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Analytical forms of the deuteron wave function in coordinate space and deuteron form factors

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ABSTRACT

Charge G_C, quadrupole G_Q and magnetic G_M deuteron form factor were calculated by analytic forms of the deuteron wave function in the coordinate space for nucleon-nucleon potentials NijmI, NijmII, Nijm93, Reid93 and Argonne v18. Theoretical calculations are compared with the experimental data from the leading collaborations (Bates, BLAST, Bonn, JLab, Mainz, Naval Research Lab, NIKHEF, Orsay, Saclay, SLAC, Stanford, VEPP3, VEPP4) and reviews (Abbott, Boden, Garcon, Karpius). The obtained position of the zero for the deuteron form factors for these five potentials was compared with the values for other potential models and experimental values. Further use of form factors for obtaining polarization observables is discussed.

***Keywords*:** deuteron, wave function, form factor, position of the zero, polarization observables

1. INTRODUCTION

The urgent tasks of the physics of the nucleus and elementary particles are the study of the properties of the deuteron and the interaction of nucleons with each other. In the study of the characteristics of the structure of deuteron, the main attention is paid to describing the forms and behavior of the deuteron wave function (DWF) in coordinate and impulse representations. Sometimes DWF contains knots near the coordinates [1, 2]. This indicates some inconsistencies and inaccuracies in the implementation of numerical algorithms in the process of solving the

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problem of searching for radial functions. Or it is due to the peculiarities of the nucleon-nucleon potential models for the description of deuteron [3].

In paper [4] the influence of the choice of analytic forms for the approximation on the calculation of the density distribution and the transition density in a deuteron is considered.

In [5] the values of the deuteron charge, quadrupole and magnetic form factors are calculated, using wave functions obtained from chiral effective theory, when the potential includes one-pion exchange, chiral two-pion exchange and genuine contact interactions. In paper [6] an overview of measurements of the deuteron electromagnetic form factors and a comparison with a selection of theoretical descriptions is provided. A phenomenological Lagrangian approach is applied to study the electromagnetic properties of deuteron in paper [7], where deuteron electromagnetic form factors are expressed in light-front representation in the transverse plane.

2. ANALYTICAL FORMS OF THE DEUTERON WAVE FUNCTION IN COORDINATE SPACE

In the detailed review [3] in a chronological order (from 1940 to 2015 years), the static parameters of the deuteron are systematized, which were received by the DWF for the different potential models. The presence or absence of knots near the origin for the radial DWF in the coordinate space is indicated. According to the notations in the cited literature, an overview of analytical forms for DWF was conducted.

The most used analytical forms of DWFs in the coordinate space are as follows:

1) The analytical form developed by the Paris Group [8] for its own potential remains the most widely used now:

$$\begin{cases} u(r) = \sum_{j=1}^{N} C_j \exp\left(-m_j r\right), \\ w(r) = \sum_{j=1}^{N} D_j \exp\left(-m_j r\right)\left[1 + \frac{3}{m_j r} + \frac{3}{\left(m_j r\right)^2}\right], \end{cases} \qquad (1)$$

where $m_j = \beta + (j-1)m_0$; $\beta = \sqrt{ME_d}$; $m_0 = 0.9$ fm^{-1}; M – the nucleon mass; E_d – the coupling energy of the deuteron. The search for coefficients of analytical form (1) was made for the Paris [8] and Bonn [1] potentials.

2) Parameterization of DWF for a realistic super-deep local Moscow potential was recorded as Gaussian expansions [9]

$$\begin{cases} u(r) = r\sum_{i=1}^{N} A_i \exp(-a_i r^2), \\ w(r) = r^3\sum_{i=1}^{N} B_i \exp(-b_i r^2). \end{cases} \qquad (2)$$

The coefficients for formulas (2) were also obtained for the CD-Bonn potential and for the "dressed" dybaryon model (DDM) [10].

3) In order to explain the D-state of a deuteron and the correct asymptotic behavior, a non-relativistic DWF was proposed in [11]

$$\begin{cases} u(r) = \dfrac{N}{\sqrt{4\pi}} \sum_{k=1}^{n_u} C_k e^{-\alpha_k r}, \\ u(r) = \dfrac{N}{\sqrt{4\pi}} \rho \sum_{k=1}^{n_w} D_k \, \mathrm{e}^{-\beta_k r} \left(1 + \dfrac{3}{\beta_k r} + \dfrac{3}{(\beta_k r)^2}\right), \end{cases} \tag{3}$$

where α_i, β_i, C_i, D_i, N, ρ – the real parameters of the model; $n_u = n_w = 3$.

In papers [12-14] DWF was used in the form

$$\begin{cases} u(r) = r^{3/2} \sum_{i=1}^{N} A_i \exp(-a_i r^3), \\ w(r) = r \sum_{i=1}^{N} B_i \exp(-b_i r^3). \end{cases} \tag{4}$$

In the case of number of terms of the sums $N = 11$, the coefficients A_i, a_i, B_i, b_i of analytical forms (4) for NijmI, NijmII, Nijm93, Reid93 and Argonne v18 potentials are given in [13, 14]. Calculated DWFs not contain excess knots near the origin of coordinates.

