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V.K.Mitrjushkin, P.K.Rashidov, S.V.Trubnikov

ON NONRELATIVISTIC APPROACH TO ELASTIC ed-SCATTERING AND THE DEPENDENCE ON NUCLEON FORM FACTORS

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1. INTRODUCTION

Theoretical studies performed in recent years on elastic ed-scattering give rather a contradictory picture of the present status of the theory of this process (see, e.g., reviews [1-3]).

It is clear that a consistent theory of ed-scattering should be relativistic; it should include the contribution both of the impulse approximation (triangle diagram in Fig.1) and of diagrams with excitation of isobars (Fig.2) and with exchange meson currents (Fig.3).

It must also be taken into consideration that all particles in an intermediate state are, in general, off the mass shell, and γNN-vertex in Fig.1 contains eight form factors. Deuteron electromagnetic form factors $A(Q^2)$, $B(Q^2)$ depend on nucleon electromagnetic form factors which in turn are ill known (especially G_{En}).

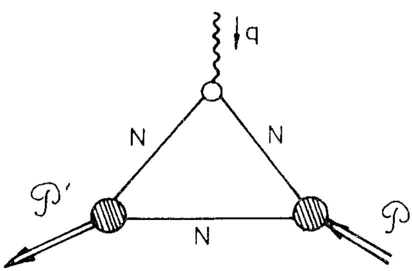


Fig.1

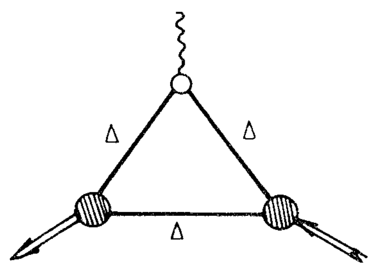


Fig.2

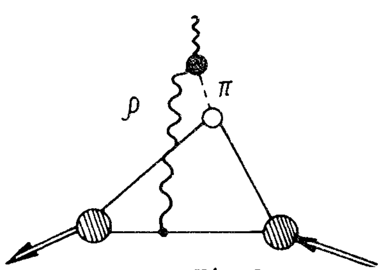


Fig.3

A relativistic scheme of calculation of deuteron electromagnetic form factors in the impulse approximation was developed in a series of works by F.Gross et al. [4-8] (the Gross four-component formalism). This formalism allows the "relativization" of any realistic non-relativistic potential obtained from data on elastic NN-scattering.

Main assumptions of this formalism are as follows:

- The nucleon-spectator is on the mass-shell;
- γNN -vertex behaves like the vertex of a free nucleon and contains only two nucleon form factors.

By the first assumption one performs the reduction of four functions of invariant variables in the covariant parametrization of the npd-vertex to four deuteron wave functions which are then obtained as solutions of a quasipotential-type equation with one-boson-exchange potentials.

The deuteron electromagnetic form factors calculated within this formalism in the relativistic impulse approximation for several realistic potentials are in disagreement with experimental data at large Q^2.

It is to be stressed that these assumptions may turn out to be significant. In recent paper [9] it has been shown that the inclusion of all eight form factors of the nucleon in the γNN -vertex can change the deuteron electromagnetic form factors value at $Q^2 \sim 100\ fm^{-2}$ by an order which allows, in principle, us to fit theory to experiment. The assumption that the nucleon-spectator may be off the mass shell leads, in accordance with work [10] to the same results.

Various approaches to relativistic impulse approximation were also developed in papers [11-15]. Neither of them, though being rather successful, gives the consistent description of relativistic impulse approximation.

The estimation of the contributions of exchange meson currents was often changed during the last six years, especially, in connection with the appearance of new experimental data on elastic ed-scattering. It may happen as has been discussed, e.g., in paper [6] that the contribution of the $\rho\pi\gamma$ -vertex in Fig.3 can be important at $Q^2 \geq 25\ fm^{-2}$. It is to be noted here that till now there are no calculations of the contributions of exchange meson currents in a consistent relativistic formalism (see discussion in refs. [6,8]). At the same time one should mention an assertion made in ref. [16] that the exchange meson current contribution should cancel with the contribution of the part of the γNN-vertex responsible for going beyond the mass shell of that vertex. An actual and still unclear question is that concerning the contribution of the 6q-state while describing the deuteron static characteristics and electromagnetic form factors (see, e.g., refs. [17-19]).

