ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
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ИССЛЕДОВАНИЙ

ДУБНА

E2 - 12014

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1978

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Submitted to ЯФ

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О P-нечетных асимметриях в процессах глубоконеупругого рассеяния поляризованных лептонов и антилептонов на нуклонах

Рассматриваются P-нечетные асимметрии в процессах глубоконеупругого рассеяния поляризованных лептонов и антилептонов на нуклонах. Получен ряд соотношений между асимметриями, в основе которых лежит предположение о V, A структуре нейтрального тока. В рамках теории Вайнберга-Салама для изоскалярной мишени получены соотношения между асимметриями и другими измеряемыми величинами, основанные лишь на трансформационных свойствах адронного нейтрального тока. Показано, что в случае, если вклад в асимметрии изоскалярного тока мал (это предположение подтверждается партонной моделью) и если $\sin^2\theta = \frac{1}{4}$, то $\frac{A_-}{q^2}$ и $\frac{A_+}{q^2}$ (A_- и A_+ P-нечетные асимметрии в рассеянии лептонов и антилептонов) 1. равны по величине и противоположны по знаку, 2. слабо зависят от кинематических переменных, 3. $\frac{A_-}{q^2} = -9 \cdot 10^{-5}$

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1978

Bilenky S.M. **E2 - 12014**

On P-Odd Asymmetries in Deep-Inelastic Scattering of Polarized Leptons and Antileptons on Nucleons

P-odd asymmetries in deep inelastic scattering of polarized leptons and antileptons on nucleons are considered. Relations between asymmetries based only on the assumption that the neutral current has V and A structure are obtained. In the framework of the Weinberg-Salam theory for the case of the isoscalar target some relations between asymmetries and other measurable quantities are derived by using only transformation properties of the hadronic neutral current. If contributions to asymmetries from the isoscalar current are neglected (this assumption is supported by the parton model) and $\sin^2\theta = \frac{1}{4}$, then the $\frac{A_-}{q^2}$ and $\frac{A_+}{q^2}$ (A_- and A_+ are P-odd asymmetries in scattering of the lepton and antilepton, resp.) 1. are equal in absolute value and opposite in sign; 2. practically do not depend on kinematical variables; 3. $\frac{A_-}{q^2} = -9 \cdot 10^{-5}$.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1978

The discovery by Novosibirsk [1] and Stanford [2] groups of the parity violating lepton-hadron weak interaction is one of the most important latest developments. The Novosibirsk group has measured the angle of rotation of the plane of polarization of the photon beam passing through ^{209}Bi vapour. The experimental data obtained are consistent with the prediction [3] of the $SU(2) \times U(1)$ Salam-Weinberg gauge theory [4]. The Stanford group has measured the P-odd asymmetry in deep inelastic scattering of longitudinally polarized electrons on nucleons. For the deuterium target the result obtained is

$$\frac{A}{q^2} = (-9,5 \pm 1,6)10^{-5} \quad 1/(\mathrm{GeV})^2, \tag{1}$$

where A is the asymmetry and q^2 the momentum transfer squared. Within the Weinberg-Salam theory and by using the parton model, from (1) it follows [2]

$$\sin^2\theta = 0.20 \pm 0.03. \tag{2}$$

The parameter $\sin^2\theta$ can be also determined from the neutrino data. So, in refs. [5,6] the following values

$$\begin{aligned} \sin^2\theta &= 0,22 \pm 0.05, \\ \sin^2\theta &= 0.24 \pm 0.02 \end{aligned} \tag{3}$$

were obtained.

Note also that the phenomenological analysis of all neutral current data obtained in neutrino beams allows [7] an unambiguous determination of all the coefficients of the hadron neutral current. This unique solution accords with the Weinberg-Salam theory at $\sin^2\theta \simeq 1/4$.

