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MANIFESTATION OF THE RELATIVISTIC EFFECTS AND CONSERVING CURRENTS IN THE INTERFERENCE LONGITUDINALLY-TRANSVERCE STRUCTURE FUNCTION IN (e, e'p)-REACTIONS ON FEW-BODY SYSTEMS

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A study is made of the effects of Lorentz invariance and nuclear current conservation in calculations of the A_ϕ-asymmetry of the cross sections for (e,e'p) reactions on few-body systems. The A_ϕ-value is shown to be very sensitive to different relativistic effects and to nuclear current conservation. In the quasi-elastic region ($q^2/2m\nu\sim1$, $p_{mis}/m\ll1$) this value is determined only by the degree of linear polarization of the virtual photon, and the electromagnetic current structure, while at c.m. proton emission angles $\theta_p^{cm}>50^0$ the A_ϕ-asymmetry is determined by both the reaction mechanisms and the intranuclear dynamics.

3 figs., 12 refs.

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ПРОЯВЛЕНИЕ РЕЛЯТИВИСТСКИХ ЭФФЕКТОВ И СОХРАНЯЮЩИХСЯ ТОКОВ В ИНТЕРФЕРЕНЦИОННОЙ ПРОДОЛЬНО-ПОПЕРЕЧНОЙ СТРУКТУРНОЙ ФУНКЦИИ В (e,e'p)-РЕАКЦИЯХ НА МАЛОНУКЛОННЫХ СИСТЕМАХ: Препринт ХФТИ 92-46. С.И.Нагорный,Ю.А.Касаткин,В.А.Золенко.-Харьков:ХФТИ, 1992.-II с.

Изучаются следствия Лоренц-ковариантности и калибровочной инвариантности и расчетах A_ϕ-асимметрии сечений (e,e'p)-реакций на малонуклонных системах. Показано, что величина A_ϕ очень чувствительна к различным релятивистским эффектам и сохранению ядерного тока. В квазиупругой области ($q^2/2m\nu \sim 1$, $p_{mis}/m \ll 1$) она определяется лишь степенью линейной поляризации виртуального фотона и структурой электромагнитного тока, а при углах вылета протона $\theta_p^{cm}>50^0$ A_ϕ-асимметрия определяется как механизмами реакции, так и внутриядерной динамикой.

Работа финансируется Государственным комитетом Украины по вопросам науки и технологий: "Проект поляризация".

The nuclear structure functions of the $^2H(e,e'p)n$ reaction in the quasi-elastic region ($x_F=-q^2/2m\nu\approx 1.14$, where $q=(\nu,\vec{q})$ is the 4-momentum of the photon, m-the nucleon mass) have recently been separated and the A_ϕ-asymmetry has been measured at the NIKHEF[1]:

$$A_\phi=[d^3\sigma(\phi=0) - d^3\sigma(\phi=\pi)]/[d^3\sigma(\phi=0) + d^3\sigma(\phi=\pi)] \qquad (1)$$

at $q^2=-0.21(GeV/c)^2$ and $p_{mis}\leq 0.18$ GeV/c. In (1), $d^3\sigma$ is the differential cross section of the reaction with registration of ep-coincidences, ϕ is the angle between the planes formed by electron and hadron momenta.

The theoretical analysis of A_ϕ-asymmetry performed in [1] with due account of one- and multi-particle mechanisms, including plane-wave impulse approximation (PWIA), the final-state interaction (FSI), meson exchange currents (MEC) and isobar configurations (IC) has revealed a strong (by a factor of about 2) difference between the nonrelativistic (PWIA+FSI+MEC+IC) and relativistic (PWIA+FSI) calculations.

This paper has been intended to establish the reasons for this strong difference and to investigate the effects of both the Lorentz covariance of theory and the exact conservation of nuclear electromagnetic (EM) current on the calculations of A_ϕ. It will be shown that A_ϕ-asymmetry has the scaling behavior at $x_F\approx 1$ and $p_{mis}/m\ll 1$.

