THE LEFT-RIGHT ASYMMETRY IN DEUTERON ELECTRODISINTEGRATION BEYOND QUASI-ELASTIC SCATTERING

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The properties of the left-right asymmetry in the deuteron electrodisintegration, $d(e, e'p)n$, are investigated within the framework of the unitarized version of the relativistic impulse approximation. This asymmetry determines the difference of the differential cross-sections at two values of the azimuthal angle, namely, $\varphi = 0°$ and $\varphi = 180°$. The relative significance of various mechanisms which determine the above reaction is studied under the particular conditions of the kinematics beyond the region of quasi-elastic e-N scattering. The influence of final state n•-interaction and choice of the deuteron wave function on the angular dependence of the asymmetry is investigated. Special attention is paid to the analysis of consequences of the hadronic electromagnetic current conservation.

Introduction

The separation of various contributions to the differential cross-section of the $d(e, e'p)n$ reaction allows one to obtain additional information on the mechanisms of this reaction. The corresponding experiments were conducted recently [1 – 5], in the region of the relatively small values of the four-momentum square transfer. Similar experiments shall be given more attention to on accelerators with continuous (and high-intensity) electron beams: ELSA, BATES, JLAB (CEBAF) [6].

The measurement of the differential cross-section difference of the $d(e, e'p)n$ reaction at two values of the azimuthal angle φ (namely: $\varphi = 0$ and $\varphi = 180°$) allows one to obtain the left-right asymmetry A_φ. Though all particles in the initial and final states are nonpolarized, the asymmetry A_φ may, nevertheless, be related to the class of the simplest polarization characteristics of the $e^- d \to e^- np$ reaction. The point is that it is caused by the virtual-photon linear polarization which is non-zero even in the nonpolarized electron scattering.

The asymmetry A_φ belongs to the class of T-even polarization characteristics of the $e^- d \to e^- np$ reaction. The conditions for the hadronic electromagnetic current conservation and P-invariance of the hadron electromagnetic interaction 'impose“ (in the framework of the one-photon-exchange mechanism for $e^- d \to e^- np$) several properties upon the asymmetry A_φ. These properties are of general nature, being independent on the specific meachanism of the $e^- d \to e^- np$ reaction:

– A_φ is determined via interference of the longitudinal and transverse components of the electromagnetic hadronic current and, therefore, this observable of the deuteron electrodisintegration $\gamma^* d \to np$ has no analogy in the deuteron photodisintegration.

– The asymmetry $A_\varphi \sim \sin\theta$ (θ is the angle between the three-momenta of a proton and a virtual photon in the n-p pair c.m.s.) due to the conservation of the total helicity of the particles in the reaction $\gamma^* d \to np$;

– T-even asymmetry A_φ is determined by the real part of a certain bilinear combination of the scalar amplitudes of the $\gamma^* d \to np$ reaction, whereas the T-odd asymmetry Σ_e (in the case of longitudinally polarized electron scattering on a nonpolarized target, the reaction $d(\vec{e}, e'p)n$) is determined by the imaginary part of the same combination.

From the theoretical point of view [7 – 9], the asymmetry A_φ is discussed at present as regards the relative value of relativistic corrections to standard nonrelativistic calculations. This relativism was found to start working for this quantity at very early stages. The experiments indicate the significance of relativistic corrections to this quantity [2, 10].

Meanwhile, the A_φ measurement is also important to solve the problem of hadron electromagnetic current conservation in the reaction $\gamma^* d \to np$. Therefore, the method of 'ensuring" the conservation of the electromagnetic current in the reaction $\gamma^* d \to np$ may be tested, or corrected, in the asymmetry calculations in order to illustrate the issue in point.

