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SHORT-RANGE STRUCTURE ON THE DEUTERON

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1. Introduction

The investigation of reactions with participation of the deuteron at high and intermediate energies helps in solving many fundamental problems which are at the focus of interest of modern physics. On the one hand, the deuteron is the only known bound state of two nucleons and therefore it is a convenient object to test nuclear models in frame of which nuclear interactions are explained as baryons interacting through the exchange of mesons. On the other hand, the reactions initiated by the fastly moving deuterons are particularly attractive for testing approaches which are used to describe relativistic bound states.

During the 1990s there have been an essential progress in the experimental knowledge of deuteron electromagnetic structure. The start of experiments at the Th. Jefferson National Accelerator Facility (JLab) has made available high energy electron beams with high currents and large polarizations. Several experiments have significantly extended the energy and momentum transfer range of deuteron electromagnetic studies, including A and T_{20} for elastic *ed* scattering and photodisintegration cross sections and polarizations. An exhaustive review of the current experimental and theoretical status of this area has been given in [1]

As to hadron probes, until recently measurements of cross sections of the deuteron fragmentation on nuclei [2, 3] were the main source of information about the deuteron structure. Those data could be satisfactorily explained in the framework of relativistic momentum approximation using standard deuteron wave functions. The acceleration of the beam of polarized deuterons [4] at the Dubna Synchrophasotron allowed polarization investigations to be made. Over the past ten years new experimental results on the polarization observables in deuteron inclusive breakup on nuclei [5]-[11] and *dp* backward elastic scattering [12]-[14] have been obtained at Dubna and Saclay. These results have demonstrated that the traditional picture of the deuteron as a bound state of a neutron and a proton fails for short distances between them.

A review and comparison of results of investigations of the short-range structure of deuteron obtained with electron and hadron probes seems to be instructive.

2. Static properties of the deuteron

Static properties of deuteron are known with a high precision; some are recalled here [15]:

binding energy	$E_B = 2.224575(9)$ MeV,
radius	$R = 1/\alpha = 4.318946$ fm,
mean-square radius	$< r^2 >_d^{1/2} = 1.971(6)$ fm,
electric quadrupole moment	$Q_d = 0.2859(3)$ fm^2,
magnetic moment	$M_d = 0.857406(1)$ n.m.

The radius (the scale parameter) $R = 1/\alpha = 1/(m_N E_B)^{1/2}$ is more representative than $< r^2 >_d^{1/2}$ of the deuteron size. The fact that the deuteron has a positive electric quadrupole moment implies that it is not spherical but it has a cigar like shape in configuration space, its long axis being parallel to its spin projection $M = +1$. This feature is dynamically expressed by the D-component of the deuteron wave function $\psi^{JM}(\mathbf{r})$:

$$\psi^{JM}(\mathbf{r}) = \frac{u(r)}{r} Y_{01}^{JM}(\hat{\mathbf{r}}) + \frac{w(r)}{r} Y_{21}^{JM}(\hat{\mathbf{r}}), \qquad (1)$$

where $u(r)$ and $w(r)$ are the radial wave functions of S and D-states and Y_{LS}^{JM} are spherical harmonics. The availability of the D-component is also responsible for the fact that the deuteron magnetic moment is not equal the sum of the proton and neutron momenta.

Static properties of the deuteron are related to the components of the deuteron wave function through the relations

$$< r^2 >_d = \frac{1}{4} \int_0^\infty r^2 (u^2 + w^2) dr, \quad Q_d = \frac{1}{\sqrt{50}} \int_0^\infty r^2 w (u - \frac{1}{\sqrt{8}} w) dr.$$

From the deuteron wave function one can obtain body form factors:

monopole electric	$F_E = \int (u^2 + w^2) j_0(qr/2) dr,$
quadrupole electric	$F_Q = 2 \int w (u - 8^{-1/2} w) j_2(qr/2) dr,$
longitudinal magnetic	$F_L = \frac{3}{2} \int w^2 (j_0(qr/2) + j_2(qr/2)) dr,$
transverse magnetic	$F_S = \int (u^2 - \frac{1}{2} w^2) j_0(qr/2) dr$
	$+2^{-1/2} w (u + 2^{-1/2} w) j_2(qr/2) dr.$

3. Deuteron wave functions

In momentum space the nonrelativistic NN wave function of the deuteron can be written in the form [16]:

$$\psi_\mu(\mathbf{k},\mu_1,\mu_2) = \sum_{L=0,2} < \frac{1}{2}\mu_1 \frac{1}{2}\mu_2 \,|\, 1\, M_S >< L\, M_L\, 1\, M_S \,|\, 1\, M > \frac{u_L(k)}{k} Y_{LM_L}(\hat{\mathbf{k}}), \quad (2)$$

where μ_1, μ_2 are the nucleon spin projections on the quantization axis in the rest frame of every nucleon, $< ....|.. >$ are the Clebsh-Gordan coefficients, $Y_{LM_L}(\hat{\mathbf{k}})$ are spherical harmonics, and $\hat{\mathbf{k}} = \mathbf{k}/k$.

