Spin Effects in the Reactions with Relativistic Deuterons

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Introduction

Deuteron properties are divisible into two essentially different parts.

- Hystorically the problem of non-relativistic treatment of the deuteron has occupied the first place. Such deuteron properties as `the binding energy, radius, quadrupole and magnetic moments, mixing of states with different orbital momenta, main mechanisms of processes with deuteron, etc.` depend, to a first approximation, on the non-relativistic motion of nucleons. They were experimentally well measured and theoretically understood in terms of non-relativistic quantum theory.

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- However, as energies of deuterons and momenta of their nucleons increase, one enters the area of **relativistic physics**. Relativistic phenomena should play a very important role at sufficiently small internucleon distances and also in the dynamics of collisions of deuterons at high energies.

Relativism sources

Relativistic aspects of the deuteron structure and dynamics arise from two different sources.

- Above all, they arise when internal momenta of nucleons become sufficiently high. They take place in the rest frame of the deuteron and are important for consideration of **the short range correlations**.

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Relativistic aspects of the deuteron structure and dynamics arise from two different sources.

- Above all, they arise when internal momenta of nucleons become sufficiently high. They take place in the rest frame of the deuteron and are important for consideration of **the short range correlations**.
- Another source of relativistic effects is **the motion of the deuteron as a whole**.

Internal and external motions

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- However in many cases colliding systems cannot be put into the rest frame of the deuteron, and it is necessary to analyze experiments with quickly moving deuterons.
- In such cases one comes up against the problem of the interrelation between internal and external motions.

Experiments with moving deuteron

In a sense, the main difficulty is the dependence of the internal wave function on the total momentum of the deuteron, i.e. **inseparability of the internal motion from the external one**.

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- The most clear way of doing this is to work with the Feynman diagram formalism (i.e. **quantum field formalism**), where amplitudes are explicitly Lorenz-invariant.
- However, here one is up against a very nontrivial problem of obtaining full vertices and propagators.

Infinite momentum frame

Eventually, alternative approaches to treatment of the relativistic deuteron were developed.

- The method closest to the usual Feynman technique is the use of **an infinite momentum frame**, i.e. a special frame where the deuteron momentum tends to infinity in the limit [*S.Weinberg*]. The same results may be obtained by employing a special way of quantization of relevant fields — **quantization on the light front** [*P.A.M.Dirac, S.Brodsky*].

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- The main advantage of these approaches is the disappearance of some subsets of the diagrams (back-going diagrams) and the possibility of introducing the concept of the internal wave function with a property of being independent of the total (external) momentum of the deuteron. [*V.Karmanov, J.Carbonell*].

Hamiltonian theory with interaction

- Another approach to treat relativistic composite systems is based on special insertion of the interaction into the Hamiltonian theory of two- and three-particle systems, so that the relevant Schrödinger equation turns out to be relativistic invariant. This approach is usually called **the relativistic quantum theory** [*F.Coester, B.Keister*].

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- Thus, at the moment there are different approaches to treating the relativistic properties of composite systems.

Forms of dynamics

- Each form of dynamics is associated with **a hypersurface** on which the commutation relations for the generators of Poincaré group are defined, or the way the 10 generators are split into **kinematical** and **dynamical** ones.

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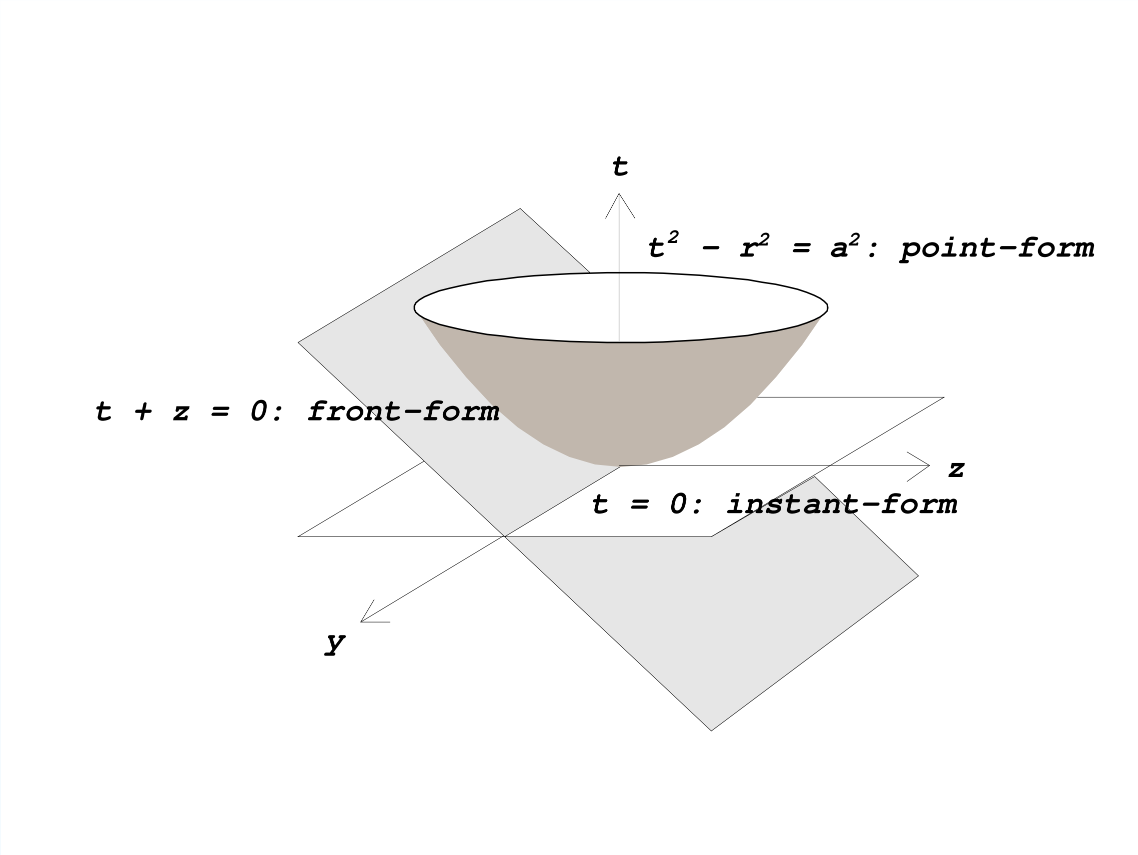
forms of dynamics	kinematical generators	dynamical generators
time instant	p_1, p_2, p_3 J_1, J_2, J_3	p_0 K_1, K_2, K_3
light front	$p^+ = p_0 + p_3, p_1, p_2$ $E_1 = \frac{1}{2}(K_1 + J_2)$ $E_2 = \frac{1}{2}(K_2 - J_1)$ K_3, J_3	$p^- = p_0 - p_3$ $F_1 = K_1 - J_2$ $F_2 = K_2 + J_1$

Hypersurfaces of different forms of dynamics



In place of the usual spatial coordinate system (t, x, y, z), light-front dynamics makes use of the light-front coordinate system (x^+, x^-, x, y), with $x^\pm = t \pm z$. A four-vector is expressed as (p^+, p^-, p_1, p_2), where $p^\pm = p_0 \pm p_3$.