The predicted θ dependence of A_φ turns out to be extremely interesting for refinement of the $\gamma^* d \to np$ reaction mechanism. The characteristic change of the A_φ sign in the region of $\theta_0 \approx 90°$, predicted by the standard models of deuteron electrodisintegration, causes an increasing of the sensitivity of A_φ to such contributions as final-state interaction, isobar configurations, and dibaryon resonances. The measurement of A_φ in a broad range of θ angles appears urgent, since it allows one to test a matching of the essential ingredients of the $e^- d \to e^- np$ model, such as hadron electromagnetic current conservation, unitarization of the $\gamma^* d \to np$ amplitude, and relative significance of the various mechanisms of the reaction. The latter is particularly important beyond the kinematics of quasi-free e-N scattering, when k^2 and E_{np} must be connected by the relation: $k^2 = M^2 - W^2$, $W = E_{np} + 2m$, where W is the invariant mass of the p-n system in the final state of the reaction, $k^2 = k_0^2 - \vec{k}^2$, $M(m)$ is the deuteron (nucleon) mass. A non-trivial dynamics, as is known, arises outside of the region of quasi-free e-N scattering. In order to illustrate this point, it will suffice to remember that the anomalous behaviour of the proton polarization in $\gamma d \to np$ [6, 11], revealed outside the region where the one-nucleon-exchange contributions dominate, have not found its adequate theoretical explanation to date.

1. Left-Right Asymmetry in the Reaction d(e, e′p)n

In the case of the standard one-photon-exchange mechanism of the $e^- d \to e^- np$ reaction, the general structure of its differential cross-section is determined by the P-invariance of hadron electromagnetic interactions and the electromagnetic current conservation for the reaction $\gamma^* d \to np$:

$$\frac{d^3\sigma}{dE' d\Omega_e d\Omega_p} = N\,[H_{xx} + H_{yy} + \varepsilon\cos(2\varphi)(H_{xx} - H_{yy}) - 2\varepsilon\frac{k^2}{k_0^2}H_{zz} - \cos\varphi\sqrt{2\varepsilon(1+\varepsilon)}\frac{\sqrt{-k^2}}{k_0}(H_{xz} + H_{zx})],$$

$$N = \frac{\alpha^2 E' p}{64\pi^3 EMW}[-k^2(1-\varepsilon)]^{-1},$$

$$\varepsilon = \left(1 - 2\frac{(\vec{k}_{\text{l.s.}})^2}{k^2}\,\mathrm{tg}^2\left(\frac{1}{2}\theta_e\right)\right)^{-1}. \quad (1)$$

Here, we use the following notations: $E(E')$ is the initial (scattered) electron energy in the laboratory frame (l.s.) of the $e^- d \to e^- np$ reaction, $d\Omega_e(d\Omega_p)$ is the solid angle of the scattered electron (detected proton) in the l.s. (n-p pair c.m.s.), k_0 is the energy of the virtual photon γ^* in $\gamma^* d \to np$ c.m.s., W is the total n-p pair energy, θ_e is the electron scattering angle in the l.s., φ is the azimuthal angle between the plane, where the initial and scattered electron three-momenta lie, and another plane, where lie three-momenta $\vec{k}$ (the virtual photon) and $\vec{p}$ (the final proton). The H_{ik} tensor is defined by the bilinear combination of the electromagnetic current components in the reaction $\gamma^* d \to np$:

$$H_{ik} = \overline{J_i J_k^*}, \quad (2)$$

where the bar denotes the averaging over initial deuteron polarizations and summation over final nucleon polarizations.

The tensor structure of H_{ik} may be represented in the following general form:

$$H_{ik} = h_1\hat{m}_i\hat{m}_k + h_2\hat{n}_i\hat{n}_k + h_3\hat{k}_i\hat{k}_k + h_4(\hat{k}_i\hat{m}_k + \hat{k}_k\hat{m}_i) + ih_5(\hat{k}_i\hat{m}_k - \hat{k}_k\hat{m}_i), \quad (3)$$

where $\hat{\vec{k}} = \vec{k}/|\vec{k}|$, $\hat{\vec{n}} = \vec{k}\times\vec{p}/|\vec{k}\times\vec{p}|$, $\hat{\vec{m}} = \hat{\vec{n}}\times\hat{\vec{k}}$, h_i are the real structure functions (SF), depending on three kinematical variables, $h_i = h_i(k^2, W, \theta)$.