The agreement between (2) and (3) is a forcible argument in favour of the Weinberg-Salam $SU(2) \times U(1)$ gauge theory. It should be mentioned, however, that data [2] are in the region of relatively small $q^2 (\langle q^2 \rangle \simeq 1.6\ (\mathrm{GeV})^2)$ where the breaking of scaling can be large enough. Further verification of the theory requires the investigation of deep inelastic scattering of polarized electrons by nucleons in a larger kinematical region and the study of P-odd effects in other lepton-nucleon processes.

In this paper we analyze deep inelastic scattering of polarized leptons on unpolarized nucleons

$$\ell^- + N \to \ell^- + X \tag{4a}$$

and of polarized antileptons on nucleons

$$\ell^+ + N \to \ell^+ + X . \tag{4b}$$

At first, we shall derive some general relations between P-odd asymmetries in processes (4). Then we consider the lepton scattering on nuclei with zero isotopic spin. Based on the Weinberg-Salam theory, we shall deduce without dynamical assumptions certain relations between P-odd asymmetries in processes (4) and cross sections of the processes

$$\nu_\mu(\bar\nu_\mu) + N \to \mu^-(\mu^+) + X. \tag{5}$$

At last we shall obtain relations between these observables, and study the behaviour of asymmetries in the case if the contribution of the isoscalar current to asymmetry is neglected (this contribution estimated by the parton model is of an order of 20% of the isovector contribution).

The effective Hamiltonian of lepton-hadron weak interaction due to the neutral currents can be written in the form

$$H = \frac{G}{\sqrt{2}} 2 j_\alpha \cdot j^h_\alpha \tag{6}$$

with

$$j_\alpha = \sum_{\ell = e, \mu, \dots} \bar\ell \gamma_\alpha (g_V + g_A \gamma_5) \ell \tag{7}$$

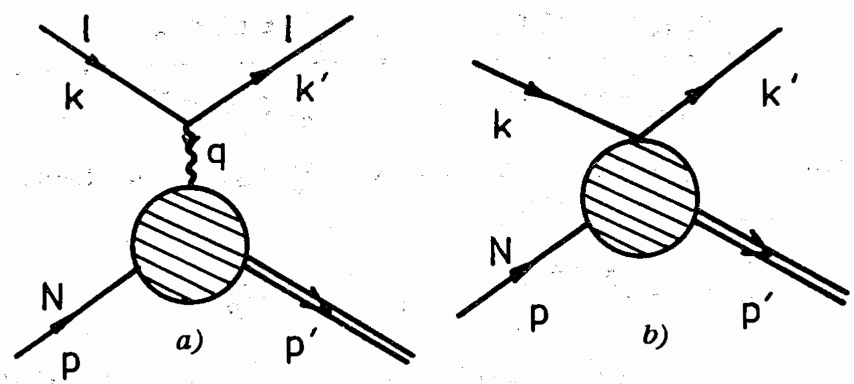
the lepton neutral current, and

$$j^h_\alpha = \sum_{q = u, d, \dots} \bar q \gamma_\alpha (v_q + a_q \gamma_5) q \tag{8}$$

hadron neutral current. In the Weinberg-Salam theory the g_V, g_A, v_u, a_u,... are equal to

$$\begin{aligned} g_V &= -\frac{1}{2} + 2\sin^2\theta, & g_A &= -\frac{1}{2}, \\ v_u &= \frac{1}{2} - \frac{4}{3}\sin^2\theta, & a_u &= \frac{1}{2}, \\ v_d &= -\frac{1}{2} + \frac{2}{3}\sin^2\theta, & a_d &= -\frac{1}{2}, \dots . \end{aligned} \tag{9}$$

To the lowest order in weak and electromagnetic interaction we obtain the following matrix elements of processes (4) (see the *Figure*)



