ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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WHAT DO WE KNOW ABOUT T-ODD, BUT P-EVEN INTERACTION?

PREPRINT 90-69

НОВОСИБИРСК

WHAT DO WE KNOW IN FACT ABOUT T-ODD, BUT P-EVEN INTERACTIONS?

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Abstract

Radiative corrections, due to the P-odd part of electroweak interaction, transform the T-odd, but P-even interaction into a T-odd and P-odd one. The experimental information about T-odd, P-odd effects is sufficiently rich to obtain in this way new limits on the parameters of T-odd, P-even electron-nucleon and nucleon-nucleon interactions, as well as on some β-decay parameters. These limits are much better than those known previously. For identical spin 1/2 particles there is no local T-odd, P-even interaction at all.

Talk at the V.M.Shekhter Memorial Seminar, Leningrad Institute of Nuclear Physics, Gatchina, 19 April,

1. The direct experimental information on the T-odd, P-even interactions is rather poor. Best limits on the relative magnitude of the corresponding admixtures to nuclear forces lie around 10^{-3} [1-4]. We shall relate below all interactions to the Fermi weak interaction constant G. Since the nuclear scale of weak interactions is $Gm_{\pi}^{2} \sim 2\cdot 10^{-7}$, those limits can be formulated as 10^{4}G. Recent experimental project [5] aims at improving these limits by three orders of magnitude.

The information on the corresponding electron-nucleon interaction is practically absent at all. One can mention here only recent suggestion of an atomic experiment which can hopefully reach an accuracy $\sim 3\cdot 10^{4}$G [6] (see also [7]).

As to T-odd, P-even electron-electron interaction, its possible manifestations in positronium are discussed in Ref.[8].

And at last, upper limits on the relative magnitude of T-odd, P-even correlations in β-decay lie at best around 10^{-3} [9-14].

Below it will be shown that experimental data on the T- and P-odd effects lead to much more strict upper limits on the T-odd and P-even NN, eN and β-decay interaction constants, As to the corresponding local electron-electron interaction, it simply does not exist.

2. Let us start from the consideration of the T-odd and P-even scattering amplitude for fermions of spin 1/2. To find the number of these amplitudes it is convenient to go over to the annihilation channel and to classify the particle-antiparticle states of a given total angular momentum j with respect to P- and CP-parity:

1. $s = 0,\quad l = j.\quad P = (-1)^{j+1},\quad C = (-1)^{j},\quad CP = -1.$

2. $s = 1,\quad l = j.\quad P = (-1)^{j+1},\quad C = (-1)^{j+1},\quad CP = 1.$

3. $s = 1,\quad l = j+1,\quad P = (-1)^{j},\quad C = (-1)^{j},\quad CP = 1.$

4. $s = 1,\quad l = j-1,\quad P = (-1)^{j},\quad C = (-1)^{j},\quad CP = 1.$

There are, obviously, two CP-odd and P-even amplitudes:

$$1 \to 2,\qquad 2 \to 1.$$

By the way, the number of P-odd amplitudes, both CP-even and CP-odd, is larger, four in both cases (see, e.g., book [15]).

To construct explicitly T-odd, P-even amplitudes we recall that T-odd, P-odd interaction of an electric dipole moment d with an electromagnetic field strength $F_{\mu\nu}$ is (see, e.g., [15])

$$V_d = \frac{d}{2}\,\bar{\psi}\,\gamma_5\sigma_{\mu\nu}\psi\,F_{\mu\nu} \qquad (1)$$

Substituting a fermion vector current for the vector-potential, we would get four-fermion T-odd, P-odd interaction. Obviously, to obtain T-odd, P-even one, we have to substitute for the vector-potential an axial current. In this way we get two following four-fermion operators:

$$(G/\sqrt{2})(q_1/2m_p)\ \bar{\psi}_1 i\gamma_5\sigma_{\mu\nu}(p'_1-p_1)_\nu\psi_1\ \bar{\psi}_2\gamma_\mu\gamma_5\psi_2, \qquad (2)$$

$$(G/\sqrt{2})(q_2/2m_p)\ \bar{\psi}_1\gamma_\mu\gamma_5\psi_1\ \bar{\psi}_2 i\gamma_5\sigma_{\mu\nu}(p'_2-p_2)_\nu\psi_2. \qquad (3)$$

As it was mentioned above, we measure the interaction discussed in the units of the Fermi weak interaction constant G; m_p is the proton mass, its choice as the necessary dimensional parameter being also a matter of convention; $q_{1,2}$ are dimensionless.