Choosing the z-axis in (1) along $\vec{k}$ and the y-axis along $\vec{n}$, it is easy to find a connection between the components of H_{ij} tensor and SF's $h_1 - h_5$:

$$H_{xx} \pm H_{yy} = h_1 \pm h_2,\ H_{zz} = h_3,$$

$$H_{xz} + H_{zx} = 2h_4,\ H_{xz} - H_{zx} = -2ih_5. \quad (4)$$

In its turn, SF's h_i may be related to the scalar amplitudes of the $\gamma^* d \to np$ reaction. These amplitudes determine the spin structure of the matrix element of

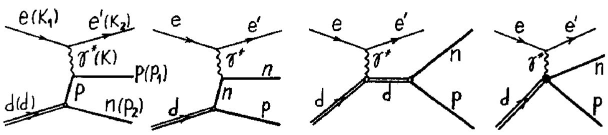

Fig.1. Feynman diagrams of the relativistic IA for $\gamma^* d \to np$

the $\gamma^* d \to np$ reaction:

$$M(\gamma^* d \to np) = \varphi_2^+ F \sigma_2 \tilde{\varphi}_1^+,$$

$$F = \vec e\cdot\hat{\vec m}\,\vec U\cdot\hat{\vec k}(f_1\vec\sigma\cdot\hat{\vec k} + f_2\vec\sigma\cdot\hat{\vec m}) + \vec e\cdot\hat{\vec m}\,\vec U\cdot\hat{\vec m}(f_3\vec\sigma\cdot\hat{\vec k} +$$

$$+ f_4\vec\sigma\cdot\hat{\vec m}) + \vec e\cdot\hat{\vec m}\,\vec U\cdot\hat{\vec n}(if_5 + f_6\vec\sigma\cdot\hat{\vec n}) + \vec e\cdot\hat{\vec n}\,\vec U\cdot\hat{\vec k}(if_7 +$$

$$+ f_8\vec\sigma\cdot\hat{\vec n}) + \vec e\cdot\hat{\vec n}\,\vec U\cdot\hat{\vec m}(if_9 + f_{10}\vec\sigma\cdot\hat{\vec n}) +$$

$$+ \vec e\cdot\hat{\vec n}\,\vec U\cdot\hat{\vec n}(f_{11}\vec\sigma\cdot\hat{\vec k} + f_{12}\vec\sigma\cdot\hat{\vec m}) +$$

$$+ \vec e\cdot\hat{\vec k}\,\vec U\cdot\hat{\vec k}(f_{13}\vec\sigma\cdot\hat{\vec k} + f_{14}\vec\sigma\cdot\hat{\vec m}) +$$

$$+ \vec e\cdot\hat{\vec k}\,\vec U\cdot\hat{\vec m}(f_{15}\vec\sigma\cdot\hat{\vec k} + f_{16}\vec\sigma\cdot\hat{\vec m}) +$$

$$+ \vec e\cdot\hat{\vec k}\,\vec U\cdot\hat{\vec n}(if_{17} + f_{18}\vec\sigma\cdot\hat{\vec n}). \quad (5)$$

where $\vec e(\vec U)$ is the virtual photon (deuteron) polarization 3-vector in the $\gamma^* d \to np$ c.m.s., φ_1 and φ_2 are the two-component nucleon spinors.

Using (2), (3) and (5), we obtain the following formulae for SF's:

$$h_1 = \frac{2}{3}\left[\frac{\nu^2}{M^2}(|f_7|^2 + |f_8|^2) +\right.$$

$$\left.+ |f_9|^2 + |f_{10}|^2 + |f_{11}|^2 + |f_{12}|^2\right],$$

$$h_2 = \frac{2}{3}\left[\frac{\nu^2}{M^2}(|f_1|^2 + |f_2|^2) +\right.$$

$$\left.+ |f_3|^2 + |f_4|^2 + |f_5|^2 + |f_6|^2\right],$$

$$h_3 = \frac{2}{3}\left[\frac{\nu^2}{M^2}(|f_{13}|^2 + |f_{14}|^2) +\right.$$

$$\left.+ |f_{15}|^2 + |f_{16}|^2 + |f_{17}|^2 + |f_{18}|^2\right],$$

$$h_4 = \frac{2}{3}\,\mathrm{Re}\,A, \quad h_5 = \frac{2}{3}\,\mathrm{Im}\,A, \quad (6)$$

$$A = \frac{\nu^2}{M^2}(f_{13}f_1^* + f_{14}f_2^*) + f_{15}f_3^* + f_{16}f_4^* + f_{17}f_5^* + f_{18}f_6^*,$$

where ν is the deuteron energy in the $\gamma^* d \to np$ c.m.s.

