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INVESTIGATION OF THE TENSOR ANALYZING POWER A_{yy} IN THE REACTION $A(\vec{d},p)X$ AT LARGE TRANSVERSE MOMENTA OF PROTON

S.V.Afanasiev[1], V.V.Arkhipov[1], L.S.Azhgirey[2], Yu.T.Borzunov[1], E.V.Chernykh[1], L.B.Golovanov[1], G.Filippov[1,4], A.Yu.Isupov, V.A.Kashirin[1], A.N.Khrenov[1], V.I.Kolesnikov[1], V.P.Ladygin[1], N.B.Ladygina[1], A.G.Litvinenko[1], A.I.Malakhov[1], I.I.Migulina[1], V.N.Penev[1,4], S.G.Reznikov[1], P.A.Rukoyatkin[1], A.Yu.Semenov[1], I.A.Semenova[1], V.I.Sharov[1], G.D.Stoletov[2], A.P.Tzvinev[1], N.P.Yudin[3], S.A.Zaporozhets[1], V.N.Zhmyrov[2], L.S.Zolin[1]

An experiment on the studying of the tensor analyzing power A_{yy} in the reaction $A(\vec{d},p)X$ at large transverse momenta of proton using a polarized deuteron beam of LHE accelerator complex has been proposed. These measurements could provide the valuable information on the spin structure of the deuteron at short distances. The estimation of the beam request for SPHERE set-up is performed.

The investigation has been performed at the Laboratory of High Energies, JINR.

Исследование тензорной анализирующей способности A_{yy} в реакции $A(\vec{d},p)X$ при больших поперечных импульсах протона

С.В.Афанасьев и др.

Предложен эксперимент по изучению тензорной анализирующей способности A_{yy} в реакции $A(\vec{d},p)X$ при больших поперечных импульсах протона на поляризованном пучке ускорительного комплекса ЛВЭ. Эти измерения могли бы дать важную информацию о спиновой структуре дейтрона на малых расстояниях. Проведены оценки необходимого для эксперимента времени с использованием установки СФЕРА.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

1. Motivation

During the last few decades the deuteron structure has been the subject of extensive experimental and theoretical work. Considerable amount of data in the inclusive deuteron breakup with the emission of the proton at zero angle, $A(d,p)X$, and deuteron-proton elastic

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[1] LHE, JINR, Dubna, 1414980 Moscow Region, Russia

[2] LNP, JINR, Dubna, 141980 Moscow Region, Russia

[3] MSU, Moscow, Russia

[4] INPNE, 1784 Sofia, Bulgaria

scattering at 180°, $p(d,p)d$, reactions were accumulated [1]—[14] in order to obtain the reliable information concerning the behaviour of the deuteron wave function (DWF) at short distances between nucleons.

The measurements of the cross section of the inclusive breakup $A(d,p)X$ reaction with the proton emitted at zero angle at different A initial energies and for different values of the target [1]—[4] have shown the deviation from the calculations performed within IA using standard deuteron wave functions, especially in the vicinity of the intrinsic momenta of the proton in the deuteron $k \sim 0.3$ GeV/c, where a relatively broad shoulder is observed. This structure was explained by Kobushkin and Vizireva by the additional contribution of the exotic $|6Q\rangle$ configuration in the deuteron wave function [15], and by other authors taking into account the mechanisms with the virtual pion production [16,17,18].

The other important point is the dependence of the cross section shape on the atomic value of the target A observed at all energies: at $k \geq 150$ MeV/c the ratio of breakup cross sections on carbon and hydrogen is about a factor of 3.5 in comparison with a factor of ~5.6 following from the power dependence $A^{2/3}$ at half of momentum of the proton (Fig.1a).

Measurements of the tensor analyzing power T_{20} [3,4,5] performed at Saclay and Dubna have demonstrated the strong deviation from the IA predictions at $k \geq 0.2$ GeV/c. Recent measurements of the tensor analyzing power up to $k \sim 1$ GeV/c performed by two Dubna groups on carbon [6] and on proton and carbon [7] also have shown the dependence on the A value of the target at $k \geq 0.20$ GeV/c (see Fig.1b). These new data demonstrate the trend to achieve the constant asymptotic value predicted by the QCD motivated model [19], but the «experimental» asymptotic values are different for the carbon and hydrogen target.

The behaviour of the spin transfer coefficient from vector polarized deuteron to proton κ_0 [8,9,10] disagrees with the calculations using standard deuteron wave functions at $k \geq 0.2$ GeV/c. One cannot give the definite conclusion about A dependence of κ_0 because of large error bars for Dubna data, taken on carbon target.

Breakup data on cross section, T_{20}, κ_0 demonstrate in the first approximation the independence from the initial energy, what gives the possibility to consider the k as the approximate scaling variable. On the other hand, the A dependence of the cross section shape and T_{20}-value demonstrate that the additional to IA mechanisms (virtual π production [16,17,18]) may be important in this kinematics.

The backward elastic scattering $dp \to pd$ at medium and high energies is one of the simplest processes with the large momentum transfer and,therefore, can be used to study the high-momentum tail of the DWF.