From sross-sections to polarization measurements

The above considerations have made the investigation of relativistic deuteron collisions very desirable, and it has sufficiently long history.

- At first **the momentum distribution** of the proton emerging from the deuteron as a result of some simple mechanisms was usually investigated. Those data can be interpreted within the framework of the light-front dynamics with the pole mechanisms [*L.S.Azhgirey et al.,NP A528(1991)621*].

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- Later the possibility of measuring **the spin properties** of collisions of relativistic deuterons with nuclei appeared. Investigation of polarization observables in the high-energy processes with deuterons are particularly well suited to study the short range structure of the deuteron.

Failure of non-relativistic description

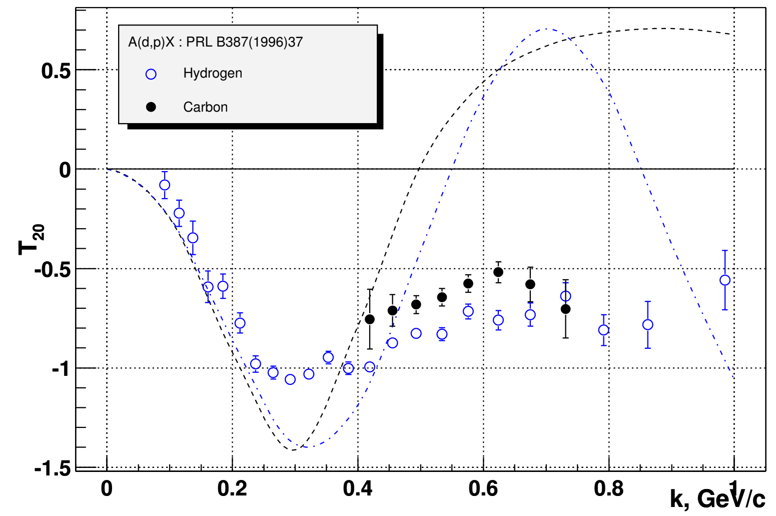
Investigations of polarization properties of the deuteron fragmentation reaction (d, p) [*Saclay; Dubna*] have amassed a convincing body of evidence that the description of the deuteron structure by means of wave functions derived from non-relativistic functions through **the kinematical transformation 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.

T_{20} of deuteron breakup vs k

The expression for the tensor analyzing power T_{20} of deuteron breakup in the impulse approximation has the form

$$T_{20} \sim w(k)[\sqrt{8}u(k) - w(k)],$$

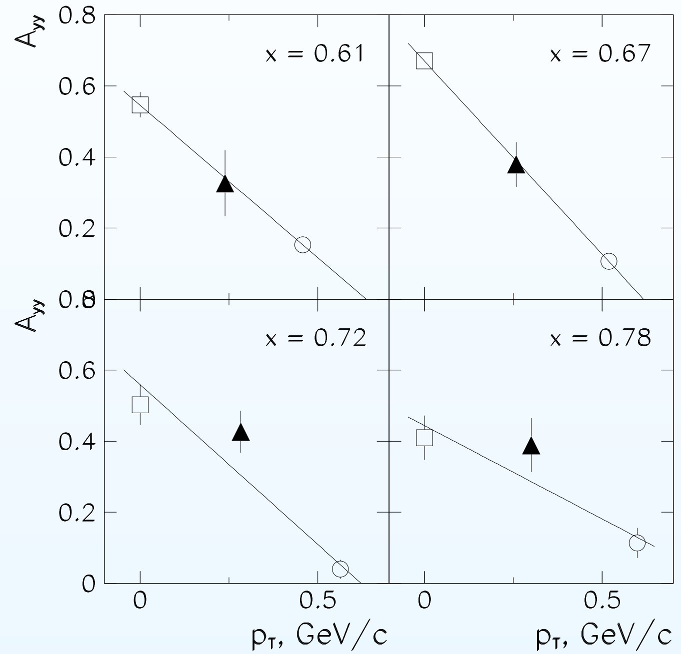
where $u(k)$ and $w(k)$ are the deuteron momentum space wave functions for S and D states, respectively, and k is the internal momentum of the nucleons in the deuteron. With standard deuteron wave functions, the T_{20} dependence on k can be expected to change the sign at $k \sim 0.5$ GeV/c, but this expectation lacks support from experiment.



The T_{20} dependence on k in inclusive deuteron breakup at 9 GeV/c and 0° on hydrogen and carbon [*L.S.Azhgirey et al., PLB 387(1996)37*].

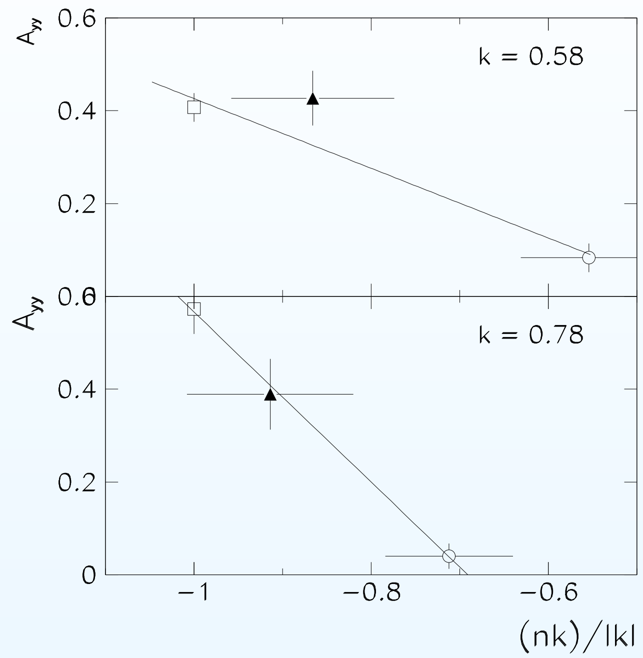
A_{yy} of deuteron breakup vs p_T

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 [*L.S.Azhgirey et al., YaF 66(2003)719*] show that the measured A_{yy}-values at fixed value of the longitudinal proton momentum have the dependence on the transverse proton momentum p_T that differs from that calculated with standard deuteron wave functions.



A_{yy} data vs p_T at fixed $x = 0.61, 0.66, 0.72$, and 0.78. The open circles, solid triangles, and open squares represent the data at 9 GeV/c and $0°$, 4.5 GeV/c and 80 mr, and 9 GeV/c and 85 mr, respectively.