DWF (4) were used to calculate the tensor polarization [14], the polarization characteristics of A(d,d')X reactions [15], the vector and tensor asymmetries [16] and others.

3. DEUTERON FORM FACTORS

The differential cross-section for elastic scattering of unpolarized electrons by unpolarized deuterons is given by the formula in the assumptions of the first Born approximation and the conditions of relativistic invariance [17-21]

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \left[A(p^2) + B(p^2) tg^2\left(\frac{\theta_e}{2}\right)\right]. \tag{5}$$

The formula (5) was obtained by Rosenbluth [22].

Here $\left(\dfrac{d\sigma}{d\Omega_e}\right)_{Mott} = \dfrac{1}{f}\left[\dfrac{\alpha\cos(\theta_e/2)}{2E\sin^2(\theta_e/2)}\right]^2$ – the scattering cross-section on a spinless unstructured particle; α = 1/137 – the became a fine structure; $f = 1 + \dfrac{2E}{m_d}\sin^2\left(\dfrac{\theta_e}{2}\right)$ – return factor; θ_e – the angle of electron scattering in the laboratory system; p – the deuteron momentum in units fm^{-1}; E – the energy of the initial electron; $A(p)$ and $B(p)$ – functions of the electric and magnetic structure (structural functions), which are determined by the electromagnetic structure of the deuteron

$$A = G_C^2 + \frac{8}{9}\eta^2 G_Q^2 + \frac{2}{3}\eta G_M^2 ; \quad B = \frac{4}{3}\eta(1+\eta) G_M^2 , \tag{6}$$

where $\eta = \frac{p^2}{4m_d^2}$; m_d = 1875.63 MeV – deuteron mass. Here charge $G_C(p)$, quadrupole $G_Q(p)$ and magnetic $G_M(p)$ deuteron form factors contain information on the electromagnetic properties of the deuteron [21, 23-26]:

$$G_C = G_{EN} D_C ; \; G_Q = G_{EN} D_Q ; \; G_M = \frac{m_d}{2m_p}(G_{MN} D_M + G_{EN} D_E). \tag{7}$$

Here the form factors D_i are:

- the monopoly electric form factor $D_C = \int_0^\infty [u^2 + w^2] j_0 dr$;

- the quadrupole electric form factor $D_Q = \frac{3}{\sqrt{2}\eta}\int_0^\infty \left[uw - \frac{w^2}{\sqrt{8}}\right] j_2 dr$;

- the transverse magnetic form factor $D_M = 2\int_0^\infty \left[\left(u^2 - \frac{w^2}{2}\right) j_0 + \left(\frac{uw}{\sqrt{2}} + \frac{w^2}{2}\right) j_2\right] dr$;

- the longitudinal magnetic form factor $D_E = \frac{3}{2}\int_0^\infty w^2 [j_0 + j_2] dr$;

where $G_{EN} = G_{Ep} + G_{En}$; $G_{MN} = G_{Mp} + G_{Mn}$ – the isoscalar electric and magnetic form factors. Here u and w – radial DWF in the coordinate space; j_0, j_2 – the spherical Bessel functions of zero and second order from the argument $pr/2$; G_{Ep} and G_{En} – the proton and neutron isoscalar electric form factors; G_{Mp} and G_{Mn} – the proton and neutron isoscalar magnetic form factors.

4. CALCULATIONS AND CONCLUSIONS

On Figures 1-3 in logarithmic and usual scales shows the charge $G_C(p)$, quadrupole $G_Q(p)$ and magnetic $G_M(p)$ deuteron form factors. The original dipole fit for the proton and neutron form factors (DFF) [27] was used for theoretical calculations:

$$G_{Ep} = F_N ; \qquad G_{En} = 0 ; \qquad G_{Mp} = \mu_p G_{Ep} ; \qquad G_{Mn} = \mu_n G_{Ep} ; \tag{8}$$

where the nucleon form factor is written in the form of a dipole:

$F_N(p^2) = \left(1 + p^2 / 18.235\, fm^{-2}\right)^{-2}$; μ_p = 2.7928 i μ_n = -1.9130 – the magnetic proton and neutron moments in nuclear magnetons.

For calculations were used DWFs (4), which were obtained for the potentials of Nijmegen group (NijmI, NijmII, Nijm93, Reid93) and for potential Argonne v18 [13, 14].

This designation is N1, N2, N93, R93 and Av18 in Figures 1-3 respectively. Theoretical calculations are compared with experimental data:

- for charge form factor $G_C(p)$ – the collaborations Orsay [28], Bates [29, 30], JLab [31], NIKHEF [32], VEPP3 [33-35], VEPP4 [36], BLAST [6, 37] and the reviews Boden [38], Garcon [30] and Abbott [39];

- for quadrupole form factor $G_Q(p)$ – the collaborations Orsay [28], Bates [29, 30], JLab [31], VEPP3 [33-35], VEPP4 [36], BLAST [6, 37] and the reviews [30] and Abbott [39];

- for magnetic form factor $G_M(p)$ – the collaborations Stanford [40-42], Orsay [28, 43], Naval

Research Lab [44] and the review Karpius [45]. Also, the experimental values of the magnetic form factor were obtained for Mainz [46], Bonn [47], Saclay [48], SLAC [49, 50], using the relationship between $G_M(p)$ and structural function B.

