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TENSOR AND VECTOR ANALYSING POWERS A_{yy} AND A_y IN THE ^{12}C$(d,p)X$ AND ^{12}C$(d,d)X$ REACTIONS AT INITIAL DEUTERON MOMENTUM OF 9 GeV/c AND EMISSION ANGLE OF 85 mrad

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The first data on tensor and vector analysing powers A_{yy} and A_y in the ^{12}C$(d,p)X$ and ^{12}C$(d,d)X$ reactions have been obtained at incident deuteron momentum of 9 GeV/c and emission angle for the secondary particles of 85 mrad. Value of A_{yy} in inclusive deuteron breakup remains positive at the highest measured momenta of proton, that is in contradiction with the predictions of the model using conventional deuteron wave functions. Values of A_y in this reaction are small but non-negligible. The data on A_{yy} and A_y in deuteron inelastic scattering could bring new important information on the baryonic resonance properties in the vicinity of masses ~ 2.2 GeV/c^2.

The investigation has been performed at the Laboratories of High Energies and Nuclear Problems, JINR.

Тензорная и векторная анализирующие способности A_{yy} и A_y в реакциях ^{12}C$(d,p)X$ и ^{12}C$(d,d)X$ при начальном импульсе дейтронов 9 ГэВ/с и угле испускания 85 мрад

С.В.Афанасьев и др.

Представлены первые данные по тензорной и векторной анализирующим способностям A_{yy} и A_y в реакциях ^{12}C$(d,p)X$ и ^{12}C$(d,d)X$ при начальном импульсе дейтрона

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9 ГэВ/с и угле испускания вторичных частиц 85 мрад. Значение A_{yy} в реакции фрагментации дейтрона остается положительным до максимального измеренного импульса протона, что находится в противоречии с предсказаниями модели, использующей стандартные дейтронные волновые функции. Значения A_{yy} в этой реакции малы, но не пренебрежимы. Данные по A_{yy} и A_y в неупругом рассеянии дейтрона могут дать новую важную информацию о свойствах барионных резонансов в области масс ~2,2 ГэВ/с^2.

Работа выполнена в Лабораториях высоких энергий и ядерных проблем ОИЯИ.

1. Introduction

The deuteron inclusive breakup with the emission of the proton at zero angle and deuteron-proton backward elastic scattering reactions are traditionally used to obtain the information on the internal structure of the deuteron. The interest to these reactions was recently aroused by new experimental results on the tensor analysing power T_{20} and spin transfer coefficient from the deuteron to the proton κ_0 obtained at Dubna and Saclay [1—9].

The tensor analysing power T_{20} in the deuteron breakup at 0 ° has been measured up to internal momenta of a nucleon $k \sim 1$ GeV/c [3,4], defined in infinite momentum frame [10—12]. It is found that T_{20} value was in agreement with impulse approximation (IA) prediction using conventional deuteron wave functions (DWFs) up to $k \sim 200$ MeV/c, but remarkably deviates from it at higher momenta. The good agreement with the experiment was obtained up to $k \sim 600$ MeV/c only in the model taking into account additional to IA mechanisms [13]. At higher k, the T_{20} data demonstrate a significant deviation from any calculations performed within relativistic IA only or with including of additional to IA contributions [13], with additional components in the DWF due to relativistic effects [14,15,16]. The data on T_{20} in *dp* backward elastic scattering [8—9] also show significant difference from the prediction of the pole mechanism [17] or 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 definite disagreement with any calculations based on 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 proton [3,4,9]. These values are incompatible with the predictions using DWFs from any reasonable nucleon-nucleon potential. Various attempts were undertaken to explain the T_{20} data taking into account the non-nucleon degrees of freedom in the deuteron. 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 ° 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 the 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 analysing 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, the higher internal momenta of nucleons can be studied than in the deuteron stripping at 0 °. The measurements of the cross section under these kinematic conditions [23] (at the laboratory angles 103, 139 and 157 mm) 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 the stripping and scattering of the deuteron nucleon on the target nucleon. Since, the contribution of the double rescattering diagrams and the diagrams with the virtual pion production is expected to be small from the IA, the reaction mechanism is essentially simplified. Therefore, it is hoped that the new polarization measurements will give valuable information on the short range deuteron structure [25,26].

