ELECTROMAGNETIC FORM FACTORS OF DEUTERON ELECTRODISINTEGRATION NEAR THRESHOLD

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Polarization effects near threshold of the electrodisintegration of the deuteron, $e^- + d \to e^- + p + n$, are analysed. Polarization observables are defined in terms of 5 electromagnetic form factors (EFF) of S-state two-nucleon production. The EFF are calculated in the framework of the relativistic impulse approximation with the final state interaction taken into account. Sensitivity of the obtained results to both the choice of the deuteron wave function and the way of parametrization of the nucleon electromagnetic current off mass shell is investigated.

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1. *Introduction*

The importance of investigating polarization effects (PE) in ed-scattering has already been indicated in the literature [1–3]. The development of polarized electron beams [4], polarized deuterium targets [5], and polarimeters of new design for measuring final particle polarizations [6] has made it possible to carry out various polarization experiments. Thus experiments on electrodisintegration of the deuteron (EDD) with a tensor polarization were initiated at Novosibirsk [7].

Different problems of PE applied to EDD have been considered in Refs [1, 2, 8–10]. It is evident that PE near the EDD threshold are of great importance, since the available experimental data obtained in this region with electrons scattered at backward angles are treated as an evidence of a large contribution of mesonic exchange currents [11–13]. In so doing, it is usually neglected that the "one-body" contribution to the EDD cross section is calculated using standard methods of nonrelativistic nuclear physics in the framework of the impulse approximation with a further extrapolation of the results to the region of high momentum transfers.

In the present paper we analyse the PE in the EDD near threshold. It was shown earlier

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[14] how, proceeding from such general properties of hadron electrodynamics as the electromagnetic current (EC) conservation and P-invariance, the amplitude of the process $\gamma^*+\mathrm{d} \to \mathrm{n}+\mathrm{p}$ (where γ^* denotes a virtual photon) can be parametrized in terms of 5 electromagnetic form factors (EFF) of two-nucleon production to the S-state.

To estimate the corresponding PE near threshold, we have calculated the EFF in the framework of the relativistic impulse approximation (RIA). Naturally, a realistic parametrization of these form factors in the threshold region must satisfy the unitarity condition for the multipole amplitudes of the $\gamma^*+\mathrm{d} \to \mathrm{n}+\mathrm{p}$ process.

Here we also investigate in detail the sensitivity of the form factors obtained to the choice of the γ^*NN-vertex, which is related to the uncertainty of the nucleon EC parametrization off the mass shell.

2. *Polarization effects*

The matrix element of the EDD within the one-photon approximation has the form

$$\mathcal{M} = \frac{e^2}{k^2} \cdot j_\mu J_\mu, \qquad j_\mu = \bar{u}(k_2)\gamma_\mu u(k_1), \tag{1}$$

where J_μ is the EC of the $\gamma^*\mathrm{d} \to \mathrm{np}$ transition, $k_1(k_2)$ is the 4-momentum of the initial (final) electron, $k = k_1 - k_2$.

Taking advantage of the conservation of leptonic EC j_μ and hadronic EC J_μ, the matrix element (1) can be written as

$$\mathcal{M} = e \cdot e_\mu J_\mu \equiv e \cdot \boldsymbol{e}^* \boldsymbol{J}, \qquad e_\mu = \frac{e}{k^2} \cdot j_\mu, \qquad \boldsymbol{e}^* = \frac{\boldsymbol{e}\boldsymbol{k}}{k_0^2}\boldsymbol{k} - \boldsymbol{e}. \tag{2}$$

In the c.m.s. of the reaction $\gamma^*+\mathrm{d} \to \mathrm{n}+\mathrm{p}$ we can write $\mathcal{M} = e\varphi_p^+ \mathcal{F} \sigma_2 \tilde{\varphi}_n^+$, where $\varphi_p(\varphi_n)$ is the spinor of p(n). In the general case, $\mathcal{F}$ is characterized by 18 scalar (generally, complex) functions of three independent kinematic variables [2]. Near the EDD threshold, however, the spin structure of the amplitude $\mathcal{F}$ is substantially simplified [14] and can be defined by five EFF

$$\begin{aligned} \mathcal{F} &= ig_1 \cdot \boldsymbol{e}^* \boldsymbol{U} \times \hat{\boldsymbol{k}} + g_2 \cdot \boldsymbol{\sigma}\hat{\boldsymbol{k}} \cdot \boldsymbol{e}^* \boldsymbol{U} + g_3 \cdot \boldsymbol{e}^* \boldsymbol{\sigma} \cdot \boldsymbol{U}\hat{\boldsymbol{k}} \\ &\quad + g_4 \cdot \boldsymbol{e}^* \hat{\boldsymbol{k}} \cdot \boldsymbol{\sigma}\hat{\boldsymbol{k}} \cdot \boldsymbol{U}\hat{\boldsymbol{k}} + g_5 \cdot \boldsymbol{e}^* \hat{\boldsymbol{k}} \cdot \boldsymbol{U}\boldsymbol{\sigma}, \\ &\hat{\boldsymbol{k}} \equiv \boldsymbol{k}/|\boldsymbol{k}|, \qquad g_i \equiv g_i(k^2), \end{aligned} \tag{3}$$

where $\boldsymbol{U}$ is the deuteron polarization vector.