The amplitude of EM process on the nucleus is determined by the set of diagrams satisfying the requirements of nuclear current conservation and containing the contributions of one- and multi-particle mechanisms[2-6]. However, it is well known that in the quasi-elastic region at $x_F\approx 1$ and $p_{mis}/m\ll 1$ the dominant role belongs to the one-particle mechanism[5,7-9]. In this case, the multiparticle effects such as FSI and MEC are suppressed kinematically and the cross section for the (e,e'p) reaction may be represented in a factorized form[7-9]:

$$d^3\sigma = K\, \sigma_{ep}\, \rho(p_{mis}) \quad . \tag{2}$$

where K is the kinematic factor, $\rho(p_{mis})$ is the nucleon momentum distribution in the nucleus, and the dependence on the angle ϕ is focussed only in the "elementary act", i.e., (half)off-shell electron nucleon scattering σ_{ep}. Substituting (2) in (1) we obtain that at $x_F \approx 1$ and $p_{mis}/m \ll 1$ the A_ϕ-asymmetry depends neither on the number of the nucleus-target and its structure, nor on different multiparticle effects:

$$A_\phi \approx [\sigma_{ep}(0)-\sigma_{ep}(\pi)]/[\sigma_{ep}(0)+\sigma_{ep}(\pi)]. \tag{3}$$

Various kinds of off-shell effects' accaunting in σ_{ep} have been considered[10,11]. In the covariant form, the cross section of γ^*-quantum absorption by off-shell nucleons is determined by the convolution of electron $l_{\mu\nu}$ and hadron $W_{\mu\nu}$ tensors: $\sigma_{ep} \approx l_{\mu\nu} W_{\mu\nu}$. In view of the Lorentz covariance, CPT and gauge invariance (GI), this product can be represented in terms of four structure functions (for nonpolarized electrons):

$$\sigma_{ep}=C(\sigma_U + \kappa\, \sigma_L + \kappa\, \sigma_T \cos 2\phi + [\kappa(1+\kappa)]^{1/2} \sigma_I \cos\phi), \tag{4}$$

where $C=(2\alpha E_2 \cos\frac{\theta_e}{2}/q^2)^2(-q^2/2\vec{q}^{\,2})\kappa^{-1}$, $\alpha=1/137$, E_2 and θ_e are, respectively, the final electron energy and scattering angle; $\kappa=(1-2\vec{q}^{\,2}/q^2 tg^2\theta_e/2)^{-1}$ determines the degree of linear polarization of the virtual photon. The structure functions $\sigma_{U,L,T,I}$ in (4) are related to $W_{C,T,S,I}$[8,10] as:

$$\sigma_U=W_T+W_S,\ \sigma_L=-2q^2/\vec{q}^2W_C,\ \sigma_T=W_S,\ \sigma_I=(-2q^2/\vec{q}^2)^{1/2}W_I. \qquad (5)$$

The structure functions are easily calculated if one takes into account that

$$l_{\mu\nu} = 2(k_{1\mu}k_{2\nu}+k_{1\nu}k_{2\mu}) + q^2g_{\mu\nu},\ \ k_1^2=k_2^2=0, \qquad (6)$$
$$W_{\mu\nu}\sim \mathrm{Sp}\{(\hat{p}+m)J_\mu(\hat{p}'+m)J_\nu\},\ p^2=m^2, p'^2=(p-q)^2\neq m^2.$$

Here k_1 and k_2 are the 4-momenta of initial and final electrons ,p' and p are the 4-momenta of the nucleon before and after γ^*-quantum absorption. J_μ is the EM current of the virtual nucleon, $J_\nu=\gamma_0J_\nu^+\gamma_0$, $\hat{p}=p_\mu\gamma_\mu$, γ_μ being the 4x4 Dirac matrices.