The normalization condition is

$$1 = \int_0^\infty [u^2(r) + w^2(r)]dr = \int_0^\infty [u^2(p) + w^2(p)]p^2 dp. \quad (3)$$

The D-state probability

$$P_D = \int_0^\infty w^2 dr = (5 \pm 2)\%, \quad (4)$$

is the measure of the strength of the tensor component of the NN force. It has large uncertainty because $w(r)$ is known badly at short distances (or large internal momenta).

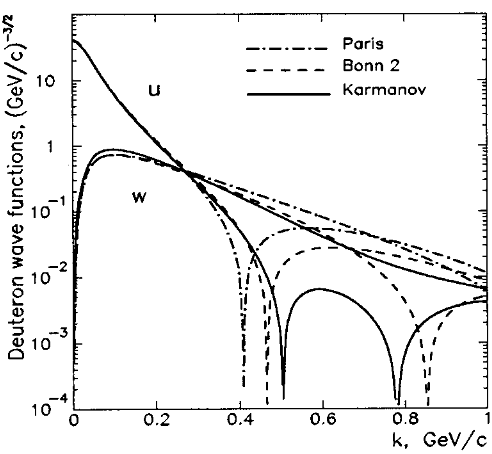


Fig. 1: Momentum space deuteron wave functions.

The parameters of the deuteron wave function are defined from the Schrödinger equation using potentials adjusted to fit the NN scattering data at energies below the pion production threshold. The modern potential models give good descriptions of the NN data below 350 MeV, including the deuteron static parameters. At large distances between nucleons in the deuteron, corresponding to small momenta of their relative motion, these models give almost identical results; they differ in their short-range structure predicting different high-momentum components of the deuteron wave function. The S and D-state wave functions for the Paris [17] and Bonn B [18] potentials are shown in Fig. 1. This figure also shows f_1 and f_2-components of the relativistic wave function of Karmanov et al. [19] to be discussed later.

4. Electron-deuteron scattering

In the simplest picture of the elastic *ed* scattering this interaction is described by assuming that the electron exchanges a single virtual photon when scattering from the deuteron. In this approximation the scattering cross-section of unpolarized electrons by unpolarized deuterons [1],

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{NS} \left[A(Q^2) + B(Q^2) tan^2\left(\frac{\Theta}{2}\right)\right], \tag{5}$$

is expressed through the cross section for scattering from a particle without internal structure $(d\sigma/d\Omega)_{NS}$ (Mott scattering cross section) and structure functions $A(Q^2)$ and $B(Q^2)$. Here Q^2 is the square of the 4-momentum transferred by the electron, with $q = d' - d$ and $Q^2 = -q^2$. The structure functions depend on the three electromagnetic form factors,

$$\begin{aligned} A(Q^2) &= G_C^2(Q^2) + \frac{8}{9}\eta^2 G_Q^2(Q^2) + \frac{2}{3}\eta G_M^2(Q^2), \\ B(Q^2) &= \frac{4}{3}\eta(1+\eta) G_M^2(Q^2), \end{aligned} \tag{6}$$

where $\eta = Q^2/4m_d^2$. The charge G_C, magnetic G_M and quadrupole G_Q form factors describe distributions of the electric charge and magnetic momentum in the deuteron, and in impulse approximation they are related to the body form factors F_E, F_Q, F_L and F_S through

$$\begin{aligned} G_C &= 2\,G_{ES}\,F_E, \\ G_Q &= 2\,G_{ES}\,F_Q, \\ G_M &= \frac{m_d}{m_N}(2\,G_{MS}\,F_S + G_{ES}\,F_L), \end{aligned} \tag{7}$$

where G_{ES} and G_{MS} are isoscalar nucleon form factors

$$\begin{aligned} G_{ES} &= (G_{Ep} + G_{En})/2, \\ G_{EM} &= (G_{Mp} + G_{Mn})/2. \end{aligned} \tag{8}$$

From forward-angle cross section measurements one can determine A, because B and $tan^2\Theta/2$ are small here. The magnetic form factor G_M is determined from large angle measurements, since the A contribution vanishes as $\Theta \to 180°$. Separating the charge G_C and quadrupole G_Q form factors requires polarization measurements. The polarization of the outgoing deuteron can be measured in a second, analyzing scattering. Of the polarization quantities, T_{20} has been most often measured, because it does not require a polarized beam or a measurement in different scattering planes. At forward electron scattering angles one may approximate T_{20} by [20]

$$T_{20} \approx -\sqrt{2}\frac{2x + x^2}{1 + 2x^2} \tag{9}$$

where $x = 2\eta G_Q/3G_C$. The minimum of $T_{20} \approx -\sqrt{2}$ is reached for $x = 1$.

