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Parameterization of the Deuteron form Factors and the Tensor Polarizations

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Abstract: *For parameterization deuteron wave functions as a product of exponential function r^n by the sum of the exponential terms A_i*exp(-a_i*r^2) are received analytical forms for spherical S_0 and quadrupole S_2 deuteron form factors. The modern status of experimental data for deuteron tensor polarizations t_{20} and t_{21} is analysed. On received analytical forms for spherical and quadrupole form factors calculated deuteron tensor polarization t_{2i}. The result $t_{20}(p)$ in wide area of momentas for NijmI, NijmII, Nijm93, Reid93 and Argonne v18 potentials agreed well with the literature results for other potential nucleon-nucleon models, and with experimental data of world collaborations (Bates, BLAST, JLab, NIKHEF, VEPP-3, Saclay) and reviews (Boden, Garcon, Abbott). Reduced quantity tensor polarization t_{20R} it is compared to experimental data. The obtained results will allow studying the deuteron electromagnetic structure, its form-factors, differential cross section of double scattering in more detail in future, and also for calculations the theoretical values of spin observables in dp- scattering.*

Keywords: *deuteron, wave function, form factors, tensor polarization, approximation.*

1. INTRODUCTION

Deuteron is the most elementary nucleus. He consists of the two strongly interacting elementary particles: a proton and a neutron. The simplicity and evidentness of the deuteron's structure makes it a convenient laboratory for studying and modeling nucleon-nucleon forces. Now, deuteron has been well investigated both experimentally and theoretically.

It should also be noted that such potentials of the nucleon-nucleon interaction as Bonn, Moscow, Nijmegen group potentials (NijmI, NijmII, Nijm93, Reid93 [1]), Argonne v18 [2], Paris, NLO, NNLO and N^3LO, Idaho N^3LO or Oxford have quite a complicated structure and cumbersome representation. Example, the original potential Reid68 was parameterized on the basis of the phase analysis by Nijmegen group and was called as updated regularized version - Reid93. The parametrization was done for 50 parameters of the potential, where value χ^2/N_{data}=1.03 [3].

Besides, the deuteron wave function (DWF) in coordinate space can be presented as a table: through respective arrays of values of radial wave functions. It is sometimes quite difficult and inconvenient to operate with such arrays of numbers during numerical calculations. And the program code for numerical calculations is bulky, overloaded and unreadable. Therefore, it is feasible to obtain simpler and comfortabler analytical forms of DWF representation. It is further possible on the basis to calculate the form factors and tensor polarization, characterizing the deuteron structure.

DWFs in a convenient form are necessary for use in calculations of polarization characteristics of the deuteron, as well as to evaluate the theoretical values of spin observables in *dp* scattering.

The main objectives of the research in this paper are to calculate and analyze the deuteron form factors, what obtained by coefficients for new analytical forms DWF [4].

2. ANALYTICAL FORM OF THE DEUTERON WAVE FUNCTION

In 2000-x years are new analytical forms of deuteron wave function. Except the mentioned parametrization, in literature there is one more analytical form [5] for DWFs

$$\begin{cases} u(r) = \sum_{i=1}^{N} A_i \exp(-a_i r^2), \\ w(r) = r^2 \sum_{i=1}^{N} B_i \exp(-b_i r^2). \end{cases} \tag{1}$$

Parametrization (1) is improved in papers [6-9]. Minimization of values χ^2 is carried out 10^{-4}. Using DWF in coordinate and space representations, are designed a component of a tensor of sensitivity polarization of deuterons T_{20}, polarization transmission K_0, tensor analyzing power A_{yy} and tensor-tensor transmission of polarization K_y. The obtained outcomes are compared to the published experimental and theoretical results.

The coefficients A_i, a_i, B_i, b_i of analytical forms for the DWF (1) (for N=17) in coordinate space for NijmI, NijmII, Nijm93, Reid93 [1] and Argonne v18 [2] potentials have been numerically calculated in [6-9]. The obtained wave functions do not contain any superfluous knots.

Analytical forms for the deuteron wave function in coordinate space have been reviewed in detailed review [10]. Both analytical forms and parameterizations of the deuteron wave function, which are necessary for further calculations of the characteristics of the processes involving the deuteron, have been provided.