And finally, the problem of nonuniqueness (ambiguity) is so far obscure, which arises in the "relativization" of wave functions (due to the effects of retardation), and its role is not clear in calculating the deuteron electromagnetic form factors and other quantities. Because of the present situation one should again apply to well-known nonrelativistic formalism in order to establish its range of applicability for realistic potentials.

This problem is important also in view of the appearance during the last years of new data on elastic pd- and dd-scattering at high energies and attempts to describe these data in the framework of the Glauber theory [20,21,22].

The nonrelativistic approach is intensively developed in recent years. There appear still new and are modified the even known potentials of NN-interaction. These potentials are then employed in the theory of a few-body systems and in the theory of nuclear matter. Therefore it seems quite natural to analyse in detail all properties of the "working ability" of new NN-potentials for a relatively simple case of deuterons.

Among the present realistic potentials of NN-interaction a central role is played by the potential of the Paris group [23-28] (it will be called the Paris potential). This potential describes a great amount of various data on NN-scattering [26,27] and at present it is widely used in nuclear physics. Its latest modifications can be found in papers [25,28]. Therefore, a natural question arises: how well the Paris potential work in the deuteron problem? This concerns both the description of deuteron static characteristics and the calculation of deuteron electromagnetic form factors at all measured Q^2. These questions have been partially considered in literature [29], however, there is no consistent application of the most exact version of the Paris potential [28] to the deuteron problem. The present work deals with this latter problem. Section 2 is devoted to the description of the experimental data available on deuteron electromagnetic form factors $A(Q^2)$ and $B(Q^2)$ and to the calculations on the basis of Paris potential at $Q^2 \lesssim 210\ fm^{-2}$. The dependence on nucleon form factors (in the first place, on G_{En}) is analysed. In section 3 we calculate the polarization vector and tensor in elastic ed-scattering in view of the planned experiments. In section 4 we briefly discuss the problem of relativization of deuteron wave functions and related ambiguity, and also given results.

2. DESCRIPTION OF DEUTERON ELECTROMAGNETIC FORM FACTORS AND DEUTERON STATIC MOMENTS ON THE BASIS OF PARIS POTENTIAL AND ROLE OF NUCLEON FORM FACTORS

The differential cross section of elastic ed-scattering is given by

$$d\sigma/d\Omega = (d\sigma/d\Omega)_{Mott}\{A(Q^2)+B(Q^2)\,\mathrm{tg}^2\frac{\theta}{2}\}, \quad (1)$$

where $(d\sigma/d\Omega)_{Mott}$ is the Mott cross section, θ is the scattering angle of an electron on a deuteron in the lab.system, $Q^2 = -q^2 \geq 0$, $A(Q^2)$ and $B(Q^2)$ are connected with the charge, quadrupole and magnetic form factors $G_C(Q^2)$, $G_Q(Q^2)$, $G_M(Q^2)$ in the standard manner

$$A(Q^2) = G_C^2(Q^2) + \frac{8}{9}\eta^2 G_Q^2(Q^2) + \frac{2}{3}\eta\, G_M^2(Q^2),$$

$$B(Q^2) = \frac{4}{3}\eta\,(1+\eta)\,G_M^2(Q^2), \quad (2)$$

$\eta = Q^2/4M_d^2$, M_d is the deuteron mass. Form factors G_C, G_G, G_M are expressed in terms of wave functions $u(r)$ and $w(r)$ by formulae of ref. /30/ as follows

$$G_C(Q^2) = 2\,G_{EN}^s(Q^2)\,D_C(Q^2),$$

$$G_Q(Q^2) = 2\,G_{EN}^s(Q^2)\,D_Q(Q^2),$$

$$G_M(Q^2) = M_d/m_N\,[\,G_{EN}^s(Q^2)D_L(Q^2) + 2\,G_{MN}^s(Q^2)\,D_s(Q^2)], \quad (3)$$