Figure

$$\langle f|S|i\rangle_{\mp} = \pm iN\frac{e^2}{q^2}[\bar{u}(k')\gamma_\alpha u(k)\langle p'|J_\alpha^{em}|p\rangle -$$

$$-\eta\bar{u}(k')\gamma_\alpha(g_V \pm g_A\gamma_5)u(k)\langle p'|J_\alpha^h|p\rangle](2\pi)^4\delta(p'-p-q), \qquad (10)$$

where k and k' are the momenta of initial and final leptons (antileptons), resp., $q=k-k'$, p is the momentum of the initial proton, p' is the total momentum of final hadrons, j_α^{em} the hadron electromagnetic current, N the standard normalization factor due to the lepton lines, and

$$\eta = \frac{G}{\sqrt{2}}\frac{q^2}{2\pi\alpha} \simeq 1.54\cdot 10^{-4}\frac{q^2}{M^2}. \qquad (11)$$

With the longitudinal polarization of initial leptons (antileptons), λ, from (10) we easily obtain the following cross sections of deep inelastic scattering of leptons (antileptons) on unpolarized nucleons /8,9/

$$\left(\frac{d\sigma^{\mp}}{dq^2 d\nu}\right)_\lambda = \frac{d\sigma^{em}}{dq^2 d\nu}\{1+\eta[(-g_V a_V \mp g_A a_A) +$$

$$+\lambda(g_V a_A \pm g_A a_V)]\} \qquad (12)$$

with

$$a_A = \frac{e_{\alpha\beta\rho\sigma}\, k_\rho k'_\sigma W^I_{\alpha\beta}}{L_{\alpha\beta}(k,k')W^{em}_{\alpha\beta}}, \quad a_V = \frac{L_{\alpha\beta}(k,k')W^I_{\alpha\beta}}{L_{\alpha\beta}(k,k')W^{em}_{\alpha\beta}}, \qquad (13)$$

where $L_{\alpha\beta}(k,k') = k_\alpha k'_\beta - \delta_{\alpha\beta}kk' + k'_\alpha k_\beta$. The tensor

$$W^I_{\alpha\beta} = -(2\pi)^6\frac{p_0}{M}\Sigma\int[\langle p'|J_\alpha^{em}|p\rangle\langle p|J_\beta^h|p'\rangle +$$

$$+\langle p'|J_\alpha^h|p\rangle\langle p|J_\beta^{em}|p'\rangle]\delta(p'-p-q)d\Gamma \qquad (14)$$

defines the interference of contributions of electromagnetic and neutral currents to the matrix element. As is clear from (13), $a_V(a_A)$ is given by the contribution of the vector (axial) part of the neutral hadron current to $W^I_{\alpha\beta}$.

The $\frac{d\sigma^{em}}{dq^2 d\nu}$ in (12) is the cross section of deep inelastic scattering of unpolarized leptons on unpolarized nucleons (contribution of the diagram of the *Figure (a)*). This cross section reads

$$\frac{d\sigma^{em}}{dq^2 d\nu} = \frac{2\pi\alpha^2}{q^4}\frac{M^2}{(pk)^2}L_{\alpha\beta}W^{em}_{\alpha\beta}, \qquad (15)$$

where the tensor $W^{em}_{\alpha\beta}$ is of the following standard form

$$W^{em}_{\alpha\beta} = (\delta_{\alpha\beta} - \frac{q_\alpha q_\beta}{q^2})W_1 + \frac{1}{M^2}(p_\alpha - \frac{pq}{q^2}q_\alpha)(p_\beta - \frac{pq}{q^2}q_\beta)W_2, \qquad (16)$$

(W_1 and W_2 are structure functions).

The first term in square brackets of (12) is due to the contribution to the cross section from the P-even part of the weak interaction Hamiltonian, whereas the second one from the P-odd part. The information about the latter can be obtained from the measurement of the asymmetry which is determined as follows

$$A_{\mp} = \frac{1}{\lambda}\,\frac{\left(\frac{d\sigma^{\mp}}{dq^2 d\nu}\right)_\lambda - \left(\frac{d\sigma^{\mp}}{dq^2 d\nu}\right)_{-\lambda}}{\left(\frac{d\sigma^{\mp}}{dq^2 d\nu}\right)_\lambda + \left(\frac{d\sigma^{\mp}}{dq^2 d\nu}\right)_{-\lambda}}. \qquad (17)$$