The experimental data on the differential cross section of the $dp \to pd$ reaction [12] show a sharp peak at $\theta \sim 180°$ in the center of mass. On the other hand, the differential cross section at $\theta \sim 180°$ demonstrates the strong energy dependence and an enhancement in vicinity of the Δ-isobar excitation. This resonant-like energy dependence of the cross section could not be explained by the pole mechanism only. The cross section of the $dp \to pd$ process was calculated in the framework of the two-step model in which the cross section of the dp backward elastic scattering is expressed in terms of the $pp \to d\pi^+$ cross section [20,21]. Calculations of Kolybasov and Smorodinskaya [22] taking into account D-state and relativistic corrections are in satisfactory agreement with the cross section data.

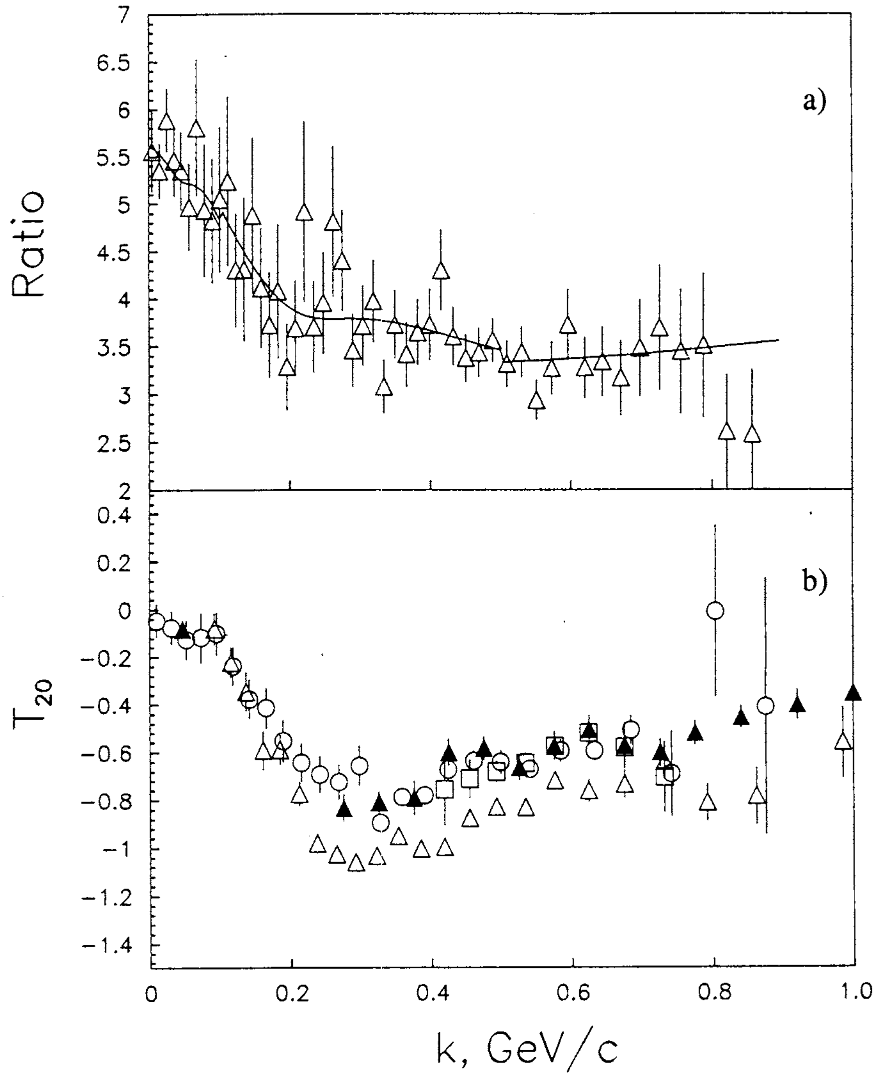

Fig.1. a) The ratio of the cross sections of deuteron inclusive breakup on carbon and hydrogen [1] at 9 GeV/c and 0° versus intrinsic momentum k; b) the tensor analyzing power T_{20} [5,6,7] in the deuteron inclusive breakup at 0°. The data obtained on hydrogen target are given by open triangles [7]

Above the Δ-isobar excitation region the data on the backward elastic scattering are described in the framework of ONE mechanism in the light-front dynamics [23].

Measurements of T_{20} [13,14] and κ_0 [13] for dp elastic scattering have shown the deviation from the ONE predictions, as well as from the behaviour of T_{20} and κ_0 in