The A_φ asymmetry may be connected easily to SF's $h_1 - h_4$:

$$A_\varphi = -2\frac{\sqrt{-k^2}}{k_0}\,\frac{\sqrt{2\varepsilon(1+\varepsilon)}\,h_4}{h_1 + h_2 + \varepsilon(h_1 - h_2) - 2\varepsilon h_3(k^2/k_0^2)}. \quad (7)$$

2. Relativistic Model of the $\gamma^* d \to np$ Amplitude

Since, in any version of the impulse approximation (IA), the one-nucleon exchange mechanisms (i.e., the neutron and proton exchange) are principal for the $\gamma^* d \to np$ amplitude, they are assumed as basic for the relativistic IA model employed here [12 – 13]. Inclusion of the deuteron and contact diagram contributions (Fig.1) is caused by the rules of the relativistic Feynman diagram technique. The deuteron structure is described by the formfactors of the relativistic *dnp*-vertex [14, 15] with one virtual nucleon. In order to specify the choice of the matrix element, the nucleon electromagnetic current is written in terms of the Dirac (F_{1p}, F_{1n}) and Pauli (F_{2p}, F_{2n}) nucleon formfactors.

Since, in the general case, the electromagnetic current, corresponding to the $\gamma^* d \to np$ reaction, is not conserved in such approximation, we are bound to make the following substitution [16]:

$$J_\mu \to J'_\mu = J_\mu - k_\mu(kJ)/k^2. \quad (8)$$

This substitution, of course, modifies the longitudinal component of the electromagnetic current for $\gamma^* d \to np$, affecting the final behaviour of the A_φ asymmetry.

And, still, the similar amplitude does not satisfy the unitarity condition. Putting it another way around, the effects of np-interaction in the final state (FSI) are not taken into account for this amplitude. In order to retain such attractive properties of the relativistic IA amplitude, as its relativistic nature and gauge invariance, we use the known unitarization procedure that is realized, using the substitution [17]:

$$f_{[A]}(k^2, W) \to f_{[A]}(k^2, W)\exp[i\delta_{[A]}(W)]. \quad (9)$$

Here, $f_{[A]}(k^2, W)$ is the multipole amplitude of the $\gamma^* d \to np$ reaction, calculated in IA, that determines the neutron-proton state with the quantum numbers $[A] = J, L$ and S; $\delta_{[A]}(W)$ is the NN-scattering phase shift in the same state [18].

The np-scattering phase shifts are known at present up to the energy of 800 MeV (in the lab frame of the np-collision) [19], corresponding to $E_{np} \le 0.4m \approx 375$ MeV. In turn, this E_{np} value limits the allowable k^2 values. For example, in the case of the quasi-elastic e-N scattering, it would mean that $Q^2 = -k^2 \le 1.5\,\mathrm{GeV}^2$. Therefore, some constraint on the validity of the discussed model arises. But it looks like as if this constraint had the external nature (constraints on E_{np}, where the np-scattering phase shifts are known) and is not related to the properties of the model itself. So, we have such a unitarized model that takes into account the FSI effects [20] for the $e^- d \to e^- np$.