Inserting (12) into (17) we get

$$A_{\mp} = \eta(g_V a_A \pm g_A a_V). \qquad (18)$$

(throughout only the terms linear in G are kept). We also consider the following asymmetry /10/:

$$B(\lambda)=\frac{\left(\frac{d\sigma^-}{dq^2d\nu}\right)_\lambda-\left(\frac{d\sigma^+}{dq^2d\nu}\right)_{-\lambda}}{\left(\frac{d\sigma^-}{dq^2d\nu}\right)_\lambda+\left(\frac{d\sigma^+}{dq^2d\nu}\right)_{-\lambda}}. \tag{19}$$

The $B(\lambda)$ is a "natural" observable in $\mu^{\mp}$-meson experiments. From (19) and (12) we obtain *

$$B(\lambda)=\eta(-g_A+\lambda g_V)a_A. \tag{20}$$

Now, using (18) and (20) we derive some relations between $A_{\mp}$, B and other measurables.

1. Combining (18) and (20) we get the following relation between $A_{\mp}$ and B **

$$B(\lambda_1)-B(\lambda_2)=\frac{1}{2}(\lambda_1-\lambda_2)(A_-+A_+). \tag{21}$$

Further it can be easily verified that /12/

$$a_A|_{y\to 0}=0. \tag{22}$$

($y=\frac{\nu}{E}$, E is the lab. energy of initial leptons).

Indeed, $W^I_{\alpha\beta}$ has the following general form /13/

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* In asymmetry $B(\lambda)$ the interference of the one-photon diagram of the *Figure (a)* and two-photon diagram also give contribution. We will not discuss it. Note only that it can be calculated within the parton approach /11/.

** Relation (21) does not contain the contribution from the interference of the one- and two-photon diagrams.

$$W^I_{\alpha\beta}=(\delta_{\alpha\beta}-\frac{q_\alpha q_\beta}{q^2})W^I_1+\frac{1}{M^2}(p_\alpha-\frac{pq}{q^2}q_\alpha)(p_\beta-\frac{pq}{q^2}q_\beta)W^I_2+$$

$$+\frac{1}{2M^2}e_{\alpha\beta\rho\sigma}q_\rho p_\sigma W^I_3, \tag{23}$$

where W^I_i are functions of variables q^2 and ν. From (23) and (13) it follows (independent variables are q^2, ν and y)

$$a_A=\frac{-[1-(1-y)^2]\frac{q^2}{2M\nu}\nu W^I_3}{[2(1-y)\nu W_2+\frac{q^2}{2M\nu}y^2 2MW_1]}. \tag{24}$$

From this relation it is easy to see (22). Using (18) we get from (22) the following relation

$$A_-|_{y\to 0}=-A_+|_{y\to 0}. \tag{25}$$

From (20) and (22) we also get

$$B(\lambda)|_{y\to 0}=0 \tag{26}$$

The relations (21), (25) and (26) are based on the only assumption of the V,A structure of the lepton-hadron weak interaction Hamiltonian.

2. In the Weinberg-Salam theory the hadron neutral current reads

$$j^h_\alpha=v^3_\alpha+a^3_\alpha-2\sin^2\theta j^{em}_\alpha+\dots, \tag{27}$$

where

$$v^3_\alpha+a^3_\alpha=\bar u\frac{1}{2}\gamma_\alpha(1+\gamma_5)u-\bar d\frac{1}{2}\gamma_\alpha(1+\gamma_5)d \tag{28}$$

is the isovector (dots in (27) mean the contribution to the neutral current form s, c and other heavier quarks). From the neutrino data it follows [14] that the amount of s, c and other heavier quarks in the nucleon is few per cent of that of u and d quarks. In what follows we shall neglect the contribution of these quarks into the neutral current. The hadron neutral current can be rewritten in the following form

$$j_\alpha^h = (1-2\sin^2\theta)\, j_\alpha^{em} + a_\alpha^3 - \frac{1}{3} v_\alpha^S, \tag{29}$$

where

$$v_\alpha^S = \bar{u}\frac{1}{2}\gamma_\alpha u + \bar{d}\frac{1}{2}\gamma_\alpha d \tag{30}$$

is the isoscalar.