In this paper we present the first data on tensor and vector analysing powers A_{yy} and A_y in two reactions, ^{12}C(d, p)X and ^{12}C(d, d)X, obtained at 9 GeV/c of the initial deuteron momentum and 85 mrad of the secondary particle detected angle in the laboratory. In the next section the details of the experiment are given. The data analysis procedure is described in section 3. The obtained results are discussed in section 4. Conclusions are given in the last section.

2. Experiment

The experiment has been performed at the Synchrophasotron of the Laboratory for High Energies of JINR and SPHERE set-up [26] shown in Fig.1. The polarized deuterons were produced by the ion source POLARIS [27]. The deuteron beam polarization was changed spill by spill, with the order (0, –, +), where «0» means the absence of polarization, «–» and «+» correspond to the sign of tensor polarization. The primary deuteron beam polarization was measured using the 2-arm ALPHA polarimeter [28] based on dp elastic scattering. The tensor and vector polarizations of the beam 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 $p^-_x = 0.209 \pm 0.013$ (stat) $\pm\ 0.004$ (sys), res-

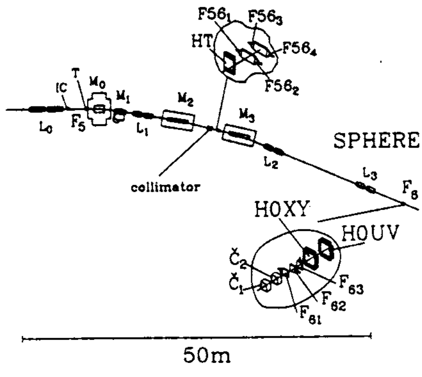

Fig.1. Layout of the SPHERE set-up with beam line VP1. M_i and L_i designate magnets and lenses, respectively; IC, ionization chamber; T, target; F_{61}, F_{62}, F_{63}, trigger counters; $\check{C}_1$ and $\check{C}_2$, Čerenkov counters; $F56_{1-4}$, scintillator counters; and HT, scintillator hodoscope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

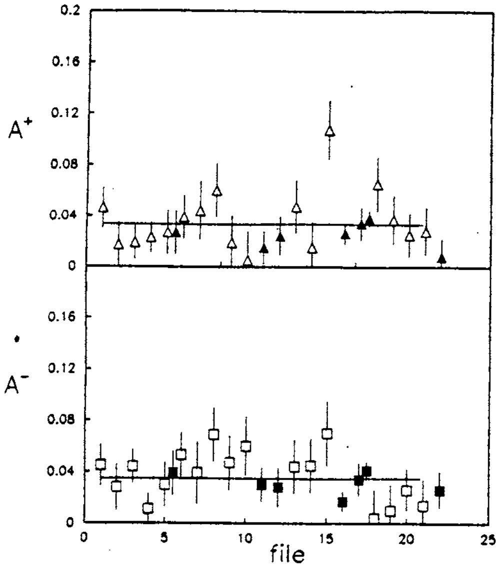

Fig.2. The asymmetries $A^{\pm}$ from relative polarimeter [29]. The open and full symbols are the values of asymmetries $A^{\pm}$ obtained during the control measurements of polarization and data taking, respectively

pectively. The systematic errors are due to the uncertainties in the analysing powers A_{yy} and A_y for dp elastic scattering. The stability of the vector admixture of the deuteron beam polarization was controlled during data taking by an on-line polarimeter based on the measurement of asymmetry from quasielastic pp scattering [29] installed at focus F4 of the beam line VP1. Asymmetries for «+» and «–» polarization states are defined as follows:

$$A^{+}=\frac{n_l^{\pm}/n_r^{\pm}-n_l^{0}/n_r^{0}}{n_l^{\pm}/n_r^{\pm}+n_l^{0}/n_r^{0}}, \qquad (1)$$

where $n_{l,r}^{\pm,0}$ are normalized counting rates from the left and right arms of the polarimeter for different polarization states of the deuteron beam. The results of measurements are shown in Fig.2. The open and full symbols represent the values of asymmetries $A^{\pm}$ obtained during the control measurements of the polarization and data taking, respectively. The averaged values of asymmetries obtained during the control measurements are 0.033 ± 0.004 and 0.035 ± 0.004 for «+» and «–» polarization states, respectively. The corresponding averaged values of asymmetries obtained during data taking are 0.029 ± 0.004 and 0.031 ± 0.004. Both results are in good agreement. 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 analysing power T_{20} is well known. The results of these measurements were in good agreement with the world T_{20} data [1,2,3,4].

The slowly extracted 9 GeV/c deuteron beam with a typical intensity of $\sim 2 \cdot 10^9$ **d**/spill was directed onto carbon target placed at focus F5 of the beam line VP1 (see Fig.1). Thickness of the target was either 6.5 g/cm^2 or 27.2 g/cm^2. The intensity of the beam was monitored by the ionization chamber IC placed in front of the target.

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 mrad from the target were directed by means of 3 bending magnets (M_0 was off) and 3 doublets of lenses into focus F6. The acceptance of the set-up was obtained from Monte-Carlo simulation [26]. The polar angle acceptance was $\Delta\theta \approx \pm 8$ mrad. The momentum acceptance depending on the momentum varied between $\Delta p/p \approx \pm 0.02$ and ± 0.03.

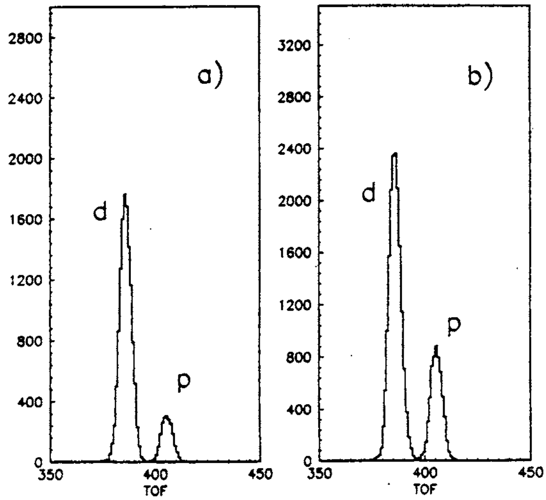

Fig.3. The time of flight spectra, demonstrating the use of Čerenkov counter in trigger: a) without the using, b) with $\check{C}_1$ in trigger

Coincidences of signals from scintillator counters F_{61}, F_{62} and F_{63} were used as a trigger. At the highest momentum of secondary particles, the Čerenkov counter $\check{C}_1$ with an aerogel radiator having a refractive index 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 spectra demonstrating the use of the Čerenkov counter in trigger are shown in Fig.3.

3. Data Analysis

The time-of-flight (TOF) information with a base line of ~ 28 m between the start counter *F*61 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.4.

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

The tensor, A_{yy}, and vector, A_y, analysing powers for both reactions were obtained from the following expressions:

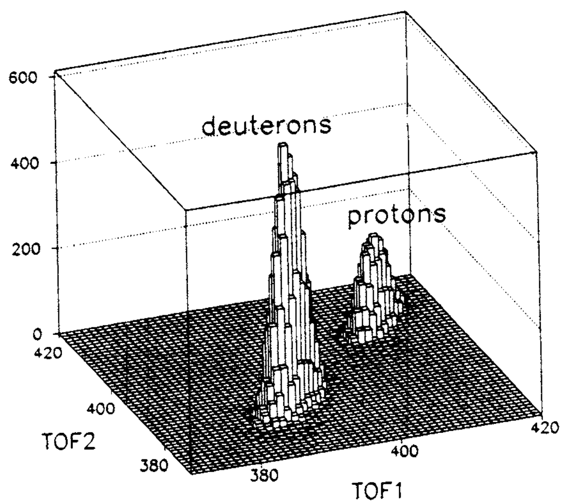

Fig.4. Two-dimensional plot of 2 different TOF over a baseline of ~ 28 m at a beam line momentum of 7.04 GeV/c. The deuterons are in part suppressed by the Čerenkov counter