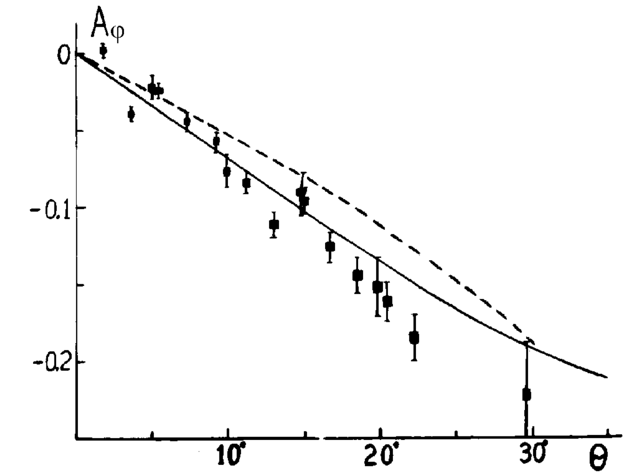

Fig.2. Comparison of the A_φ asymmetry, calculated in our model (the solid curve), with the experimental data from [10]. The dashed curve is the result of the non-relativistic calculation [21]. The Paris DWF [23] and $G_{En} = 0$ [24] are used in the calculations

3. Numerical Calculations and their Discussion

It is natural to see how our model describes the available experimental data on A_φ. Therefore, we found first the θ-dependence of the asymmetry for the conditions of the Bonn experiment [10] (Fig.2). One can see that the proposed model agrees reasonably with the experimental data. The non-relativistic calculations [21] including the relativistic corrections do not contradict our predictions.

In order to perceive the significance of various mechanisms, involved in the formation of the θ-dependence of the A_φ asymmetry under particular kinematical conditions, namely, outside the quasi-elastic e-N scattering kinematics, we calculated A_φ at a particular value of the four-momentum square transfer, $Q^2 = 0.5\,\mathrm{GeV}^2$, and the parameter of virtual photon linear polarization, $\varepsilon = 0.5$. In order to ascertain the kinematics in its final form, we choose $E_{np} = 300$ MeV, i.e., k^2 and E_{np} are chosen outside the quasi-elastic e-N scattering kinematics, since $Q^2 = 0.5\,\mathrm{GeV}^2$ in this kinematics must correspond to $E_{np} = 125$ MeV.

It would be natural to begin this analysis with the determination of sensitivity of the A_φ asymmetry to the choice of the deuteron wave function (DWF), i.e., the NN-interaction potential. This sensitivity proves rather noticeable in the range of angles $\theta = 40 \div 100°$. Note that the value of the A_φ asymmetry in the minimum ($\theta \approx 70°$) changes nearly two times during the transition from the Reid soft-core DWF [22] to the Buck – Gross DWF [15]: the Paris DWF [23] occupies the intermediate position. The value of θ angle, at which the asymmetry changes its sign, depends also on the DWF choice (Fig.3).

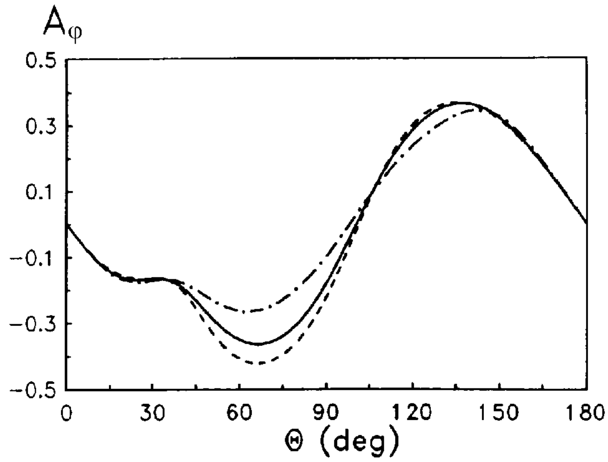

Fig.3. Angular dependence of the A_φ asymmetry for various DWF's: the solid curve corresponds to the calculations with the Paris DWF [23], the dot-dashed line to the Buck – Gross DWF with $\lambda = 0$ [15], and the dashed line to the Reid soft-core DWF [22]

All calculations are performed at $G_{En} = \mu_n \tau G_{Ep}/(1 - 5.6\tau)$, $\tau = k^2/4m^2$, $\mu_n = -1.913$ [24]. At the chosen kinematical conditions, the sensitivity of A_φ asymmetry to various parametrizations of the neutron electric formfactor turns out to be negligible.