3. DEUTERON ELECTROMAGNETIC FORM FACTORS

Measurement of polarization characteristics of a response of deuteron fragmentation *A(d,p)X* at the intermediate and high energies remains one of the basic tools for examination of a deuteron structure. For a quantitative understanding of the deuteron structure, *S*- and *D*- states and polarization characteristics, one should consider different models of the nucleon-nucleon potential. The deuteron charge distribution is not well known from the experiment, because it is done only through the use of polarization measurements, and the unpolarized elastic scattered differential cross sections [11-13]. However, it can be determined [11]. Differential cross section of elastic scattering of unpolarized electrons by unpolarized deuterons without measuring polarization of the repulsed electrons and deuterons it is determined by the formula within the framework of assumptions of the first Born approach and conditions of relativistic invariancy [12-14]

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} S;$$

$$S = A(p) + B(p) tg^2\left(\frac{\theta}{2}\right).$$

Here θ - the scattering angle in the laboratory system; $f = 1 + \frac{2E}{m_d}\sin^2\left(\frac{\theta}{2}\right)$; p - the deuteron momentum in fm^{-1}; *A(p)* and *B(p)* - functions of the electric and magnetic structure:

$$A = G_C^2 + \frac{8}{9}\eta^2 G_Q^2 + \frac{2}{3}\eta G_M^2; \qquad B = \frac{4}{3}\eta(1+\eta)G_M^2;$$

where $\eta = \frac{p^2}{4m_d^2}$; m_d=1875.63 MeV - deuteron mass. Charge $G_C(p)$, quadrupole $G_Q(p)$ and magnetic $G_M(p)$ deuteron form factors contain information about the electromagnetic properties of the deuteron [14]:

$$G_C = G_{EN} D_C; \qquad G_Q = G_{EN} D_Q; \qquad G_M = \frac{m_d}{2m_p}\left(G_{MN} D_M + G_{EN} D_E\right). \tag{2}$$

Here G_{Ep}, G_{En} (G_{Mp}, G_{Mn}) - neutron and proton electric (magnetic) form factors.

It is convenient to divide the spherical (monopole or charge) S_0 and quadrupole S_2 form factors [15] into two parts which correspond to different multiplicities of the deuteron wave function for *S*- and *D*-states:

$$S_0(p/2)=S_0^{(1)}+S_0^{(2)}; \tag{3}$$

$$S_2(p/2)=2S_2^{(1)}-\frac{1}{\sqrt{2}}S_2^{(2)}; \tag{4}$$

where elementary spherical and quadrupole form factors

$$S_0^{(1)}=\int_0^\infty u^2 j_0 dr; \qquad S_0^{(2)}=\int_0^\infty w^2 j_0 dr; \tag{5}$$

$$S_2^{(1)}=\int_0^\infty uwj_2 dr; \qquad S_2^{(2)}=\int_0^\infty w^2 j_2 dr. \tag{6}$$

In (5) and (6) j_0, j_2 - the spherical Bessel functions from the argument $pr/2$. In [16] formulas (3) and (4) have been written down with argument pr.
Then components of deuteron form factors G_C, G_Q, G_M (2) in definitions elementary spherical and quadrupole form factors (5) and (6) will get the form as

$$D_C=S_0^{(1)}+S_0^{(2)}; \qquad D_Q=\frac{3}{\sqrt{2}\eta}\left(S_2^{(1)}-\frac{1}{\sqrt{8}}S_2^{(2)}\right);$$

$$D_M=2\left(S_0^{(1)}-\frac{1}{2}S_0^{(2)}+\frac{1}{\sqrt{2}}S_2^{(1)}+\frac{1}{2}S_2^{(2)}\right); \qquad D_E=\frac{3}{2}\left(S_0^{(2)}+S_2^{(2)}\right).$$

Then formulas (5) and (6) for DWFs (1) will be written down as

$$S_0^{(1)}=\pi\sum_{i,j=1}^{N}\frac{A_iA_j}{p}erf\left(\frac{p}{4\sqrt{a_i+a_j}}\right); \tag{7}$$

$$S_0^{(2)}=-\frac{\sqrt{\pi}}{64}\sum_{i,j=1}^{N}\frac{B_iB_j\left(p^2-24(b_i+b_j)\right)e^{-\frac{p^2}{16(b_i+b_j)}}}{(b_i+b_j)^{7/2}}; \tag{8}$$

$$S_2^{(1)}=\sum_{i=1}^{N}A_iB_i\left\{\frac{12\pi}{p^3}erf\left(\frac{p}{4\sqrt{a_i+b_i}}\right)-\frac{\sqrt{\pi}\left(p^2+24(a_i+b_i)\right)e^{-\frac{p^2}{16(a_i+b_i)}}}{4p^2(a_i+b_i)^{3/2}}\right\}; \tag{9}$$

$$S_2^{(2)}=\frac{\sqrt{\pi}}{64}\sum_{i,j=1}^{N}\frac{B_iB_jp^2e^{-\frac{p^2}{16(b_i+b_j)}}}{(b_i+b_j)^{7/2}}; \tag{10}$$

where $erf(z)=\frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$ - error function.