This interaction could arise through the exchange by a neutral pseudovector boson, if its vertices contain the mixture of the operators $\gamma_\mu\gamma_5$ and $i\gamma_5\sigma_{\mu\nu}(p'-p)_\nu$ of opposite CP-parity [16].

On mass shell the above spinor structures can be transformed into

$$i\gamma_5(p'_1+p_1)_\mu\times\gamma_\mu\gamma_5, \qquad (2a)$$

$$\gamma_\mu\gamma_5\times i\gamma_5(p'_2+p_2)_\mu. \qquad (3a)$$

We omit here evident general scalar factors and field operators $\psi_{1,2}$; the first and second spin-momentum operators in both expressions refer to the first and second particles respectively. The representation (2a),(3a) is more convenient for most calculations and will be used below.

It should be pointed out that for identical fermions ($\psi_1=\psi_2$) the interaction discussed vanishes in

the local limit, to be more exact, if q's are independent of the momentum transfer. Technically, the direct and exchange amplitudes cancel after Fierz transformation. The following identities are useful for this proof and calculations below:

$$\sigma_{\mu\nu}\times\gamma_\mu(p'_2+p_2)_\nu=\gamma_5(p'_1+p_1)_\mu\times\gamma_\mu\gamma_5 \qquad (4)$$

$$\sigma_{\mu\nu}\times\gamma_\mu\gamma_5(p'_2+p_2)_\nu=-m_2\gamma_5\sigma_{\mu\nu}\times\sigma_{\mu\nu}+\gamma_5\sigma_{\mu\nu}(p'_1-p_1)_\nu\times\gamma_\mu. \qquad (5)$$

Let us note in the conclusion of this section that T-odd, P-even quark-gluon and quark-photon interactions do not exist at all (see, e.g., [15]).

3. We go over now to the calculation of the electroweak radiative corrections to the operators (2), (3). Some hint on the gain in the limits that can be obtained in this way, is given by the following argument, close in spirit to the corresponding estimates from Refs.[17,18]. Let us consider the contribution to the neutron electric dipole moment from the combined action of the usual P-odd, T-even weak interaction and the discussed T-odd and P-even interaction, the strength of the latter being q times smaller than that of the previous one. This contribution constitutes obviously

$$d_n/e \sim m_p^{-1}(Gm_\pi^2)^2 q \sim 10^{-27} q \text{ cm}. \qquad (6)$$

From the comparison with the last experimental result[19]

$$d_n/e < 1.2\cdot 10^{-25}\,\text{cm}, \qquad (7)$$

we get the limit $q<10^2$ which is about two orders of magnitude better than the above mentioned direct limits. This estimate is obviously of a very crude nature. In particular, the dipole moment arises here at least in one-loop approximation which leads to a small geometrical factor. It suppresses the above estimate at least by an order of magnitude. But even with all the uncertainties taken into account, this example is quite instructive. Below we shall concentrate not on the large-distance effects as in this example, but on the short-distance ones. The electroweak corrections to the operators (2),(3) are of the order α/π (up to some chiral suppression factor, quite essential one; see below), but not Gm_π^2, and at least part of these corrections can be calculated reliably.

Let us consider the radiative corrections to the operators (2), (3) due to the Z-boson exchange. The Z-boson interaction Lagrangian looks like

$$-\frac{e}{2\sin\theta\cos\theta} Z_\alpha \bar{\psi}\gamma_\alpha(v+a\gamma_5)\psi \qquad (8)$$

where e is the electric charge, θ is the electroweak mixing angle, v and a are the fermion vector and axial charges. Along with the vertices generated by the Lagrangian (8), we get additional

ones by making the derivatives in the operators (2),(3) covariant with respect to the Z-field:

$$p_\mu\psi \to [p_\mu - \frac{e}{2\sin\theta\cos\theta}(v+a\gamma_5)Z_\mu]\psi \qquad (9)$$

which modifies the vertices in the two different forms of the T-odd interaction discussed as follows

$$i\gamma_5(p'+p)_\mu \to i\gamma_5(p'+p)_\mu - \frac{e}{2\sin\theta\cos\theta}2vZ_\mu i\gamma_5, \qquad (10)$$

$$i\gamma_5\sigma_{\mu\nu}(p'-p)_\nu \to i\gamma_5\sigma_{\mu\nu}(p'-p)_\nu - \frac{e}{2\sin\theta\cos\theta}(-2a)Z_\nu i\sigma_{\mu\nu}. \qquad (11)$$

After this modification the results of calculations are independent of the form of the operators, (2),(3) or (2a), (3a).

The corrections to the vertex $\gamma_\mu\gamma_5$ in the operators discussed arise obviously only when the fermion mass or the momentum transfer are taken into account. But the corresponding Feynman integrals converge so well that the corrections mentioned become proportional not to α/π, but to G, and are therefore negligible.

