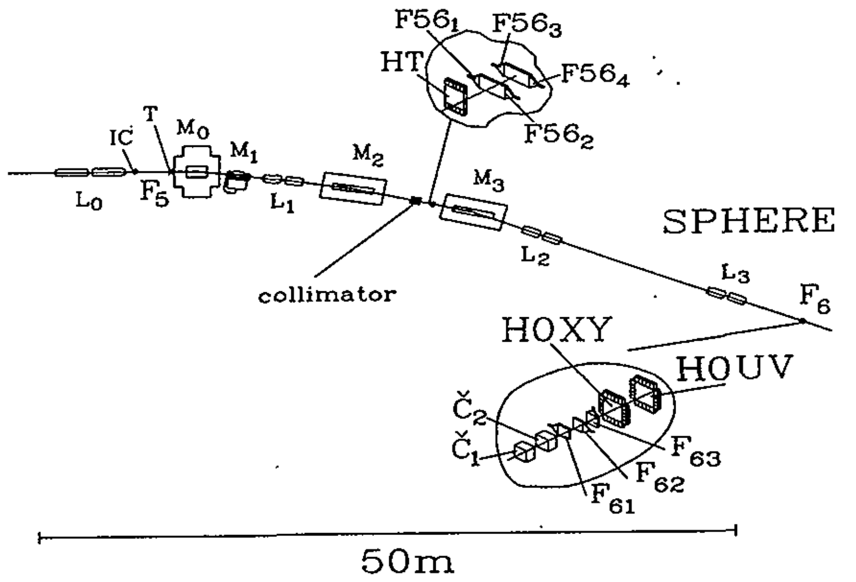

Fig.1. Layout of the SPHERE setup with beam line $VP1$. M_i and L_i designate magnets and lenses, respectively; IC ionization chamber; T target; F_{61}, F_{62}, F_{63} trigger counters; $\check{C}_1$ and $\check{C}_2$ Čherenkov counters; $F56_{1-4}$ scintillator counters and HT scintillator hodoscope for TOF measurements; $HOXY$ and $HOUV$ beam profile hodoscopes.

The data were taken at 6 momenta for secondary particles: 4.57, 5.40, 5.88, 6.11, 6.63 and 7.04 GeV/c. The particles emitted at 85 mr from the target were transported by means of 3 bending magnets (M_0 was off) and 3 doublets of lenses in focus F6. The acceptance of the setup was obtained from Monte-Carlo simulation [26]. The polar angle acceptance was $\Delta\theta \approx \pm 8$ mr. The momentum acceptance depending on the momentum varied between $\Delta p/p \approx \pm 0.02$ and ± 0.03.

Coincidences of signals from scintillator counters F_{61}, F_{62} and F_{63} were used as trigger. At the highest momentum of secondary particles, the Čherenkov counter $\check{C}_1$ with an aerogel radiator having a refractive index of 1.033, was used at the trigger level to suppress partly inelastically scattered deuterons from the $^{12}C(d,d)X$ reaction with the same momentum as the detected protons without any loss of breakup protons. The reduction factor of the trigger was ~ 2.

The time-of-flight (TOF) information with a base line of $\sim$ 28m between the start counter $F61$ and the stop counters $F56_1 - F56_2$, $F56_3 - F56_4$ and a scintillator hodoscope HT was used in off-line analysis for particle identification. The TOF resolution was better than 0.2 ns (1σ). The residual background was completely eliminated by the requirement that particles are detected in at least two prompt TOF windows. A two-dimensional plot of TOF for the detected events at a beam line momentum of 7.04 GeV/c is shown in Fig.2.