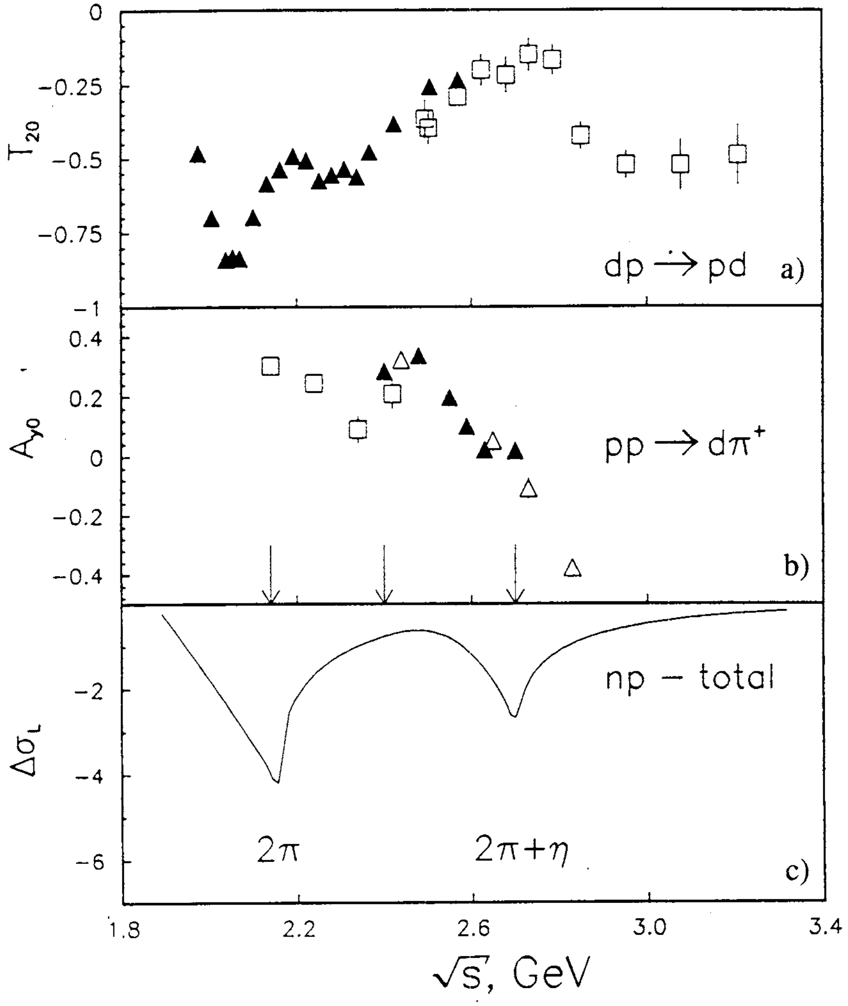

Fig.2. a) Tensor analyzing power T_{20} in the *dp* backward elastic scattering versus energy of *NN* pair in the center of mass; b) vector analyzing power A_{y0} of the $pp \to d\pi^+$ reaction at ~90° of pion in the center of mass, the arrows are the observed structures at 2.14, 2.4 and 2.7 GeV/c^2; c) the predictions of Kochelev for $\Delta\sigma_L$ in the *NP* total cross section.

deuteron breakup at large *k*, which is not explained yet theoretically. Calculation with the inclusion of the additional components of the deuteron wave function [15,24,25,26,27] as well as considering of the mechanisms additional to ONE [18,28,29] cannot explain the observed features of the experimental data in deuteron breakup and *dp* backward elastic scattering.

It seems, the observed structures in the behaviour of T_{20} in *dp* background elastic scattering are not related with the deuteron structure. In Fig.2 we present T_{20} [13,14], analyzing power A_{y0} at 90° in the center of mass for $pp \to d\pi^+$ process [30], and the prediction of Kochelev for $\Delta\sigma_L$ [31][1] in *np* interaction versus energy of NN pair in the center of mass, $\sqrt{S}$. One can see the correlation between the structures in the behavior of T_{20} and the structures at $\sqrt{S} \sim 2.14$, 2.4 and 2.7 GeV/c in $pp \to d\pi^+$ process [30] and *NN* scattering. These structures are predicted in the quark and instanton models [31,32].

In principle, the using of the polarized target and polarimeter could allow one to measure a number of additional observables in the deuteron breakup and *dp* scattering at 180° [33]. The complete experiment on the full determination of the amlitudes of the *dp* backward scattering process requires the measurements of 10 observables [34] and is impossible to be realized at LHE Accelerator Complex at the moment.

Thus one can see that the additional to the simple IA (in case of $A(d,p)X$ at zero angle) and ONE (in case of the *dp* backward elastic scattering) mechanisms are important and, therefore, the extraction of the information on the deuteron structure is difficult. In this relation we should like to attract attention to another way of investigation of short range deuteron structure.

This is (apart from the exclusive experiments) the measurements of the deuteron inclusive breakup with the emission of the proton at large transverse momenta.

Measurements of the momentum spectra of protons at emission angles of 103, 139 and 157 mrad in the deuteron inclusive breakup reaction on hydrogen, deuterium and carbon targets at 9 GeV/c [35] have demonstrated the universality of the high-momentum part of the spectra, i.e., weak dependence of the momentum distribution shape on the atomic number of the target, *A*. In Fig.3 the ratio of cross section to carbon and hydrogen at 103 mrad is presented. One can see, that at high momenta this ratio is close to the power law $A^{2/3}$.

The calculations performed within the framework of hard scattering model are in good agreement with the data obtained on the hydrogen target. The authors managed to get the following result: (i) The main contribution to reaction comes from the stripping and scattering of the deuteron nucleon on the target proton, whereas the interference between these processes and virtual pion production is small. So one can consider that the mechanism of the reaction is known and is relatively simple; (ii) Strong sensitivity of the reaction to the NN potential: The using of Paris DWF [36] gives the better agreement between theory and experiment; (iii) The nucleons inside a deuteron keep their individuality up to the relative momenta ~1 GeV/c. (iv) The reaction is sensitive to the spin structure of deuteron.

Another interesting feature of these data is the so-called *Z*-scaling [37], what means the universality (i.e., the independence from the emission angle and *A* value) of the high momentum part of the proton spectra normalized on the $pp \to pX$ cross section versus minimal momentum of spectator in the deuteron rest frame *Z*.

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[1] The curve is taken from the paper: Sharov V.I. et al. — JINR Rapid Com., 1996, No.3[77], p.13.