CP-even corrections to the CP-odd vertex $i\gamma_5(p'+p)_\mu$ cannot transform it into CP-even structures γ_μ and $\sigma_{\mu\nu}(p'-p)_\nu$. The only structure that can arise, is $i(p'-p)_\mu$. The representation (11) for the initial axial vertex is more convenient here for the calculations. The first term in it leads automatically to the conserved vector current and cannot therefore induce the structure $i(p'-p)_\mu$ non-conserved at non-vanishing momentum transfer. Only the second term in vertex (11) is operative here and leads through the diagrams 1a,b to the following contribution to the induced T- and P-odd interaction:

$$\frac{G}{\sqrt{2}} \frac{\alpha}{16\pi \sin^2\theta \cos^2\theta} \log \frac{\Lambda^2}{M^2} (q_1/m_p)(-2m_2 v_1 a_1)(1 \times i\gamma_5) \quad (12)$$

Here M is the Z-boson mass, Λ is a cut-off parameter, e.g., the mass of the pseudovector boson mediating the T-odd interaction. The cut-off dependence of our results is due to the nonrenormalizability of the T-odd, P-even interaction discussed. The same nonrenormalizability leads to much stronger divergencies in higher loops. E.g., diagram 2 for the induced electric dipole moment diverges quadratically. Even at the quite modest cut-off value $\Lambda \sim 100$ Gev this two-loop diagram leads to the upper limit for the constant q at the level 10^{-4}. However, in the absence of a self-consistent theory for the interaction discussed, we prefer not to rely on the estimates obtained through the calculations with power-like divergencies. We shall consider (at least in this paper) one-loop diagrams only. Moreover, trying to be as conservative as possible in our numerical estimates, we shall assume the log arising to be of the order of unity.

To simplify the formulae we shall assume for the mixing parameter the approximate value $\sin^2\theta = 0.25$. Then the weak vector and axial charges of electron, u- and d-quarks are respectively:

$$v_e = -\frac{1}{2}(1-4\sin^2\theta) \to 0, \quad a_e = -\frac{1}{2}$$

$$v_u = \frac{1}{2}(1-\frac{8}{3}\sin^2\theta) \to \frac{1}{6}, \quad a_u = \frac{1}{2}, \quad (13)$$

$$v_d = -\frac{1}{2}(1-\frac{4}{3}\sin^2\theta) \to -\frac{1}{3}, \quad a_d = -\frac{1}{2}.$$

In formula (12) v_1 and a_1 are the charges of the first particle to which the unit operator 1 corresponds, m_2 is the mass of the second fermion, its operator being $i\gamma_5$.

The calculation of the so to say irreducible diagrams of the type 3a-c is quite straightforward. It is worth mentioning that the term $q_\alpha q_\beta/M^2$ in the vector boson propagator does not work here due to the vector current conservation for which the inclusion of vertex (10) (or (11)) is essential. The net result for the induced T- and P-odd amplitude is

$$\frac{G}{\sqrt{2}} \frac{\alpha}{3\pi} \log \frac{\Lambda^2}{M^2} (q_1/m_p)\{2m_2 v_1 [3a_2 i\gamma_5 \times 1 - (a_1+a_2) 1 \times i\gamma_5] - \quad (14)$$

$$- a_1 v_2 [m_2 i\gamma_5 \sigma_{\mu\nu} \times \sigma_{\mu\nu} - i\gamma_5 \sigma_{\mu\nu} (p'_1 - p_1)_\nu \times \gamma_\mu]\}.$$

We keep here only the terms of the order of α/π neglecting those $\sim G$.

A consistent, gauge-independent calculation of the W-boson exchange contribution to the induced amplitudes is much more model-dependent and will not be discussed here in detail. It can be expected however to be even larger than that of the Z-exchange due to small numerical values of the weak charges v and a (see (13)). So, the Z-exchange contribution serves as an estimate from below for the effect discussed. As to the Higgs boson exchange, in the standard model it conserves parity and is therefore of no interest to us.