It is necessary to pay attention to the change of the sign of values of form factors: at 4.5-4.8 fm^{-1} for $G_C(p)$; at 12.7-14.6 fm^{-1} for $G_Q(p)$; at 6.2-8.3, 7.9-8.4 and 11.6-13.8 fm^{-1} for $G_M(p)$. Position of the zero for the charge form factor $G_C(p_0)$ is given in Table 1.

The calculated values for the potential models NijmI, NijmII, Nijm93, Reid93, Av18 are indicated in the first rows of this Table. The obtained values are compared with the data for other potential models and experimental values.

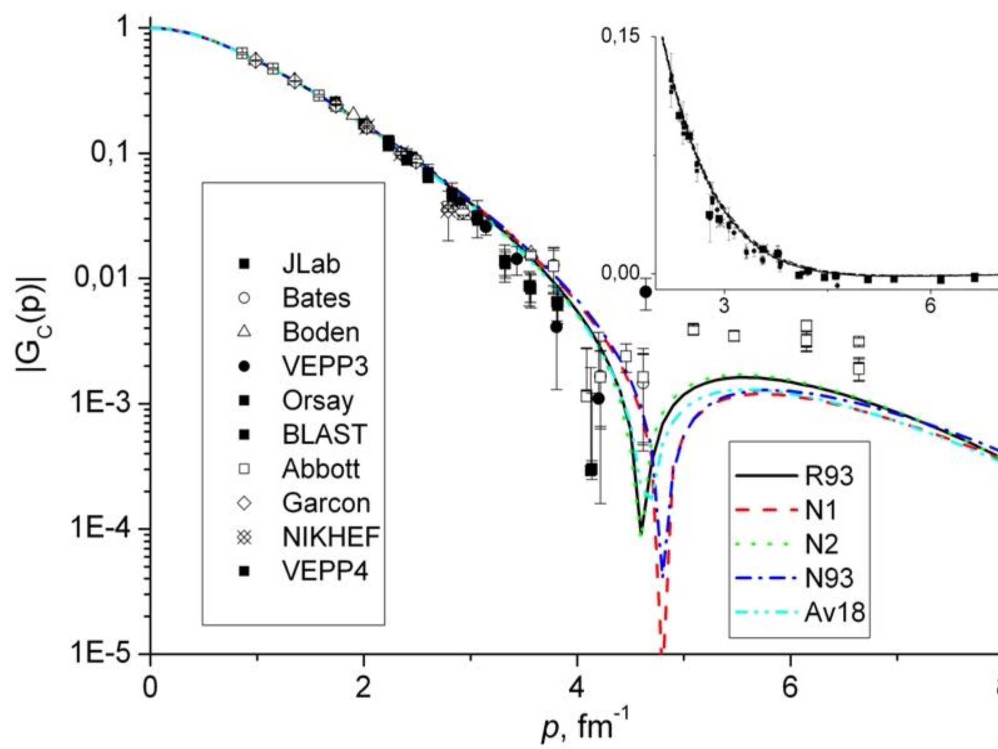

Figure 1. Charge form factor $G_C(p)$

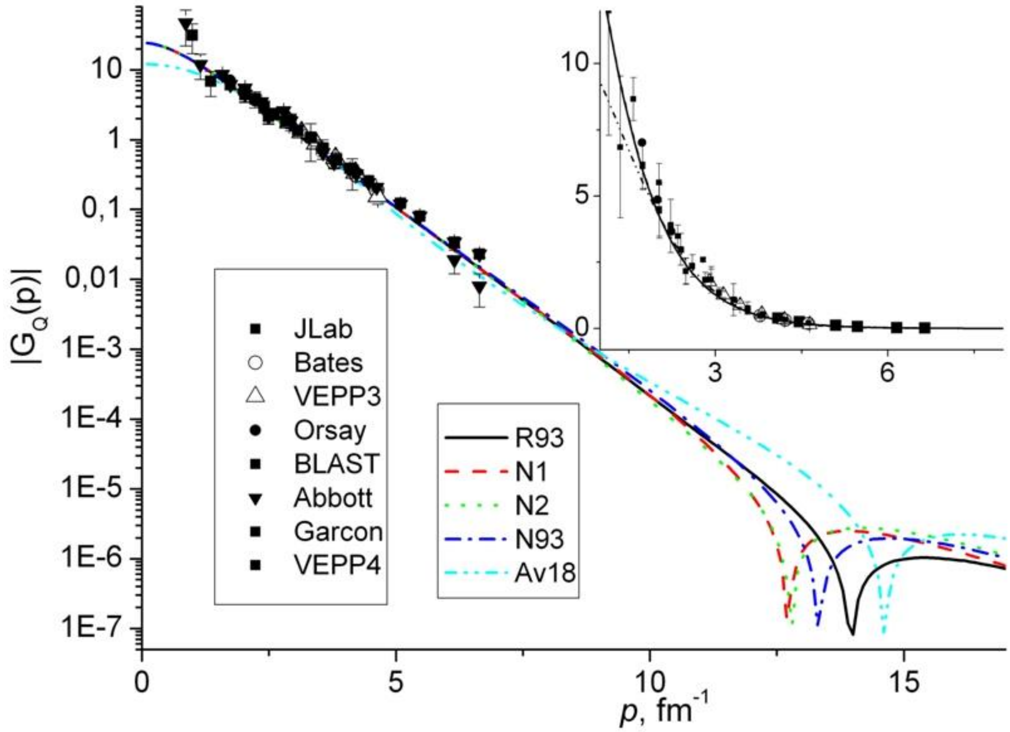

Figure 2. Quadrupole form factor $G_Q(p)$

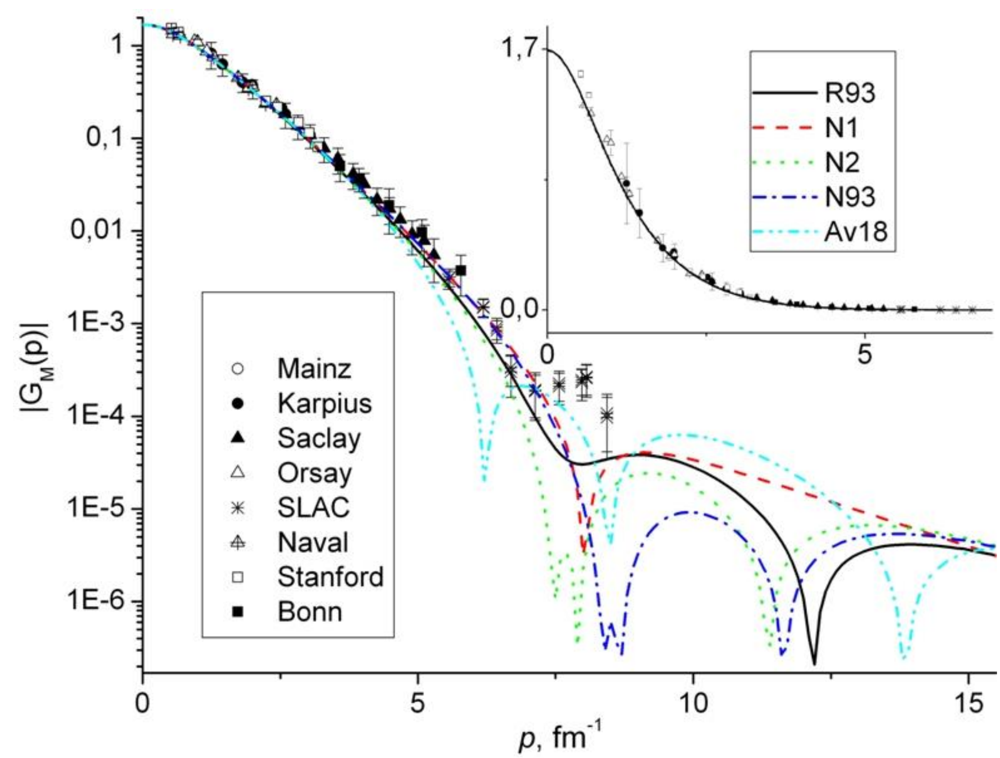

Figure 3. Magnetic form factor $G_M(p)$

Table 1. Position of the zero for the charge form factor $G_C(p_0)$

Potential model or experimental data	p_0, fm^{-1}
NijmI, NijmII, Nijm93 /for DWF (4)/	4.7; 4.5; 4.8
Reid93, Av18 /for DWF (4)/	4.6; 4.6
Bonn-B of the IJLG, GK-85, IJL and Hohler nucleon form factors [51]	4.28; 4.27; 4.25; 4.21