The comparison of the simple nonrelativistic theory with the data on A, B and T_{20} obtained at high Q^2 (say, $Q^2 > 2$ GeV^2) shows [1] that these data cannot be explained in the frame of nonrelativistic calculations and present strong evidence for the presence of meson exchange currents, relativistic effects, or possibly new (quark) physics.

The study of deuteron form factors is complicated by the fact that they are a product of the body form factors and the nucleon isoscalar form factors. Until recently it was assumed that the nucleon form factors are well studied. But the recent JLab measurements of the ratio of the electric and magnetic form factors of proton [21] show that new G_{ES} values differ significantly from the dipole behaviour and may have an impact on the theoretical interpretation of the data.

There are a few ways of taking into account relativity in nuclei and the past several works have been devoted to study the relativistic effects in the deuteron. A number of relativistic deuteron wave functions of quasipotential type was given in [22]. The relativistic one boson exchange model was used to describe NN scattering and the deuteron bound state on the basis of the spectator equation [23, 24]. The Bethe-Salpeter equation [25] was solved and used to calculate the deuteron form factors in [26, 27]. Another approach for the description of relativistic bound systems is the light front dynamics [19, 28, 29]. An extended review of different theoretical approaches to account relativistic effects in studies of the electromagnetic structure of the deuteron can be found in [1].

It should be noted that the difference between different deuteron models is smaller than the discrepancy between the results of different approaches. Furthermore, the deuteron wave function appears in the expressions for form factors being weighted by spherical Bessel functions. It is reasonably safe to suggest that the information about the short-range deuteron structure can be derived from elastic *ed* scattering data only on a complicated mechanism grounds.

5. Description of relativistic composite hadron systems: light front dynamics

Along with the measurements of the deuteron electromagnetic structure, a considerable amount of data concerning the short-range deuteron structure has been accumulated during last years using high energy hadronic probes. Whereas the data on differential cross section of deuteron inclusive breakup on nuclei have been satisfactorily described in framework of the relativistic impulse approximation using the standard deuteron wave functions (see, for example, [2, 3, 30]), polarization observables in the reactions with the polarized deuterons are not reproduced within this approach. Two examples of discrepancies between the predicted and experimental values are shown in Figs. 2 [14] and 3 [31].

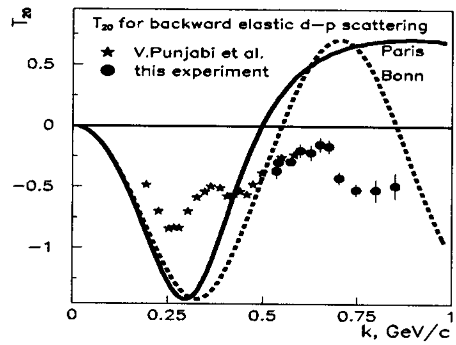


Fig. 2: Parameter T_{20} in backward elastic scattering versus k. Solid and broken curves are one-nucleon exchange predictions using the Paris [17] and Bonn B [18] deuteron wave functions, respectively.

In nuclear reactions at high energies the information about deuteron structure is obtained in experiments with fastly moving deuterons. The main difficulty of this study lies in the necessity of a relativistic treatment. The advantage is that the high-momentum components of the internal motion of constituents are more open to inspection. A convenient model for this type of reaction, based on a generalization of the relativistic hard-collisions models of composite hadrons [32], was developed by Blankenbecler et al. [33, 34]. A key element here is the notion of infinite momentum frame that is intimately related to the term of light front dynamics coined by Dirac some time ago [35]. Qualitatively the idea is that when a composite system is viewed from a fastly moving frame then interactions among constituents are slowed down because of time dilation so that the internal dynamics becomes essentially that of almost free constituents.

The type of quantum mechanics depends on the form of a fixed spice-like surface in four-dimensional space-time where a Hilbert space of states is defined. The various options for choosing this spice-like surface were classified by Dirac [35]. This choice defines the way in which the 10 generators $P^{\mu} = (P^0, \mathbf{P})$, $M^{\mu\nu} = (\mathbf{J}, \mathbf{K})$ of Poincaré group are split into kinematical and dynamical generators, or hamiltonians.