Note that expression (3) is also valid for the production into the S-state of (np) with a nonzero relative momentum. Then $g_i = g_i(k^2, E_{\mathrm{np}})$ (where $E_{\mathrm{np}} = W - 2m$, W is the (np) invariant mass, m is the nucleon mass) and the quantities g_{1-5} can be related to the scalar amplitudes f_i (Appendix 1) defined in [2]. It should also be noted that the EFF g_1 describes the absorption of the isovector γ^* (M1 $\to {}^1S_0$-transition), while the EFF g_{2-5} describe the absorption of the isoscalar γ^* (transitions to the ${}^3S_1$-state of nucleons).

The EFF g_i determine all PE in $\gamma^*+\mathrm{d}\to\mathrm{n}+\mathrm{p}$ near threshold. It appears most convenient to carry out the general analysis of PE in terms of the structure functions (SF). Thus, the tensor $H_{ij}=\overline{J_iJ_j}$ (where the bar denotes the summation over nucleon polarizations) for the polarized deuterium target in the T-invariant hadron electrodynamics is defined by a combination of eight SF:

$$H_{ij}=\bar{\delta}_{ij}u_1+\hat{k}_i\hat{k}_ju_2+i\varepsilon_{ijl}\xi_lu_3+i\varepsilon_{ijl}\hat{k}_l\xi\hat{k}\cdot u_4$$
$$+S_{ab}\hat{k}_a\hat{k}_b\cdot(\bar{\delta}_{ij}u_5+\hat{k}_i\hat{k}_ju_6)+S_{ij}u_7+(S_{ia}\hat{k}_a\hat{k}_j+S_{ja}\hat{k}_a\hat{k}_i)u_8,$$
$$u_i\equiv u_i(k^2,E_{\mathrm{np}}),\qquad \bar{\delta}_{ij}\equiv\delta_{ij}-\hat{k}_i\hat{k}_j \tag{4}$$

where $\xi_i(S_{ij})$ characterize the vector (tensor) polarization of the deuteron. Formula (4) describes the PE not only near threshold. This is a general expression for the dependence of the inclusive tensor both on vector and tensor polarizations of the target.

Expression (4) results in the following general structure of the differential cross section for the EDD near threshold at scattering of longitudinally polarized electrons with the helicity

$$\lambda/2(z=\hat{k},\ y=k\times k_1/|k\times k_1|,\ x=y\times z):$$
$$\frac{d^2\sigma}{dE'd\Omega_e}=\frac{\alpha^2}{64\pi^3}\frac{E'}{E}\frac{|p|}{MW}\frac{4\pi}{(-k^2)}[v_1+\kappa v_2$$
$$+\lambda\sqrt{1-\kappa^2}\,\xi_zv_3+\lambda\sqrt{\kappa(1-\kappa)}\,\xi\times v_4+Q_{zz}v_5$$
$$+\kappa(Q_{xx}-Q_{yy})v_6+\kappa Q_{zz}v_7+\sqrt{\kappa(1-\kappa)}\,Q_{xz}v_8],$$
$$\kappa^{-1}=1-2\frac{k^2_{\mathrm{l.s.}}}{k^2}\mathrm{tg}^2\frac{\theta_e}{2}, \tag{5}$$

where $E(E')$ is the initial (final) electron energy, and θ_e is the electron scattering angle in the lab system, p and k_0 are the c.m.s. momentum of the nucleon and the energy of virtual photons, respectively; M is the deuteron mass.

Components of the deuteron quadrupole polarization tensor Q_{ij} in the lab system are related to components of the tensor S_{ij} by the boost along the z-axis: $S_{xz}=Q_{xz}\cdot\omega/M$, $S_{zz}=Q_{zz}(\omega/M)^2$, where ω is the c.m.s. deuteron energy. Relationships between the quantities v_i and the EFF g_{1-5} and SF u_i are presented in Appendix 2.

While analysing relative contributions of the S-wave multipole form factors to v_i, it is advisable to make use of the following inequalities:

$$0\leqslant T_z\leqslant 1,\qquad T_z=\tfrac{2}{3}\frac{v_3}{v_1};$$

$$-1\leqslant T_{xx}-T_{yy}\leqslant 1,\qquad T_{xx}-T_{yy}=\tfrac{2}{3}\frac{v_6}{v_1};$$

$$-1\leqslant T^{(\mathrm{T})}_{zz}\leqslant 2,\qquad T^{(\mathrm{T})}_{zz}=\tfrac{2}{3}\frac{v_5}{v_1};$$

$$-1 \leqslant T_x \leqslant 1, \qquad T_x = \frac{v_4}{v_1+v_2};$$

$$-1 \leqslant T_{xz} \leqslant 1, \qquad T_{xz} = \tfrac{1}{2}\,\frac{v_8}{v_1+v_2};$$

$$-0.5 \leqslant T^{(L)}_{zz} \leqslant 1, \qquad T^{(L)}_{zz} = \tfrac{1}{3}\,\frac{v_7}{v_2}. \tag{6}$$

These inequalities result from the formulae of Appendix 2. The closeness of T_z to $+1$ and $T_{xx}-T_{yy}$, $T^{(T)}_{zz}$ to -1 must indicate the dominance of the EFF g_1 (of the M1 $\to {}^1S_0$--transition) contribution to the amplitude of transverse γ^* absorption. If one of the amplitudes of the E2 $\to {}^3S_1$ — or M1 $\to {}^3S_1$-transitions is zero, then $T_{xx}-T_{yy}$ and $T^{(T)}_{zz}$ values must coincide. If $T^{(L)}_{zz} \to +1$, then the $\mathrm{E2_L} \to {}^3S_1$-transition dominates in the amplitude of the longitudinal γ^* absorption, and if $T^{(L)}_{zz} \to -1/2$, then the main contribution comes from the $\mathrm{E0_L} \to {}^3S_1$-transition.