Bonn-B, FULLF, OBEPF of the GK-92 nucleon form factors [51]	4.28; 4.26; 4.10
Nijm93, NijmI, NijmII of the GK-92 nucleon form factors [51]	4.18; 4.28; 4.15
Bonn-B, FULLF, OBEPF as resulting from IA+RC+MEC [52]	4.28; 4.26; 4.08
Nijm93, NijmI, NijmII as resulting from IA+RC+MEC [52]	4.15; 4.27; 4.15
5RM [21], 4RIA [30]	4.8-5.1; 4.3-4.6
Graz II [27]	5.67; 14.7
Moscow, NijmI, NijmII [53]	4.1; 4.6; 4.4
CD-Bonn, Paris [53]	4.4; 4.9
NijmI, NijmII, Paris, CD-Bonn [54]	4.6; 4.35; 4.35; 4.9
Argonne18, Moscow, Idaho, eD [54]	4.4; 4.1; 3.6; 4.3
IA: Reid68, Bonn, Paris, Nijmegen [55]	4.3; 4.5; 4.5; 4.4
MEC: Doleschall D4, Doleschall D7 [55]	4.9; 4.7
MEC: Reid68, Bonn, Paris, Nijmegen [55]	4.0; 4.0; 4.0; 4.0
TP [6], NijmI, NijmII [56]	4.19; 4.9; 4.7
CIA, RIA [57], Graz II [58]	4.24-4.53; 5.7-5.9
CD-Bonn, Paris, PIH [56], NIA [26]	5.2; 4.6; 4.3; 4.6
9RIA [59]	4.5; 9.2-12.3
9DWF [60], 5NC [32]	4.5-6.0; 3.8-4.7
IA AV14, IA+MEC AV14 [29]	4.5; 4.0
Paris, Av14, Bonn-E [30]	4.5; 4.4; 5.3
TCM [61], QCB82, QCB86 [62]	4.2; 4.4; 4.5