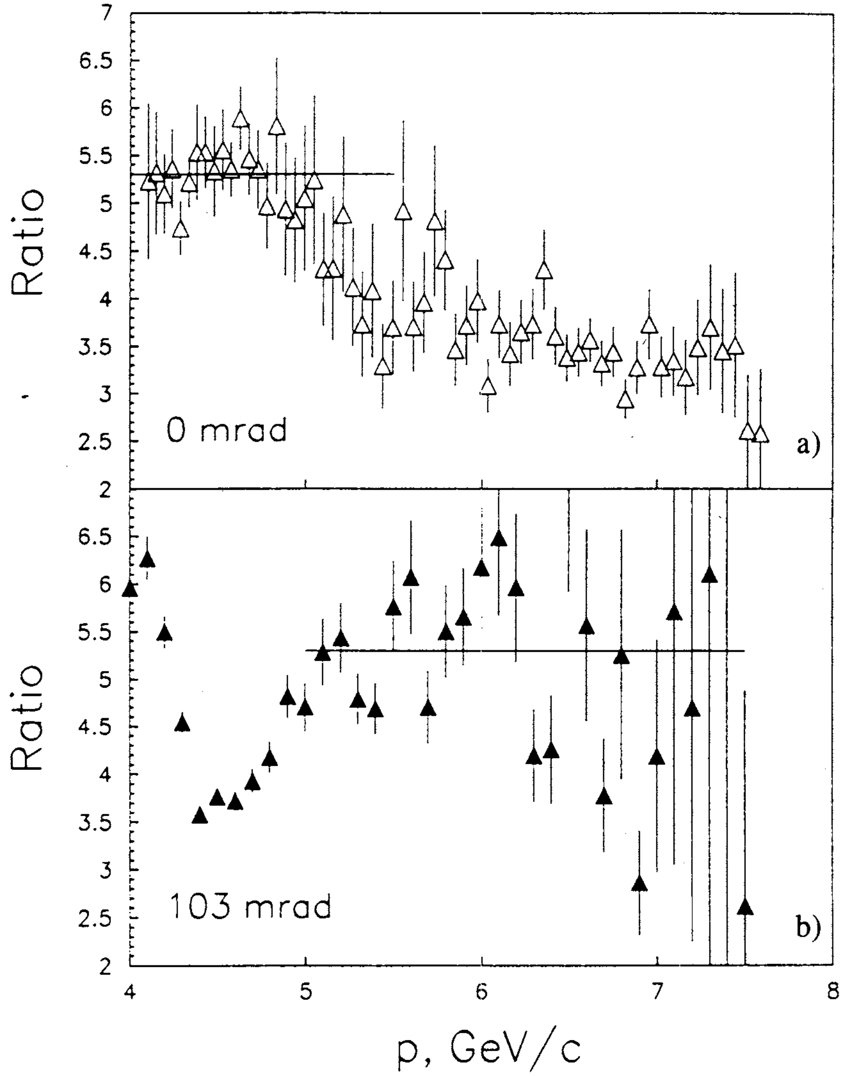

Fig.3. The ratio of the cross sections of deuteron inclusive breakup on carbon and hydrogen at 9 GeV/c versus momenta of proton: a) at 0 mrad; b) at 103 mrad. The solid lines follow the power law $A^{2/3}$

These peculiarities of the reaction allow us to suggest the measuring of the tensor analyzing power A_{yy} in the inclusive deuteron breakup reaction $A(\overrightarrow{d}p)X$ at non-zero angle [37], where the part of additional to IA diagrams (virtual π production) can be neglected, and therefore, the obtained information is more easy to be interpreted in comparison with the polarization data obtained at zero angle.

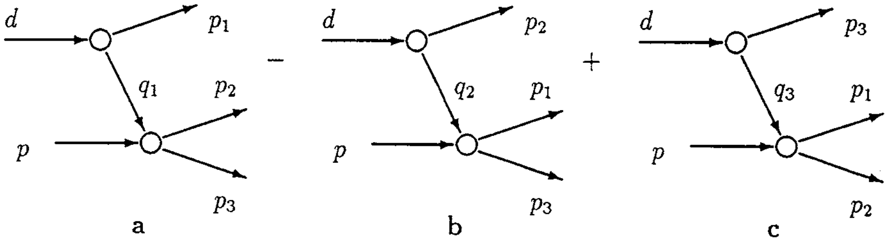

Fig.4. Impulse approximation diagrams describing the deuteron breakup on hydrogen at large transverse momenta of protons. Here d is an incident deuteron, p is a target proton, p_1 is a proton detected, q_1, q_2, q_3 are off-shell nucleons, and p_2, p_3 are nucleons

The global features of proton spectra in the region of the transverse momenta of 0.5—1 GeV/c produced in the $A(d, p)X$ reaction by unpolarized deuterons with the initial momentum of 9 GeV/c, were satisfactorily described taking into account only nucleon degrees of freedom by means of interfering sum of the three Feynman diagrams shown in Fig.4. Diagram (a) describes the detection of a proton emitted as a result of the deuteron direct fragmentation, and diagrams (b) and (c) correspond to the situation when the detected particle experiences an additional interaction.

The analysis of spin effects of mechanisms shown in Fig.4 was carried out in the paper of Azhgirey and Yudin [37]. The analyzing power T_{kq} for the $H(d, p)X$ reaction is defined in the standard manner:

$$T_{kq} = \frac{\sum \int Sp(\mathcal{M} t_{kq} \mathcal{M}^{\dagger}) d\tau}{\sum \int Sp(\mathcal{M}\mathcal{M}^{\dagger}) d\tau}. \tag{1}$$

Here $\mathcal{M}$ is the total amplitude of the mechanisms shown in Fig.4, $d\tau$ is the phase space element over that the summation is taken (in the case of an inclusive description of the reaction), and t_{kq} are the k-rank spin-tensor operators for the initial state.