The polarization of the nucleon produced in the $e^-+d \to e^-+n+p$ reaction can be analysed in a similar way. In this case, the proton polarization vector $\boldsymbol{P}$ (the deuteron being unpolarized) can be written as:

$$\boldsymbol{P}\cdot\frac{d^2\sigma}{dE'd\Omega_e} = \frac{\alpha^2}{64\pi^3}\,\frac{E'}{E}\,\frac{|\boldsymbol{P}|}{MW}\,\frac{1}{1-\kappa}\,\frac{4\pi}{(-k^2)}\,[\boldsymbol{x}\cdot\lambda\sqrt{\kappa(1-\kappa)}\,P_1$$

$$-\boldsymbol{y}\cdot\sqrt{\kappa(1+\kappa)}\,P_2+\boldsymbol{z}\cdot\lambda\sqrt{1-\kappa^2}\,P_3]. \tag{7}$$

P_{1-3} can be written in terms of the EFF g_i as

$$P_1 = \frac{2\sqrt{-2k^2}}{3k_0}\cdot \mathrm{Re}\left[-(g_1+g_2)g_5^* + \left(\frac{\omega}{M}\right)^2 g_3(g_2+g_3+g_4+g_5)^*\right],$$

$$P_2 = -\frac{2\sqrt{-2k^2}}{3k_0}\,\mathrm{Im}\,(g_1 g_5^*),$$

$$P_3 = \tfrac{2}{3}\,\mathrm{Re}\left(2g_1g_2^* + \left(\frac{\omega}{M}\right)^2 |g_3|^2\right). \tag{8}$$

Note that P_x, $P_y = 0$ at $\theta_e = 0°$ and $180°$ (it is a natural kinematic restriction valid not only near threshold). The P_y component (transverse polarization) is nonzero only if the EFF are complex. The expression for the final neutron polarization can be derived from (8) by changing the sign before the EFF g_1.

To estimate a relative contribution of the real and imaginary parts of the EFF g_i, we employ the unitarity condition (Fermi-Watson theorem [15]). According to this condition, the multipole amplitude phases of the $\gamma^*+d \to n+p$ process must coincide with the corresponding phases of (np) scattering up to the pion production threshold ($E_{np} \leqslant 140$ MeV). The reality of the EFF g_i at $E_{np} = 0$ is a result of the unitarity condition.

The expressions obtained above demonstrate the necessity of setting up polarization experiments in order to measure all five EFF even at the EDD threshold (where only the S-state of the (np)-system is of importance). With the knowledge of the contributions of longitudinal and transverse γ^*-quanta to the cross section, it is possible to determine the magnitudes of all EFF by measuring the corresponding asymmetries of scattering of unpolarized electrons by the tensor polarized deuteron.

Measurements of the asymmetries caused by the vector polarization of the deuteron, and the polarization vector components of the final nucleon (the deuteron being unpolarized) are important for extracting information on the relative phases of the EFF. However, even these measurements are not sufficient enough to provide a complete set of experiments in the $e^- + d \to e^- + n + p$ near threshold.

3. *Unitarity condition and the final state interaction*

We calculate the EFF g_i by the use of the RIA [9] defined by four Feynman diagrams (Fig. 1a–d). The presence of the deuteron diagram (Fig. 1c) is an important feature of this approximation, since its contribution increasing near threshold due to the propagator factor $(W^2 - M^2)^{-1} \simeq (4m\mathscr{E}_d)^{-1}$ (where $\mathscr{E}_d$ is the deuteron binding energy) leads to the results [16] qualitatively different from the corresponding nonrelativistic calculations [12, 13]. The interaction of nucleons in the final $^1S_0$-state was taken into account in [16] by the use of the unitarity condition, while the real part of the multipole amplitude was simply set equal to the corresponding Born amplitude (Fig. 1).

The EFF $g_i(k^2, E_{np})$ can be calculated in a different way making use of the dispersion relations for the multipole amplitudes [17]. As a result, we have

$$g_1(x) = \exp[i\delta_s(x)] \cdot \Bigg[g_{1B}(x) \cdot \cos\delta_s(x) + \frac{\exp[\varrho(x)]}{\pi} P \int_0^\infty dx' \frac{g_{1B}(x') \exp[-\varrho(x')] \sin\delta_s(x')}{x' - x} \Bigg],$$

$$\varrho(x) = \frac{x + x_1}{\pi} P \int_0^\infty dx' \frac{\delta_s(x')}{(x' - x)(x' + x_1)}, \qquad x \equiv p^2, \tag{9}$$