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

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

where n^+, n^- and n^0 are the numbers of protons (or deuterons) for different states of the beam polarization, normalized to the corresponding beam intensities (monitor values from *IC*).

4. Results and Discussion

The results on analysing powers are presented in Tables 1 and 2 for the ^{12}C(d, p)X and ^{12}C(d, d)X reactions, respectively.

Table 1. A_{yy} and A_y in deuteron inclusive breakup on carbon at 85 mrad 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	Δp (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

Table 2. A_{yy} and A_y in the deuteron inelastic scattering on carbon ^{12}C(d, d)X at 85 mrad and 9 GeV/c; M_X is the mass of undetected system, t is the 4-transferred momentum (corrected for the energy loss in the target)

M_X GeV/c^2	t (GeV/c)^2	A_{yy}	dA_{yy}	A_y	dA_y
1.940	−0.654	0.285	0.026	0.213	0.043
2.101	−0.736	0.113	0.027	0.172	0.047
2.279	−0.888	0.170	0.044	0.124	0.071
2.351	−0.979	0.001	0.068	0.001	0.114
2.480	−1.213	−0.056	0.083	−0.049	0.140

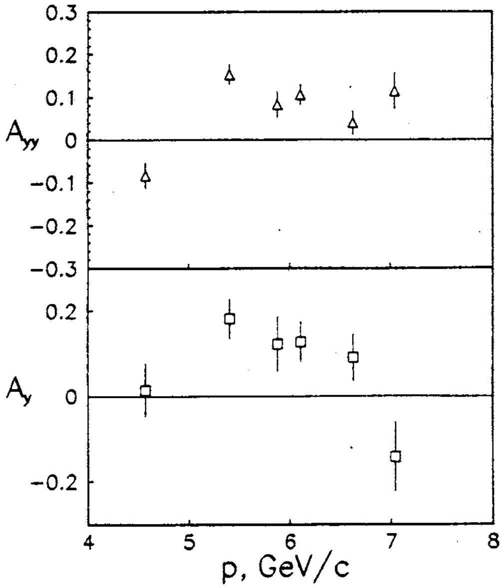

Fig.5. Tensor A_{yy} and vector A_y analysing powers in the $^{12}C(d, p)X$ reaction versus momentum of the proton in the laboratory

4.1. Deuteron Inclusive Breakup. The results on A_{yy} and A_y are presented in Fig.5 as a function of the proton momentum in the laboratory frame. The tensor analysing power A_{yy} is positive at high momenta of protons and equals about 0.1 in absolute value. The vector analysing power A_y is small but non-negligible. This could be interpreted as a significant contribution of the spin-flip part of the *NN* amplitude at these rather high energies.

In Fig.6. the A_{yy} data are compared with the predictions performed in the framework of the hard scattering model in the paper of Azhgirey and Yudin [25], where the analysis of spin effects was carried out for the *H(d, p)X* reaction at large transverse momenta of proton. The global features of proton spectra in the region of the transverse momenta of 0.5—1 GeV/c produced in the *H(d, p)X* reaction by unpolarized deuterons with the initial momentum of 9 GeV/c, were satisfactorily described in the frame of this model [24,23], taking into account nucleon degrees of freedom only. The theoretical curves are obtained following the procedure described in Ref.25, taking into account the influence of finite acceptance of the set-up. The finite acceptance correction can be quite large, but cannot change substantially the behaviour of A_{yy}. One can see that calculations using conventional DWFs [30—33] fail to reproduce the behaviour of the experimental data on A_{yy}, especially at high momenta of the proton.