As a result one can obtain the following expression for the tensor analyzing power T_{2q} taking into account the contributions of the direct fragmentation (diagram of Fig.4a) and hard scattering (diagrams of Fig.4b,c):

$$\begin{aligned} T_{2q} \left(\frac{p_{10} d\sigma}{d\mathbf{p}_1} \right)_0 &= \\ = \frac{2\sqrt{3}}{(2\pi)^3} \Bigg(F(x, \mathbf{p}_{1T}) \frac{I(n,p)}{I(d,p)} \frac{1}{(1-x)^2} \sigma(np \to pX) &+ \\ + \int F(y, \mathbf{q}_T) \frac{I(N,p)}{yI(d,p)} \frac{1}{y(1-y)} \frac{p_{10} d\sigma(Np \to p_1 X)}{d\mathbf{p}_1} dy\, d\mathbf{q}_T &+ \\ + (\textit{interference term}) \Bigg), \end{aligned} \tag{2}$$

where

$$F(x, \mathbf{p}_{1T}) = \sqrt{\frac{4\pi}{5}}\, Y_{2q}(\hat{\mathbf{k}}) \left(u(\mathbf{k})\, w(\mathbf{k}) - \frac{1}{2\sqrt{2}} w^2(\mathbf{k}) \right),$$

$(p_{10} d\sigma / d\mathbf{p}_1)_0$ is the invariant differential cross section for the fragmentation of unpolarized deuterons, $I(n, p)$, $I(d, p)$ are the invariant fluxes of the colliding particles, x and y have the meaning of fractions of the longitudinal deuteron momentum taken away in IMF by a spectator and the second fragment, respectively, and $\hat{\mathbf{k}}$ is the unit vector in the direction of the nucleon momentum $(x, \mathbf{k}_T)$ in the deuteron rest frame. The relation between the momentum $\mathbf{k}$ and the detected proton momentum $\mathbf{p}_1$ in the light front dynamics, where the deuteron is considered as a wave packet of two free nucleons, is determined on the basis of the expressions

$$x = \frac{p_{10} + p_{13}}{d_0 + d_3} = \frac{k_0 + k_3}{2k_0}, \quad \mathbf{p}_{1T} = \mathbf{k}_T, \quad x + y = 1, \tag{3}$$

with the result that

$$k_0^2 = \mathbf{k}^2 + m_N^2 = \frac{m_N^2 + \mathbf{k}_T^2}{4x(1-x)} .$$

The explicit expression for the (interference term) is too combersome to be given here; its contribution to the value of T_{2q} does not exceed few percent.

The predictions for the tensor analyzing powers T_{20} and T_{22}, which are simply related to A_{yy} :

$$A_{yy} = -\sqrt{2}\left[\frac{1}{2} T_{20} + \sqrt{\frac{3}{2}}\, T_{22} \right] \tag{4}$$

for the initial momentum 9 GeV/c and the proton angle in the laboratory 139 mrad are given in Ref.37. It was demonstrated the strong sensitivity of A_{yy} to the used DWF obtained from the different *NN* potentials. The calculations of A_{yy} at 80 mrad using the DWFs corresponding to the different *NN* potentials are shown in Fig.5. One can see that the using of Paris [36] and Reid [38] *NN* potentials gives the similar behaviour of A_{yy}, whereas the predictions of Bonn [39] and Moscow potentials [40] differ significantly even at relatively small momenta of proton.

Therefore, the measurements of the tensor analyzing power A_{yy} can be used as an independent test to make a choice between the different potentials.

The sufficient point of the hard scattering model is that the *NN* amplitude is purely non-spin-flip (this approximation seems to be reasonable in the momentum region under consideration, nearly ~5 GeV/c). As the consequence vector analyzing power iT_{11} (or A_y)