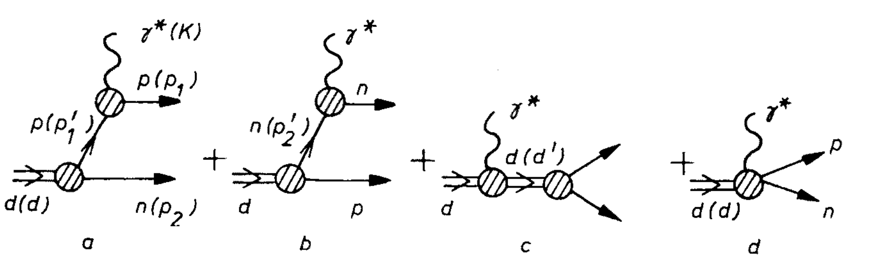

Fig. 1. Feynman diagrams of the Born approximation for the $e^- + d \to e^- + n + p$ process

where x_1 is the subtraction point, g_{1B} is the Born diagram contribution (Fig. 1) to the EFF g_1, δ_s is the (np)-scattering phase. Neglecting the x dependence of g_{1B} (it is justified at $|\boldsymbol{k}| \gg |\boldsymbol{p}|$), Eq. (9) takes the form

$$g_1(x) = g_{1B} \cdot \exp\left[\varrho(x) + i\delta_s(x)\right]. \tag{10}$$

Describing the phase δ_s by the effective range formula

$$\sqrt{x} \operatorname{ctg} \delta_s = -a_s^{-1} + r_{0s}x/2$$

and setting $r_{0s}^2 x_1 \gg 1$, we obtain the result of [18], i.e.,

$$\exp\left[\varrho(x)\right] = \left[\frac{xr_{0s}^2 + \left(\sqrt{1 - \frac{2r_{0s}}{a_s}} + 1\right)^2}{xr_{0s}^2 + \left(\sqrt{1 - \frac{2r_{0s}}{a_s}} - 1\right)^2}\right]^{\frac{1}{2}}. \tag{11}$$

The factor (11) results in a bump in the EDD cross section near threshold due to the final nucleon interaction in the $^1S_0$-state.

Near threshold, the EFF g_{2-5} are dominated by the deuteron diagram contribution. Since the $d' \to np$ transition is expressed here in terms of the $^3S_1 - {}^3D_1$-state wave functions, we proceed from the assumption that the absolute EFF g_{2-5} value is defined by the Born approximation, while the phase is given by the unitarity condition:

$$g_{2-5}(x) = g_{2-5B}(x) \cdot \exp\left[i\delta_t(x)\right], \tag{12}$$

where δ_t is the (np)-scattering phase in the $^3S_1$-state.

In our calculations we have used the parameter values from [19]: $a_s = -23.679$, $r_{0s} = 2.505$, $a_t = 5.395$, $r_{0t} = 1.752$ (in units [fm]), which are consistent with the experimental phases of (np)-scattering up to $E_{np} \simeq 5$ MeV.

4. *Uncertainty of the γ^*NN-vertex parametrization*

RIA calculations require the knowledge of the values of the invariant form factors for dnp-, γ^*NN-, and γ^*dd-vertices. For the dnp-vertex, we utilize the solution of the quasi-potential equation of Gross [20] and the deuteron wave function (DWF) of the Paris potential; the γ^*dd-vertex is described, similarly to [9], by elastic electromagnetic form factors of the deuteron.

It is well known that the γ^*NN-vertex can be written in different ways: either in terms of the form factors F_{1N}, F_{2N}, or the form factors G_{EN}, G_{MN} [22],

$$O_\mu = F_{1N}(k^2)\gamma_\mu - \frac{\sigma_{\mu\nu}k_\nu}{2m} F_{2N}(k^2), \tag{13}$$

$$O_\mu = \frac{1}{2m(1+\tau)}\left(P_\mu G_{EN}(k^2) + i\varepsilon_{\mu\nu\alpha\beta}P_\nu k_\alpha \gamma_\beta \gamma_5 \frac{G_{MN}(k^2)}{2m}\right), \tag{14}$$

or in the "intermediate" form

$$O_\mu = G_{MN}(k^2)\gamma_\mu - \frac{P_\mu}{2m} F_{2N}(k^2), \tag{15}$$

where $\tau = -k^2/4m^2$, $G_{EN} = F_{1N} - \tau F_{2N}$, $G_{MN} = F_{1N} + F_{2N}$, P_μ is the sum of the initial and final nucleon momenta. All these ways lead to the same result, if the nucleon is on the mass shell. However, if we use these parametrizations for calculating amplitudes of the $\gamma^* + d \to n + p$ process, then we obtain, naturally, different formulae for the EFF g_i. A similar effect for electrons scattered by nuclei was investigated previously in [23].

The "catastrophic diagram" contribution (Fig. 1d) is found according to the method of [24] through minimal substitution of the electromagnetic interaction term to the dnp-vertex with taking into account the nonlocality described by the nucleon form factors. To provide the hadronic EC conservation, we have made the replacement $J_\mu \to J_\mu - k_\mu J \cdot k/k^2$. Comparison of the expressions for the EFF g_1 in the Born approximation at $E_{np} = 0$ (Appendix 3) with an analogous result obtainable from the standard impulse approximation (see, e.g., Ref. [13]) shows that the main difference from a nonrelativistic approach for the $(M1 \to {}^1S_0)$-transition amplitude is determined by the DWF P-wave contribution.