A_{yy} of deuteron breakup vs $(\mathbf{n} \cdot \mathbf{k})$

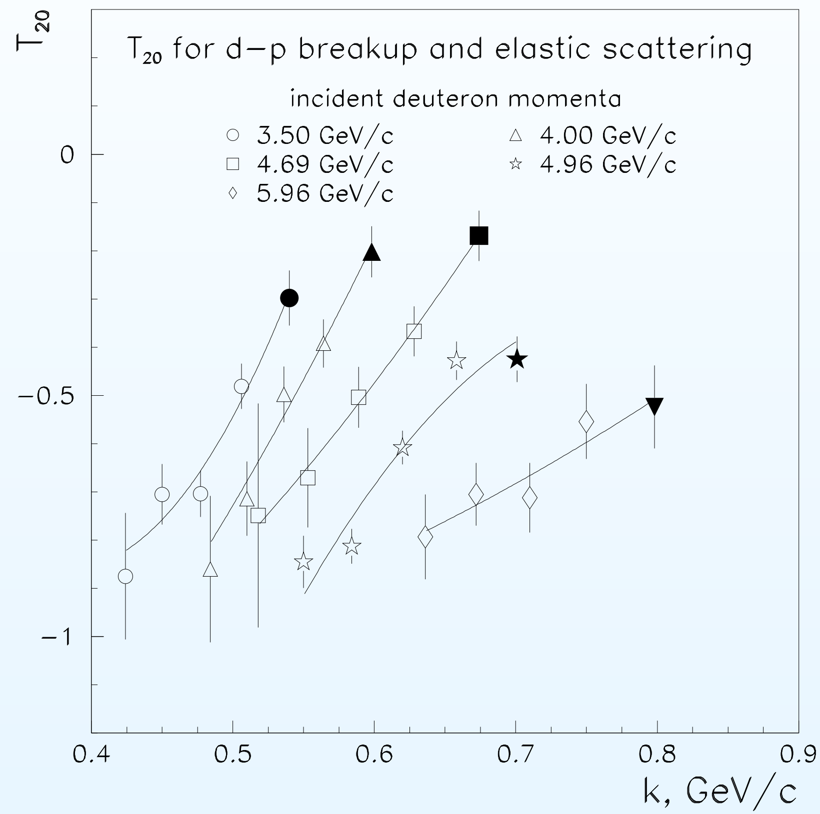


The above-mentioned data show that the values of A_{yy} being plotted at fixed values of k tend to decrease as the variable $(\mathbf{n}\cdot \mathbf{k})$ grows (vector $\mathbf{n}$ is the unit normal to the surface of the light front).

A_{yy} data vs the $(\mathbf{n} \cdot \mathbf{k})$ variable at fixed k of ~ 560 and ~ 740 MeV/c. The open circles, solid triangles, and open squares represent the data obtained at 9 GeV/c and $0°$, 4.5 GeV/c and 80 mr, and 9 GeV/c and 85 mr, respectively.

Pion-free deuteron breakup process

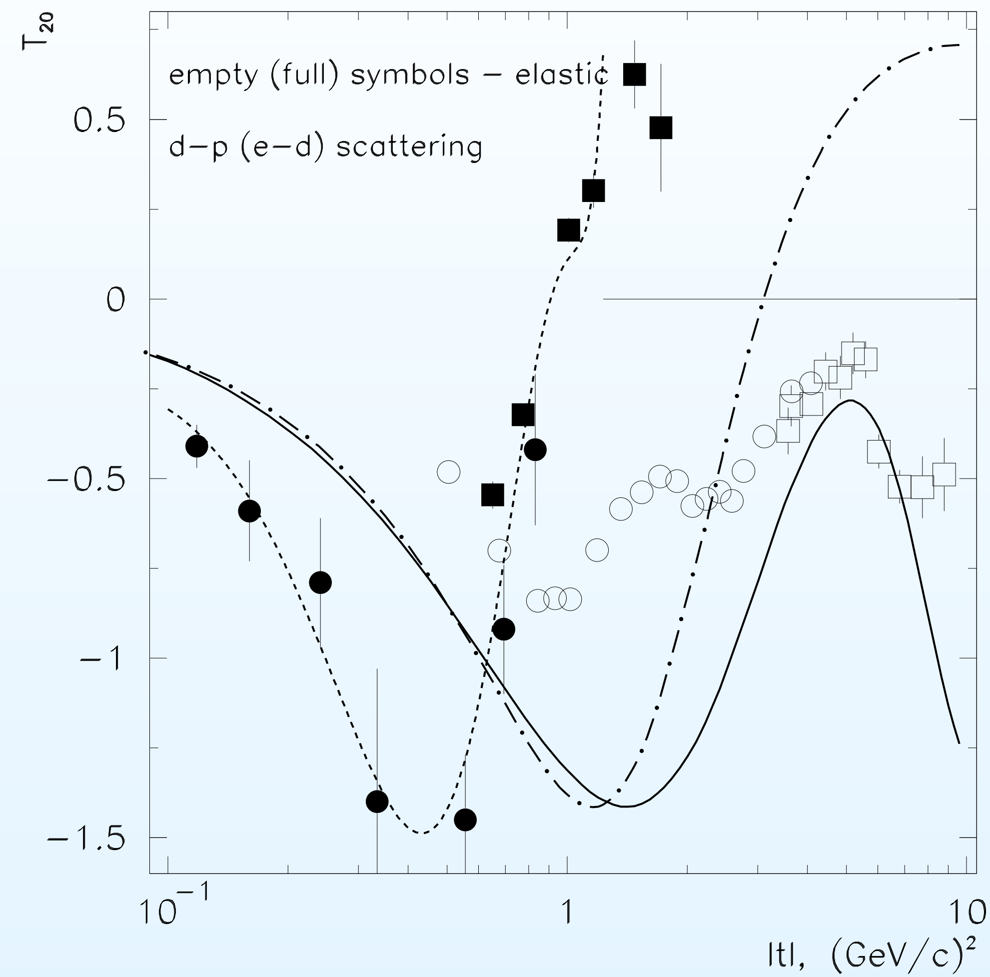
The pion-free deuteron breakup process $dp \to ppn$ in the kinematical region close to that of backward elastic dp scattering at a given value of k depends on the incident momentum of deuteron [L.S.Azhgitey et al. PLB 44(1997)444]



The T_{20} dependence of deuteron breakup on k at different initial deuteron momenta.

Investigations with EM probes

It should be noted that different aspects of deuteron structure are explored by means of electromagnetic and hadron probes. To realize this, it is instructive to compare t-dependencies of the tensor analyzing power T_{20} for elastic ed [M.Garcon et al.; D.Abbott et al.] and backward dp [V.Punjabi et al.; L.Azhgirey et al.] scatterings.