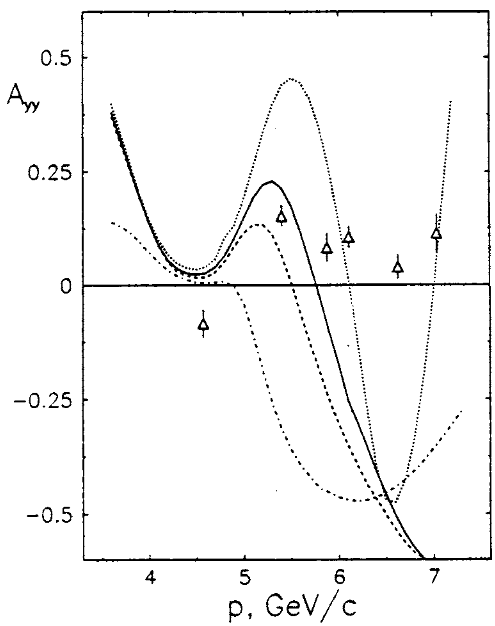

Fig.6. A_{yy} data as compared with the predictions of the hard scattering model [25] using different conventional DWFs. The solid, long-dashed, dotted and dash-dotted lines represent the results of calculations with Paris [30], RSC [31], Bonn [32] and Moscow [33] DWFs, respectively

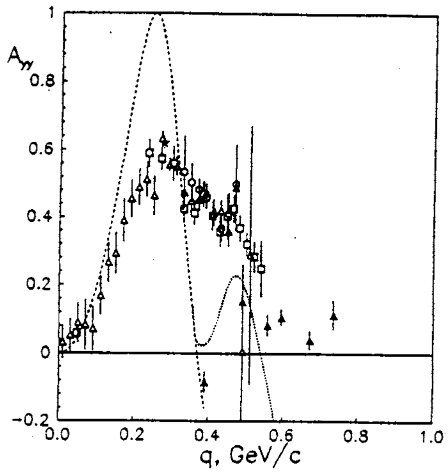

Fig.7. A_{yy} data from this experiment (filled triangles) as compared with the data obtained at 0 ° on carbon target from Ref.2 (open triangles), Ref.3 (open squares) and Ref.4 (open circles) versus proton momentum in the rest frame of the deuteron q. The star shows the result of polarization checking during the present experiment. The dashed and dotted lines are the results of calculations using Paris DWF [30] for 0 and 85 mrad proton emission angles, respectively

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

The calculations show that the stripping dominates over the deuteron nucleon scattering on the target nucleon at 85 mrad and large proton momenta [24], and therefore the observables can depend on the variable characterizing relative momenta of the nucleon inside the deuteron. Figure 7 shows the A_{yy} data from this experiment 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:

$$q = \sqrt{q_{||}^2 + q^2}, \tag{3}$$

where $q_{||}$ and q 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. Similar behaviour of A_{yy} is predicted in the model taking into account quark degrees of freedom and multiple scattering [21]. The same tendency in the behaviour of the tensor analysing 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 are 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 definite 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 indivi-

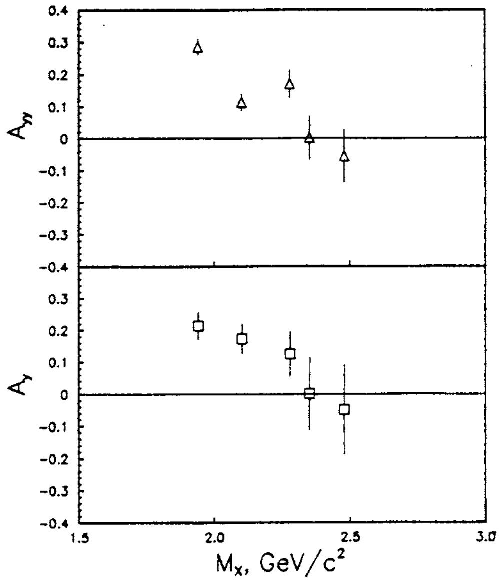

Fig.8. Tensor A_{yy} and vector A_y analysing powers in the $^{12}C(d, d)X$ reaction versus the mass of undetected system M_X

duality at high relative momenta of ~ 1 GeV/c, but our knowledge of the deuteron structure at short distances, where the nucleons are strongly overlapped, needs to be revised.