5. *Numerical calculations*

In conclusion, we discuss the results of RIA calculations for EFF g_i and SF with the final state interactions taken into account. Let us consider the threshold region, where $|\boldsymbol{k}| \gg |\boldsymbol{p}|$. The EDD amplitude can be defined here in terms of the EFF g_i. Besides, we take into account the E_{np}-dependence of the multipole amplitudes only in the deuteron propagator and the dnp-vertex function. The final state interaction is described via the unitarization procedure.

The standard parametrization $G_{Ep} = G_{Mp}/\mu_p = G_{Mn}/\mu_n = \left(1 - \frac{k^2}{0.71}\right)^{-1}$, $G_{En} = 0$ has been used for the EFF of nucleons. For the EFF of the deuteron, the calculated results of [25] and the measured data from [26] up to $-k^2 = 2.5\,(\mathrm{GeV}/c)^2$ have been used.

The analysis of the EDD differential cross section values calculated in the kinematics of the experiment [11], shows that only for a particular form of the nucleon EC and the Buck-Gross DWF ($\lambda = 1$) with an anomalous large contribution of the ${}^3P_1$-wave, the results of the calculations (Fig. 2) are consistent with the experimental data. Note that with $\lambda = 1$ it is not possible to describe the inclusive spectra of electrons from d(e,e')np [9]. The results are sensitive to the λ value of the Buck-Gross DWF (Fig. 3) mainly because of the DWF ${}^3P_1$-wave contribution to the EFF of the $M1 \to {}^1S_0$-transition (Fig. 4). While this sensitivity is qualitatively different with parametrizations (13), (15) of the nucleon EC, parametrizations (13), (14) lead to close results and weakly depend on the P-wave contribution of the DWF. With parametrizations (13), (14) there is a partial cancellation between P-wave DWF contributions to g_1 from different invariant form factors of the dnp-vertex (see Appendix 3). The contributions to g_1 from S- and D-waves of the DWF are

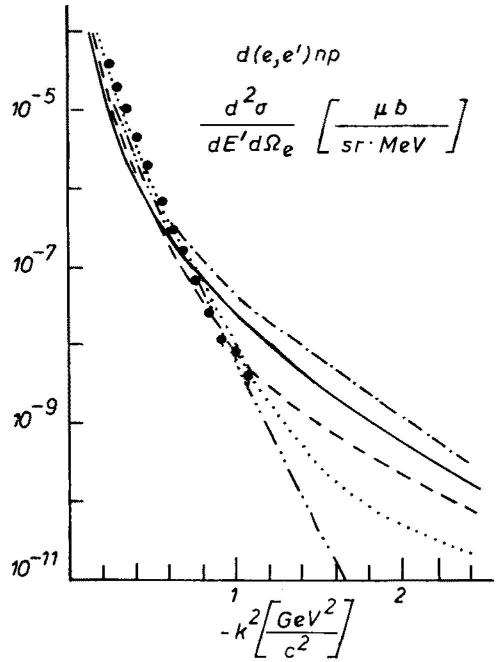

Fig. 2

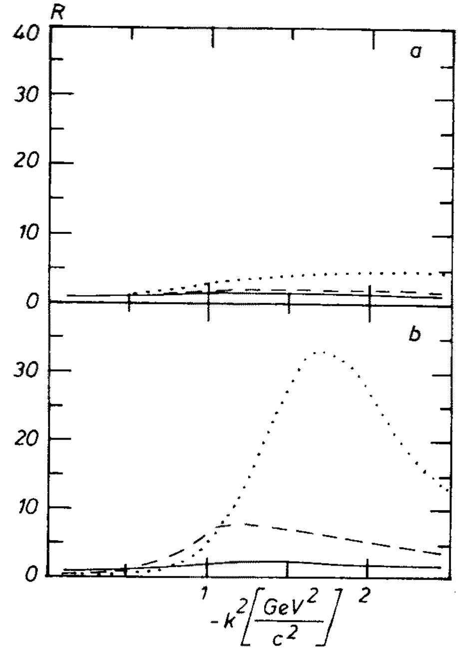

Fig. 3

Fig. 2. Differential cross section for the inclusive electrodisintegration of the deuteron at $\theta_e = 155°$, $E_{np} = 1.5$ MeV. Full, dashed, and dotted curves correspond to the calculations with the Buck-Gross DWF for $\lambda = 0, 0.4, 1$, respectively. The dash-dotted curve shows the calculation with the Paris DWF, and the double-dash-dotted curve depicts the transverse γ^* contribution in the $\lambda = 1$ case. The nucleon EC is given by (15); experimental points were taken from Ref. [11]

Fig. 3. Sensitivity of the results for $d^2\sigma/dE'd\Omega_e$ to the choice of the DWF with nucleon EC parametrizations given by (13) — (a), and (15) — (b). The ratio $R = d^2\sigma$ (Paris DWF)$/d^2\sigma$ (Buck-Gross DWF $\lambda = 0, 0.4, 1$) is shown. Correspondence of the curves to the DWF is the same as for Fig. 2

the same for (13) and (15), whereas for (13) and (14) these contributions differ by a factor of $(1+\tau/2)/(1+\tau)$.

Taking into account the absorption of longitudinal γ^*-quanta at $\theta_e = 155°$ is of special importance at $-k^2 > 1$ $(\mathrm{GeV}/c)^2$ (Fig. 2). The σ_L magnitude is essentially determined by the deuteron diagram which makes σ_L insensitive to the details of nucleon pole diagram calculations.