4. Tensor Polarizations

Tensor polarization t_{2i} [13, 14] of the repulsed deuterons is determined using the form factors (2):

$$t_{20}(p)=-\frac{1}{\sqrt{2}S}\left(\frac{8}{3}\eta G_C(p)G_Q(p)+\frac{8}{9}\eta G_Q^2(p)+\frac{1}{3}\eta\left[1+2(1+\eta)tg^2\left(\frac{\theta}{2}\right)\right]G_M^2(p)\right), \tag{11}$$

$$t_{21}(p)=\frac{2}{\sqrt{3}S\cos\left(\frac{\theta}{2}\right)}\eta\sqrt{\eta+\eta^2\sin^2\left(\frac{\theta}{2}\right)}G_M(p)G_Q(p), \tag{12}$$

$$t_{22}(p)=-\frac{1}{2\sqrt{3}S}\eta G_M^2(p). \tag{13}$$

The ratio of the cross section with a tensor polarized deuteron target to elastic electron-deuteron scattering cross sections σ_0 can be written as function that depends from tensor polarizations [17]

$$\frac{\sigma}{\sigma_0} = 1 + \frac{P_{zz}}{\sqrt{2}} \sum_{i=0}^{2} d_{2i} t_{2i}\,; \quad d_{20} = \frac{3\cos^2\varphi - 1}{2}; \qquad d_{21} = -\sqrt{\frac{3}{2}} \sin(2\varphi)\cos\phi\,;$$

$$d_{22} = \sqrt{\frac{3}{2}} \sin^2\varphi \cos(2\phi)\,;$$

where P_{zz} is the degree of deuteron tensor polarization, and the angles φ and ϕ define the polarization orientation in a frame where the z axis is along the virtual photon direction and the x axis is in the scattering plane.

For calculations in [18], it is useful to define new quantities as $A_0 = A - B/2(1+\eta)$ and $\tilde{t}_{20}$ from [19] as

$$\tilde{t}_{20} = -\frac{\frac{8}{3}\eta G_C G_Q + \frac{8}{9}\eta^2 G_Q^2}{\sqrt{2}\left(G_C^2 + \frac{8}{9}\eta^2 G_Q^2\right)} \tag{14}$$

derived respectively from A and t_{20} by eliminating the magnetic contribution:

$$\tilde{t}_{20} = \frac{S t_{20} + B/4\sqrt{2}\varepsilon(1+\eta)}{A_0}.$$

The values t_{20} is the largest one in the region of momentum transfer. When one can neglect the magnetic part (forward angles θ and ηG_M^2 much smaller than $G_C G_Q$ and $\eta^2 G_Q^2$), t_{20} depends only on the ratio [20, 21]

$$x = \frac{2}{3}\frac{\eta G_Q}{G_C}. \tag{15}$$

Then the formula for $\tilde{t}_{20}$ will be written down in the following form [20]

$$\tilde{t}_{20} = -\sqrt{2}\,\frac{x(x+2)}{1+2x^2}. \tag{16}$$

The tensor polarization t_{20} of the recoiling deuteron in elastic *ed*- scattering can be written [22]

$$\tilde{t}_{20} = -\sqrt{2}\,\frac{x(x+2) + y/2}{1 + 2(x^2 + y)},$$

where $y = \frac{2\eta}{3}\left(\frac{G_Q}{G_C}\right)^2 f(\theta); \quad f(\theta) = \frac{1}{2} + (1+\eta)tg^2\left(\frac{\theta}{2}\right).$

The alternative form for tensor polarization is specified in [23] as

$$\tilde{t}_{20} = -\frac{\eta}{\sqrt{2}}\,\frac{3\beta + \eta}{\frac{9}{8}\beta^2 + \eta^2},$$

where $\beta = G_C / G_Q$. In [24] it is considered the quantity $\tilde{t}_{20} = \frac{1}{1-\delta}\left(t_{20} + \frac{\delta}{2\sqrt{2}}\right)$, in which the small correction by $\delta = \frac{B}{S}\left[\frac{1}{2(1+\eta)} + tg^2\left(\frac{\theta}{2}\right)\right]$ eliminates the dependence on angles θ and magnetic form factor G_M, resulting in form (14). Dividing out the leading p^2 dependence provides a reduced quantity tensor polarization [24]

$$t_{20R} = -\frac{3}{\sqrt{2}Q_d p^2}\tilde{t}_{20}, \tag{17}$$

in which details of the low-p region are enhanced. As value for deuteron quadrupole moment is determined through the formula $Q_d = G_Q(0)/m_d^2$, that can be written down the formula (17) in such form [23]

$$t_{20R} = \frac{G_Q}{G_Q(0)} \frac{G_C + \frac{\eta}{3}G_Q}{G_C^2 + \frac{8}{9}\eta^2 G_Q^2},$$

which is normalized as $t_{20R}(0) = 1$ for p^2=0.