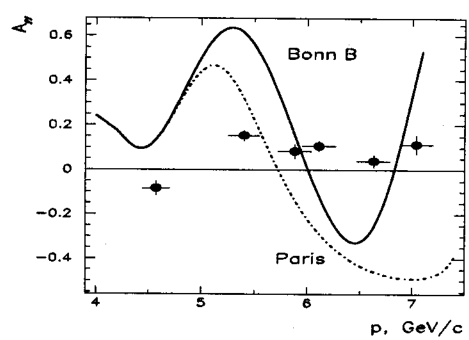


Fig. 3: A_{yy} in reaction $^{12}C(d,p)X$ at an initial deuteron momentum of 9 GeV/c and a proton emission angle of 85 mr as compared with the predictions of relativistic impulse approximation with Bonn B [18] and Paris [17] deuteron wave functions.

The most familiar instant-form mechanics corresponds to choosing to construct states at a fixed time $t_0 = 0$. Here the kinematical generators are the momentum operator $\mathbf{P}$ and the angular momentum operator $\mathbf{J}$, hamiltonians are the energy operator P^0 and the Lorentz boost operator

K. A special feature of the instant-form dynamics is the inseparability of the variables that characterize the motion of a nucleus globally from the inner variables that describe the motion of constituents. In consequence of this the transformation of the wave function when going over from one reference frame to another, e.g., from the nucleus rest frame to IMF, is nontrivial.

Alternatively, front-form quantum mechanics constructs states on a fixed light front, customarily defined to be $t^+ = t + z = 0$. Here the kinematical generators of the Poincaré group are operators (or their combinations) $P_+ = P_0 + P_3$, P_1, P_2, $E_r = \frac{1}{2}(K_r + \epsilon_{rs} J_s)$, K_3, J_3, and hamiltonians are $P_- = P_0 - P_3$, $E_r = K_r - \epsilon_{rs} J_s$. Here $r, s = 1, 2$, ϵ_{rs} is the antisimmetric tensor: $\epsilon_{12} = -\epsilon_{21} = 1$. The kinematical operators form the subgroup of the Poincaré group and leave the hyperplane $t - z = 0$ invariant. A remarkable feature of this dynamics for the composite system with a finite number of constituents is that the variables describing the inner motion uncoupled from the variables describing the motion of the system as a whole. For a system that consists of two constituents a and b, one forms the momentum of the center-of-mass

$$P_+ = P_+^a + P_+^b, \quad \mathbf{P}_T = \mathbf{P}_T^a + \mathbf{P}_T^b, \tag{10}$$

and the internal variables

$$\xi = P_+^a / \mathbf{P}_+, \quad \mathbf{k}_T = (1 - \xi)\mathbf{P}_T^a - \xi \mathbf{P}_T^b. \tag{11}$$

that are invariant under the action of the kinematical operators. The point in favour of light front dynamics is that here because of the absence of Z-diagrams the effects of the structure of a relativistic system are naturally described by means of a wave function having a probabilistic meaning [36].

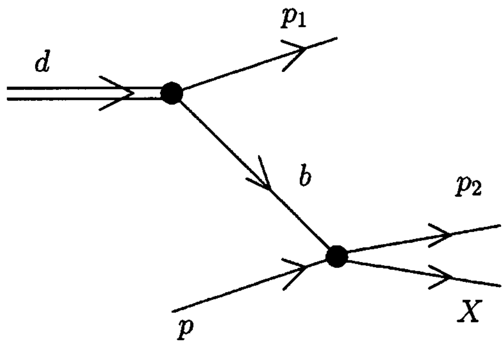


Fig. 4: The simplest diagram to describe reactions initiated by relativistic deuterons with proton emission in a forward direction.

The basic diagram of the hard collisions model [33, 34] for the $^1H(d,p)X$ reaction is shown in Fig. 4. Here p_1 is spectator nucleon, b is virtual (off-shell) nucleon, p_2 is the proton from 'hard' scattering, and X are everything else. In accordance with the Feynman rules the invariant amplitude M for this diagram is of the form:

$$M = \frac{M(d \to bp_1)\, M(bp \to p_2 X)}{l^2 - m^2}, \tag{12}$$

where $M(d \to bp_1)$ and $M(bp \to p_2X)$ are the invariant amplitudes of the deuteron breakup into the particles b, p_1 and of the reaction $bp \to p_2X$, respectively, and l^2 is a four-momentum squared of the off-shell particle b.