$$G_{EN}^s = 1/2\,(G_{Ep}+G_{En}),$$

$$G_{MN}^s = 1/2\,(G_{Mp}+G_{Mn}),$$

where G_{Ep}, G_{En}, G_{Mp}, G_{Mn} are electric and magnetic form factors of the proton and neutron, respectively, and

$$D_C(Q^2) = \int_0^\infty dr\, j_0\left(\frac{Qr}{2}\right)\{u^2(r)+w^2(r)\},$$

$$D_Q(Q^2) = \frac{3}{\sqrt{2}\,\eta}\int_0^\infty dr\, j_2\left(\frac{Qr}{2}\right)\{u(r)\,w(r) - \frac{1}{\sqrt{8}}w^2(r)\},$$

$$D_L(Q^2) = \frac{3}{2}\int_0^\infty dr\, w^2(r)\,\{j_0\left(\frac{Qr}{2}\right)+j_2\left(\frac{Qr}{2}\right)\},$$

$$D_S(Q^2) = \int_0^\infty dr\, j_0\left(\frac{Qr}{2}\right)\{u^2(r) - \frac{1}{2}w^2(r)\} + \frac{1}{\sqrt{2}}\int_0^\infty dr\, j_2\left(\frac{Qr}{2}\right)\{u(r)\,w(r) + \frac{1}{\sqrt{2}}w^2(r)\}. \quad (4)$$

While describing the deuteron form factors $A(Q^2)$ and $B(Q^2)$ it is essential to make an appropriate choice of the nucleon electromagnetic form factors. In particular, the present experimental data provide a reliable conclusion on the "dipole" decrease of the proton magnetic form factor at large Q^2, i.e.,

$$G_{Mp}(Q^2) \underset{Q^2 \gg m_N^2}{} 1/(Q^2)^2. \quad (5)$$

Table

Case	I	II	III	IV
$G_{Ep} = \frac{1}{\mu_p} G_{Mp}\cdot$	$\frac{1}{(1+\frac{Q^2}{0,71})}$	$\Gamma_1\Gamma_2\,e^{-2a\Gamma_1 Q^2}$	"L" /32/	"BC" /33/
G_{En}	0	$\tau\lvert\mu_n\rvert G_{Ep}$	$\frac{\tau\lvert\mu_n\rvert G_{Ep}}{1+4\tau}$	$\frac{\tau\lvert\mu_n\rvert G_{Ep}}{1+5,6\tau}$

$\tau = Q^2/4m_N^2$, where m_N is the average nucleon mass.

In the Table we report some of the most popular parametrizations for G_{Mp} taken from refs. /31-33/. The parametrization $G_{Mp}^{(I)}(Q^2)$ gives good qualitative description of the proton magnetic form factor to $Q^2 \lesssim 30$ (GeV/c)^2. The expression $G_{Mp}^{(II)}$ results from the relativistic oscillator model /31/ and "works" almost with the same accuracy as $G_{Mp}^{(I)}$ (with respect to χ^2). Expressions $G_{Mp}^{(I)}$ and $G_{Mp}^{(II)}$ are somewhat preferable as compared to $G_{Mp}^{(III)}$ and $G_{Mp}^{(IV)}$ for the description of data by criterion χ^2.

Experimental data on G_{Ep}, G_{Mn} are not so abundant (the measured region is up to $Q^2 \lesssim 2\div3$ (GeV/c)^2). The existing data do not contradict the common assumption that

$$G_{Ep}(Q^2) = \frac{1}{\mu_p}G_{Mp}(Q^2) = \frac{1}{\mu_n}G_{Mn}(Q^2), \quad (6)$$

which we will keep in what follows.