We will consider the lepton and antilepton scattering on nuclei with equal number of protons and neutrons. Throughout in what follows $d\sigma$ will mean the cross section averaged over p and n. In this case the cross section does not contain the terms, which are products of matrix elements of isoscalar and isovector currents. So, we obtain

$$\alpha_A = \frac{e_{\alpha\beta\rho\sigma}\, k_\rho k'_\sigma W_{\alpha\beta}^{V;A}}{L_{\alpha\beta} W_{\alpha\beta}^{em}}, \tag{31}$$

$$\alpha_V = 2(1-2\sin^2\theta) - \frac{2}{9}\alpha_V^S. \tag{32}$$

Here

$$W_{\alpha\beta}^{V;A} = -(2\pi)^6 \frac{p_0}{M} \Sigma \int [\langle p'|V_\alpha^3|p\rangle\langle p|A_\beta^3|p'\rangle + \langle p'|A_\alpha^3|p\rangle\langle p|V_\beta^3|p'\rangle]\delta(p'-p-q)d\Gamma \tag{33}$$

and α_V^S characterizes the contribution to α_V from the isoscalar current:

$$\alpha_V^S = \frac{L_{\alpha\beta} W_{\alpha\beta}^S}{L_{\alpha\beta} W_{\alpha\beta}^{em}} \tag{34}$$

with

$$W_{\alpha\beta}^S = -(2\pi)^6 \frac{p_0}{M} \Sigma \int \langle p'|V_\alpha^S|p\rangle\langle p|V_\beta^S|p'\rangle \delta(p'-p-q)d\Gamma. \tag{35}$$

By using the isotopic invariance of strong interactions, one can easily verify that the numerator of (31) is proportional to the difference of the cross sections of the processes

$$\nu_\mu + N \to \mu^- + X, \tag{36}$$

$$\bar{\nu}_\mu + N \to \mu^+ + X. \tag{37}$$

The denominator of (31) is proportional to the cross section of deep inelastic scattering of unpolarized leptons on unpolarized nucleons (see (15)). Therefore we get

$$\alpha_A = \frac{2\pi^2\alpha^2}{G^2 q^4} \frac{\left(\frac{d\sigma^{cc}}{dq^2 d\nu}\right)_\nu - \left(\frac{d\sigma^{cc}}{dq^2 d\nu}\right)_{\bar{\nu}}}{\frac{d\sigma^{em}}{dq^2 d\nu}}. \tag{38}$$

So, provided the Weinberg-Salam theory is valid, the α_A is determined by the measurables.

Next, based on (9), (18) and (32), the $A_\mp$ and α_A can easily be related to α_V^S:

$$\frac{1}{\eta\alpha_A}[A_-(\alpha_A - 1) - A_+(\alpha_A + 1)] + 1 = \frac{2}{9}\alpha_V^S. \tag{39}$$

From this relation one can find the parameter α_V^S. Since

$$\alpha_V^S > 0 \tag{40}$$

from (39) it follows that the observables in question should obey the inequality

$$\frac{1}{\eta\alpha_A}[A_-(\alpha_A-1)-A_+(\alpha_A+1)]+1>0. \qquad (41)$$

The check of (41) would testify, without using the dynamical assumptions, to the validity of the Weinberg-Salam theory.

3. The summation of A_- and A_+ gives

$$A_-+A_+=2\eta g_V\alpha_A, \qquad (42)$$

whence

$$\frac{A_-+A_+}{2\eta\alpha_A}+\frac{1}{2}=2\sin^2\theta. \qquad (43)$$

The left-hand side of the latter relation contains the measurables, therefore the $\sin^2\theta$ can be determined straightforward from experimental data, without assumptions. This method of determining $\sin^2\theta$ is analogous to the one /15/ used to obtain $\sin^2\theta$ from the neutrino cross section data. The latter allows the determination of $\sin^2\theta$ entering into the hadron neutral current, whereas (43) entering into the lepton neutral current. Note that in the so-called alternative Bjorken theory /16/ the parameters defined by these methods have different physical meaning and can differ as well.