In IMF [33, 34]

$$\frac{M(d \to bp_1)}{l^2 - m^2} = \frac{\psi(y, \mathbf{l}_T)}{y}, \tag{13}$$

where y indicates the fraction of the total longitudinal momentum of d transferred to b:

$$y = \frac{b_0 + b_3}{d_0 + d_3}, \tag{14}$$

and $\mathbf{l}_T$ is the transverse momentum of b relative to the interaction axis, and $\psi(y, \mathbf{l}_T)$ is the wave function depending generally on two variables.

If X is the fixed state f, for differential cross section of detecting particle p_2 one can obtain

$$\frac{E_{p_2}\, d\sigma}{d\mathbf{p}_2} = \frac{2m_p}{\pi a d_3} \int_{l_{T\,min}}^{l_{T\,max}} \int_0^{\alpha_{max}} \frac{(1-y_1)|\mathbf{b}|^2}{y_1|y_1 - y_2|} G_{b/d}(y_1, \mathbf{l}_T) \frac{d\sigma}{dt'}(bp \to p_2 f) l_T\, dl_T\, d\alpha, \tag{15}$$

where $d\sigma(bp \to p_2 f)/dt'$ is the cross section of the exclusive reaction $b\,p \to p_2\, f$ with the invariant variables $s' = (b+p)^2$, $t' = (b-p_2)^2$ in the lower vertex of the diagram, $a = d^2 + (d_0 + d_3)[m_p - (p_2)_0 + (p_2)_3]$, α is an angle between $\mathbf{l}_T$ and $\mathbf{p}_{2T}$, and y_1, y_2 can be found from the four-momenta conservation in the interaction vertex. The structure function

$$G_{b/d}(y, \mathbf{l}_T) = \frac{1}{2(2\pi)^3} \frac{|\psi(y, \mathbf{l}_T)|^2}{y(1-y)}, \tag{16}$$

signifies the probability of finding a constituent of type b in the nucleus d with a fractional momentum y and a transverse momentum $\mathbf{l}_T$.

If the particle p_1 is detected, the invariant differential cross section for the direct fragmentation of deuterons by protons $^1H(d,p)X$ can be written as

$$\frac{E_{p_1}\, d\sigma}{\mathbf{p}_1} = \sigma_T(s')\, x\, G_{p_1/d}(x, \mathbf{p}_{1T})\, F(\mathbf{p}_1), \tag{17}$$

where $x = [(p_1)_0 + (p_1)_3]/(d_0 + d_3)$, $\sigma_T(s')$ is the total cross section for the np interaction, and function $F(\mathbf{p}_1)$ ensures vanishing of the differential cross section at the kinematical boundary of the $^1H(d,p)np$ reaction.

The structure function can be expressed in terms of the usual nonrelativistic wave function by the relation

$$\int G_{b/d}(y, \mathbf{l}_T)\, dy\, d\mathbf{l}_T = \int |\psi(\mathbf{k})|^2\, d\mathbf{k} = 1. \tag{18}$$

However, as it has been noted above, attempts to describe the polarization observables in reactions initiated by polarized deuterons have not met with success.

Moreover, it was observed that the deuteron structure function at short distances, where relativistic effects are significant, may depend on more than one variable [14, 37].

The relativistic deuteron wave function in the light front dynamics has been obtained by Karmanov et al. [19]. This function depends on two vector variables: on the momentum **k** of nucleons in deuteron in their rest frame and on extra variable **n** — the unit normal to the light front surface. Due to this fact it is determined by six invariant functions instead of two ones in the nonrelativistic case, each of them depending on two scalar variables k and $z = cos(\widehat{\mathbf{kn}})$. The deuteron wave functions depends now on the orientation of the quantization plane and has the form:

$$\Psi^{M}_{\sigma_2\sigma_1} = w^{\star}_{\sigma_2}\psi^{M}(\mathbf{k},\mathbf{n})\sigma_y w_{\sigma_1}, \tag{19}$$

where $M = 0, \pm 1$ are the projections of spin $\mathbf{J} = \mathbf{1}$ on the quantization axis, and

$$\psi(\mathbf{k},\mathbf{n}) = \frac{1}{\sqrt{2}}\sigma f_1 + \frac{1}{2}\left[\frac{3}{k^2}\mathbf{k}(\mathbf{k}\cdot\sigma) - \sigma\right] f_2 + \frac{1}{2}\left[3\mathbf{n}(\mathbf{n}\cdot\sigma) - \sigma\right] f_3 + \frac{1}{2k}[3\mathbf{k}(\mathbf{n}\cdot\sigma) + 3\mathbf{n}(\mathbf{k}\cdot\sigma) - 2\sigma(\mathbf{k}\cdot\mathbf{n})]f_4 + \sqrt{\frac{3}{2}}\frac{i}{k}[\mathbf{k}\times\mathbf{n}]f_5 + \frac{\sqrt{3}}{2k}[[\mathbf{k}\times\mathbf{n}]\times\sigma]f_6. \tag{20}$$