The deuteron diagram contribution is also essential for transversal photoabsorption cross section σ_T (v_1, Fig. 5) and fairly masks the minimum in the k^2 dependence of the cross section which is present in all nonrelativistic impulse approximation calculations due to the behaviour of the $M1 \to {}^1S_0$-transition amplitude. The k^2 dependence of v_1 is determined by the balance between $M1 \to {}^1S_0$- and $M1 \to {}^3S_1$-transition contributions. Both these contributions have minima: the former due to the destructive interference between the amplitudes of the transition from (np) ${}^3S_1$, ${}^3D_1$, ${}^3P_1$ bound states to the ${}^1S_0$-state, and the latter — due to the minimum of the deuteron magnetic form factor (at $-k^2 = 1.5$ $(\mathrm{GeV}/c)^2$

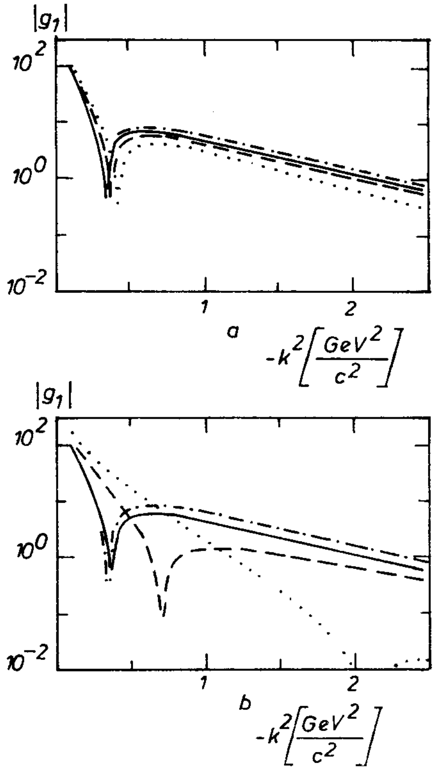

Fig. 4

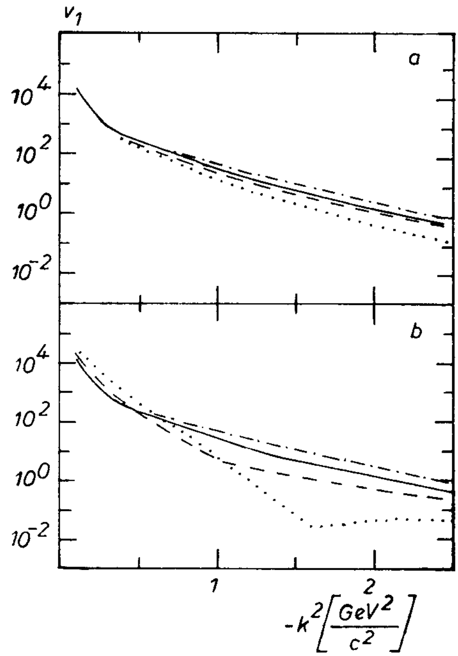

Fig. 5

Fig. 4. The EFF g_1 ($E_{np} = 1.5$ MeV) for different parametrizations of the DWF with the nucleon EC given by (13) — (a), and (15) — (b). Symbols have the same meaning as in Fig. 2

Fig. 5. SF v_1 of the transverse γ^* absorption (see Fig. 2)

in the model [25] employed here; the experimental data obtained recently [26] confirm the presence of the minimum of the magnetic deuteron form factor).

Thus we may conclude that for correct treatment of experimental data for the EDD near threshold it is necessary to carry out various polarization experiments to determine form factor values of the corresponding multipole transitions, in addition to the separation of transverse and longitudinal contributions of the γ^* absorption.

The results for T_z, $T_{xx}-T_{yy}$, $T_{zz}^{(T)}$ (Figs. 6, 7) show, in particular, that the contribution of the EFF g_1 dominates in the amplitude of transverse γ^* absorption at $-k^2 < 0.15$ $(\text{GeV}/c)^2$ as well as in the region of minimum of the deuteron magnetic form factor. The quantity $T_{xx}-T_{yy}$ presents a particular interest, since it has a negative value when the EFF g_1 contribution is dominant.

As for the final-proton polarization vector $\boldsymbol{P}$, here the suppression (reversal of sign) of the EFF g_1 or g_5/k_0 immediately results in a similar behaviour of the P_y component (Fig. 8). According to our calculations, the EFF g_5 changes its sign at $-k^2 = 0.45$ $(\text{GeV}/c)^2$