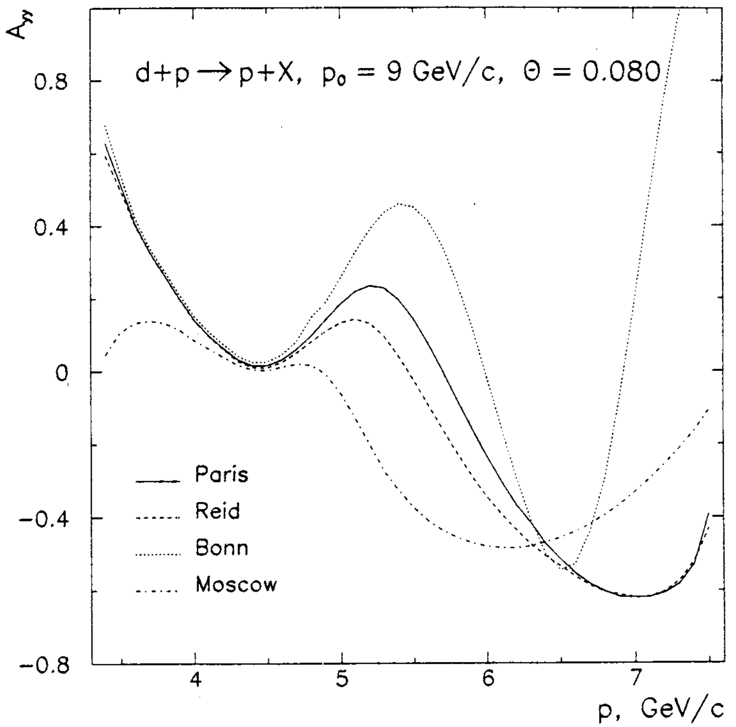

Fig.5. Tensor analyzing power A_{yy} in deuteron breakup reaction *H*(*d*, *p*)*X* at 9 GeV/c of the initial deuteron momentum and 80 mrad of the proton emission angle. The predictions for Paris [36], Reid [38], Bonn [39] and Moscow [40] *NN* potentials are given by the solid, dashed, dotted and dashed-dotted lines, respectively

equals zero. The value of this observable is very important to estimate the validity of the hard scattering model and the importance of the spin-flip amplitude of *NN* scattering at high energies. On the other hand, it would be extremely interesting to measure iT_{11} at lower energies, where spin-flip part of the amplitude is relatively large.

2. Experimental Method

We propose to measure the tensor analyzing power A_{yy} in the deuteron inclusive breakup process with the detection of the emitted proton at non-zero angle using a slow extracted polarized deuteron beam of LHE Accelerator Complex and SPHERE set-up (Fig.6).