TPE [5], MMQCM [63]	4.4-4.8; 4.5-5.2
RIA [64]	4.5-5.2; 11.4-13
QCM [65]; OBEPQ-A, B, C [66]	4.4; 4.1-4.5
IMP [67, 68]	3.9; 9.4; 12
IMP+EXC [67, 68], Graz II [69]	4.4; 5.6-5.9
OGEP [70]	3.5-5.0; 9.5-11.0
Nijm93, OPEP [71]	4.8-4.9
Paris, Hamada-Johnston [72]	4.5-5.0
Meson Exchange potential, Hamada-Johnston [73]	4.1-4.4; 4.5
Isobar channels model A-F [74], Skyrme approach [75]	4.0-4.5; 4.1
TGA, MMD, Kelly parametrizations for form factors [76]	4.0; 4.3-5.4; 4.1
IM BBBA, IM+Exchange BBBA, IM+Exchange BI parametrizations for form factors [77]	5.3; 4.9; 4.9
IM BI parametrization for form factors [77]	5.3; 13.8
Paris [78]	4.5; 12.2
Reid [78]	4.4; 12.2
Paris, RSC (dipole form factor) [75]	4.2-4.6; 4.0
Model Chemtob-Furui with the Paris DWF [79]	4.8-4.9
Quark cluster and conventional theory [80]	4.1; 4.4
Orthogonality constraint quark model [81]	4.7
Reid SC [81], Quark cluster theory [82]	4.4; 5.9
Approach of the reduced transition amplitudes [83]	4.5
Paris [83], six-quark model [84]	9.5; 4.2-4.5
Certov-Mathelitsch-Moravcsik DWF [85]	3.8-5.0
Nonrelativistic DWF [11], LO [86]	4.5; 4.0
NLO [86]	3.2; 4.0
NNLO [86]	2.9; 4.3
χPT NLO, NNLO Idaho [86]	3.7-3.8; 3.6

Nijm93, OPEP+short R=1.5 and 2.5 fm [86]	4.2; 4.3
NLO, N^3LO [87]	4.2; 3.8
LO AV18, TOT AV18 [88, 89]	4.7; 4.2
LO N^3LO [88, 89]	3.8; 4.2
TOT N^3LO [88, 89]	3.6; 3.9
Triplet-even potential 2 and 3 [90]	5.1; 4.5
Meson exchange model F_0F_1'; RSC [91]	4.4; 5.2
RSC [92]; BSLT, ET [93]	4.5; 4.6; 4.2
Reid soft-core [94]	4.8; 11.0-12.2
Phenomenological Lagrangian approach; Tomasi-Gustafsson-Gakh-Adamuscin parameterization [95]	3.8; 3.9
Quark cluster model [96]; RSC [97]	4.2; 4.5
Graz-II (NR, BSLT, BS, SA) [98]	5.1-5.9
Reid SC, Hamada-Johnston, Glendenning-Kramer [99]	4.3-4.4
One-pion-exchange model [100]	4.8-5.8
Argonne v18, Reid93 with G-K and MMD form factors [101]	6.8; 11.8-13.3
Bethe-Salpeter equation OBE model [97]	4.4-4.5
TM [36, 37]; 5NRM [33]	4.1-4.3; 4.1-4.5
Parameterization for exp. [39]	4.21±0.08
Par. III [36, 37]	4.19±0.05
Par. I [33]	$4.11^{+1.34}_{-1.00}$
Par. I [33]	4.17±0.57
Experiment [30]	4.39±0.16

Here are 5RM – 5 relativistic models (AV18, Paris, CDBonn, IIB, W16); 9DWF [60] – 9 models of DWF (Reid SC, Reid HC, Paris, Bonn, Yamaguchi, Graz I, Mongan II, KLS, HH); 5NC – 5 non-relativistic computations [32], which include effects of meson exchange streams; 4RIA [30] – 4 models for relativistic impulse approximation (RIA, RIA+ρπγ, RIA+ρπγ+ωσγ and RIA in the cone formalism for the Argonne v14 potential); IMP+EXC, IMP [67, 68] – the impulse approximation with and without exchange for RSC (Reid soft core); TM [36, 37] – theoretical curves of non-relativistic models with relativistic correlations, relativistic models and effective field theory; 5NRM [33] – non-relativistic impulse approximation (NRIA) with the Paris potential, non-relativistic approaches with relativistic corrections and meson exchange currents (MECs), two relativistic approaches of Phillips and Krutov-Troitsky. Other designations in Table 1 are given according to the cited literature.