So, from (3)-(6), the A_ϕ-asymmetry in the quasi-elastic region is determined only by the degree of linear polarization of the virtual photon and the EM current structure:

$$A_\phi=[\varkappa(1+\varkappa)]^{1/2}\sigma_I/[\sigma_U+\varkappa(\sigma_L+\sigma_T)]. \qquad (7)$$

To evaluate the A_ϕ sensitivity to off-shell effects in γ^*NN vertices, we shall calculate the structure functions for two forms of the nucleon EM current (which are equivalent only on mass shell):

$$J_\mu^{(1)}=\bar{u}(p)\{(F_1+F_2)\gamma_\mu-(p+p')_\mu F_2/2m\}u(p'), \qquad (8)$$

$$J_\mu^{(2)}=\bar{u}(p)\{F_1\gamma_\mu-\sigma_{\mu\nu}q_\nu F_2/2m\}u(p'),\ \sigma_{\mu\nu}=[\gamma_\mu\gamma_\nu]/2, \qquad (9)$$

where u(p) are bispinors, $F_{1,2}(q^2)$ are on-shell EM form factors of nucleons. Using (4)-(9),we get the universal expression for A_ϕ at $\varepsilon_F \simeq 1$, $p_{mis}/m \ll 1$:

$$A_\phi=a\ [S(0) - S(\pi)]/[b + a(S(0) + S(\pi))], \qquad (10)$$
$$S(\phi)=4(pk_1)(pk_2) + q^2m^2$$

The function $S(\phi)$ represents the Lorentz-covariant properties of the A_ϕ-asymmetry, and a,b values are determined by the $\gamma^* NN$ vertex structure:

for current (8) for current (9)

$$a=F_1^2+(\tau-x)F_2^2\,, \qquad a=F_1^2+\tau F_2^2\,, \tag{11}$$

$$b=16m^4\tau(\tau-x)(F_1+F_2)^2, \qquad b=16m^4\tau[\tau(F_1+F_2)^2-x(F_1^2+(\tau-x)F_2^2)].$$

The variables $\tau=-q^2/4m^2$ and $x=(m^2-p'^2)/4m^2$ determine off-shell effects for photons and nucleons, respectively. According to (10)-(11), at $\tau \gg x$ the A_ϕ value does not depend on the form of the EM current, whereas at $\tau \sim x$ this dependence may be significant.

In fig.1, the results of A_ϕ-asymmetry calculations by eqs. (10)-(11) for two forms of the EM current, (8) and (9), are shown by solid curves 1 and 2, respectively. It is seen that the "scaling" curves 1 and 2 practically coincide with Tjon's relativistic calculation /1/ (dotted curve), and the uncertainties in A_ϕ due to a different choice of the EM current are negligible (3-4%) under the conditions of the experiment /1/ ($\tau \gg x$) and are comparable with MEC contribution /1/. Thus, neither the nuclear structure (curves 1 and 2 are universal for any nucleus) nor the multiparticle effects of FSI and MEC types have a real effect on the A_ϕ-asymmetry value in the vicinity of the quasi-elastic peak.

To study the reasons for a strong difference of nonrelativistic and relativistic calculations in [1], let us perform a nonrelativistic reduction in the current (9) and get the structure functions in the form of decomposition in 1/m powers (see /8/):

$$
\begin{aligned}
\sigma_U^{NR} &= (F_1+F_2)^2\vec{q}^2/2m^2 + [\vec{p}\times\vec{q}]^2F_1^2/(\vec{q}^2m^2) + O(1/m^4),\\
\sigma_L^{NR} &= (-2q^2/\vec{q}^2)(F_1^2-F_1(F_1+2F_2)\vec{q}^2/4m^2) + O(1/m^4),\\
\sigma_T^{NR} &= [\vec{p}\times\vec{q}]^2F_1^2/(\vec{q}^2m^2) + O(1/m^4),\\
\sigma_I^{NR} &= -2(-2q^2/\vec{q}^2)^{1/2}|[\vec{p}\times\vec{q}]|\ F_1^2/(|\vec{q}|m^2) + O(1/m^3).
\end{aligned}
\qquad (12)
$$