5. Calculations

The behavior of the value χ^2 depending on the number of expansion terms N in (1) for DWFs has been studied. With the account of the minimum values N=11 or 12 for these forms we have built DWFs in the coordinate space, which do not contain superfluous knots. Charge and quadrupole form factors $S_i^{(j)}$ by formulas (7)-(10) are shown in Figs. 1 and 2. The calculations have been carried out using Reid93 and Argonne v18 potentials. Calculations are made for the original dipole fit for the proton and neutron form factors (DFF) [25, 26]: $G_{Ep} = F_N$; $G_{En} = 0$; $G_{Mp} = \mu_p G_{Ep}$; $G_{Mn} = \mu_n G_{Ep}$; where nucleon form factor $F_N(p^2) = \left(1 + \frac{p^2}{18.235\, fm^{-2}}\right)^{-2}$.

In Figs. 1 and 2 is specified for form factors near the beginning of coordinates the behaviour in logarithmic and usual scale. Zeros of form factors are distinctly visible. Visual difference of forms factors for potentials Reid93 and Argonne v18 in usual scale is absent. But in logarithmic scale the essential difference between these forms factors is well visible. Essential difference of forms factors typically in the area of momentas is more 10 fm^{-1}.

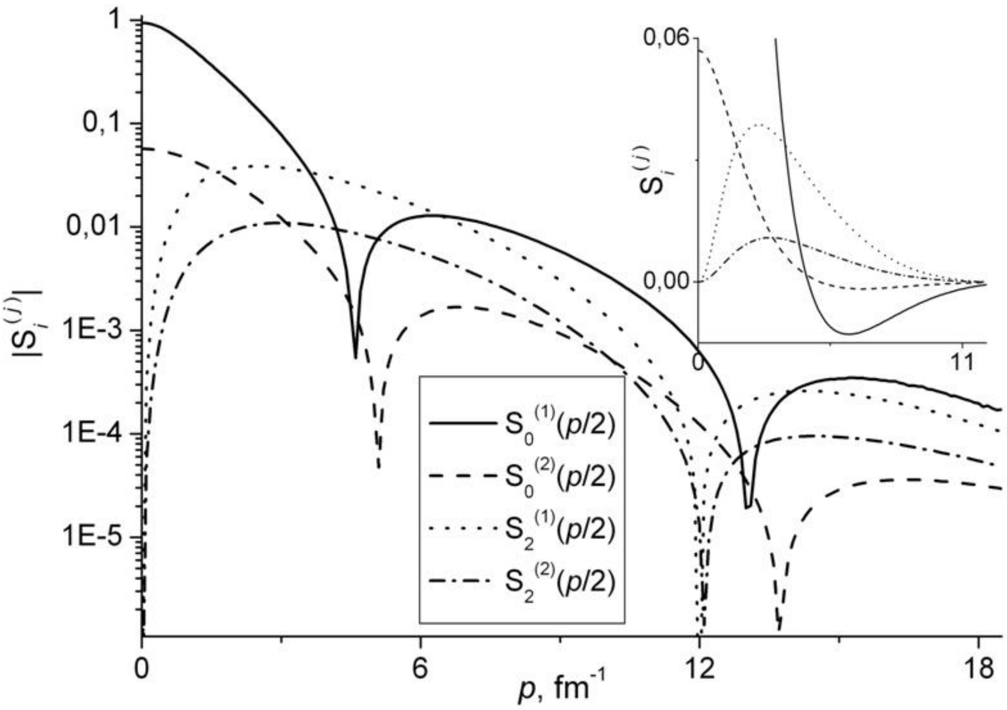