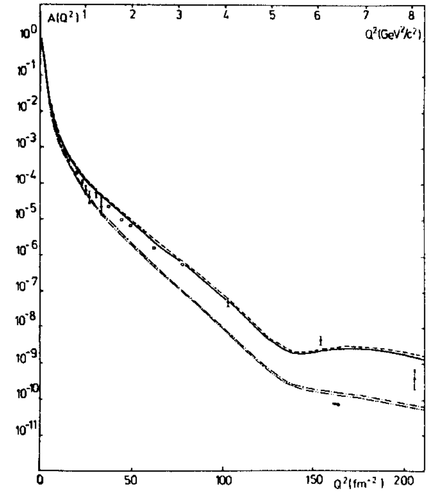


Fig.4. Description of the A-deuteron form factor for different nucleon form factors: —— $G_{Mp}^{(II)}$ and $G_{En}^{(II)}$, —·— $G_{Mp}^{(I)}$ and $G_{En}^{(I)}$ - - - $G_{Mp}^{(I)}$ and $G_{En}^{(II)}$, —··— $G_{Mp}^{(II)}$ and $G_{En}^{(I)}$ (see the Table).

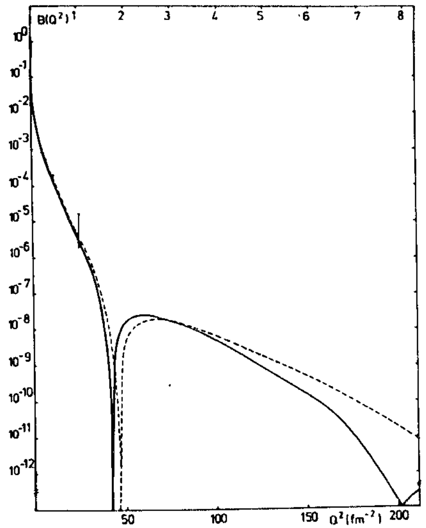


Fig.5. Description of the B-deuteron form factor for different nucleon form factors: —— $G_{Mp}^{(II)}$ and $G_{En}^{(I)}$, - - - $G_{Mp}^{(II)}$ and $G_{En}^{(II)}$ (see the Table).

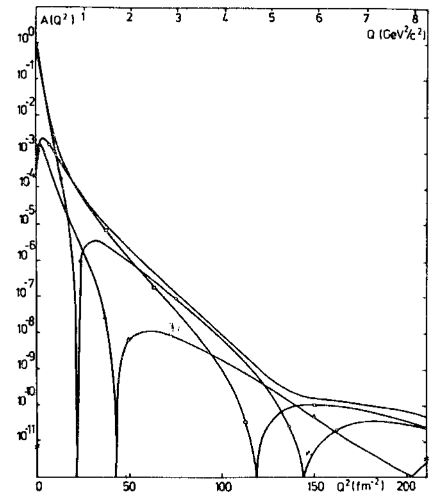


Fig.6. Contributions of charge G_C, quadrupole G_Q, magnetic G_M form factors into the A-deuteron form factor for the case $G_{Mp}^{(II)}$ and $G_{En}^{(I)}$ —o— contribution of G_C, —□— contribution of G_Q, —· — contribution of G_M.

Still more scarce information is on the neutron electric form factor $G_{En}(Q^2)$. It is known to be small however the deuteron form factors are rather sensitive to changes of G_{En} (for the corresponding discussion see, e.g., ref. /34/). The most simple, but, perhaps, not the most right way would be to put G_{En} zero. In paper /35/ a nontrivial expression for $G_{En}(Q^2)$ was proposed on the basis of O(4,2)-symmetry considerations ($G_{En}^{(II)}$ in the Table). A wide use is made also of phenomenological expressions. For the description of experimental data we made as follows: at values of smaller than 0.04 fm^{-4} we used polynomial approximation, taking into account asymptotics for u(r) and w(r) as $r \to 0$, respectively; further we parametrized u(r) and w(r) following paper /28/.