Data on the deuteron breakup

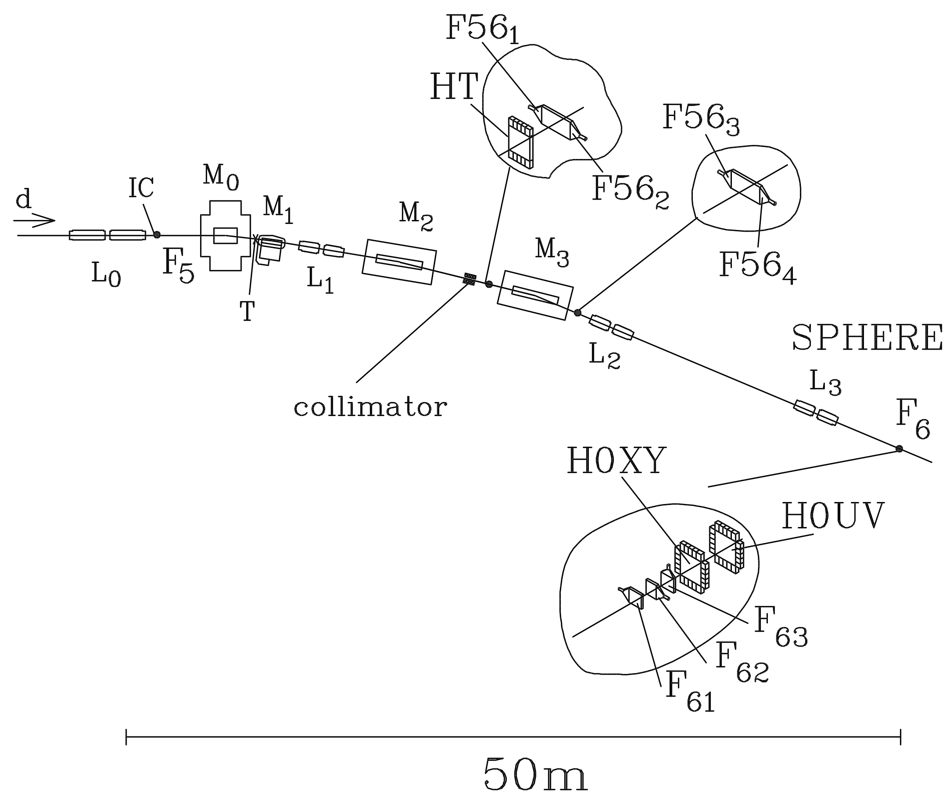
The aim of this report is to compare existing data on the tensor analyzing power A_{yy} of (d,p) reaction with predictions of a relativistic description based on the light-front dynamics.

In the region of large transverse momenta, parameter A_{yy} of the deuteron breakup on nuclei was measured at the following conditions.

deuteron momentum, GeV/c	proton emission angle	target	reference
9	0.085	^{12}C	S.V.Afanasiev et al.,PL B434(1998)21 L.S.Azhgirey et al.,YF 62(1999 1796
4.5	0.080	^{9}Be	V.P.Ladygin et al. F-B Syst. 32(2002)127 L.S.Azhgirey et al.,YF 66(2003)719
5	0.180	^{9}Be	L.S.Azhgirey et al.,PL B595(2004)151

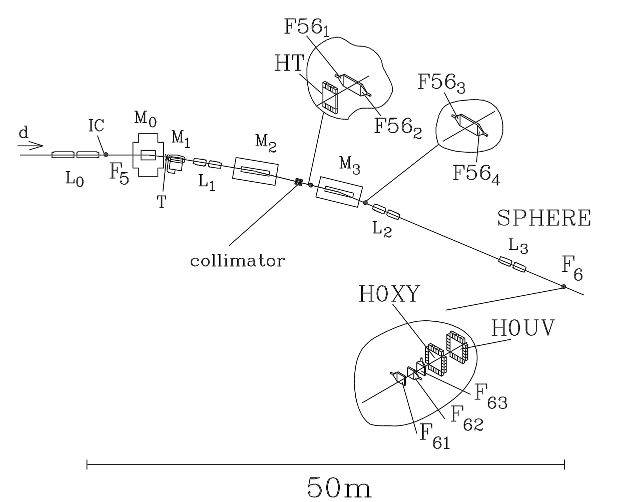
Layout of experiments

Experiments on the measurements of the tensor analysing power $A_(yy)$ of the deuteron breakup with the proton emission at nonzero angles were performed with a polarized deuteron beam from the Dubna Synchrophasotron and the SPHERE setup described elsewhere [*S.V.Afanasiev et al.,PL B434(1998)21*].

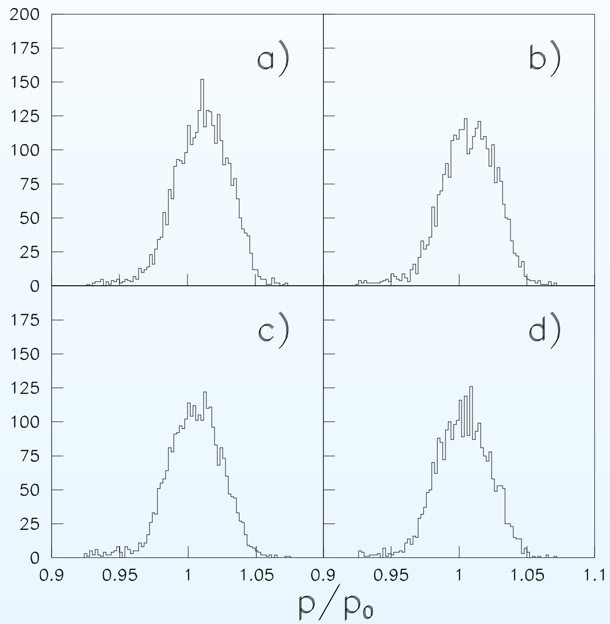


Setup characteristics in 5 GeV/c-deuteron run

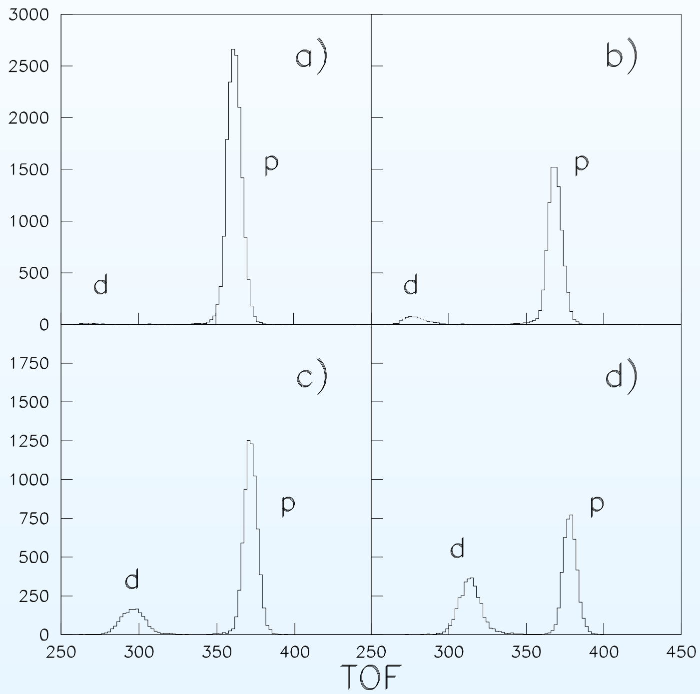
beam momentum	5 GeV/c
beam intensity	5$\cdot 10^8$ d/spill
tensor polarization	$p_{zz}^+ = 0.716 \pm 0.043$
	$p_{zz}^- = -0.756 \pm 0.027$
vector polarization	$p_z^+ = 0.173 \pm 0.008$
	$p_z^- = 0.177 \pm 0.008$
beam sizes	$\sigma_x \sim 4mm,\ \sigma_y \sim 9mm$
target	Be, 16 cm thick
angle of detection	178 mr
momenta of secondaries	2.7, 3.0, 3.3, 3.6 GeV/c
momentum acceptance	$\Delta p/p \sim \pm 2\%$
polar angle acceptance	± 18 mr
TOF base line	28 m
TOF resolution	0.2 ns