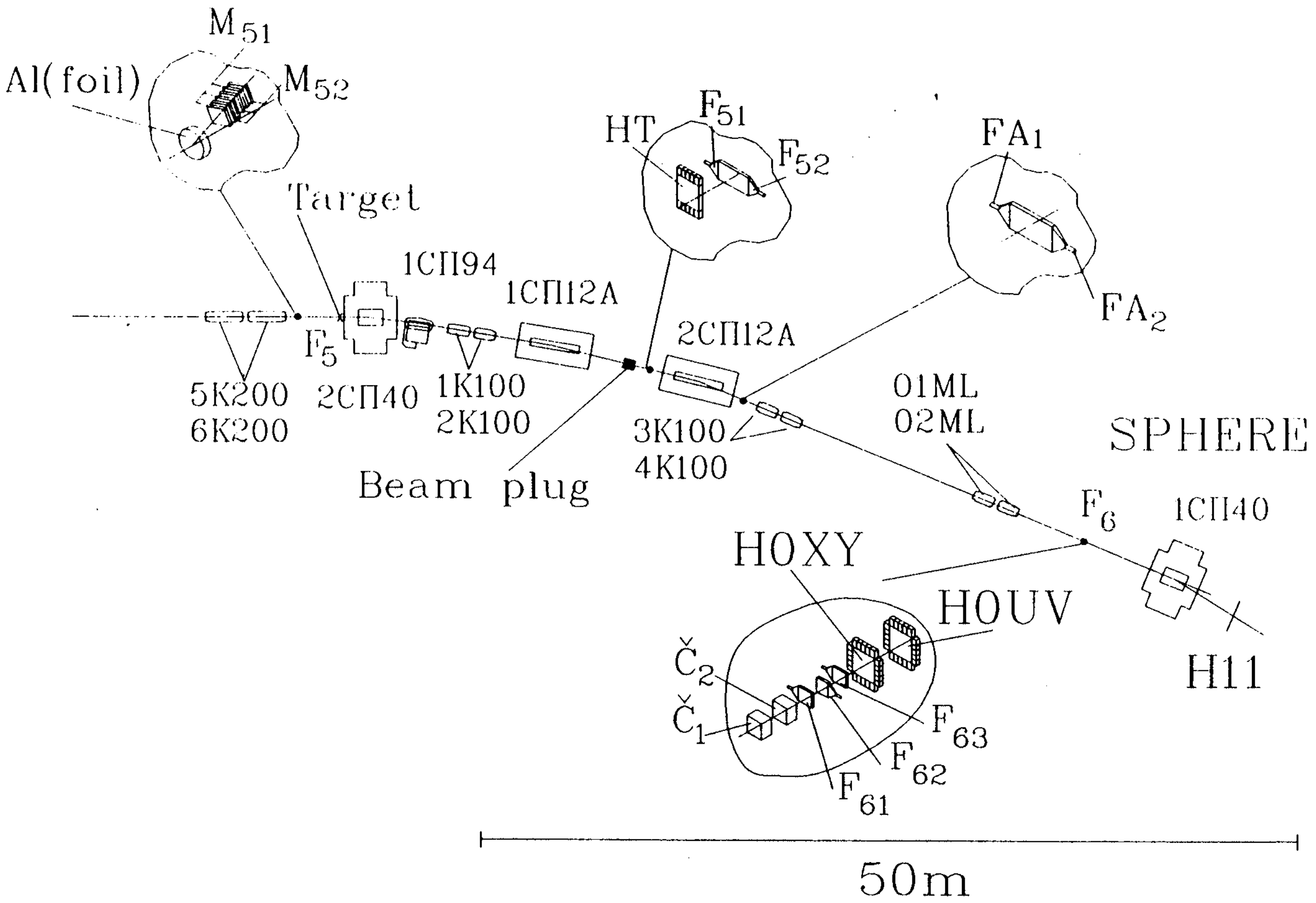

Fig.6. Layout of SPHERE set-up

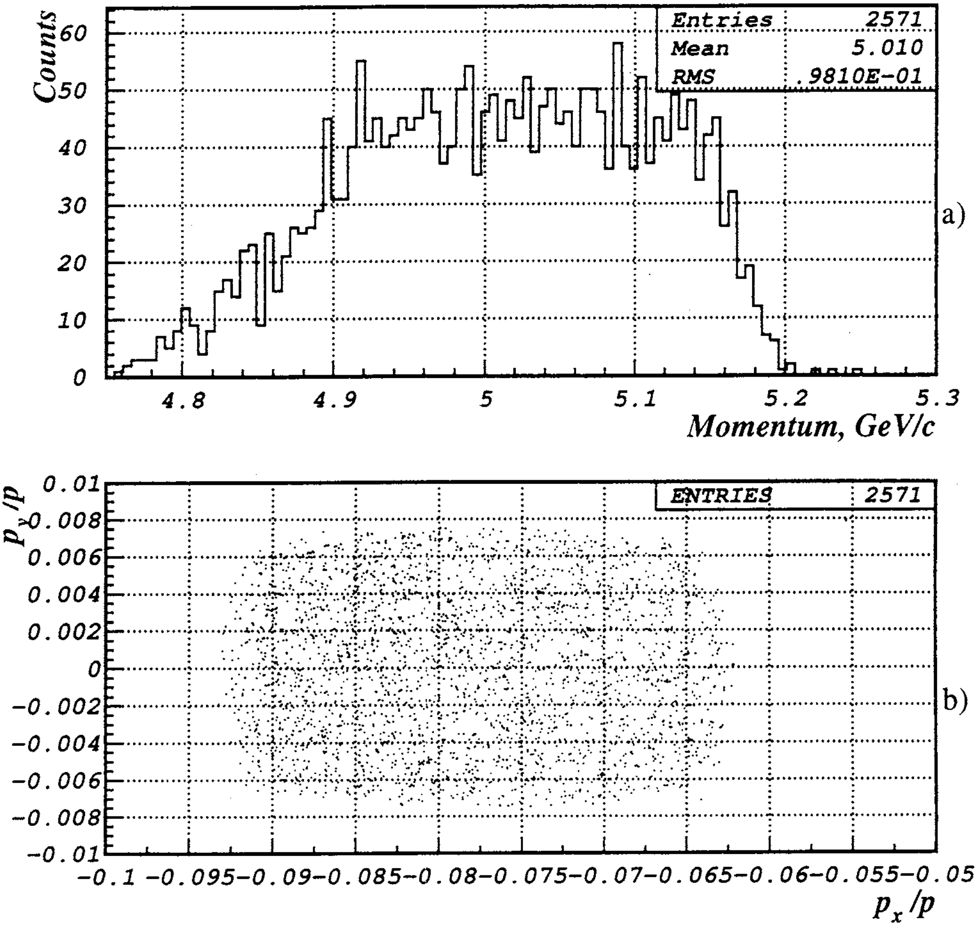

Fig.7. Results of the Monte-Carlo simulation for a) the momentum and b) the angular acceptances of the set-up

The momentum and angular acceptances of the set-up obtained from the Monte-Carlo simulation at ~80 mrad of the proton emission angle and 5 GeV/c of the proton momentum and presented in Fig.7 are $\Delta p/p \approx \pm 0.02$ and $\Delta\theta \approx \pm 8$ mrad, respectively.

The relative monitoring of the beam intensity will be provided by the ionization chamber disposed in front of the liquid hydrogen or carbon target placed at focus F5 of the beam transport line VP1. The counting rate from the scintillator counters telescopes M_{51}, M_{52} will be used as the independent relative monitors also. The measurement of the deuteron beam polarization will be done using ALPHA polarimeter [41] based on the *dp* elastic scattering as the analyzing reaction. The control of the beam polarization will be achieved using a relatively high energy polarimeter [42]. The absolute calibration will be