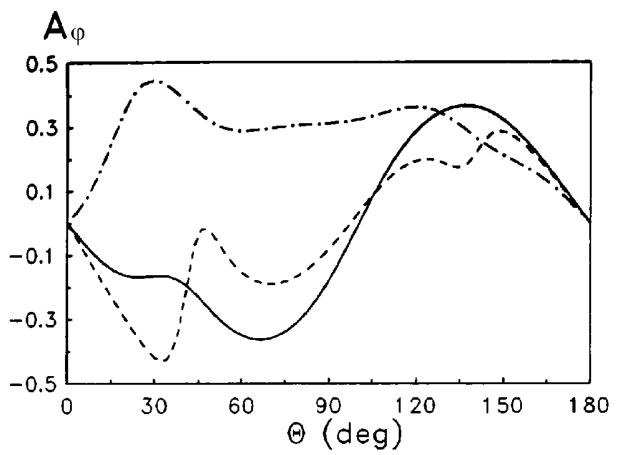

Fig.4. Dependence of the A_φ asymmetry on the $\gamma^* d \to np$ mechanism: the solid curve corresponds to the standard calculations, the dot-dashed line to those without the gauge contribution, and the dashed line to those without the contribution of the *D*-wave of DWF (the Paris DWF is used)

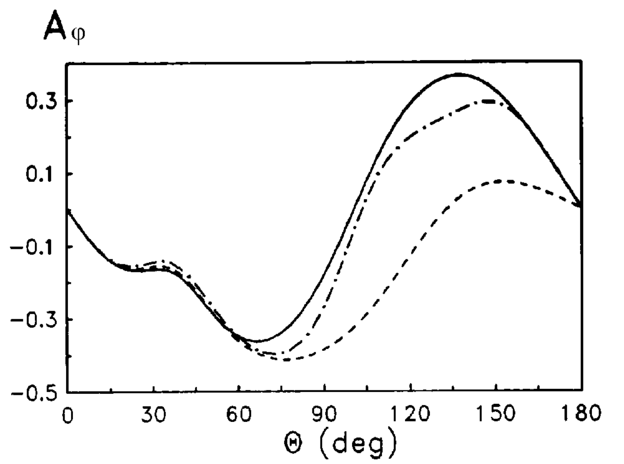

Fig.6. Influence of the neutron-exchange diagram contribution on the θ-dependence of the A_φ asymmetry. The solid curve indicates the standard calculation results, the dot-dashed line corresponds to the change $\mu_n \to -\mu_n$, and the dashed line to those without the neutron-exchange diagram contribution. The remaining designations are the same as in Fig.5

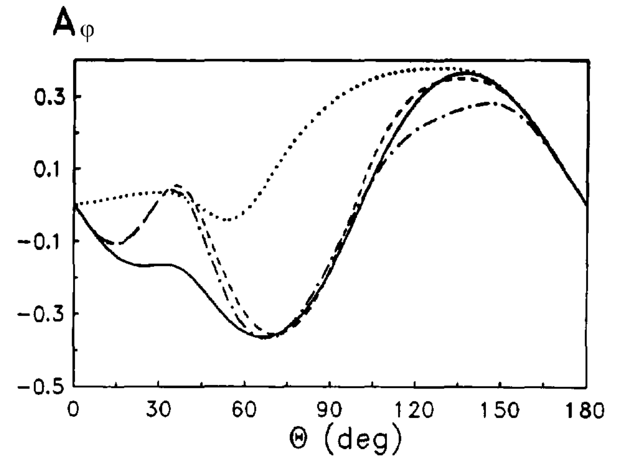

Fig.5. Influence of the proton-exchange diagram contribution on the θ dependence of the A_φ asymmetry. The solid curve stands for the standard calculation results, the dot-dashed line corresponds to the change $F_{1p} \to -F_{1p}$, the dashed line to $F_{2p} \to -F_{2p}$, and the dotted line to those without the proton-exchange diagram contribution (the Paris DWF was used)