Acceptances, TOF

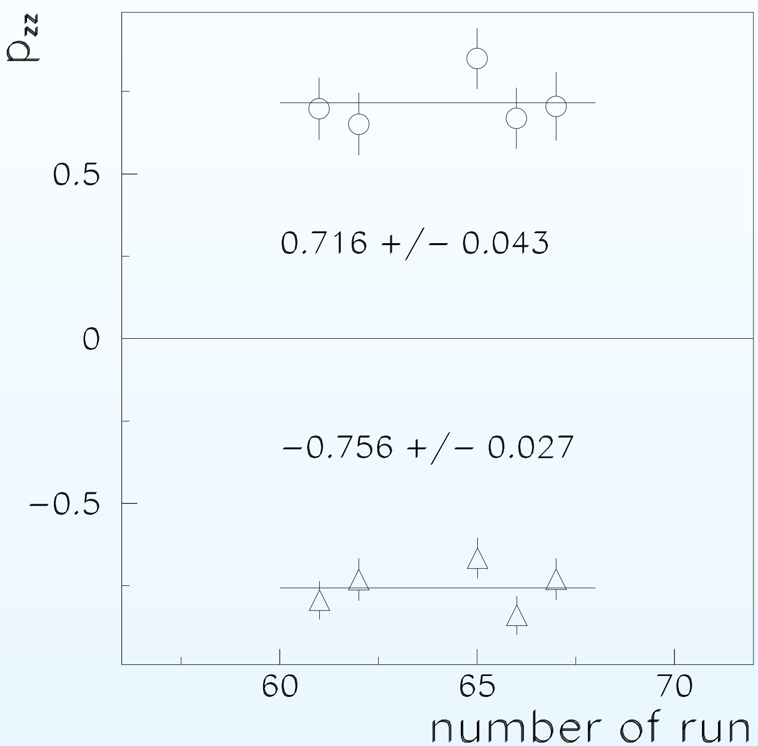


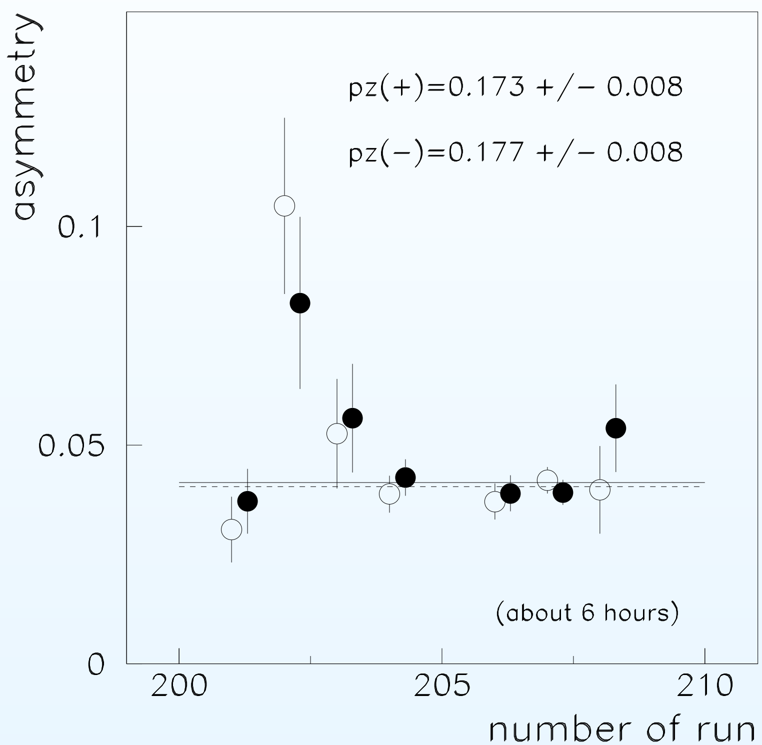
The momentum acceptances of the setup for protons at secondary proton momenta of 2.7, 3.0, 3.3, and 3.6 GeV/c.



The TOF spectra for different magnetic elements tuning.

Beam polarizations





Tensor polarization of the deuteron beam in the experiment.

Asymmetry during monitoring vector component of the deuteron beam polarization.

Necessity of two independent variables

- From the comparison of the data obtained at 4.5 GeV/c [*L.S.Azhgirey et al.,YF 66(2003)719*] with those at 9 GeV/c for the zero proton emission angle [*L.S.Azhgirey et al.,PL B387(1996)37*] and a proton emission angle of 85 mrad [*S.V.Afanasiev et al.,PL B434(1998)21*] it was concluded that the relativistic deuteron structure function needs to be described with two **independent** variables — longitudinal and transverse components of the internal motion momentum.

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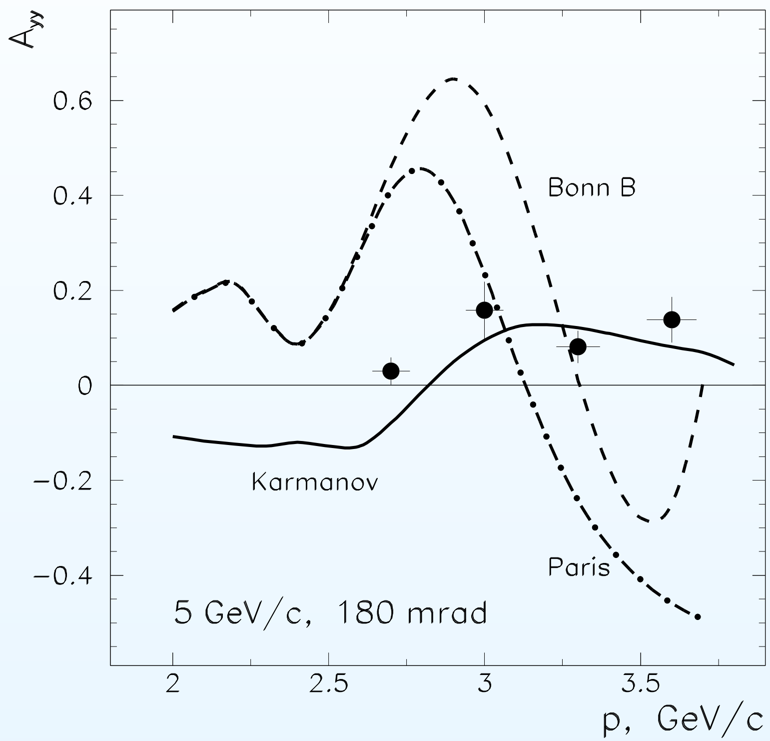
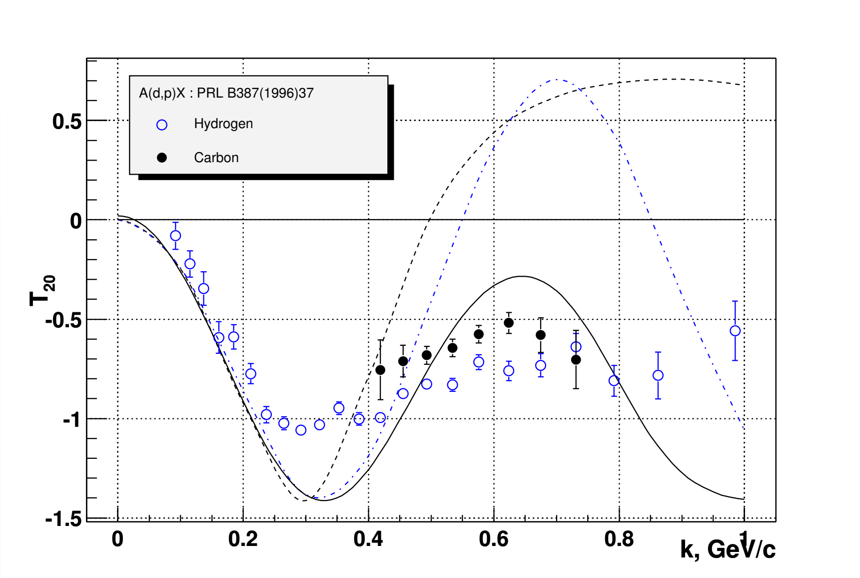
- On the other hand, the behaviour of the A_{yy} data at 5 GeV/c [*L.S.Azhgirey et al.,PL B595(2004)151*] has been explained within the framework of the light-front dynamics using Karmanov's relativistic deuteron wave function without invoking non-nucleonic degrees of freedom.