The results of calculation of $A(Q^2)$ and $B(Q^2)$ with different sets of $G_{Mp}(Q^2)$ and $G_{En}(Q^2)$ are shown in Figs.4-6. As is seen, in the pure nonrelativistic approach with a modified Paris potential form factors $A(Q^2)$ are well described at least up to $Q^2 \leq 1.5$ $(GeV/c)^2$. With a further growth of Q^2 the choice of nucleon electromagnetic form factors becomes very essential. This dependence can, in principle, completely "cancel" the contribution of all other degrees of freedom, therefore at present without a substantial improvement of measurements and (or) theoretical calculations it is difficult to make reliable conclusions on the actual role of extra (relativistic in relativistic impulse approximation, mesonic, baryonic, and quark) degrees of freedom in the deuteron. The transversal part $B(Q^2)$ of the cross section of elastic ed-scattering is also described in the nonrelativistic approach at all measured Q^2. It is to be noted, however, that at $Q^2 > 14$ fm^{-2} there are no experimental data, and at $Q^2 \sim 25.6$ fm^{-2} only an upper bound is obtained for $B(Q^2)$. Therefore, new measurements of $B(Q^2)$ for $Q^2 > 14$ fm^{-2} seem to be highly actual.

To complete the discussion we mention also the deuteron static moments. The deuteron quadrupole moment Q_d and weight of the D-state calculated with the analytically parametrized Paris potential /28/ are

$$Q_d = 0.279 \text{ fm}^2$$

$$P_d = 0.0577.$$

At this value of P_d the deuteron magnetic moment μ_d calculated by the nonrelativistic formula equals

$$\mu_d = 0.847 \text{ (n.m.)}\,^*.$$

*In ref /25/ for the same P_d the value $\mu_d = 0.853$ is given; the algorithm of calculation is not specified.

Comparing the calculated values with experimental data

$Q_d = 0.2860 \pm 0.0015\ fm^2$,

$\mu_d = 0.857406 \pm 0.000001$ (n.m.)

we see that the Paris potential describes Q_d and μ_d with a low accuracy. The radius r_d of the deuteron charge structure function equals

$$r_d^2 = -6 D_c'(0) = \frac{1}{4} \int_0^\infty [u^2(r) + w^2(r)]\, r^2\, dr, \qquad (7)$$

and it is in the Paris potential

$r_d = 1{,}97$ fm.

i.e., with high accuracy it reproduces the value $r_d \simeq 1.95-1.96$ fm known in literature [2,36,37]*.

3. THE TENSOR AND VECTOR OF POLARIZATION IN ELASTIC ed-SCATTERING

In this section we limit ourselves to discussion of the most important two polarization observables. The discussion of predictions for the polarization tensor and vector is of a special interest in view of the polarization experiments planned in the nearest future. Measurements of these quantities will made it possible to more accurately estimate the validity of either potential for the description of NN-interaction and will provide a criterion for the estimation of the contribution of the six-quark state into the deuteron. The component of polarization tensor is given by the formula (see, e.g., ref. [6])

$$T(Q^2) = \frac{4\sqrt{2}}{3}\eta\, \frac{G_C(Q^2)\, G_Q(Q^2) + \frac{1}{3}\eta\, G_Q^2(Q^2)}{G_C^2(Q^2) + \frac{8}{9}\eta^2\, G_Q^2(Q^2)} \qquad (8)$$

This polarization observable is marked by a quality of being independent of the nucleon form factors.

In a recent paper [7] it was proposed to measure components of the polarization vector and tensor of the recoil deuteron

*The accurate value of r_d is also important in connection with the theory of the Lamb shift (see, e.g., a discussion in paper [38]).

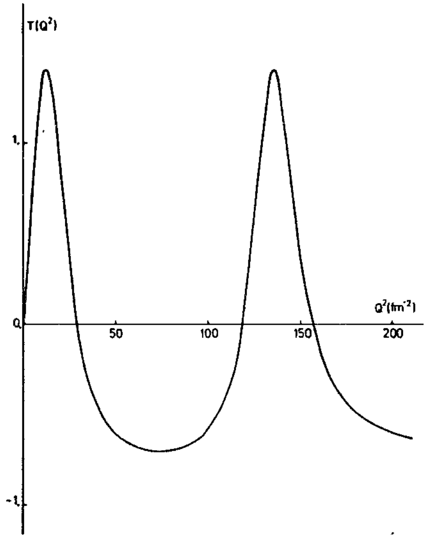


Fig.7. The component of polarization tensor in elastic ed-scattering.