4. We start our concrete estimates from the case of the electron-nucleon interaction. Here the induced electron-quark operator is

$$\frac{G}{\sqrt{2}}\frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\, v\{q_e\,[\,\frac{m}{2m_p}\, i\gamma_5\sigma_{\mu\nu}\times\sigma_{\mu\nu} - \frac{1}{2m_p}\, i\gamma_5\sigma_{\mu\nu}(p'_1-p_1)_\nu\times\gamma_\mu]+ \tag{15}$$

$$+q\frac{m_e}{m_p}[(1-2a)i\gamma_5\times 1 - 3\cdot 1\times i\gamma_5]\}.$$

Here m and m_e are the quark and electron masses respectively, v and a are the quark vector and axial charges, q_e and q are the dimensionless constants in the T-odd, P-even operators with the explicit momenta belonging to electrons and quarks respectively. In all the products the first operator refers to electrons, the second one to quarks. The operator (15) should be summed over u- and d- quarks and the expectation values should be taken of it over a nucleon and then over a nucleus.

In the static approximation for nucleons the only

term in (15) that depends on both electron and nucleon spin is $\gamma_5\sigma_{\mu\nu}\times\sigma_{\mu\nu}$. We can roughly estimate the nucleon expectation value of the quark operator $\sigma_{\mu\nu}$ as $\bar{N}\sigma_{\mu\nu}N$. Then the estimate for the dimensionless effective constant of T- and P-odd tensor electron-neutron interaction is

$$k_2 = \frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_d}{2m_p}v_d q_e \sim 10^{-6}q_e. \tag{16}$$

The upper limit on the constant k_2 that follows from the experiment with ^{199}Hg [20] leads to the following result:

$$q_e < 1. \tag{17}$$

We assume here for the d-quark mass the value $m_d = 7$ MeV. About the same limit on q_e follows from the experiment with TlF [21].

We go over now to the nuclear-spin-independent effects. The corresponding analysis of the term $i\gamma_5\sigma_{\mu\nu}(p'_1-p_1)_\nu\times\gamma_\mu$ at $\mu = 0$ leads to somewhat weaker than (17) limit on q_e. So, let us consider the term $i\gamma_5\times 1$. The proton and neutron expectation values for the d-quark scalar operators are [22-24]

$$\langle p|\bar{d}d|p\rangle = 5, \qquad \langle n|\bar{d}d|n\rangle = 6. \tag{18}$$

So, we get the following result for the expectation value of this operator over a heavy nucleus:

$$\langle\bar{d}d\rangle \cong 5.5\ A. \tag{19}$$

Then the dimensionless constant of the T- and P-odd electron-nucleus interaction independent of nuclear spin is

$$k_1 = \frac{\alpha}{3\pi} \log \frac{\Lambda^2}{M^2} \frac{m_e}{m_p} 11 v_d q_d \cong 2\cdot 10^{-6} q_d \qquad (20)$$

The experiments with ^{199}Hg[20], TlF[21] and Cs[25] lead to comparable upper limits on k_1 on the level 10^{-5}. So, we get in this way

$$q_d < 5. \qquad (21)$$

As to the last term in formula (15), the expectation values of the quark operators over a nucleon are at small momentum transfer

$$\langle N|i\bar{u}\gamma_5 u|N\rangle = - \langle N|i\bar{d}\gamma_5 d|N\rangle = \frac{f_\pi g_r}{\sqrt{2}(m_u+m_d)} i\bar{N}\gamma_5\tau_3 N \qquad (22)$$

The u-quark mass is $m_u = 4$ MeV, the π-meson constant $f_\pi = 130$ Mev, the strong coupling constant $g_r = 13.6$, τ_3 is the isotopic spin. For the corresponding constant k_3 (see Refs.[26,15]) we get now the following value:

$$k_3 = \frac{\alpha}{3\pi} \log \frac{\Lambda^2}{M^2} \frac{m_e}{m_p} \frac{f_\pi g_r}{\sqrt{2}(m_u+m_d)} (-\tfrac{1}{2}q_u - q_d) \cong 10^{-4}(-\tfrac{1}{2}q_u - q_d) \qquad (23)$$

The upper limits on k_3 from the experiments with ^{199}Hg and TlF [20,21] constitute about $10^{-4} - 10^{-3}$. So, in this way we obtain

$$q_{u,d} < 1 - 10 \qquad (24)$$

The estimates performed independently by M.G.Kozlov and myself show that the account for the long-distance effects in the interplay of the usual

neutral current weak interaction and the discussed T-odd, P-even interaction leads to the limits on the constants $q_{e,u,d}$ which are much weaker than those obtained above via the short-distance mechanism.

5. We go over now to the discussion of T-odd, P-even quark-quark interaction. The number of the corresponding independent structures increases here due to the possibility to supply the tensor operators with the color matrices t^a.