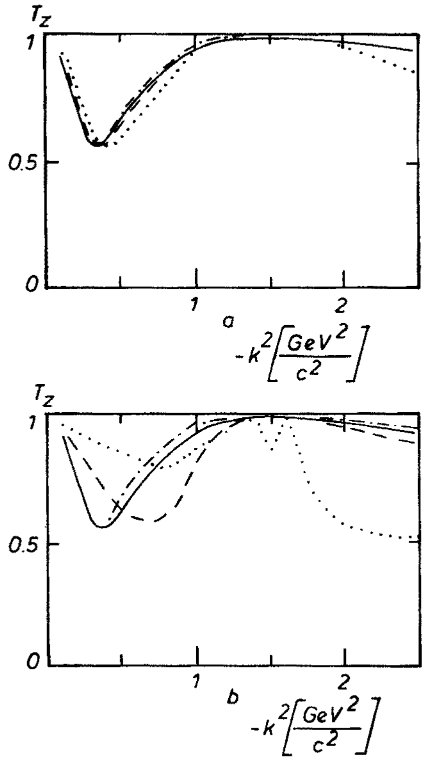

Fig. 6. k^2 dependence of T_z, see Fig. 2

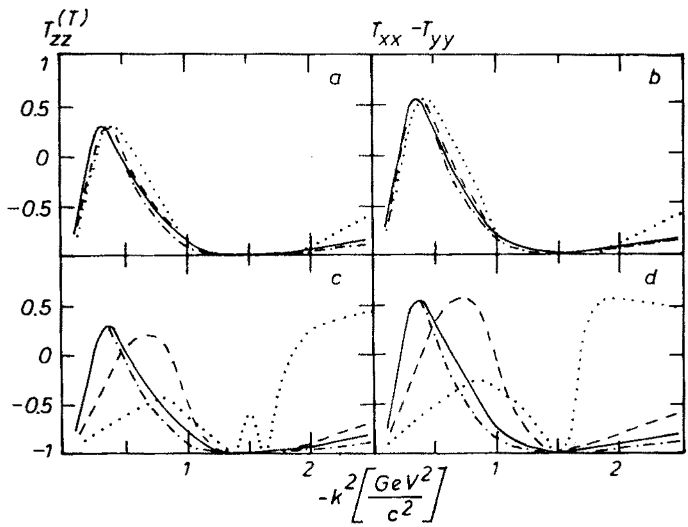

Fig. 7. The k^2 dependence of $T_{zz}^{(T)}$ (a, c) and $T_{xx}-T_{yy}$ (b, d). For notation, see Fig. 2

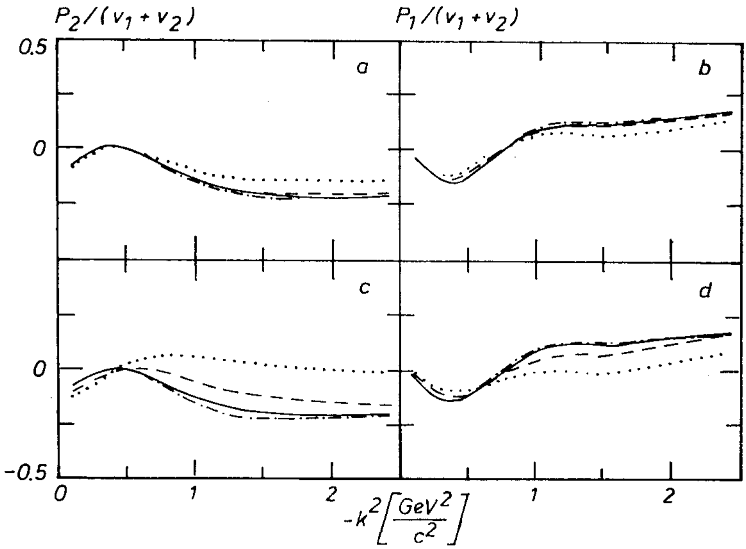

Fig. 8. Ratios $P_2/(v_1+v_2)$ — (a, c), and $P_1/(v_1+v_2)$ — (b, d). For notation, see Fig. 2

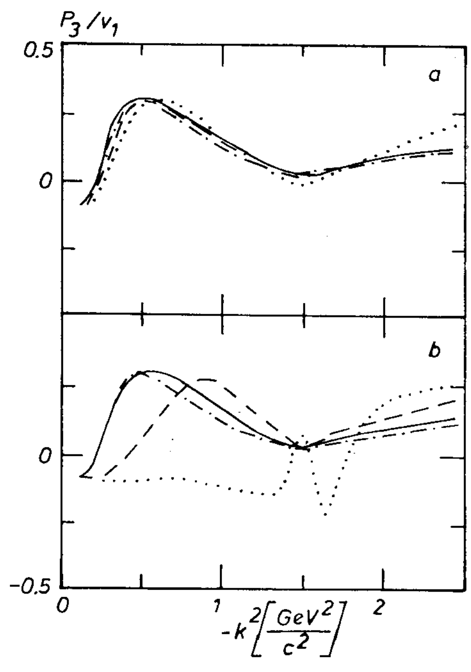

Fig. 9. Ratio P_3/v_1. For notation, see Fig. 2

because of the reversal of sign of the deuteron charge form factor. The model also predicts the P_z component of the proton polarization to be greatest (Fig. 9) for polarized electron scattering at backward angles.

6. Conclusions

The RIA predictions for the observables in EDD near threshold depend on the nucleon EC parametrization, this dependence being caused mainly by the *P*-wave contribution of the DWF. Thus, another source of uncertainties arises in addition to mesonic exchange currents, isobaric configurations and quark degrees of freedom in the deuteron.

PE measurements near the EDD threshold could be of advantage in reducing theoretical model uncertainties. Of particular interest here is the extraction of the $(\mathrm{M1} \to {}^1S_0)$--transition amplitude. To accomplish this, it is enough to measure the corresponding asymmetries of unpolarized electron scattering by the tensor polarized deuteron along with the separation of transverse and longitudinal γ^* contributions to the cross section.