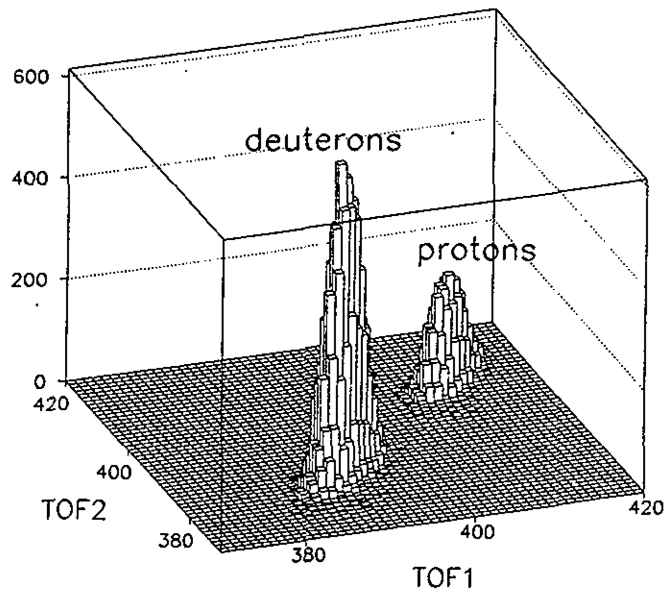

Fig.2. Two-dimensional plot of 2 different TOF over a baseline of $\sim$ 28 m at a beam line momentum $\sim$ 7.0 GeV/c. The deuterons are in part suppressed by the Čherenkov counter.

The measurement without target was made at a 6.11 GeV/c secondary particle momentum. The yield ratio of protons without target to 27.2 g/cm^2 carbon target was less than ~ 0.006.

The tensor A_{yy} and vector A_y analyzing powers were obtained from:

$$A_{yy} = 2\left[\frac{p_z^-}{p_z^- p_{zz}^+ - p_z^+ p_{zz}^-}\left(\frac{n^+}{n^0} - 1\right) - \frac{p_z^+}{p_z^- p_{zz}^+ - p_z^+ p_{zz}^-}\left(\frac{n^-}{n^0} - 1\right)\right]$$
$$A_y = -\frac{2}{3}\left[\frac{p_{zz}^-}{p_z^- p_{zz}^+ - p_z^+ p_{zz}^-}\left(\frac{n^+}{n^0} - 1\right) - \frac{p_{zz}^+}{p_z^- p_{zz}^+ - p_z^+ p_{zz}^-}\left(\frac{n^-}{n^0} - 1\right)\right], \quad (1)$$

where n^+, n^- and n^0 are the numbers of protons for different states of the beam polarization, normalized to the corresponding beam intensities.

The results on A_{yy} and A_y are presented in Table 1 as a function of the proton momentum in the laboratory frame, p, and in the rest frame of the deuteron, q. The tensor analyzing power A_{yy} is positive at high momenta of protons and equals about 0.1 in absolute value. The vector analyzing power A_y is small but non-negligible. This could be interpreted as a significant contribution of the spin-dependent part of the NN amplitude at these rather high energies.

Table 1. A_{yy} and A_y in deuteron inclusive breakup on carbon at 85 mr and 9 GeV/c. p is the proton momentum in the laboratory corrected for the energy loss in the target, Δp is the width of the momentum interval, q is the momentum in the deuteron rest frame

p GeV/c	$\Delta p(FWHM)$ GeV/c	q GeV/c	A_{yy}	dA_{yy}	A_y	dA_y
4.57	0.26	0.389	-0.084	0.030	0.015	0.062
5.40	0.30	0.488	0.153	0.023	0.181	0.047
5.88	0.33	0.557	0.083	0.031	0.122	0.064
6.11	0.32	0.593	0.106	0.024	0.127	0.047
6.63	0.32	0.671	0.040	0.027	0.090	0.055
7.04	0.32	0.734	0.114	0.042	-0.143	0.081

In Fig.3 the A_{yy} data plotted versus proton momentum in the laboratory are compared with the predictions of the hard scattering model [25] for the $H(d,p)X$ reaction. The theoretical curves are obtained following the procedure described in ref.[25], taking into account the influence of finite acceptance of the setup. The calculations are made using the conventional DWFs obtained from realistic nucleon-nucleon potentials [30]-[33]. One can see that these calculations fail to reproduce the behaviour of the experimental data, especially at high momenta of the proton.