One can see that the A_φ asymmetry is negative at $\theta \le 90°$ (the proton-exchange diagram 'works“ in this range of angles) and positive at $\theta > 90°$ (where the neutron-exchange diagram 'works“). Similar behaviour is described essentially by the angular dependence $\sin\theta\cos\theta (\sim \sin 2\theta)$ which is rather natural for the A_φ asymmetry. As noted above, the asymmetry is determined by the product of the longitudinal and transverse components of the electromagnetic current, corresponding to the $\gamma^* d \to np$ reaction. If the $\vec{J}$ current is directed mainly along the three-momentum of one nucleon in the final state (in the $\gamma^* d \to np$ c.m.s.), then the $\sin 2\theta$-dependence becomes simply inevitable. Such a current is caused by the convection contribution which is proportional to the nucleon electric formfactor. The nucleon magnetic moments generate a somewhat different θ-dependence. The features, related to the difference in the behaviour of the proton and neutron electromagnetic formfactors, modify definitely the θ-dependence of the A_φ asymmetry, bringing about the non-symmetric behaviour in the region of small and large θ angles.

The longitudinal-transverse interference in A_φ causes also a specific sensitivity of the asymmetry to the way of tackling the gauge invariance problem of the $\gamma^* d \to np$ reaction matrix element. The important thing is to know that gauge invariance affects essentially the longitudinal current component and, as a result, the θ-dependence of the asymmetry. In order to know the scale of such an influence, we simply eliminate the so-called gauge contribution to the current, $k_\mu k\, J/k^2$. The A_φ behaviour changes dramatically, with the greatest changes occurring at $\theta \le 120°$ (Fig.4) and the asymmetry turning out to be positive all over the θ region. In the region of large angles, the gauge contribution influence is smaller. It is related to the evident circumstance that the contribution of the neutron-exchange mechanism to this term is determined by the neutron Dirac formfactor F_{1n}. The character of the asymmetry change in the region of large θ angles shows the influence of exactly this formfactor on the θ-dependence of A_φ in this range of angles.

As expected, the *D*-wave in the deuteron ground state has a strong influence on the A_φ behaviour (Fig.4), the θ-dependence at $\theta \leq 90°$ becoming more complicated.

In order to know the relative significance of various nucleon electromagnetic formfactors in the θ-dependence of A_φ, we made some manipulations, namely: changed the signs of the formfactors in the matrix element of the $\gamma^* d \to np$ reaction (to learn the nature of interference effects) and eliminated the contribution of one of the relativistic IA diagrams.

The significance of the interference contribution, proportional to the product $F_{1p}F_{2p}$, is known immediately (Fig.5), if one calculates A_φ after sign-changing F_{1p} or F_{2p}. Since the results of the substitution $F_{1p} \to -F_{1p}$ and $F_{2p} \to -F_{2p}$ turn out to be different, we conclude that in the region, where the proton-exchange diagram dominates, there occurs a considerable interference between proton- and neutron-exchange diagrams, enhanced by the effects of the exchanged np-interaction. These effects may also be observable in the region of large angles where the exchanged np-interaction 'generates" a contribution of the proton-exchange diagram in an alien region. Moreover, the elimination of the proton-exchange diagram contribution drastically reduces the A_φ values in the range of angles $\theta < 90°$, leading to non-zero A_φ values nevertheless. One can see, that at $\theta > 135°$, the A_φ behaviour is determined by the neutron-exchange diagram contribution, only.

The change of the sign of the neutron magnetic formfactor makes A_φ modify its behaviour in the 'neutron" range of angles (i.e., at large θ values) (Fig.6). However, this change is not so great as for a similar substitution in case of the proton-exchange diagram. The result for A_φ, corresponding to the elimination of the neutron-exchange diagram, demonstrates the significance of the exchange np-interaction for the θ-dependence.

Conclusions

The above analysis of the angular dependence of the A_φ asymmetry allows us to conclude that:

— the effects of the exchange np-interaction in the final state appear to be very important for the final θ-dependence formation of the A_φ asymmetry. These effects essentially 'mix" the contributions of the proton- and neutron-exchange diagrams and ensure 'making their way" to alien ranges of angles;

— interference of the formfactors $F_{1p}F_{2p}$ (in the small-angle region) and $F_{1n}F_{2n}$ (in the large-angle region) turns out to be essential;

— the A_φ asymmetry turns out to be insensitive to a choice of the neutron electric formfactor parametrization, appearing to have a much greater sensitivity to the DWF choice.

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