Fig1. *Spherical and quadrupole form factors* $S_i^{(j)}$ *for Reid93 potential*

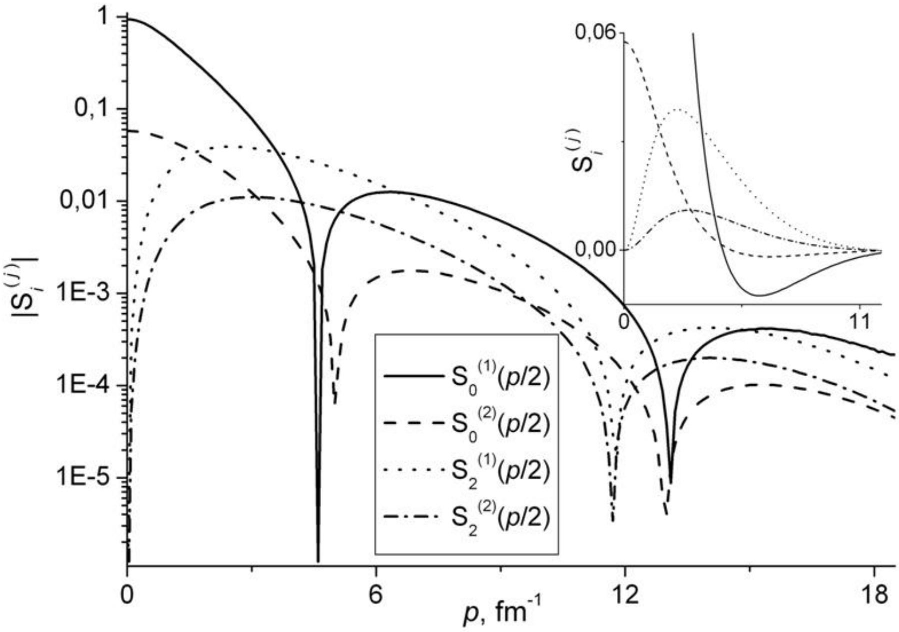

Fig2. *Spherical and quadrupole form factors* $S_i^{(j)}$ *for Argonne v18 potential*

Formulas for spherical and quadrupole form factors (7)-(10) can be used for calculations of tensor polarizations (11), (12) and (17) taking into account form factors (2). Tensor polarization t_{20}, $|t_{20}|$, $\tilde{t}_{20R}$ and t_{21} at a scattering angle of θ=70^0 for NijmI, NijmII, Nijm93, Reid93 and Argonne v18 potentials (Figs. 3-6) has been carried out and the obtained results have been compared with the published experimental and theoretical datas. In these figures the designation of potentials is used accordingly - N1, N2, N93, R93 and Av18.

A detailed comparison of the obtained values of $t_{20}(p)$ (the scattering angle θ=70^0) for NijmI, NijmII, Nijm93, Reid93 and Argonne v18 potentials (Fig. 3) with the up-to-date experimental data of Bates [19, 27, 28], JLab [11, 29], VEPP-3 [17, 30-32], NIKHEF[33, 34], Saclay [35], BLAST [24, 36, 37] collaborations and Boden [38], Garcon [19], Abbott [18] reviews. There is a good agreement is for the momentas p=1-4 fm^{-1}.