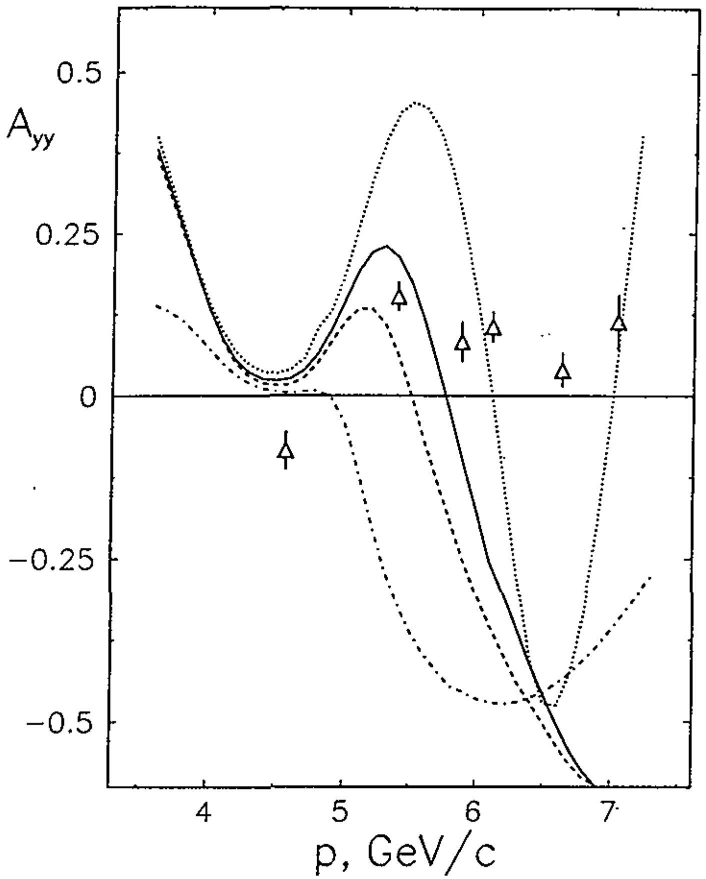

Fig.3. A_{yy} data as compared with the predictions of the hard scattering model [25] using different conventional DWFs. The solid, long-dashed, dotted and dash-dotted lines represent the results of calculations with Paris [30], RSC [31], Bonn [32] and Moscow [33] DWFs, respectively.

The present experimental data were obtained on a carbon target. However, the data on the tensor analyzing power at 0° [1, 3, 4] demonstrate that the systematic difference observed for hydrogen and nuclear targets is only approximately 20%.