In the case of identical quarks we can get rid of the tensor interaction by means of the Fierz transformation:

$$T = \frac{20}{3} S + 4S^c, \qquad T^c = \frac{128}{9} S + \frac{4}{3} S^c \qquad (25)$$

where

$$T = i\gamma_5\sigma_{\mu\nu} \times \sigma_{\mu\nu}, \qquad T^c = i\gamma_5\sigma_{\mu\nu} t^a \times \sigma_{\mu\nu} t^a,$$

$$S = i\gamma_5 \times 1, \qquad S^c = i\gamma_5 t^a \times 1 \cdot t^a.$$

Then the induced T- and P-odd interaction (14) transforms to

$$\frac{G}{\sqrt{2}} \frac{\alpha}{3\pi} \log \frac{\Lambda^2}{M^2} \frac{q^w}{m_p} va[-m(\frac{14}{3} S + 4S^c) + D], \qquad (26)$$

$$\frac{G}{\sqrt{2}} \frac{\alpha}{3\pi} \log \frac{\Lambda^2}{M^2} \frac{q^c}{m_p} va[-m(\frac{128}{9} S - \frac{2}{3} S^c) + D^c], \qquad (27)$$

where

$$D = i\gamma_5\sigma_{\mu\nu}(p_1' - p_1)_\nu \times \gamma_\mu, \qquad D^c = i\gamma_5\sigma_{\mu\nu}(p_1' - p_1)_\nu t^a \times \gamma_\mu t^a.$$

The operators (26) and (27) correspond respectively to the cases when the initial T-odd, P-even interaction does and does not contain t^a matrices.

We shall consider now, following Ref.[27], the contribution of the operators (26), (27) to the neutron electric dipole moment and to T- and P-odd nuclear forces, in fact in the latter case to the T- and P-odd π^0NN vertex.

When calculating the neutron dipole moment by the factorization method [27], the operator S^c is equivalent to $\frac{4}{3}S$. As to the factorizable contributions of the operators D and D^c to both neutron dipole moment and π^0NN vertex, they are proportional to the quark masses, but enter the results with much smaller numerical factors than the total contributions of S and S^c (see below). The nonfactorizable contributions of the operators D, D^c are of course much larger than the factorizable ones. But according to rough estimates these nonfactorizable terms are still of the same order of magnitude as the net contributions of S and S^c. The explanation of this suppression consists in small geometrical factors appearing due to loops in the corresponding Feynman diagrams. If these contributions of D and D^c turned out to be larger, our limits would be only better. As to the serious cancellation between these contributions and those of S and S^c, it looks extremely unlikely. So, we shall

not attempt here more sophisticated estimates of these nonfactorizable contributions (say, by the sum rules method) and neglect from now on D and D^c at all.

Then the curly bracket in (26) becomes equivalent to -10mS, that in (27) to $-\frac{40}{3}$mS (including the factorizable contributions of D and D^c would change the factors slightly, from 10 to 9 and from $\frac{40}{3}$ to 12). So, we come to the operators $iu\gamma_5 u\cdot\bar{u}u$ and $i\bar{d}\gamma_5 d\cdot\bar{d}d$ with the dimensionless constants ($G/\sqrt{2}$ is singled out)

$$k_{u,d} = \frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_{u,d}}{m_p}v_{u,d}\,a_{u,d}\,(-10q^w_{u,d}) \cong \begin{cases} 3\cdot 10^{-6}q^w_u \\ 10^{-5}q^w_d \end{cases} \qquad (28)$$

when starting from operator (26), and

$$k_{u,d} = \frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_{u,d}}{m_p}v_{u,d}\,a_{u,d}\,(-\frac{40}{3}q^c_{u,d}) \cong \begin{cases} 4\cdot 10^{-6}q^c_u \\ 14\cdot 10^{-6}q^c_d \end{cases} \qquad (29)$$

when starting from (27). According to the calculations of Ref.[27], the limit (7) on the neutron dipole moment gives the following bounds on the constants $k_{u,d}$:

$$k_u < 10^{-4}, \quad k_d < 1.2\cdot 10^{-4} \qquad (30)$$

So, we come in this way to the following upper limits on the constants q :

$$q^w_u < 30, \quad q^w_d < 12, \quad q^c_u < 25, \quad q^c_d < 10. \qquad (31)$$

For the comparison of the induced interactions (26),(27) with the upper limits on the T- and P-odd nuclear forces we use again the factorization approximation. When calculating the π^0NN coupling constant the equivalence between the operators looks as follows: $S^c \to -\frac{4}{15}S$. Then the dimensionless constants $k_{u,d}$ are (compare with (28)-(29)):

$$k_{u,d} = \frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_{u,d}}{m_p}v_{u,d}a_{u,d}\left(-\frac{18}{5}q^w_{u,d}\right) \cong \begin{cases} 10^{-6}q^w_u \\ 4\cdot 10^{-6}q^w_d \end{cases} \qquad (32)$$

when starting from operator (26), and

$$k_{u,d} = \frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_{u,d}}{m_p}v_{u,d}a_{u,d}\left(-\frac{72}{5}q^c_{u,d}\right) \cong \begin{cases} 5\cdot 10^{-6}q^c_u \\ 17\cdot 10^{-6}q^c_d \end{cases} \qquad (33)$$

when starting from (27) (including the factorizable contributions of D and D^c would only slightly change the coefficients, from $\frac{18}{5}$ to $\frac{19}{5}$ and from $\frac{72}{5}$ to $\frac{44}{3}$).