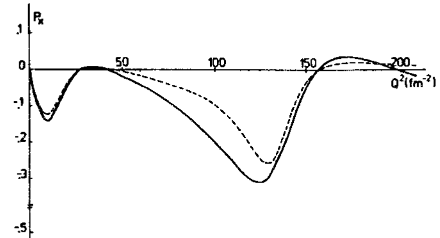


Fig.8. P_x-component of polarization vector in elastic ed-scattering for different nucleon form factors: —— $G_{En}^{(I)}$, - - - $G_{En}^{(II)}$ (see the Table).

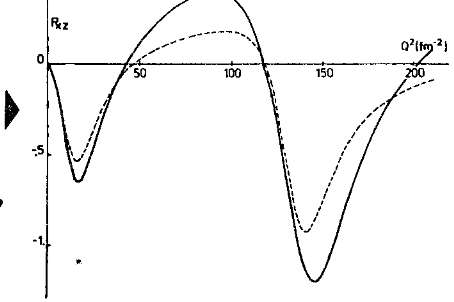


Fig.9. P_{xz}-component of polarization tensor in elastic ed-scattering for different nucleon form factors: —— $G_{En}^{(I)}$, - - - $G_{En}^{(II)}$ (see the Table).

in elastic scattering of polarized electrons which have the form

$$P_x = -\frac{1}{I_0}\,\frac{4}{3}\,\sqrt{\eta(1+\eta)}\; G_M\left(G_C + \frac{1}{3}\eta\, G_Q\right) tg\frac{\theta}{2},$$

$$P_z = \frac{1}{I}\,\frac{2}{3}\,\eta\,\sqrt{(1+\eta)\left(1+\eta\, \sin^2\frac{\theta}{2}\right)}\; G_M^2\, \frac{tg\theta/2}{\cos\theta/2}, \qquad (9)$$

$$P_{zz} = -\frac{1}{I}\left\{\frac{8}{3}\eta\, G_C G_Q + \frac{8}{9}\eta^2\, G_Q^2 + \frac{1}{3}\eta\left[1+2(1+\eta)\, tg^2\frac{\theta}{2}\right] G_M^2\right\},$$

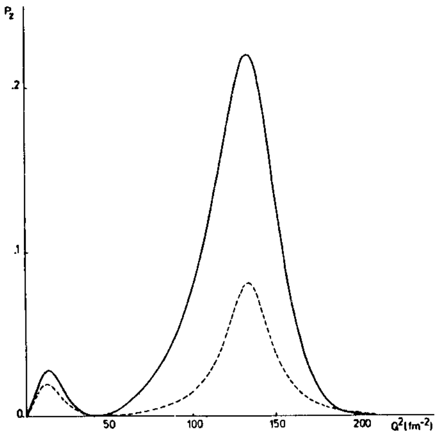
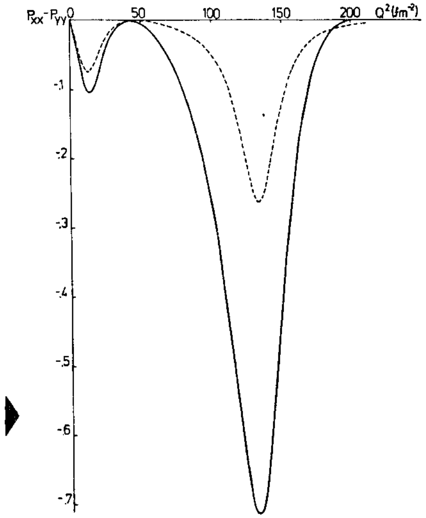


Fig.11. Difference P_{xx}- and P_{yy}- -components of polarization tensor in elastic ed-scattering for different nucleon form factors: —— $G^{(I)}_{En}$, ---- $G^{(II)}_{En}$ (see the Table).

Fig.10. P_z-component of polarization vector in elastic ed-scattering for different nucleon form factors: —— $G^{(I)}_{En}$, --- $G^{(II)}_{En}$ (see the Table).