In contrast to the charge form factor, the position of the zero for quadrupole and magnetic form factors (Tables 2 and 3) are found on the right side. Unfortunately, there are no experimental values for pulses greater than 7 and 9 fm^{-1} for quadrupole and magnetic form factors, respectively.

Table 2. Position of the zero for the quadrupole form factor $G_Q(p_0)$

Potential model or experimental data	p_0, fm^{-1}
NijmI, NijmII, Nijm93 /for DWF (4)/	12.7; 12.7; 13.3
Reid93, Av18 /for DWF (4)/	13.9; 14.6
9RIA [59], RIA [64]	8.7-10.9; 8.9-12.2
IMP [67, 68]	9.2; 10.8
Isobar channels model A-F [74], OGEP [70]	6.6-7.9; 8.0-10.0
TGA, MMD parametrizations for form factors [76]	7.6; 7.7
IM BI, IM+Exchange BBBA, IM+Exchange BI parametrizations for form factors [77]	12.8; 13.2; 12.8
Paris, Reid [78], LO N3LO [88, 89]	11.3; 11.5; 6.8
Approach of the reduced transition amplitudes [83]	11.0
Paris [83], RSC [94]	21.7; 9.9-10.8
Argonne v18, Reid93 with G-K and MMD form factors [101]	11.0-12.3

Table 3. Position of the zero for the magnetic form factor $G_M(p_0)$

Potential model or experimental data	p_0, fm^{-1}
NijmI /for DWF (4)/	8.0
NijmII /for DWF (4)/	7.4; 7.9; 11.3
Nijm93 /for DWF (4)/	8.3; 8.6; 11.6
Reid93 /for DWF (4)/	12.1

Av18 /for DWF (4)/	6.2; 8.4; 13.8
Moscow, NijmI, NijmII [53]	5.3; 6.9; 6.0
CD-Bonn, Paris [53]	6.7; 5.8
9DWF [60], TCM [61]	5.5-7.5; 7.2
QCB82, QCB86 [62], QCM [65], NIA [26]	7.1; 7.2; 6.5; 6.6
5RM [21], MMQCM [63]	5.6-6.1; 6.8-7.5
RIA [64]	6.5; 11.1
IMP [67, 68]	6.5; 8.2
six-quark model [84], RSC [94]	6.8; 6.8-7.3
OGEP [70]	4.5-7.0; 9.5-12
OPEP [71], Quark cluster model [102]	4.5; 7-7.5
Isobar channels model A-F [74]	5.9-7.0
TGA, MMD, Kelly parametrizations for form factors [76]	6.8; 7.0; 7.4
Light-front representation [7]	5.85
IM BBBA, IM BI, IM+Exchange BI parametrizations for form factors [77]	7.0; 7.0; 7.2
IM+Exchange BBBA parametrization for form factors [77]	7.2; 13.5
dipole and GK parametrizations for form factors [75]	7.2; 6.4
Model Chemtob-Furui with the Paris DWF [79]	6.7
Quark cluster and conventional theory [80]	7.2; 6.7
Orthogonality constraint quark model [81]	5.2-5.7
Reid SC [81], Quark cluster theory [82]	6.1-6.6; 6.3
LO N3LO [88, 89]	4.4; 5.0
BSLT, ET [93]	6.0; 5.8
BSLT++, ET++ [93]	5.7; 5.2
Tomasi-Gustafsson-Gakh-Adamuscin parameterization [95]	6.8
Quark cluster model [96], Graz-II (SA) [98]	5.6-6.2; 4.5
Argonne v18, Reid93 with G-K and MMD form factors [101]	6.2

Bethe-Salpeter equation OBE model [97]	6.0-6.2
NijmI, NijmII, Paris, CD-Bonn [54]	6.9; 5.8; 5.8; 6.7
Argonne18, Moscow, Idaho, eD [54]	6.05; 5.2; 4.25; 7.4
Parameterization for exp. [39, 50]	7.2±0.3

The obtained values of deuteron form factors can be used to calculate the following values of polarization observable as:

- the functions of the electric and magnetic structure *A(p)* and *B(p)* according to formulas (6);
- the tensor t_{2j} and vector t_{1i} polarizations [21];
- the tensor analyzing power A_{yy} and vector (tensor) polarization transfer coefficients $k_a^{a'}$ ($k_{aa}^{a'a'}$) in the framework of the model of ω-meson exchange [103];
- the spin correlation coefficients $C_{xz}^{(0)}$, $C_{zz}^{(0)}$ and tensor asymmetries $A_{xx}^{(0)}$, $A_{xz}^{(0)}$, $A_{zz}^{(0)}$ for lepton-deuteron scattering within the limit of zero lepton mass [104].

References

[1] R. Machleidt, *Phys. Rev. C* 63, 024001 (2001).

[2] V.I. Kukulin et al., *Phys. Rev. C* 57, 535 (1998).

[3] V.I. Zhaba, Deuteron: properties and analytical forms of wave function in coordinate space // e-print arXiv:nucl-th/1706.08306.