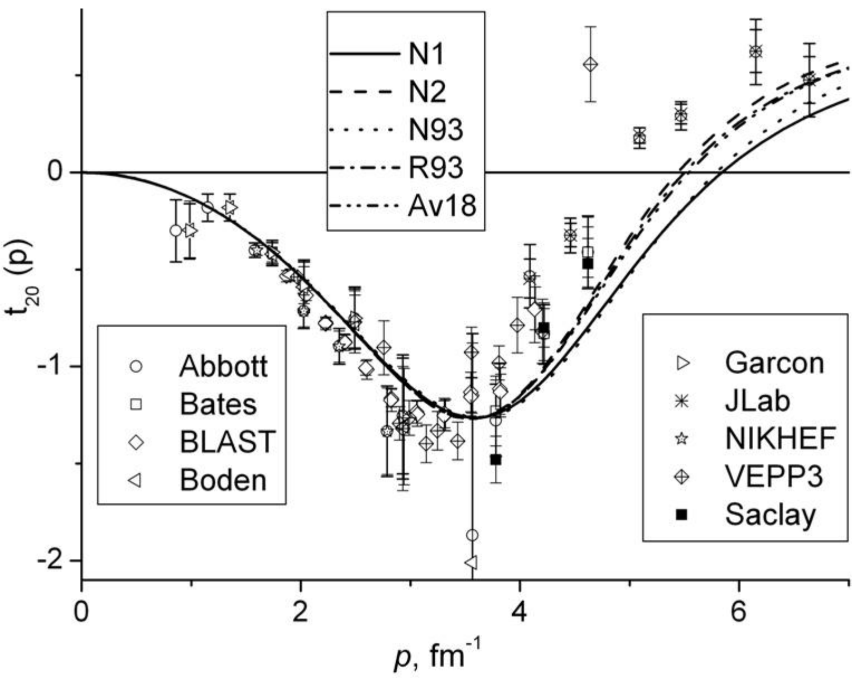

Fig3. *Tensor polarization* t_{20}

The calculated value $t_{20}(p)$ is in good agreement with the results of papers, where the theoretical calculations have been conducted: with available datas [19] for the Paris, Argonne v14 and Bonn-E potentials and with data [39] for Moscow, NijmI, NijmII, CD-Bonn and Paris potentials. It is in a good agreement with the value $t_{20}(p)$ calculated in [24] for elastic *ed*-scattering for models with the inclusion of nucleon isobaric component, within light-front dynamics and quark cluster model, for Bonn-A, Bonn-B and Bonn-C, Bonn Q, Reid-SC and Paris A-VIS potentials. There is a good agreement of the obtained values of $t_{21}(p)$ with the data for models NRIA and NRIA+MEC+RC [19]. Besides, $t_{20}(p)$ and $t_{21}(p)$ coincide well with the results according to the effective field theory [24].

The experimental data for $t_{21}(p)$ and $t_{22}(p)$ in a wide range of momentas is missing in the scientific literature. Therefore, this is of current importance to get these values both theoretically and experimentally. It is also appropriate to calculate polarization characteristics of deuteron (sensitivity tensor components to polarization of deuterons T_{20}, polarization transmission K_0 and tensor A_{yy} and vector A_y analyzing power) and compare them with theoretical calculations [6, 40], as well as with the experimental data [15].

For the greater presentation results in the form dependence of the tensor polarization module $|t_{20}|$ on a momentas are submitted (Fig. 4).

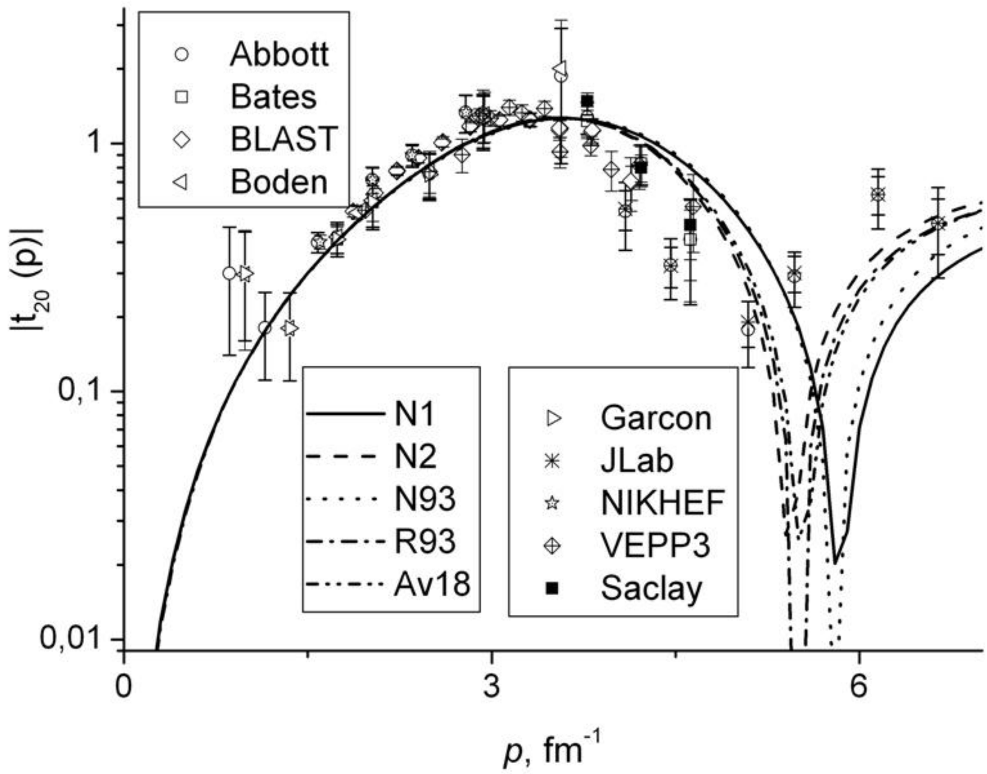

Fig4. *Tensor polarization* $|t_{20}|$

Experimental values of size tensor polarization $\tilde{t}_{20}$ it agrees data Bates [19], JLab [21], Saclay [41] collaborations and Garcon [19], Abbott [18] reviews poorly differ from values t_{20}. Therefore is inexpedient to carry out additional theoretical calculations for $\tilde{t}_{20}$.