4.2. Deuteron Inelastic Scattering. The reaction $A(d, d')X$ is selective to the isospin of the unobserved system X, which must be equal to the isospin of the target A. Since the reaction $H(d, d')X$ is selective to the isospin 1/2, this process can be used to obtain the information on the formation of the baryonic resonances $N^*(1440)$, $N^*(1520)$, $N^*(1680)$ and others.

The measurements of tensor analysing power T_{20} in $A(d, d')X$ at a zero angle in the vicinity of the baryonic resonances excitation have demonstrated that the value of T_{20} does not depend on the atomic number of the target [35]. This feature can indicate that the medium effects in this process play a minor role, and the data obtained on the nuclear target also can provide the information on the resonances with an isospin 1/2.

The data on A_{yy} and A_y in the inelastic deuteron scattering on carbon target have been obtained simultaneously with the data in the deuteron breakup. These data are presented in Fig.8 versus the mass of undetected system, M_X. At lower masses A_{yy} has the same sign as the data obtained at a zero angle [35] in the same reaction. The A_y value is also positive at relatively low masses. Both observables are

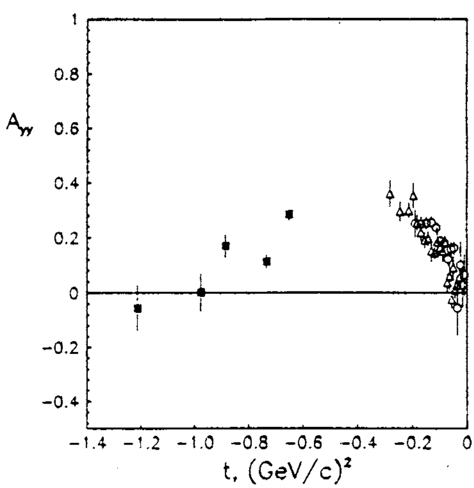

Fig.9. Tensor analysing power A_{yy} in deuteron inelastic scattering from the present experiment (full squares) shown together with the data obtained at a zero angle at 4.5 GeV/c (open triangles) and 5.5 GeV/c (open circles) [35]

consistent with zero in the vicinity of $M_X \sim 2.2$ GeV/c^2. The nonzero value of A_y could be interpreted as the spin-flip part of the elementary $NN \to NN^*$ amplitude is essential.

In Fig.9, the A_{yy} data from this experiment are shown together with the carbon data obtained at 4.5 and 5.5 GeV/c and a zero angle [35] plotted versus 4-transferred momentum t. Combining of the data obtained under different kinematic conditions could help to understand whether the large value of A_{yy} is due to the properties of the baryonic resonances, or it is defined mostly by the deuteron form factor.

5. Conclusions

To conclude the tensor and vector analysing 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 mrad 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 up to ~730 MeV/c in the rest frame of the deuteron. We observe that A_{yy} remains positive up to the largest momenta of the proton. This is in definite 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 in deuteron inclusive breakup [3,4] and dp backward elastic scattering [9] obtained at a zero transverse momenta. 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 into account the non-nucleon degrees of freedom [19,21,22].

The nonzero value of the vector analysing power A_y can be interpreted as an important role of the spin-flip part of the nucleon-nucleon amplitude.

The data on A_{yy} and A_y in the inelastic deuteron scattering on carbon target at 85 mrad were also obtained. A_{yy} data are obtained at sufficiently larger transverse momenta than at a zero angle [35]. Large value of A_y can be an indication that the spin-flip part of the elementary $NN \to NN^*$ amplitude is essential.

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