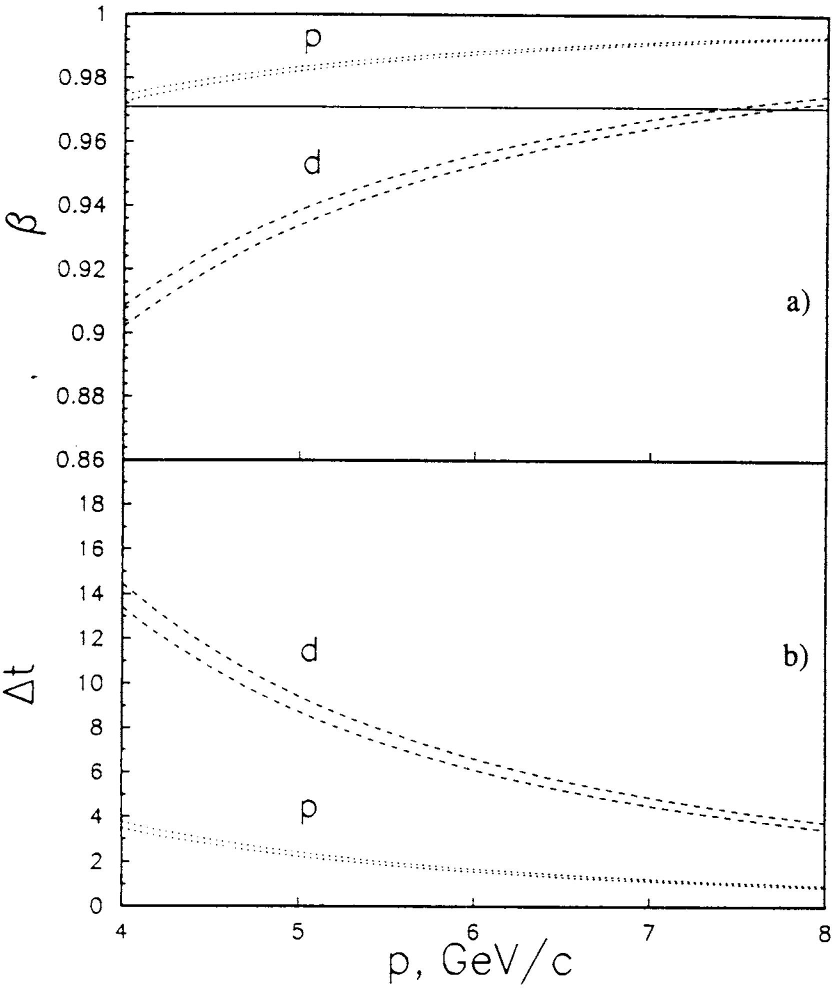

Fig.8. a) The separation of the protons and deuterons using the Cherenkov counter with the refractive index 1.033 (solid line); b) the protons and deuterons separation using time-of-flight information over the baseline ~40 m

provided by the measurements of the characteristic activities of ^{24}Na (or ^{11}C) in thin foil exposed in the beam just upstream of the target, what could give the accuracy in the determination of the cross section ~ ± 15%.

The main experimental problem is the identification and selection of the protons from the deuteron breakup against the inelastically scattered deuterons with the same momentum [43]. The suppression of the deuterons yield will be achieved by means of the Cherenkov counter at the trigger level ($\hat{C}_1$ in Fig.8). The range of the deuteron and proton velocities for the momentum acceptance $\Delta p/p \sim \pm 0.02$ is shown in Fig.8a by the dashed and dash-dotted lines, respectively. The solid line is critical velocity given by the refractive index of the Cherenkov counter as 1.033. One can see, that it is possible to separate the deuterons and protons at the trigger level at least up to their momentum ~7.2 GeV/c. The final identification of the particles will be provided using the time-of-flight information over the baseline ~40 m (Fig.8b).

The estimation of the beam time can be done using the published data [35] and the following parameters of the beam and set-up:

- The intensity of the polarized deuteron beam is $\sim 2 \cdot 10^9\ \vec{d}$/brust;
- The momentum acceptance is $\Delta p/p \approx \pm 0.02$;
- The solid angle is $\Delta\Omega \approx 5 \cdot 10^{-4}$ sr;
- The length of the target is 30 (15) cm of liquid hydrogen (carbon);
- The tensor and vector polarizations of the beam are $|p_{zz}| \sim 0.8$ and $|p_z| \sim 0.2$, respectively.

We would like to stress again the importance of using the 3-state beam in order to have the possibility of measuring A_y as for the test of validity of the hard scattering model, as well as to reduce the systematic error in the measurement of A_{yy} (if A_y is small).

The polarized cross section for different states of the beam polarization can be expressed:

$$N^+ = N^0\left(1 + \frac{3}{2}p_z^+ A_y + \frac{1}{2}p_{zz}^+ A_{yy}\right),$$

$$N^- = N^0\left(1 + \frac{3}{2}p_z^- A_y + \frac{1}{2}p_{zz}^- A_{yy}\right), \qquad (5)$$

where N^0 is the non-polarized cross section, A_{yy} and A_y are the tensor and vector analyzing powers, p_{zz}^+ and p_z^+ are the tensor and vector polarization of the beam. Since for 3-state beam $p_{zz}^+ \approx -p_{zz}^-$ and $p_z^+ \approx p_z^-$, the tensor and vector analyzing powers can be obtained as:

$$A_{yy} = \frac{1}{p_{zz}}\frac{N^+ - N^-}{N^0}, \quad A_y = \frac{1}{3p_z}\frac{N^+ + N^- - 2N^0}{N^0}. \qquad (6)$$

The corrsponding error bars are:

$$\Delta A_{yy} \approx \frac{\sqrt{6}}{p_{zz}}\frac{1}{\sqrt{N_{\text{event}}}}, \quad \Delta A_y \approx \frac{\sqrt{2}}{p_z}\frac{1}{\sqrt{N_{\text{event}}}}. \qquad (7)$$

With the typical values of the beam polarization for 3-states $|p_{zz}| \sim 0.8$ and $|p_z| \sim 0.2$ and $3 \cdot 10^4$ of useful events for one setting we expect the error bars as 0.02 and 0.05 for A_{yy} and A_y, respectively.

At the first stage of the experiment one can measure A_{yy} at 2 energies (9 and 3.5 GeV/c) and 2 angles (80 and 130 mrad) with the hydrogen and isoscalar (carbon) target.

3. Conclusions

The observed features of the cross section of the $A(d,p)X$ reaction at large transverse momenta of proton; i.e., weak dependence of the shape of the cross section on the A value of the target in the region of large proton momenta in the deuteron and the sensitivity to *NN* potential give serious motivation to use this reaction to extract the information about the high momentum tail of the DWF. The proposed experiment on the study of the tensor analyzing power A_{yy} in deuteron inclusive breakup at non-zero angle could provide the new independent source of information about deuteron spin structure at short internucleon distances up to transverse momenta ~1 GeV/c.

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