In this case, the Lorentz-covariant, CPT and GI properties of the hadron tensor $W_{\mu\nu}$ (and convolutions of $l_{\mu\nu}W_{\mu\nu}$) are certainly conserved. The A_ϕ-asymmetry values calculated using the covariant formula (7) but with nonrelativistic structure functions (12) are shown in fig. 1 by the dashed curve. Comparing the dashed and solid (2) curves we see that the nonrelativistic reduction of the EM current (9) leads only to a 14% decrease in the A_ϕ-asymmetry value from the relativistic calculations. A significant difference between our "nonrelativistic" dashed curve and Arenhovel's nonrelativistic calculation [1] (dash-dotted curve) may be due to the violation of Lorentz covariance and GI of the tensor $W_{\mu\nu}$ when calculating some of its components, W_{00}, $W_{i0,0i}$ and W_{ik} ($i,k=1,2,3$), in the quantum-mechanical approach with nonconserving hadron currents. Indeed, at $\phi=0$ and $\phi=\pi$ the electron scattering takes place on the nucleon of the nucleus with the momentum $\vec{p}'=\vec{p}-\vec{q}$ moving in the lab.system "forward" and "backward" with respect to the direction of the incident electron. Therefore, the Lorentz boosts from the nuclear rest frame to the nucleon one, where the nucleon two-component spinors are determined, at $\phi=0$ and $\phi=\pi$ and the same $p_{mis}=|\vec{p}-\vec{q}|$ are realized with different rates [12]. This effect arising due to the "small" wave functions components is not cosidered in quantum-mechanical calculations with two-component spinors. This leads to the decrease in the A_ϕ-asymmetry absolute value (as the contributions from "large" components to A_ϕ are essentially compensated).

So the significant difference between relativistic and nonrelativistic calculations [1] is due to the nonrelativistic reduction of EM current and the absence of Lorentz covariance in quantum-mechanical approaches.

To estimate the role of exact conservation of the nuclear current in A_ϕ-asymmetry calculations, we use the field-theoretic approach which allows us to take into consideration the nuclear structure and provides the GI of the theory. The amplitude of the $^2H(e,e'p)n$ process in the one-photon approximation is determined by the convolution of electron $J_\nu^{(el)}$ and nuclear $J_\nu^{(nucl)}$ currents:

$$T = J_\nu^{(el)}(g_{\mu\nu}/q^2)J_\mu^{(nucl)} \; ; \; J_\nu^{(el)}=e\bar{u}(k_2)\gamma_\nu u(k_1). \qquad (13)$$

The conserving nuclear current, being unified for the processes with photons and electrons has the form [2,4]:

$$J_\mu^{(nucl)}=eU_\alpha(d)\bar{u}(p)(F_\mu^{(p)} \frac{\hat{p}'+m}{p'^2-m^2} A_\alpha(-k_p^2) + A_\alpha(-k_n^2) \frac{\hat{n}'-m}{n'^2-m^2} F_\mu^{(n)} +$$

$$+ F_{\mu\alpha\beta}^{(d)} \frac{-g_{\beta\sigma}+d'_\beta d'_\sigma/d'^2}{d'^2-M^2} A_\sigma(-k^2) + \int_0^1 \frac{d\lambda}{\lambda} \frac{\partial}{\partial q_\mu} A_\alpha[-(k-\lambda q)^2])C\bar{u}^T(n) \qquad (14)$$

In (14) n is the 4-momentum of the neutron, U_α, d and M are the deuteron polarization vector, 4-momentum and mass, respectively. The dNN vertex structure $A_\alpha(-k^2)$ and its connection with the deuteron wave functions is given in [2], and the covariant variables are defined in the following way:

$$k=(p-n)/2, \; k_p=k-q/2, \; k_n=k+q/2, \; n'=n-q, \; d'=d+q.$$

The γNN and γdd vertices satisfying the Ward-Takakhashi identities are written as

$$F_{\mu}^{(N)}=F_{1N}\gamma_{\mu}+(z_N-F_{1N})\frac{q_{\mu}\hat{q}}{q^2}-F_{2N}\frac{\sigma_{\mu\nu}q_{\nu}}{2m}. \tag{15}$$

$$-F_{\mu\alpha\beta}^{(d)}=(d+d')_{\mu}[G_1 g_{\alpha\beta}-\frac{G_3}{2M^2}(q_{\alpha}q_{\beta}-\frac{q^2}{2}g_{\alpha\beta})]+(1-G_1)\frac{d'^2-d^2}{q^2}q_{\mu}g_{\alpha\beta}+$$

$$+2G_2(g_{\mu\alpha}q_{\beta}-g_{\mu\beta}q_{\alpha})+\frac{G_3}{4M^2}(d'^2-d^2)(g_{\mu\alpha}q_{\beta}+g_{\mu\beta}q_{\alpha}-g_{\alpha\beta}q_{\mu}). \tag{16}$$