4. Based on the parton model, one can estimate the contribution to α_V from the isoscalar current v^S_α:

$$\alpha^S_V=\frac{\frac{1}{4}\sum\limits_{q=u,d}(f_q(x)+f_{\bar q}(x))}{\sum\limits_{q=u,d}Q^2_q(f_q(x)+f_{\bar q}(x))}, \qquad (44)$$

where $f_q(x)(f_{\bar q}(x))$ is the number of q-quarks ($\bar q$-antiquarks) in the nucleon; Q_q, the quark charge. For the scattering on the isoscalar target under consideration the relation (44) gives

$$\frac{2}{9}\alpha^S_V=\frac{1}{5}. \qquad (45)$$

The first term in the (32) $\sim 1(\sin^2\theta\simeq\frac{1}{4})$. Therefore, in the parton model the contribution from the isoscalar α_V is small as compared to that from the isovector.

Omitting $\frac{2}{9}\alpha^S_V$ in (32) we obtain the following approximate (within $\sim 20\%$) relation between A_-, A_+ and α_A /17/:

$$\frac{1}{\eta\alpha_A}[A_+(\alpha_A+1)-A_-(\alpha_A-1)]=1. \qquad (46)$$

Note that neglecting the isoscalar contribution into the α_V, one can get /12/ another, different from (38), relation. Indeed, since the contributions from vector and axial current to the processes (36) and (37) coincide (chiral symmetry, neutrino data /18/), one has

$$\alpha_A=2\frac{\left(\frac{d\sigma^{cc}}{dq^2d\nu}\right)_\nu-\left(\frac{d\sigma^{cc}}{dq^2d\nu}\right)_{\bar\nu}}{\left(\frac{d\sigma^{cc}}{dq^2d\nu}\right)_\nu+\left(\frac{d\sigma^{cc}}{dq^2d\nu}\right)_{\bar\nu}}. \qquad (47)$$

5. As is well-known, all the presently available data on neutral currents are described by the Weinberg-Salam theory (with $\sin^2\theta\simeq\frac{1}{4}$). If $\sin^2\theta\simeq\frac{1}{4}$ then $g_V\simeq 0$ (see (9)) and from (18) it follows that

$$A_-\simeq -A_+\simeq -\frac{1}{2}\eta\alpha_V. \qquad (48)$$

Neglecting the small isoscalar contribution (20%, cf. p. 4), we obtain from (48)):

$$A_-\simeq -A_+\simeq -9\cdot 10^{-5}\quad q^2/(\mathrm{GeV})^2. \qquad (49)$$

Therefore, if our assumptions are valid, it should be expected that the $\frac{A_-}{q^2}$ and $-\frac{A_+}{q^2}$ depend weakly on the kinematical variables and their numerical value is close to $-0.9 \cdot 10^{-5} \frac{1}{(\mathrm{GeV})^2}$. As is seen from (1), the asymmetry measured at SLAC agrees with this value.

Finally, from (20) for $\sin^2\theta \simeq \frac{1}{4}$ we get

$$B(\lambda) \simeq \frac{1}{2} \eta a_A . \tag{50}$$

As is seen from this expression, the asymmetry B does not depend on polarization λ and its value can be fully predicted if the cross sections of (36) and (37) are known.

The measurement of asymmetries A_- and B seems to be the most "natural" problem for experiments on μ^- and μ^+ meson beams*. Note in conclusion that the muon experiment under preparation by the CERN-Dubna collaboration /20/ is planned to cover such measurements.

I would like to express my deep gratitude to B.M.Pontecorvo for useful discussions of the problems, considered here.

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*Note, the first experiment on search of the parity violation in the processes of lepton-nucleon deep inelastic scattering was carried out on the muon beam at Serpukhov /21/, following the proposal of the ITEF group /22/.

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Received by Publishing Department on November 11 1978.