Reduced quantity tensor polarization t_{20R} (Fig. 5) it is compared to experimental data BLAST collaboration [24, 36]. Also size t_{20R} it is designed under the formula (21), where t_{20} it is taken from papers for Bates [19, 27, 28], JLab [11, 29], VEPP-3 [17, 30-32], NIKHEF[33, 34], Saclay [35] collaborations and Boden [38], Garcon [19], Abbott [18] reviews, and experimental value for quadrupole moment is taken equal Q_d=0.285783 fm^2 [24]. Prediction Gilman [42] for tensor polarization at the big momentas 6-11 fm^{-1} not bad coincides with theoretical calculations.

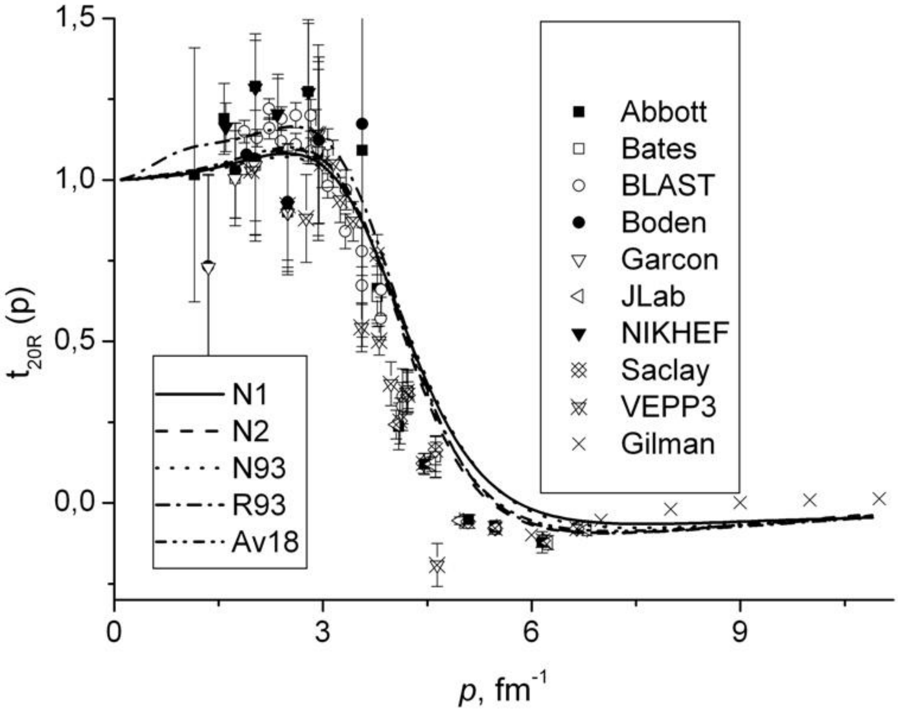

Fig5. *Reduced quantity tensor polarization* t_{20R}

The designed value of tensor polarization t_{21} (Fig. 6) it is compared to experimental datas Bates [19], BLAST [24, 37], JLab [11], Saclay [41] and VEPP-3 [17, 32] collaborations. There is a good agreement is for the momentas 2.2-3 and 4.2-6.7 fm^{-1}. Results of calculations t_{2i} for nonperturbative soft-wall AdS/QCD [23] are worse coordinated with experimental data.