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APPENDIX 1

The EFF g_{1-5} are related to scalar amplitudes f_i of Ref. [2] as (θ being the c.m.s. angle between γ^*-quantum and proton momenta):

$$g_1 = \int_{-1}^{1} d\cos\theta \cdot (f_5 - f_9)/4, \qquad g_2 = \int_{-1}^{1} d\cos\theta \cdot (f_3 + f_{11})/4,$$

$$g_3 = \int_{-1}^{1} d\cos\theta \cdot (f_2 + f_8)/4, \qquad g_2 + g_3 + g_4 + g_5 = \int_{-1}^{1} d\cos\theta \cdot f_{13}\, 2,$$

$$g_5 = \int_{-1}^{1} d\cos\theta \cdot (f_{16} + f_{18})/4,$$

and correspond to the multipole transitions

$$g_1 = (\mathrm{M1} \to {}^1S_0), \qquad g_2 + g_3 = (\mathrm{E2} \to {}^3S_1), \qquad g_2 - g_3 = (\mathrm{M1} \to {}^1S_3),$$

$$g_2 + g_3 + g_4 = (\mathrm{E2_L} \to {}^3S_1), \qquad g_5 = (\mathrm{E0_L} \to {}^3S_1).$$

APPENDIX 2

Expressions for v_i in terms of the EFF g_{1-5} are:

$$v_1 = 4(|g_1|^2 + |g_2|^2 + |g_3|^2\omega^2/M^2)/3,$$

$$v_2 = -4k^2(|g_2 + g_3 + g_4 + g_5|^2\omega^2/M^2 + 2|g_5|^2)/(3k_0^2),$$

$$v_3 = 2(|g_1|^2 + |g_2|^2),$$

$$v_4 = 2\sqrt{-2k^2}/k_0 \cdot \omega/M \cdot \mathrm{Re}\,[g_2(g_2+g_3+g_4+g_5)^* - g_3 g_5^*],$$

$$v_5 = 2(2|g_3|^2\omega^2/M^2 - |g_1|^2 - |g_2|^2),$$

$$v_6 = 2(|g_2|^2 - |g_1|^2),$$

$$v_7 = -4k^2/k_0^2 \cdot (|g_2+g_3+g_4+g_5|^2\omega^2/M^2 - |g_5|^2),$$

$$v_8 = 2\sqrt{-2k^2}/k_0 \cdot \omega/M \cdot \mathrm{Re}\,[g_2(g_2+g_3+g_4+g_5)^* - g_3 g_5^*].$$

The quantities v_i and SF u_i are related by

$$v_1 = 2u_1, \quad v_2 = -2k^2 \cdot u_2/k_0^2, \quad v_3 = 2(u_3+u_4),$$

$$v_4 = \sqrt{-2k^2} \cdot 2u_3/k_0, \quad v_5 = \omega^2/M^2 \cdot (2u_5) - u_7,$$

$$v_6 = 2u_7, \quad v_7 = -2k^2/k_0^2 \cdot \omega^2/M^2 \cdot (u_6+u_7+2u_8),$$

$$v_8 = 2\sqrt{-2k^2}/k_0 \cdot \omega/M \cdot (u_7+u_8).$$

APPENDIX 3

The Born diagram contribution (Fig. 1) to the EFF g_1 at $E_{\mathrm{np}} = 0$ has the forms ($t_0 - m^2 = k^2/2 - M\mathscr{E}_{\mathrm{d}}$):

$$g_{1\mathrm{B}} = -4m|\boldsymbol{k}|\left(\frac{F \cdot G^{\mathrm{V}}_{\mathrm{MN}}}{t_0 - m^2} - \frac{f \cdot F^{\mathrm{V}}_{2\mathrm{N}}}{4m^2}\right) \quad \text{for the parametrization of the nucleon EC given by (13)}$$

$$g_{1\mathrm{B}} = -4m|\boldsymbol{k}|\,\frac{F \cdot G^{\mathrm{V}}_{\mathrm{MN}}}{t_0 - m^2} \quad \text{for the EC (15)}$$

and

$$g_{1\mathrm{B}} = -4m|\boldsymbol{k}|\,\frac{G^{\mathrm{V}}_{\mathrm{MN}}}{1+\tau}\left(\frac{F \cdot \omega}{(t_0 - m^2)2m} - \frac{f}{4m^2}\right) \quad \text{for the EC (14),}$$

where $G^{\mathrm{V}}_{\mathrm{MN}} = 1/2(G_{\mathrm{Mp}} - G_{\mathrm{Mn}})$ is the isovector form factor of the nucleon; F, f are the invariant form factors of the dnp-vertex, which can be expressed through the relativistic DWF of S-, D-, and P-waves [20]

$$F(q) = \pi\sqrt{2M}\,(2E_q - M) \cdot \left[u(q) - \frac{w(q)}{\sqrt{2}} + \frac{m}{q}\sqrt{\tfrac{3}{2}}\,v_t(q)\right],$$

$$f(q) = -\pi\sqrt{2M}\,\frac{2E_q}{q}\sqrt{\tfrac{3}{2}}\,v_t(q),$$

where

$$E_q = \frac{M}{2} + \frac{m^2 - t_0}{2M},$$

$$q^2 = E_q^2 - m^2.$$

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