Here σ are the Pauli matrices, $w_{\sigma_1(\sigma_2)}$ are the spin functions of nonrelativistic nucleons, and $f_1, ..., f_6$ are the invariant about rotations functions of the kinematical variables, that define the deuteron state. Here

$$k = \sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{4x(1-x)} - m_p^2}, \quad (\mathbf{n}\cdot\mathbf{k}) = (\frac{1}{2} - x)\cdot\sqrt{\frac{m_p^2 + \mathbf{p}_T^2}{x(1-x)}}. \tag{21}$$

6. Backward elastic deuteron-proton scattering

Extensive measurements of the tensor analyzing power T_{20} in backward elastic *dp* scattering have been performed at Dubna and Saclay [12]-[14]. The most simple and natural mechanism of the backward elastic *dp* scattering is a pole mechanism in the $u-$channel with a transfer of a nucleon from the deuteron to the proton. However, as it is seen from Fig. 2, this approach fails to describe the experimental data using standard wave functions of the deuteron. A covariant treatment of the pole diagram based on the Bethe–Salpeter equation [27] leads to results that do not differ very strongly from those obtained in standard approaches based on a direct use of the deuteron wave function. It also appeared that the required behaviour could be obtained by by assuming a P-wave admixture in the ground state [22]. However, the excessively large quantity of the admixture is required to explain the observed momentum dependence of T_{20}. In this connection the idea has been conceived to revive the $u-$channel pole diagram taking account of the baryon resonance admixture to the deuteron [38].

The problem of isobar states in the deuteron is discussed over more than twenty years (see, for example, [39, 40]). Originally the idea arose through investigation of the differential cross–section of the backward elastic dp scattering. Now the determination of the resonance admixture has been made possible by use of new polarization data on parameter T_{20}.

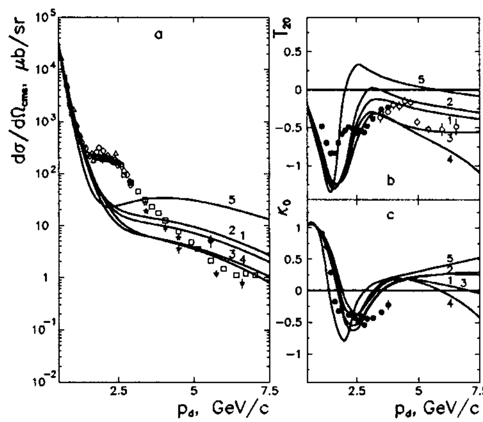


Fig. 5: Differential cross section $(d\sigma/d\Omega)_{cms}$, T_{20} and κ_0 of the backward elastic dp scattering versus the initial deuteron momentum p_d calculated in the one–baryon exchange approximation taking into account 1% admixture of the odd parity resonances $N(1520)$, $N(1535)$, $N(1650)$ and $N(1675)$ to the deuteron at $r_0 = 0.4$ fm with the deuteron wave functions for Paris potential [17] (curve 1), Reid soft core potential [42] (2), Bonn A (3) and B (4) potentials [18], and Moscow potential [43] (5). Experimental data on T_{20} from [13] (full circles) and [3] (empty circles), on κ_0 from [11], and references to the differential cross section data may be found in [38].

In the general case the use of the pole diagram assumes a knowledge of the vertex of the deuteron breakup on two nucleons, a parameterization of which is rather complicated. The use of the light front dynamics makes the relation between the vertex and a wave function more transparent [38]. Since calculations of the resonance admixture to the deuteron by means of meson exchange between nucleons [40], or using the decay of s^4p^2 six quark configuration formed at small distances [41] do not give quantitatively acceptable results, in [38] the resonance admixture was treated at a phenomenological level. The diagram considered was similar to that shown in fig. 2, with the difference that there also the exchange of baryon resonances could take place and the deuteron was formed in the lower vertex instead of $(p_2 + X)$-state. Within the light front dynamics, the invariant amplitude corresponding those diagram can be approximately represented as the sum over poles associated with the exchanges of a nucleon and of its excited states.

The following questions should be answered in solving this problem: (a) what baryon resonances need to be taken into account? (b) what is a localization of these resonances? (c) what is the magnitude of the admixture of baryon resonances to the deuteron wave function?