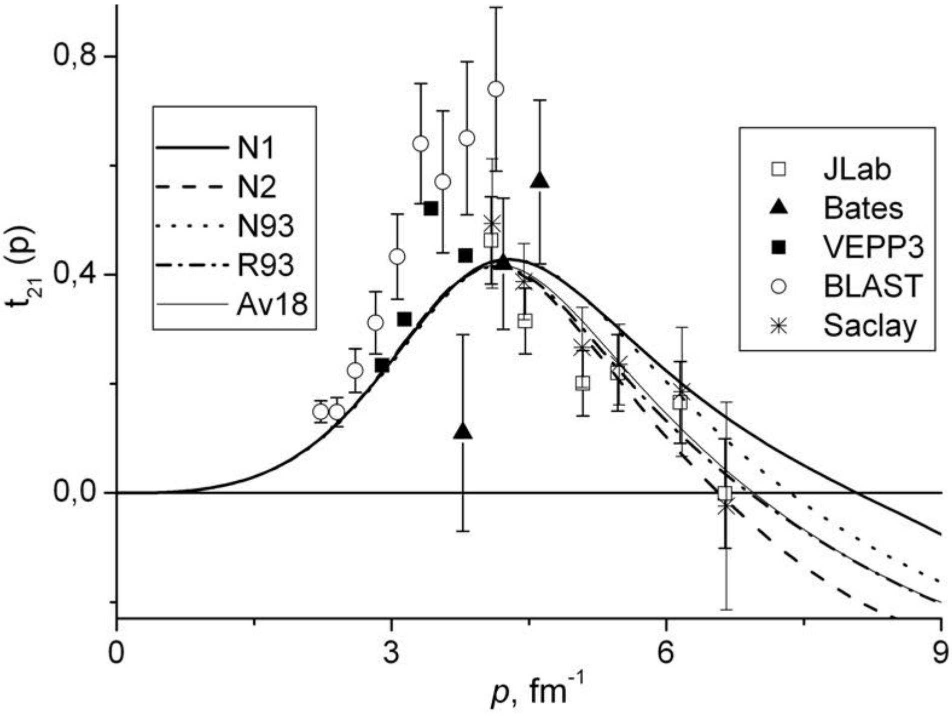

Fig6. *Tensor polarization* t_{21}

Positions of the zero p_0 of the tensor polarizations t_{20} and t_{21} are shown in Tables 1 and 2 accordingly. The received values are compared to the data for other potential models and with experimental values. Here TTC are compared to three theoretical calculations based on dispersion theory, generalized parton distributions and a cloudy bag model with relativistic constituent quarks [36]; TM are the theoretical curves are nonrelativistic models with relativistic corrections, relativistic models and effective field theory [24]; Par.III - Parametrization III in [24].

Table1. *Positions of the zero of the tensor polarization t_{20}*

Potential	p_0, fm^{-1}
NijmI	5.82
NijmII	5.44
Nijm93	5.75
Reid93	5.40
Av18	5.52
pQCD [22]	5.0-8.2
Bonn-B, FULLF, OBEPF [43]	4.91-5.16
Graz-II [26]	6.21
Reid68, Bonn, Paris [25] ($\theta=0^0$)	5.2; 5.4; 5.5
TTC [36]	4.77; 4.92; 5.17
TM [24], Par.III [24]	4.8-5.3; 5.0

Table2. *Positions of the zero of the tensor polarization t21*

Potential	p_0, fm^{-1}
NijmI	8.08
NijmII	6.51
Nijm93	7.37
Reid93	6.94
Av18	6.92
Reid68, Paris [25] ($\theta=90^0$)	7.1; 6.9
TM [24], Par.III [24]	6.8; 7.0

6. CONCLUSIONS

For parameterization DWF as a product of exponential function r^n by the sum of the exponential terms $A_i*exp(-a_i*r^2)$ (where n=0;2; i=1,2,…,11) are received analytical forms for spherical S_0 and quadrupole S_2 deuteron form factors. The modern status of experimental data for deuteron tensor polarizations t_{20} and t_{21} is analysed in this paper. On received analytical forms for spherical and quadrupole form factors calculated deuteron tensor polarization t_{2i}. Numerical calculations of the deuteron tensor polarization $t_{20}(p)$ and $t_{21}(p)$ carried out in the range of momentum 0-7 fm^{-1} accordingly.

The result $t_{20}(p)$ in wide area of momentas for NijmI, NijmII, Nijm93, Reid93 and Argonne v18 potentials agreed well with the literature results for other potential nucleon-nucleon models, and with experimental data of world collaborations (Bates, BLAST, JLab, NIKHEF, VEPP-3, Saclay) and reviews (Boden, Garcon, Abbott).

The tensor polarization t_{21} designed on wave functions is proportionate to earlier published results. Besides, reduced quantity tensor polarization t_{20R} it is compared to experimental data.

The calculations values t_{21} and t_{20R} have been carried out using phenomenological nucleon-nucleon Nijmegen group potentials (NijmI, NijmII, Nijm93 and Reid93) and Argonne v18 potential.

The obtained results will allow studying the deuteron electromagnetic structure, its form-factors, differential cross section of double scattering in more detail in future, and also for calculations the theoretical values of spin observables in *dp-* scattering. In a convenient form analytical forms for spherical S_0 and quadrupole S_2 deuteron form factors are necessary for use in calculations of polarization characteristics of the deuteron, and also for calculations the theoretical values of spin observables in *dp-* scattering.

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