The limits on the constants q that follow from the experiments with ^{199}Hg and TlF (the corresponding data on the constants $k_{u,d}$ can be obtained using the calculations from Ref.[27]) are comparable or slightly weaker than (31). However, in the near future one can expect a considerable progress in the searches for T-violation in atomic experiments and therefore a considerable improvement of the accuracy for the constants q.

6. In the case of different quarks the induced T- and P-odd operator is (note that here $a_1 + a_2 = 0$)

$$\frac{G}{\sqrt{2}}\frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{q}{m_p}a_2\{6m_2 v_1 i\gamma_5 \times 1 - v_2[m_2 i\gamma_5\sigma_{\mu\nu}\times\sigma_{\mu\nu} -$$

$$-i\gamma_5\sigma_{\mu\nu}(p'_1-p_1)_\nu \times \gamma_\mu]\} \qquad (34)$$

There is of course one more operator, with color matrices t^a in both factors.

In our estimates below for the neutron dipole moment we shall follow the approach of Ref.[28] where it was calculated in the chiral limit. The only contribution singular in the π-meson mass m_π originates here from the diagrams 4a,b where one of the πNN vertices, $g_r\sqrt{2}\, i\gamma_5$, is the strong interaction one, the second, $\bar{g}\sqrt{2}\, 1$, is CP- and P-odd. The neutron dipole moment arising in this way is

$$d_n/e \cong \frac{g_r\bar{g}}{4\pi^2}\frac{1}{m_p}\log\frac{1}{m_\pi} \qquad (35)$$

CP- and P-odd constants $\bar{g}$ generated by the operators

$$k_{ud}(\bar{u}i\gamma_5 u)(\bar{d}d), \quad k^c_{ud}(\bar{u}i\gamma_5 t^a u)(\bar{d}t^a d),$$

$$k_t(\bar{u}i\gamma_5\sigma_{\mu\nu}u)(\bar{d}\sigma_{\mu\nu}d), \quad k^c_t(\bar{u}i\gamma_5\sigma_{\mu\nu}t^a u)(\bar{d}\sigma_{\mu\nu}t^a d) \qquad (36)$$

(the factors $G/\sqrt{2}$ omitted for brevity) are obtained easily by the factorization and constitute

$$\bar{g}_{ud} = -\frac{1}{24}k_{ud}\rho G m^2_\pi f_\pi/(m_u+m_d), \quad \bar{g}^c_{ud} = -\frac{1}{18}k^c_{ud}\rho G m^2_\pi f_\pi/(m_u+m_d),$$

$$\bar{g}_t = \frac{1}{2}k_t\rho G m^2_\pi f_\pi/(m_u+m_d), \qquad \bar{g}^c_t = \frac{2}{3}k^c_t\rho G m^2_\pi f_\pi/(m_u+m_d). \qquad (37)$$

The factor $\rho = (m_\Xi - m_\Sigma)/m_s$ is very close to unity (m_Ξ, m_Σ

and) m_s are the masses of Ξ-hyperon, Σ-hyperon and s-quark respectively).

Comparing (37) with the experimental result (7), we get the following limits on the constants k:

$$k_{ud,du}<1.5\cdot10^{-4},\quad k^c_{ud,du}<10^{-4},\quad k_t<1.5\cdot10^{-5},$$

$$k^c_t<10^{-5}. \qquad (38)$$

The results on k_{ud}, k_t are comparable to those obtained in Ref.[27], the limits (38) on k^c_{ud}, k^c_t are much stronger.