The results of calculations are shown in the Fig. 5. It turned out that resonances treated should be localized at distances less than ~ 0.4 fm, and for qualitative agreement the calculation results with the experimental data it is sufficient to take into account $\sim$ 1% of the total admixture of the lightest negative-parity baryon resonances $N(1520)$, $N(1535)$, $N(1650)$, and $N(1675)$ to the deuteron wave function. It has been found also that taking into account the baryon exchange brings the results of calculations made with different deuteron wave functions are in much better agreement in between than in the case of ONE approximation.

7. Tensor analyzing power of the breakup of relativistic deuterons

Already upon the first measurements of the tensor analyzing power T_{20} of the deuteron breakup at 9 GeV/c with the emission of protons at 0° [5]-[8] a significant discrepancy between the values calculated in the relativistic impulse approximation and experimental ones has come to light. More recently, on the measurement of the tensor analyzing power A_{yy} of the reaction $^{12}C(d,p)X$ at 9 GeV/c with the emission of protons with large transverse momenta [31], this discrepancy has been compounded (see Fig. 3). The discrepancy between the theory and experiment in principle can be overcome by the addition of a P-wave into the deuteron wave function (DWF).

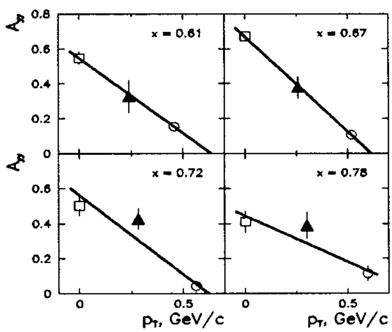


Fig. 6: Parameter A_{yy} versus p_T for four values of x shown in figure.

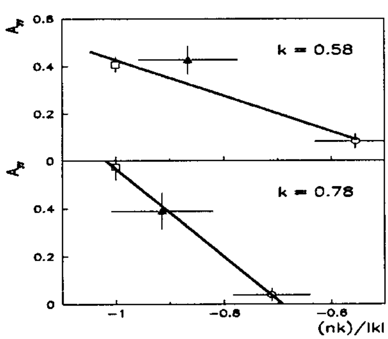


Fig. 7: Parameter A_{yy} versus $(\mathbf{n}\cdot\mathbf{k})/|k|$ for two values of k shown in figure.

True enough, the P-wave is conditioned by the different mechanisms in a number of approaches. In the paper [44] the data on T_{20} at 0° have been successfully described taking account of the P-wave arising because of the production of six-quark configuration that gives odd parity resonances at their fragmentation to the baryon channel. At the same time the calculations on the basis of the Bethe-Salpeter equation give the P-wave admixture that is inadequate to eliminate the discrepancy with experiment [27].

The measurements of polarization observables initiated by 4.5 GeV/c deuterons on Be with secondaries emitted at 80 mr in the (d,p) reaction [37] have been performed at the JINR Synchrophasotron. A comparison of the new data on A_{yy} of the (d,p) reaction with the results of previous measurements at 9 GeV/c and angles of 0° [14] and 85 mr [31], made at different values of p_T and x enabled new interesting regularities to be found: the dependence of A_{yy} on the p_T, (Fig. 6) and the dependence of A_{yy} on the variable $(\mathbf{n}\cdot\mathbf{k})/|k|$ (Fig. 7) defined above.

The accumulated A_{yy} data in the $A(d,p)X$ reaction reinforce the statement that a deuteron structure function at short distances depends on more than one variable. Previously such a possibility was pointed out by Blankenbecler et al. [33, 34]. Later Karmanov et al. [19, 28, 29] have developed a quantitative approach to represent this situation.

In [45] an analysis of the existing data on T_{20} at 0° have been made using the relativistic deuteron wave function of Karmanov et al. (20).

A general expression for the parameter T_{20} has the form

$$T_{20} = \frac{\sum_{M,M'} Sp\{\psi_M t_{20}\psi^\dagger_{M'}\}}{(1/3)Sp\{\psi_M\psi^\dagger_{M'}\}}, \tag{22}$$

where the operator t_{20} is defined by expression

$$< m' \,|\, t_{20} \,|\, m >= (-1)^{j-m'} < 1\, m\, 1 \; -m' \,|\, 2\, 0 >, \tag{23}$$

the deuteron wave function ψ_M with spin $J=1$ and its projections on the quantization axis $M=0,\pm1$ is given above by (19), $\psi^\dagger$ is the Hermitian conjugate function, and $< 1\, m\, 1 \; -m' \,|\, 2\, 0 >$ is a Clebsh-Gordan coefficient.