[4] V.I. Zhaba, *Uzhhorod Univ. Scien. Herald. Ser. Phys.* 42, 191 (2017).

[5] M.P. Valderrama et al., *Eur. Phys. J. A* 36, 315 (2008).

[6] M. Kohl, *Nucl. Phys. A* 805, 361 (2008).

[7] C.-Y. Liang et al., *Chinese Phys. C* 38 074104 (2014).

[8] M. Lacombe et al., *Phys. Lett. B* 101, 139 (1981).

[9] V.M. Krasnopol'sky et al., *Phys. Lett. B* 165, 7 (1985).

[10] M.N. Platonova, V.I. Kukulin, *Phys. Atom. Nucl.* 73, 86 (2010).

[11] Yu.A. Berezhnoy et al., *Intern. Jour. Mod. Phys. E* 14, 1073 (2005).

[12] V.I. Zhaba, *Cherkasy Univ. Bull., Phys. and Mathem. Scienc.* 349(16), 50 (2015).

[13] V.I. Zhaba, *Nucl. Phys. Atom. Energy* 17, 22 (2016).

[14] V.I. Zhaba, *Mod. Phys. Lett. A* 31, 1650139 (2016).

[15] V.I. Zhaba, *Mod. Phys. Lett. A* 33, 1850160 (2018).

[16] V.I. Zhaba, *World Scientific News* 114, 230 (2018).

[17] J.E. Elias et al., *Phys. Rev.* 177, 2075 (1969).

[18] S. Galster et al., *Nucl. Phys. B* 32, 221 (1971).

[19] T.W. Donnelly, A.S. Raskin, *Ann. Phys. (N. Y.)* 169, 247 (1986).

[20] M. Garcon, J.W. van Orden, *Adv. Nucl. Phys.* 26, 293 (2001).

[21] R. Gilman, F. Gross, *J. Phys. G* 28, R37 (2002).

[22] M.N. Rosenbluth. *Phys. Rev.* 79, 615 (1950).

[23] M. Gourdin. *Nuovo Cimento* 28, 533 (1963).

[24] F. Gross, *Phys. Rev.* 136, B140 (1964).

[25] E.L. Lomon, *Ann. Phys.* 125, 309 (1980).

[26] C. Adamuščín et al., *Phys. Rev. C* 78, 025202 (2008).

[27] A.V. Bekzhanov et al., *JETP Lett.* 99, 613 (2014).

[28] D. Benaksas et al., *Phys. Rev.* 148, 1327 (1966).

[29] I. The et al., *Phys. Rev. Lett.* 67, 173 (1991).

[30] M. Garcon et al., *Phys. Rev. C* 49, 2516 (1994).

[31] D. Abbott et al., *Phys. Rev. Lett.* 84, 5053 (2000).

[32] M. Bouwhuis et al., *Phys. Rev. Lett.* 82 3755 (1999).

[33] D.M. Nikolenko et al., *Phys. Rev. Lett.* 90, 072501 (2003).

[34] D.M. Nikolenko et al., *Phys. Atom. Nucl.* 73, 1322 (2010).

[35] S.A. Zevakov et al., Preprint INP 2006-024, Novosibirsk, 2006.

[36] D. Toporkov, *Int. J. Mod. Phys. Conf. Ser.* 40, 1660004 (2016).

[37] C. Zhang, M. Kohl, T. Akdogan et al, *Phys. Rev. Lett.* 107, 252501 (2011).

[38] B. Boden et al., *Z. Phys. C* 49, 175 (1991).

[39] D. Abbott et al., *Eur. Phys. J. A* 7, 421 (2000).

[40] J. Goldemberg, C. Schaerf, *Phys. Rev. Lett.* 12, 298 (1964).

[41] R.E. Rand et al., *Phys. Rev. Lett.* 18, 469 (1967).

[42] R.E. Rand, M.R. Yearian, *Phys. Rev. D* 8, 3229 (1973).

[43] B. Grossetete et al., *Phys. Rev.* 141, 1425 (1966).

[44] E.C. Jones et al., *Phys. Rev. C* 21, 1162 (1980).

[45] P. Karpius, Vector Polarization Observables of the Deuteron and A New Measurement of the Magnetic Dipole Form Factor GM, Ph.D. thesis (Durham: University of New Hampshire, 2005).

[46] G.G. Simon et al., *Nucl. Phys. A* 364, 285 (1981).

[47] R. Cramer et al., *Z. Phys. C* 29, 513 (1985).

[48] S. Auffret et al., *Phys. Rev. Lett.* 54, 649 (1985).

[49] R.G. Arnold et al., *Phys. Rev. Lett.* 58 1723 (1987).

[50] P.E. Bosted et al., *Phys. Rev. C* 42, 38 (1990).

[51] W. Plessas et al., *Few-Body Syst. Suppl.* 9, 429 (1995).

[52] R.F. Wagenbrunn, W. Plessas, *Few-Body Syst. Suppl.* 8, 181 (1995).

[53] N.A. Khokhlov, A.A. Vakulyuk, *Phys. Atom. Nucl.* 78, 92 (2015).