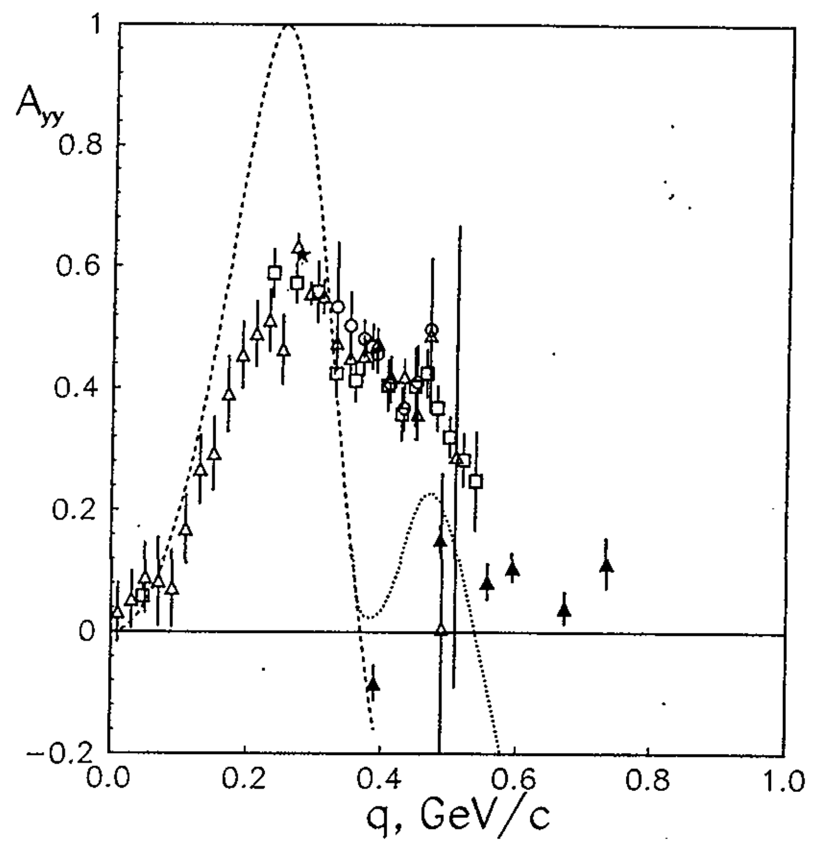

Fig.4. A_{yy} data from this experiment (filled triangles) as compared with the data obtained at 0° on carbon target from ref.[2] (open triangles), ref.[3] (open squares) and ref.[4] (open circles) versus proton momentum in the rest frame of the deuteron q. The star shows the result of polarization checking during the present experiment. The dashed and dotted lines are the results of calculations using Paris DWF [30] for 0 and 85 mr proton emission angles, respectively.

The calculations show that the stripping dominates over the deuteron nucleon scattering on the target nucleon at 85 mr and large proton momenta [24], and therefore the observables can depend on the variable characterizing relative momenta of the nucleon inside the deuteron. Fig.4 shows the A_{yy} data from this experiment together with the T_{20} data obtained at a zero transverse momentum of the proton (at a zero angle, $T_{20} = -\sqrt{2}A_{yy}$) on carbon target [2, 3, 4] plotted versus q:

$$q = \sqrt{q_{||}^2 + q_{\perp}^2}, \qquad (2)$$

where $q_{||}$ and $q_{\perp}$ are the longitudinal and transverse momenta of the proton in the rest frame of the deuteron, respectively. The values of A_{yy} are positive for all the data at large momenta q. Such a behaviour of A_{yy} in the $^{12}C(d,p)X$ reaction at 0^o was obtained in the calculations taking into account Pauli principle at the constituent quark level and multiple scattering [21]. The same tendency in the behaviour of the tensor analyzing power in dp backward elastic scattering was obtained in the model taking into account the contribution of NN^* configurations, where N^* are the baryonic resonances with negative parity [22].

As seen, the experimental situation for the deuteron breakup reaction at large transverse momenta of the proton looks like that established for the case where the detected proton is emitted at a zero angle: whereas the momentum spectra of protons is satisfactorily described in the framework of "traditional" approaches [13, 24, 34] using standard DWFs, the data on the polarization observables are in significant contradiction with the predictions of these models. This is apparently the consequence of that the polarization data are much more sensitive to the details of the deuteron structure at short distances between the constituents. Nevertheless, this feature of the data does not permit one to draw a definitive conclusion whether the non-nucleon degrees of freedom (six-quark configurations or their projection onto the baryon-baryon components) are relevant or the nucleons retain their individuality at high relative momenta of $\sim$ 1 GeV/c, but our knowledge of the deuteron structure at short distances, where the nucleons are strongly overlapped, needs to be revised.

The results of this work can be summarized as follows:

- The tensor and vector analyzing powers, A_{yy} and A_y, in the reaction $^{12}C(d,p)X$ have been measured for the first time at a 9 GeV/c initial deuteron momentum and a 85 mr proton emission angle in the laboratory. The range of measurements corresponds to transverse momenta p_T of the proton between 390 and 600 MeV/c or to proton momenta in the rest frame of the deuteron up to $\sim$ 730 MeV/c.

-We observe that A_{yy} remains positive up to the largest momenta of proton. This is in definitive contradiction with the predictions of the hard scattering model [25] using conventional DWFs [30]-[33].

-The new data on A_{yy} obtained at large transverse momenta have a positive value at high q as the data on A_{yy} in deuteron inclusive breakup [3, 4] and dp backward elastic scattering [9] obtained at a zero transverse momentum. This similarity may indicate that the results of these experiments ultimatively characterize the internal properties of the deuteron at small distances; the behaviour of A_{yy} at large q favours the models taking the non-nucleon degrees of freedom into account[19, 21, 22].

-The non-zero value of the vector analyzing power A_y can be interpreted as an important role of the spin-dependent part of the nucleon-nucleon amplitude.

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