Description with Karmanov's relativistic DWF



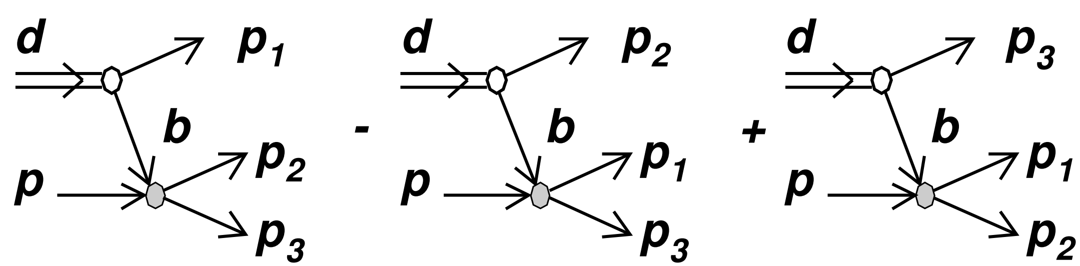
A_{yy} of the reaction ^{9}Be$(d,p)X$ at 5 GeV/c and 178 mr vs detected proton momentum p.



T_{20} of the (d,p) reaction on hydrogen and carbon at 9 GeV/c with the emission of protons at 0° vs internal momentum k.

Mechanism of the deuteron breakup

The mechanism of the deuteron breakup on protons ${}^1H(d,p)X$ can be in the simplest case represented by the Feynman diagrams:



Here d is the incoming deuteron, p is the target proton, b is the virtual off-shell nucleon, p_1 is the detected proton, and p_2, p_3 are nucleons. 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.

Tensor analyzing power

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

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

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

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

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

$$\mathcal{M}_a = \frac{\mathcal{M}(d \to p_1 b)}{(1-x)(M_d^2 - M^2(k))} \mathcal{M}(bp \to p_2 p_3),$$

where $\mathcal{M}(d \to p_1 b)$ is the amplitude of the deuteron breakup and $\mathcal{M}(bp \to p_2 p_3)$ is the amplitude of the reaction $bp \to p_2 p_3$.

Light-front variables

The ratio

$$\psi(x, p_{1T}) = \frac{\mathcal{M}(d \to p_1 b)}{M_d^2 - M^2(k)}$$

is nothing but the wave function in the channel $(b,\, N)$; 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 by

$$x = \frac{E_p + p_{pl}}{E_d + p_d}, \quad k = \sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{4x(1-x)} - m_p^2},$$

where E_d and p_d are the energy and the momentum of the incoming deuteron, respectively, p_{pl} is the longitudinal component of $\mathbf{p}_1$, and m_p is the mass of the nucleon.

Relativistic deuteron wave function

The relativistic deuteron wave function in the light-front dynamics was found in ref. [*J.Carbonell and V.A.Karmanov, NP A581(1994)625*]. It is determined by six invariant functions $f_1, ..., f_6$, each of them depending on two scalar variables k and $z = cos(\widehat{\mathbf{kn}})$, and has the following form:

$$\psi(\mathbf{k},\, \mathbf{n}) = \frac{1}{\sqrt{2}}\sigma f_1 + \frac{1}{2}\left[\frac{3}{k^2}\mathbf{k}(\mathbf{k}\cdot\sigma) - \sigma\right] f_2 + \frac{1}{2}\left[3\mathbf{n}(\mathbf{n}\cdot\sigma) - \sigma\right] f_3 +$$

$$\frac{1}{2k}[3\mathbf{k}(\mathbf{n}\cdot\sigma) + 3\mathbf{n}(\mathbf{k}\cdot\sigma) - 2\sigma(\mathbf{k}\cdot\mathbf{n})]f_4 + \sqrt{\frac{3}{2}}\frac{i}{k}[\mathbf{k}\times\mathbf{n}]f_5 + \frac{\sqrt{3}}{2k}[[\mathbf{k}\times\mathbf{n}]\times\sigma]f_6.$$

Here $\mathbf{n}$ is the unit normal to the light front surface, and σ are the Pauli matrices; $\mathbf{n}$ is defined by

$$(\mathbf{n}\cdot\mathbf{k}) = (\frac{1}{2} - x)\cdot\sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{x(1-x)}},$$

It will be assumed further that $\mathbf{n}$ is directed opposite to the beam direction, i.e. $\mathbf{n} = (0,\ 0,\ -1)$.

Analyzing power

The final expression for the analyzing power has the form

$$
\begin{aligned}
T_{2q}\left(\frac{p_{10}d\sigma}{d\mathbf{p}_1}\right)_{un} &= \frac{1}{2(2\pi)^3}\left\{\frac{I(b,p)}{I(d,p)(1-x)^2}\rho_0(2,q)\sigma(bp\to p_2X)\right. \\
&+ \int\frac{dyd\mathbf{p}_{2T}}{2y(1-y)}\frac{I(b,p)}{(1-y)I(d,p)}\rho_0(2,q) \\
&\times \left.\frac{p_{20}d\sigma}{d\mathbf{p}_2}(bp\to p_2X)[1+\mathbf{P}\cdot<\sigma>]\right\}.
\end{aligned}
$$

$(p_{10}d\sigma/d\mathbf{p}_1)_{un}$	=	cross section for unpolarized deuterons,
$I(b,p), I(d,p)$	=	invariant fluxes of the appropriate particles,
$<\sigma>$	=	vector analyzing power of NN-scattering,
$\sigma(bp\to p_2X)$	=	total cross section of NN-scattering,
$\mathbf{P}$	=	polarization vector of the nucleon in the deuteron,
$\rho_0(2,q)$	=	density matrices.

Input data for calculations

It should be emphasized that the problem has no adjusted parameters. Input data were the following.

- The invariant differential cross sections of processes taking place in the low vertices of the pole diagrams were taken into account according to the known parameterizations [*L.Azhgirey et al., YF 46(1987)1657*].