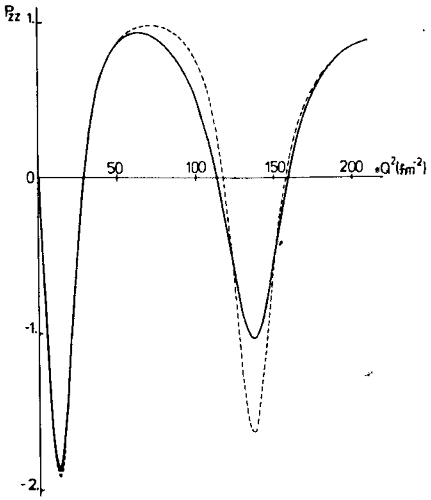


Fig.12. P_{zz}-component of polarization tensor in elastic ed-scattering for different nucleon form factors: —— $G^{(I)}_{En}$, ---- $G^{(II)}_{En}$ (see the Table).

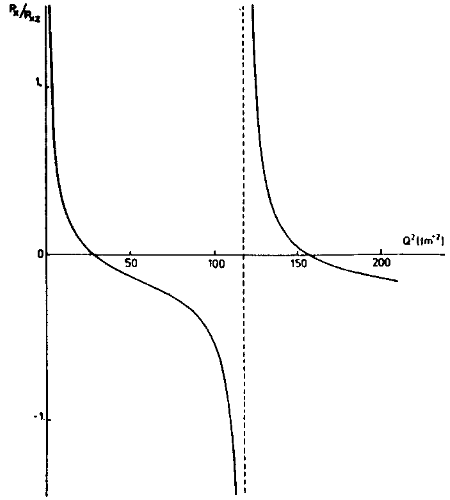


Fig.13. Ratio P_x-component of polarization vector to P_{xz}-component of polarization tensor in ed-scattering for different nucleon form factors.

(for definition and choice of axes see [7])

$$- \quad P_{xx} - P_{yy} = -\frac{1}{I_0}\,\eta\, G_M^2 \,,$$

$$- \quad P_{xz} = -\frac{1}{I_0}\, 2\eta \sqrt{\eta + \eta^2 \sin^2\frac{\theta}{2}}\; G_M G_Q \frac{1}{\cos\theta/2} \,,$$

where

$$I_0 = A(Q^2) + B(Q^2)\ \mathrm{tg}^2\frac{\theta}{2} \,.$$

In Figs.7-13 we show the values predicted for these quantities for different sets of nucleon form factors at $\theta = 40°$.

The polarization tensor has a standard form for the nonrelativistic approach in the impulse approximation. The curve for $T(Q^2)$ may change essentially in form only in "freezing-out" extra degrees of freedom in the deuteron.

New polarization variables introduced by Gross depend essentially on nucleon form factors. This dependence grows with Q^2.

4. DISCUSSION OF THE RESULTS

To summarize, we make the following conclusions:

- The nonrelativistic approach (examplified by the Paris potential) may well describe the experimental data on the longitudinal part $A(Q^2)$ of elastic ed-scattering up to the transferred momentum squared $Q^2 \lesssim 35$ fm^{-2} as well as the data on the transverse part $B(Q^2)$ (up to $Q^2 \lesssim 25$ fm^{-2}). The radius of the charge structure function of the deuteron r_d is calculated with high accuracy. At the same time the deuteron magnetic and quadrupole moments are described only qualitatively. In this aspect the Paris potential needs further improvement. The description of experimental values of deuteron electromagnetic form factors at large Q^2 is very sensitive to the choice of nucleon electromagnetic form factors including G_{En} which is little known at present. As has been shown above, a proper choice of G_{En} can give theoretical values of $A(Q^2)$, $B(Q^2)$ in satisfactory agreement with experiment. This dependence of deuteron electromagnetic form factors on the choice of nucleon electromagnetic form factors within the impulse approximation may "imitate" (or fully cancel) the contribution of all extra degrees of freedom. Therefore, it is very important problem to make the proton electromagnetic form factor $G_{E,Mp}$ as precise experimentally as possible in the whole accessible interval of Q^2 as well as to improve the methods of extraction of the neutron electromagnetic form factor from experimental data on the deuteron electrodisintegration and from all other possible sources (for instance, pion electroproduction on nucleons) and theoretical methods of calculation of the nucleon electromagnetic form factors.