The expression (22) may be written in the form:

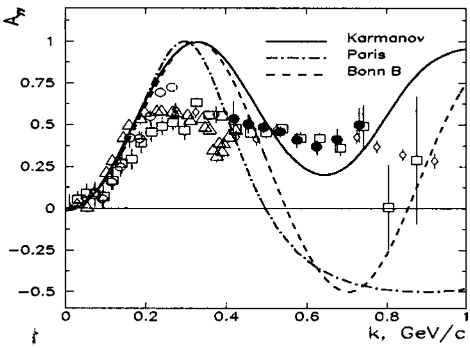
$$T_{20} = \sqrt{\frac{3}{2}}\frac{[-3Sp(\psi_z\psi_z^\dagger) + Sp(\psi\psi^\dagger)]}{Sp(\psi\psi^\dagger)}, \tag{24}$$

where we went from spherical notations to the vector ones. For the traces we have:

$$\begin{aligned} Sp(\psi\psi^\dagger) &= 3[f_1^2 + f_2^2 + (3z^2-1)f_2f_3 + f_3^2 + 4zf_4(f_2+f_3) + \\ &\quad f_4^2(z^2+3) + (1-z^2)f_5^2 + (1-z^2)f_6^2], \\ Sp(\psi_z\psi_z^\dagger) &= f_1^2 + \sqrt{2}[3(kz)^2-1]f_1f_2 + 2\sqrt{2}f_1f_3 + 4\sqrt{2}kzf_1f_4 + \\ &\quad \frac{1}{2}[3(kz)^2+1]f_2^2 + 2[3(kz)^2-1]f_2f_3 + kz[3(kz)^2+5]f_2f_4 + \\ &\quad 2f_3^2 + 8kzf_3f_4 + 3sqrt3kz[1-(kz)^2]f_2f_6 + 3sqrt3[1-(kz)^2]f_4f_6 + \\ &\quad \{[\frac{9}{2}[(kz)^2+1] - (kz)^2\}f_4^2 + \frac{3}{2}[1-(kz)^2]f_6^2, \end{aligned} \tag{25}$$

where $z = cos\theta$.

Fig. 8: Tensor analyzing power A_{yy} of the deuteron breakup with the emission of protons at 0° vs internal momentum k. Experimental data: triangles - [5], squares - [6], diamonds - [7], empty circles (H target) and full circles (C target) - [8] . Calculations are made with Paris [17] (broken curve), Bonn [18] (dotted curve) and Karmanov's [19] DWFs.



The results of calculations of $A_{yy}(0°)$ with the wave function (20) are shown in Fig. 8 by the solid curve. It is seen that as opposed to the calculations with the standard nonrelativistic deuteron wave functions [17, 18] the solid curve does not cross the horizontal axes and is in reasonable good agreement with experimental data in the region of k from 0.4 to 0.8 GeV/c. This result in our opinion is due to the fact that Karmanov's model establishes a new link between k_l and k_T that is different from those of the S and D-wave superposition in nonrelativistic DWF. Similar effect was discussed in [28] on the example of Wick-Cutcosky model, where it was shown in the clear form that a S-wave two-particle system becomes dependent on the angle in the light front dynamics. In other words it is a manifestation of the intimate connection between the internal motion and the motion of the system as a whole.

8. Conclusion

To summarize, one can say that in studies of the deuteron structure by electrons and hadrons different aspects of the deuteron wave function are explored. In electron scattering at not too high momentum transfers say, Q^2 less than $\sim$ 1 GeV^2, the description of the experimental data may well be nonrelativistic. But at larger Q^2 when meson degrees of freedom come into play, the mechanism of interaction becomes more complicated and the account of relativistic effects is required. Investigations of the short-range structure of the accelerated deuterons call for the relativistic treatment basically. One of the ways to take into account relativity in bound systems is the light front form of dynamics. This approach makes it possible, on the basis of a rather simple mechanism, to explain some experimental data obtained recently in nuclear interactions of relativistic polarized deuterons.

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Структура дейтрона на малых расстояниях

Представлен обзор результатов исследования структуры дейтрона на малых расстояниях с помощью электронных и адронных пробников. Рассматриваются результаты недавних экспериментов по упругому *ed*-рассеянию, по упругому *dp*-рассеянию назад и по развалу поляризованных дейтронов на ядрах при высоких энергиях.

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Azhgirey L. S. E1-2003-122

Short-Range Structure on the Deuteron

A review of results of investigations of the short-range structure deuteron by means of electron and hadron probes is given. The results of recent experiments on the elastic *ed* scattering, on the backward elastic *dp* scattering and breakup of polarized deuterons on nuclei at high energies are described.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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