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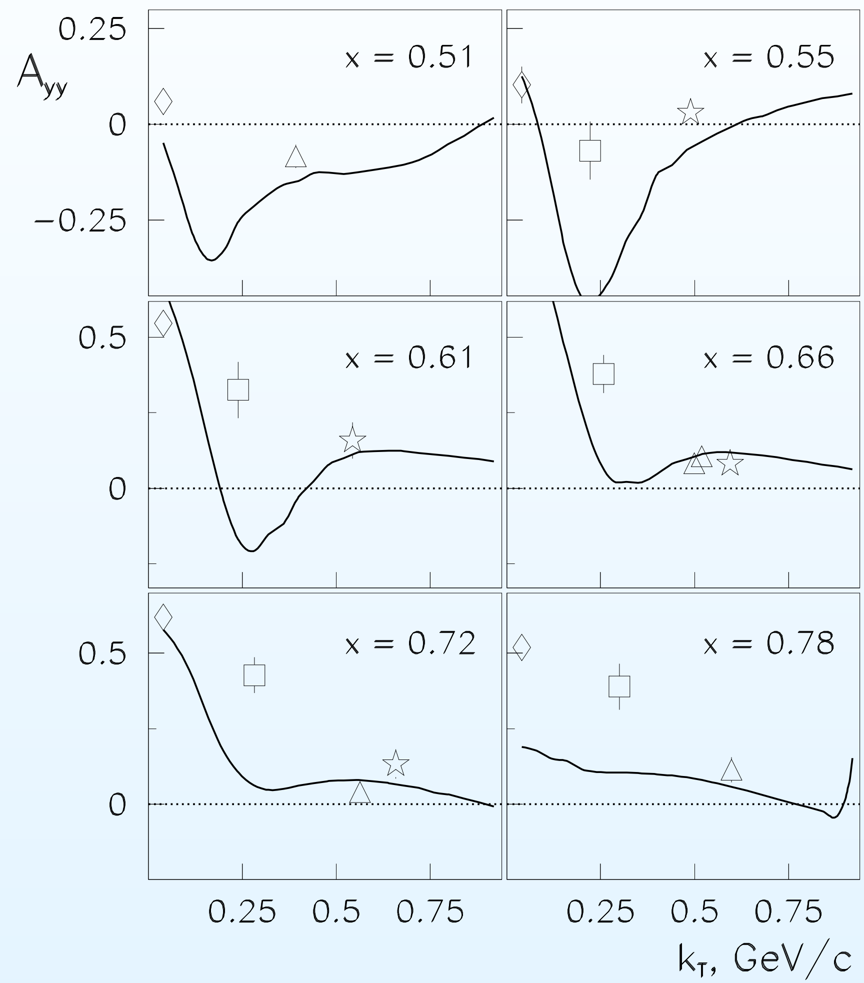
- The invariant differential cross sections of processes taking place in the low vertices of the pole diagrams were taken into account according to the known parameterizations [*L.Azhgirey et al., YF 46(1987)1657*].
- To obtain the values of the invariant functions $f_i(k, z)$ required for calculations, the spline-interpolation procedure between the table values given in Ref. [*J.Carbonell and V.A.Karmanov, NP A581(1994)625*] was used.

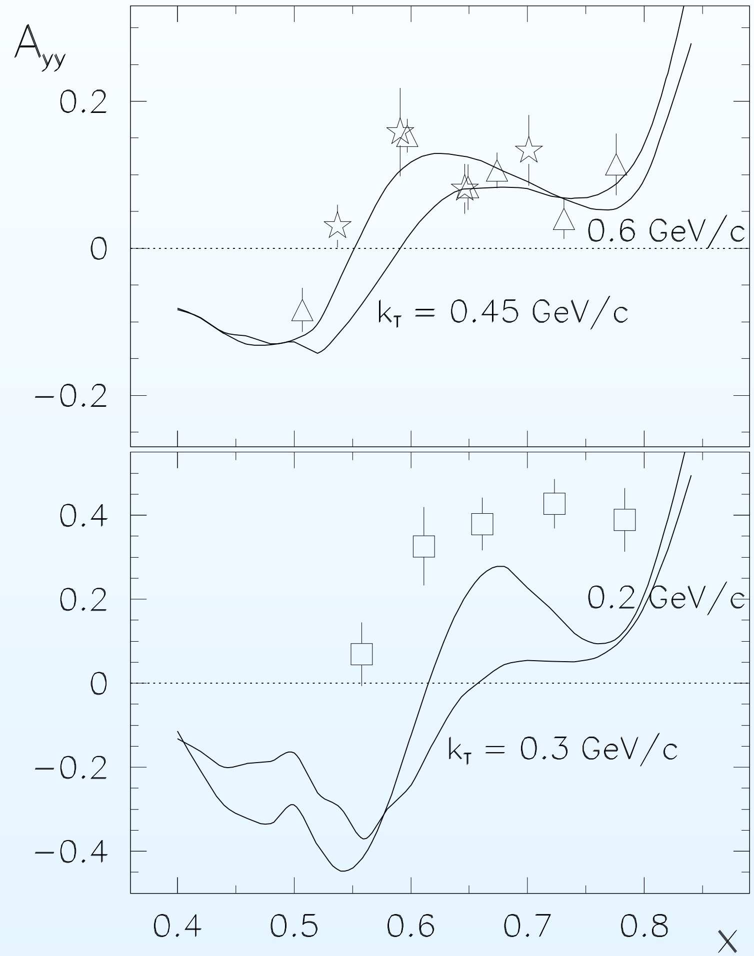
A_{yy} vs k_T

Data on A_{yy} of the reaction $A(d,p)X$ as a function of the transverse momentum k_T near fixed longitudinal momentum fractions $x \sim$ 0.51, 0.55, 0.61, 0.66, 0.72 and 0.78. Data were obtained on C at 9 GeV/c and 85 mrad (triangles), on Be at 4.5 GeV/c and 80 mrad (squares), on Be at 5 GeV/c and 180 mrad (stars), and on C at 9 GeV/c and 0 mrad (diamonds). The solid curves were calculated with Karmanov's relativistic deuteron wave function.