- At present we have scarce information on the role of extra degrees of freedom (relativistic, mesonic, baryonic, etc.) and on the behaviour of the γNN-vertex off mass shell (dependent on eight form factors).
- The most popular procedures of relativization of the deuteron electromagnetic form factors do not exhaust all available possibilities. The procedure of relativization is essentially nonunique. The relativistic corrections can substantially change the values of deuteron electromagnetic form factors in the asymptotic region.

The well-known procedure of transition from the Bethe-Salpeter wave function $\Psi^{BS}_{\mathcal{P}}(x) = \int d^4p\, e^{ipx}\Psi_{\mathcal{P}}(p)$ (where $\mathcal{P}_\mu$ is the deuteron 4-momentum, p_μ is the nucleon relative 4-momentum) to the Schrödinger wave function $\Psi^{NR}(\vec{r})$ includes: a) transition to the deuteron rest frame $\vec{\mathcal{P}} = 0$; b) neglect of the relative time, i.e., $x_0 = 0$; c) inclusion of an ancillary condition on the nucleon kinetic energy (in the deuteron at rest) and deuteron binding energy to be small as compared with the nucleon rest mass. (All the spins to equal zero are assumed).

The condition b) which means the neglect of retardation effects in the interaction of nucleons in the deuteron, for the wave functions in the impulse approximation looks as the transition

$$\Psi^{BS}_{\vec{\mathcal{P}}=0}(p) \xrightarrow{NR} \int_{-\infty}^{+\infty} dp\; \Psi^{BS}_{\vec{\mathcal{P}}=0}(p_0, \vec{p}) . \qquad (10)$$

The inverse transition from the nonrelativistic function $\Psi^{NR}(\vec{r})$ to the Bethe-Salpeter function is known to be essentially nonunique. For instance, for any wave function $\Psi(r)$ there exists an infinite set of functions of the form $\phi(xu)\,\Psi(r)$, where $u_\mu = \frac{\mathcal{P}_\mu}{M_d}$, $r = \sqrt{-x^2+\lambda(xu)^2}$, $\phi(0)=1$ and λ is an arbitrary parameter which in the nonrelativistic limit turn into $\Psi(r)$. In a relativized formalism expounded in papers /4-8/ the "relativization" of the known nonrelativistic wave functions of the deuteron S- and D-waves ($u(\vec{p})$ and $w(\vec{p})$) is reduced to the construction of the Bethe-Salpeter function, the invariant components of which in the rest frame are $u(\vec{p})$ and $w(\vec{p})$, and one nucleon is on the mass shell. Such a scheme leads to the loss

of a part of relativistic corrections caused by the retardation effects and may essential affect the results to be obtained.

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17.	Theory of condenced matter
18.	Applied researches
19.	Biophysics

Митрюшкин В.К., Рашидов П.К., Трубников С.В. E2-82-156

Нерелятивистский подход в упругом ed-рассеянии и зависимость от формфакторов нуклона

В работе изучаются предсказания нерелятивистской теории упругого ed-рассеяния с последней версией потенциала парижской группы авторов для электромагнитных формфакторов дейтрона, вектора и тензора поляризации. Исследуется зависимость всех перечисленных выше величин от выбора формфакторов нуклонов, в особенности зависимость от наименее изученного электрического формфактора нейтрона. Обсуждаются некоторые аспекты процедуры релятивизации волновых функций дейтрона.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Mitrjushkin V.K., Rashidov P.K., Trubnikov S.V. E2-82-156

On Nonrelativistic Approach to Elastic ed-Scattering and the Dependence on Nucleon Form Factors

Nonrelativistic theory predictions are studied for elastic ed-scattering with a recent version of a Paris potential for the deuteron electromagnetic form factors, polarization vector, and tensor. The dependence of all the above quantities is analysed on the choice of the nucleon form factor, in particular, of the least known neutron elastic form factor. Some aspects of the procedure of relativization of the deuteron wave functions are discussed.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1982