Here z_N is the nucleon charge. $G_{1,2,3}(q^2)$ are the EM form factors of the deuteron ($G_1(0)=1$, $G_2(0)=\mu_d$, $G_3(0)=2\mu_d+Q_d-1$), μ_d and Q_d are its magnetic and quadrupole moments. The first three terms in (14) correspond to the diagrams with proton, neutron and deuteron poles in fig.2. The contact diagram amplitude providing the conservation of nuclear current is given by the last term in (14). It can be easily seen with the help of (13)-(16) that $J_{\mu}^{(nucl)}q_{\mu}=0$ at arbitrary q^2 values.

The A_{ϕ}-asymmetry values calculated by formulas (13)-(14) with the Reid potential are represented in fig. 1 by solid curve 3. The significant difference between curves 2 and 3 is due to the contact diagram contribution. The calculations based on the first three pole diagrams only (fig. 2) coincide with Tjon's calculations[1] and with our calculations by the scaling formula (10). So, the exact conservation of the nuclear current in A_{ϕ}-asymmetry is of the same importance as the Lorentz-covariance effects are.

A high sensitivity of A_{ϕ} to the reaction mechanisms at p_{miss} is illustrated in fig. 3, where covariant calculations of the A_{ϕ}-asymmetry for the reactions $^3He(e,e'p)^2H$ and $^4He(e,e'p)^3H$ are represented as functions of the c.m. proton emission angle. The vertex functions of $^3He \rightarrow p^2H$ and $^4He \rightarrow p^3H$ were obtained[3,4,6] by using overlap integrals of the wave functions for the Reid and

Urbana potentials. The calculation results based on GI set of diagrams (fig.2.) are shown in fig. 3 by solid curves. The dotted curves correspond to the consideration of the diagrams with the proton pole only. The calculations without contact amplitudes are shown by the dashed line. From fig. 3 it is seen that the exact conservation of EM current in the A_ϕ-asymmetry calculations is also of great importance for the ^3He, ^4He nuclei. For the reaction $^3He(e,e'p)^2H$, in addition to the set of diagrams in fig. 2, the mechanisms of deuteron production from orthogonal states, i.e. from uncorrelated np-pairs have also been considered (the total calculation is shown by the dash-dotted line in fig. 3). At a fixed γ^*-quantum polarization κ at $0^o < \theta_p^{cm} < 50^o$, the complete calculations with conserving currents also show the scaling behavior of A_ϕ (cf. curve 3 in fig. 1 and the solid curves in fig. 3), and the variable κ can be considered as a scale parameter.

So, the A_ϕ-asymmetry measurements on lightest nuclei in the scaling region ($x_F \approx 1$, $p_{mis}/m \ll 1$ and $\theta_p^{cm} < 50^o$) may be used for studying the relativistic effects, off-shell structure of γNN vertices and contact interactions of photons with nuclei. The experimental data at $\theta_p^{cm} > 50^o$ and $p_{mis}/m \le 1$ may give information about the reaction mechanisms and the intranuclear dynamics.

In conclusion, it should be noted that Lorentz covariance of the theory and the nuclear current conservation are of great importance not only in the calculations of A_ϕ-asymmetry but also at studying any polarization phenomena which are due to interference contributions of different components of the EM current.