As follows now from (34) and (37), the induced T- and P-odd constants are

$$\left.\begin{matrix} k_{12} \\ k^c_{12} \end{matrix}\right\} = \frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_2}{m_p}6a_2(v_1-2v_2)\left\{\begin{matrix} q_{12} \\ q^c_{12} \end{matrix}\right. \qquad (39)$$

In this way we get

$$q_{ud}<10,\quad q_{du}<20,\quad q^c_{ud}<7,\quad q^c_{du}<15 \qquad (40)$$

To obtain the limits on these constants from the T- and P-odd nuclear forces we use again the results of Ref.[27]. Here the operator $i\gamma_5\sigma_{\mu\nu}\times\sigma_{\mu\nu}$ is ineffective. So, we get for the constants $k_{ud,du}$ the following expressions:

$$k_{ud,du}=\frac{\alpha}{3\pi}\log\frac{\Lambda^2}{M^2}\frac{m_{d,u}}{m_p}6v_{u,d}a_{d,u}q_{ud,du}\cong\left\{\begin{matrix} -3\cdot10^{-6}q_{ud} \\ -4\cdot10^{-6}q_{du} \end{matrix}\right. \qquad (41)$$

The limit on the constants $k_{ud,du}$ following from the atomic experiments, $k_{ud,du}<10^{-4}$, leads therefore to

$$q_{ud}<30,\qquad q_{du}<25, \qquad (42)$$

which is somewhat worse than (40).

The contributions of the operators $i\gamma_5 t^a\times t^a$ and $i\gamma_5\sigma_{\mu\nu}t^a\times\sigma_{\mu\nu}t^a$ to the T- and P-odd nuclear forces are so small that the limits on the constants $q^c_{ud,du}$ obtained in this way are extremely weak.

7. Now, having got the above limits on the T-odd and P-even quark-quark interaction, what can we say about the corresponding nucleon-nucleon interaction? T- and P-odd nuclear forces are dominated by π^0-meson exchange. But T-odd, P-even $\pi^0 NN$ vertex simply does not exist. The effective T-odd, P-even $\pi^{\pm}NN$ coupling, being Hermitian, looks like

$$\bar{p}\gamma_5 n\pi^+ - \bar{n}\gamma_5 p\pi^- \qquad (43)$$

and does not lead to NN scattering in the one-boson exchange approximation, since after the interchange of this vertex and the strong one, the corresponding diagrams cancel out. By the same reasons the exchange by vector bosons, both neutral and charged ones, with one vertex being usual strong and the second T-odd and P-even, also does not lead to NN scattering. Vanishing of the one-pion exchange in the T-odd, P-even NN scattering was pointed out previously in Ref.[29]. One-boson exchange of this type starts therefore with pseudovector mesons. Being mediated by heavier bosons, the effective NN interaction is suppressed as compared to simple estimates.

On the other hand, it follows already from general formulae (2),(3) that a T-odd, P-even nucleon-nucleon scattering amplitude contains an extra power of p/m_p as compared to the usual P-odd weak interaction. It means again roughly an order of magnitude suppression as compared with the mentioned naive estimate $Gm_{\pi}^2 q$.

Thus, even taking into account the uncertainties of our calculations, including the neglect of the W-boson exchange and of the nonfactorizable contributions of the operators D and D^c, one can expect that the relative strength of the T-odd, P-even nuclear forces does not exceed $10Gm_{\pi}^2$.

One should have in mind however that the observable effects of the T-odd, P-even nuclear forces may well happen to be much larger than this estimate, due to, so to say, long-distance enhancement factors, such as small energy intervals between resonances mixed by the interaction discussed.

8. Some information can be obtained in an analogous way concerning even β-decay constants. To relate them to the eN T- and P-odd interaction one should evidently switch on W-exchange. As has been mentioned already, this procedure is more ambiguous than the switching on of Z-exchange used in our previous consideration. One can hope, however, that the

estimates made below are valid at least by an order of magnitude.

The diagrams transforming β-decay interaction into T- and P-odd eN one are presented at Figs.5a-d. In our estimates we shall assume for the W-boson propagator the simple Feynman form $\delta_{\mu\nu}/(q^2-M_w^2)$ with the hope that the term $-q_\mu q_\nu/M_w^2$ in the nominator will somehow cancel out at more accurate calculations.

We shall restrict here to the T-odd quark-lepton β-decay interaction without derivatives. Then, to obtain the radiative correction of the order of magnitude α/π, but not G, the quark mass in the propagator should be neglected. Let us note that all T- and P-odd eN interaction operators without derivatives change the chirality of both fermions. Since the W-exchange vertices contain left projectors, we can investigate in this way, neglecting the quark masses, the chirality changing quark-lepton operators only:

$$(\bar{u}d)[\bar{e}(C_S+C'_S\gamma_5)\nu]+(\bar{u}\gamma_5 d)[\bar{e}(C_P\gamma_5+C'_P)\nu]-$$
$$-\frac{1}{2}(\bar{u}\sigma_{\mu\nu}d)[\bar{e}(C_T+C'_T\gamma_5)\sigma_{\mu\nu}\nu] + \text{h.c.} \qquad (44)$$

So, in this approximation nothing can be said about the axial and vector constants. On the other hand, P-even part of the electroweak correction allows us to obtain information on the P- and T-odd β-decay constants as well.