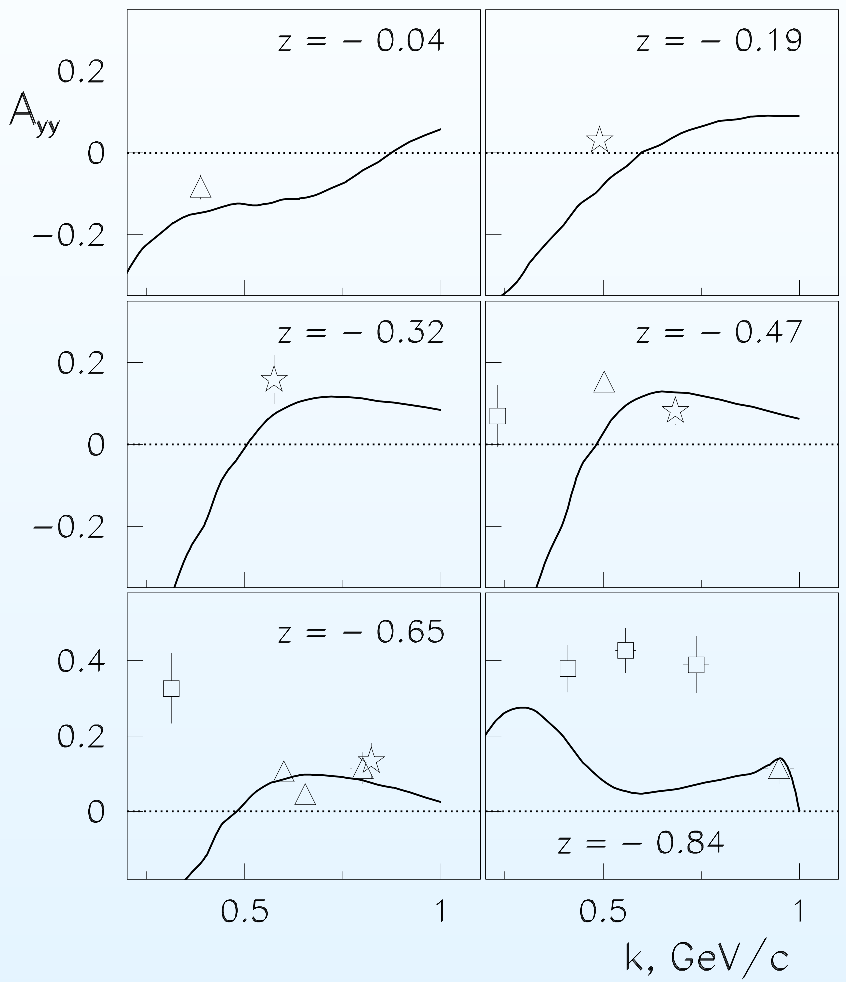
A_{yy} vs x

Data on A_{yy} of the reaction $A(d,p)X$ as a function of the longitudinal momentum fractions x at different transverse momenta k_T. Data were obtained on C at 9 GeV/c and 85 mrad (triangles), on Be at 4.5 GeV/c and 80 mrad (squares), and on Be at 5 GeV/c and 180 mrad (stars). The solid curves were calculated with Karmanov's relativistic deuteron wave function.



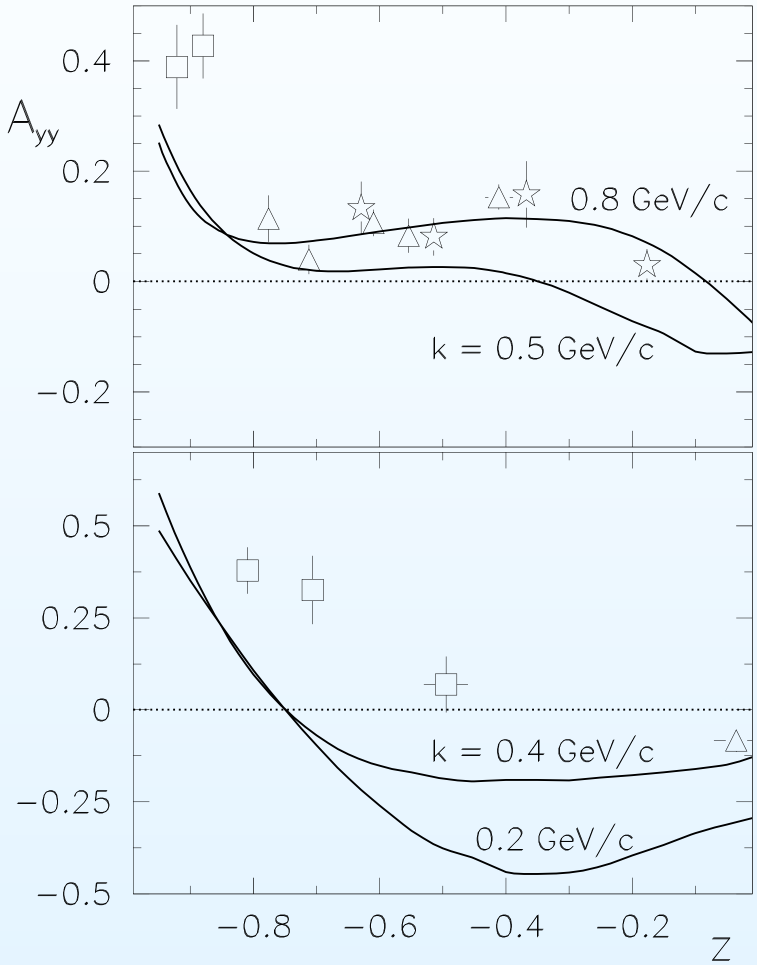
A_{yy} vs k

Data on A_{yy} of the reaction $A(d,p)X$ as a function of the momentum k near fixed values $z \sim -0.04, -0.19, -0.32, -0.47, -0.68,$ and -0.84. Data were obtained on C at 9 GeV/c and 85 mrad (triangles), on Be at 4.5 GeV/c and 80 mrad (squares), and on Be at 5 GeV/c and 180 mrad (stars). The solid curves were calculated with Karmanov's relativistic deuteron wave function.



A_{yy} vs z

Data on A_{yy} of the reaction $A(d,p)X$ as a function of the value z at different momenta k. Data were obtained on C at 9 GeV/c and 85 mrad (triangles), on Be at 4.5 GeV/c and 80 mrad (squares), and on Be at 5 GeV/c and 180 mrad (stars). The solid curves were calculated with Karmanov's relativistic deuteron wave function.



Constistently relativistic description

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- It is shown that the use of the wave function found by Carbonell and Karmanov allows the reasonable agreement of the calculations with experiment in many cases, contrary to use of standard non-relativistic deuteron wave functions.
- The main difference between Karmanov's and non-relativistic wave functions is their **different dependence** on the longitudinal and transverse internal momenta.

Taking into account additional mechanisms

- The usual non-relativistic function is represented as the linear superposition of the functions of the variables k and Ω — the superposition of usual S- and D-waves. In Karmanov's function partitioning variables are made in another way: the wave function is the function of the independent variables x and k_T, where x is the longitudinal part of the total momentum of the deuteron and k_T is the transverse part of the relative momentum of the nucleons. This function should differ greatly from the usual superposition of S- and D-waves. In our opinion, this point is nontrivial and may correspond, in terms of the usual dynamics, to taking into account, in the hidden form, some additional mechanisms.

Advantage of Karmanov's approach

- An additional advantage of Karmanov's approach may be the choice of a special frame. One directs the z-axis along the beam direction. It breaks the rotation symmetry of the theory. We suppose that one should not follow hard the covariant consideration. The wave function in general depends on the choice of the frame and if one "guesses" a correct system, the consideration will be more simple. We consider our choice as the most natural and useful one.

Further prospects

However, a general conclusion is that one can do no more than speak about qualitative agreement of the existing data on the tensor analyzing power A_{yy} by means of this function. Factors affecting the quality of description may be the following.

- Firstly, the A_{yy} data plotted at fixed x (or z) were obtained at somewhat different x (or z) that scatter about fixed values, and they are subject to the systematic errors in addition.

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- Secondly, the relativistic deuteron wave function used was obtained in definite approximations.
- Finally, our treatment of the simple pole diagram has a trial nature, but the calculations are consistently relativistic, and other contribution may be added in future to improve agreement with experiment.