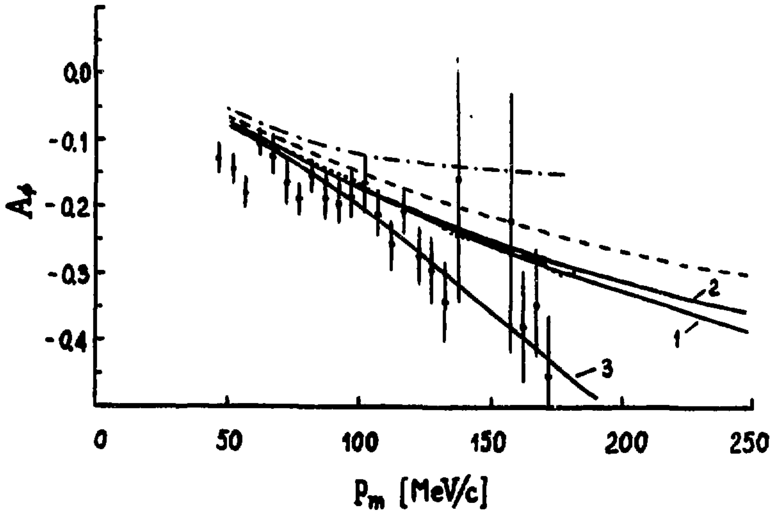

Fig. 1. The A_ϕ-asymmetry of $^2H(e,e'p)n$ cross section as a function of p_{mis} in NIKHEF kinematic conditions/1/. Solid curves 1 and 2 are the covarint calculations by scaling formula (10) for the currents (8) and (9), respectively. The dashed curve is the covariant calculation by formula (7), but with nonrelativistic structure functions (12). The dotted and dash-dotted curves are the relativistic and nonrelativistic calculations/1/. Solid line 3 is the covariant calculation with the exactly conserving current (14). The experimental data are from /1/

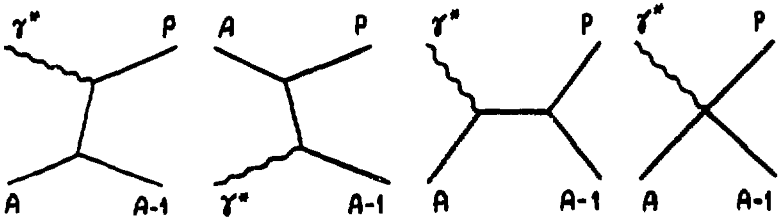

Fig. 2. The set of covariant diagrams for amplitudes of the process $A(\gamma^*,p)A-1$ providing the conservation of nuclear current

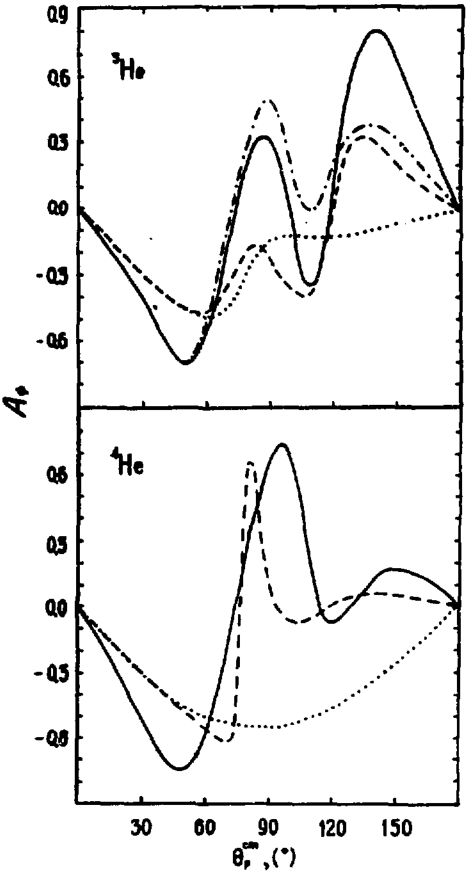

Fig. 3. A_ϕ-asymmetry for the processes $^3He(e,e'p)^2H$ and $^4He(e,e'p)^3H$ versus θ_p^{cm} at E_1=0.5 GeV $\theta_e=60^0$; E_2=0.391 GeV and E_2=0.377 GeV respectively. The dotted curves are the calculations with only the proton pole taken into account. The dashed curves are the calculations based on the first three diagrams of fig. 2. The solid curves are the calculations with the exact conserving nuclear current, taking into account the whole set of diagrams in fig. 2. The dash-dotted curve is the complete calculation with the whole set of diagrams of fig. 2 with addition of the contribution from noncorrelated pn- pairs

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ПРОЯВЛЕНИЕ РЕЛЯТИВИСТСКИХ ЭФФЕКТОВ И СОХРАНЯЮЩИХСЯ ТОКОВ
В ИНТЕРФЕРЕНЦИ..НОЙ ПРОДОЛЬНО-ПОПЕРЕЧНОЙ СТРУКТУРНОЙ ФУНКЦИИ
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