[54] N.A. Khokhlov, The deuteron wave function and neutron form factors from the elastic electron deuteron scattering. E-print: arXiv:nucl-th/1612.08172

[55] M.I. Haftel et al., *Phys. Rev. C* 22, 1285 (1980).

[56] A.F. Krutov, *Theor. Phys.* 3, 5 (2002).

[57] J.W. Van Orden et al., *Few-Body Syst. Suppl.* 9, 415 (1995).

[58] S.G. Bondarenko et al., *Phys. Atom. Nucl.* 63, 774 (2000).

[59] D.G. Arnold et al., *Phys. Rev. C* 21, 1426 (1980).

[60] L. Mathelitsch, H.F.K. Zingl, *Nuovo Cimento A* 44, 81 (1978).

[61] E. Tomasi-Gustafsson et al., *Phys. Rev. C* 73, 045204 (2006).

[62] H. Dijk, B.L.G. Bakker, *Nucl. Phys. A* 494, 438 (1989).

[63] H. Ito, A. Faessler, *Nucl. Phys. A* 470, 626 (1987).

[64] M.A. Braun, M.V. Tokarev, *Phys. Elem. Part. Atom. Nucl.* 22, 1237 (1991).

[65] A. Faessler et al., *Intern. Jour. Mod. Phys. E* 2, 39 (1993).

[66] H. Arenhovel et al., *Phys. Rev. C* 61, 034002 (2000).

[67] M. Gari, H. Hyuga, *Nucl. Phys. A* 264, 409 (1976).

[68] M. Gari et al., *Phys. Rev. C* 14, 2196 (1976).

[69] S.G. Bondarenko et al., *Prog. Part. Nucl. Phys*. 48, 449 (2002).

[70] H. Ito, L.S. Kisslinger, *Phys. Rev. C* 40, 887 (1989).

[71] D.R. Phillips, T.D. Cohen, *Nucl. Phys. A* 668, 45 (2000).

[72] N.G. Kelkar, D.B. Fierro, *Phys. Lett. B* 772. 159 (2017).

[73] I.T. Cheon, *Lett. Nuovo Cimento* 31, 347 (1981).

[74] W.P. Sitarski et al., *Phys. Rev. C* 36, 2479 (1987).

[75] E.M. Nyman, D.O. Riska, *Nucl. Phys. A* 468, 473 (1987).

[76] Y. Dong et al., *Phys. Rev. C* 78, 035205 (2008).

[77] Y. Huang,W.N. Polyzou, *Phys. Rev. C* 80, 025503 (2009).

[78] V.A. Karmanov, A.V. Smirnov, *Nucl. Phys. A* 575, 520 (1994).

[79] M. Chemtob, S. Furui, *Nucl. Phys. A* 454, 548 (1986).

[80] Y. Yamauchi et al., *Nucl. Phys. A* 443, 628 (1985).

[81] D. Robson, *Phys. Rev. C* 61, 015202 (1999).

[82] A. Buchmann et al., *Nucl. Phys. A* 496, 621 (1989).

[83] A.P. Kobushkin, A.I. Syamtomov, *Phys. Atom. Nucl.* 58, 1477 (1995).

[84] Y. Yamauchi, M. Wakamatsu, *Nucl. Phys. A* 457, 621 (1986).

[85] L. Mathelitsch, *Czech. J. Phys.* 43, 363 (1993).

[86] D.R. Phillips, *Phys. Lett. B* 567, 12 (2003).

[87] D.R. Phillips, *J. Phys. G: Nucl. Part. Phys.* 34, 365 (2007).

[88] M. Piarulli et al., *Phys. Rev. C* 87, 014006 (2013).

[89] L. Girlanda et al., *J. Phys.: Conf. Ser.* 527, 012022 (2014).

[90] N.K. Glendenning, G. Kramer, *Phys. Rev.* 126, 2159 (1962).

[91] A.D. Jackson et al., *Nucl. Phys. A* 249, P. 397 (1975).

[92] J.A. Tjon, *Few-Body Syst. Suppl.* 5, 5 (1992).

[93] E. Hummel, J.A. Tjon, *Phys. Rev. C* 49, 21 (1994).

[94] R.S. Bhalerao, *Nucl. Phys. A* 389, 557 (1982).

[95] C.-Y. Liang, Y.-B. Dong, *Chinese Phys. C* 39, 104104 (2015).

[96] A. Buchmann et al., *J. Phys. G* 14, 1037 (1988).

[97] M.J. Zuilhof, J.A. Tjon, *Phys. Rev. C* 22, 2369 (1980).

[98] G. Rupp, J.A. Tjon, *Phys. Rev. C* 41, 472 (1990).

[99] T.J. Brady et al., *Can. J. Phys.* 52, 1322 (1974).

[100] Jr. J. Adam et al., *Phys. Rev. C* 48, 370 (1993).

[101] T.W. Allen et al., *Phys. Rev. C* 63, 034002 (2001).

[102] A. Faessler, *Few-Body Syst. Suppl.* 6, 176 (1992).

[103] M.P. Rekalo, *Phys. Rev. C* 54, 3125 (1996).

[104] G.I. Gakh et al., *Phys. Rev. C* 90, 064901 (2014).