The effective T- and P-odd interaction of an electron with u-quark arising from (44) through the W-exchange (see diagrams 5a,b) is

$$\frac{G}{\sqrt{2}}\frac{\alpha}{8\pi}\log\frac{\Lambda^2}{M^2}\mathrm{Im}[6(C_T+C'_T)-(C_S+C'_S)-(C_P+C'_P)]\cdot \qquad (45)$$
$$[2(i\gamma_5\times 1+1\times i\gamma_5)+i\gamma_5\sigma_{\mu\nu}\times\sigma_{\mu\nu}].$$

Again in each operator product the first factor refers to the electron, the second one refers to the quark. The corresponding effective operator for the interaction between electron and d-quark (see diagrams 5c,d) is

$$\frac{G}{\sqrt{2}}\frac{\alpha}{8\pi}\log\frac{\Lambda^2}{M_W^2}2\mathrm{Im}[(C_S+C'_S)-(C_P+C'_P)](i\gamma_5\times 1-1\times i\gamma_5). \qquad (46)$$

In this way we get for the effective constant k_2 (see the discussion of formulae (16), (17)) the expression

$$k_2\cong\frac{\alpha}{8\pi}\log\frac{\Lambda^2}{M_W^2}\mathrm{Im}[6(C_T+C'_T)-(C_S+C'_S)-(C_P+C'_P)], \qquad (47)$$

and the following limit on the β-decay constants:

$$\mathrm{Im}[6(C_T+C'_T)-(C_S+C'_S)-(C_P+C'_P)]<4\cdot 10^{-3}. \qquad (48)$$

Using the same results (18),(19), we obtain the following value for the constant k_1:

$$k_1=\frac{\alpha}{2\pi}\log\frac{\Lambda^2}{M_W^2}5.5\ \mathrm{Im}[3(C_T+C'_T)-(C_P+C'_P)], \qquad (49)$$

and a limit on another combination of β-decay constants:

$$\mathrm{Im}[3(C_T+C'_T)-(C_P+C'_P)] < 1.5\cdot 10^{-3}. \qquad (50)$$

And at last, using formula (22), we come to the expression for the constant k_3:

$$k_3=\frac{\alpha}{2\pi}\log\frac{\Lambda^2}{M_W^2}\frac{f_\pi g_r}{\sqrt{2}(m_u+m_d)}\mathrm{Im}[3(C_T+C'_T)-(C_P+C'_P)]. \qquad (51)$$

The upper limit on the combination of β-decay constants in square brackets, obtained in this way, is slightly worse than (50).

It would be natural to say that, up to the possibility of some cancellations, the final result for the constants discussed can be formulated as

$$\mathrm{Im}(C_T+C'_T) < 0.5\cdot 10^{-3}, \qquad \mathrm{Im}(C_P+C'_P) < 1.5\cdot 10^{-3},$$
$$\mathrm{Im}(C_S+C'_S) < 4\cdot 10^{-3}. \qquad (52)$$

The limits obtained from direct experiments [9-11,13-14] lie roughly between 10^{-2} and unity, depending on the combination of the T-odd constants. All of those combinations differ, however, from ours. But what is more essential, our limits are, so to say, of less quantitative character, being dependent on some assumptions made in calculations. Nevertheless, I believe that the limits (52), being much stronger than direct ones, are quite interesting.

Here again it should be noted that T-odd correlations in the nuclear β-decays may be enhanced considerably due to "long-distance" effects in a nucleus. In this connection I wish to mention the possibility of such an enhancement due to the presence of an anomalously close nuclear level of opposite parity admixed by T- and P-odd nucleon-nucleon interaction to the initial or final level.

The last remark refers to the flavour-changing quark-lepton interaction which differs from (44) by the substitution of the s-quark for d-quark. In this case also the T-odd constants are limited from above by the results of atomic experiments. The limits are roughly five times worse than (52) due mainly to the presence of the Cabibbo angle in the flavour-changing W-exchange. As to the chirality-changing strange quark operators $\bar{s}s$, $\bar{s}i\gamma_5 s$, $\bar{s}\sigma_{\mu\nu}s$, their nucleon expectation values are of about the same magnitude as those for d-quarks [23,24]. Quite meaningful limits follow in this way even on the T-odd constants for β-decays of heavy quarks: $c \to de\nu$, $b \to ue\nu$, $t \to de\nu$. But here again "long-distance" effects, well-known in these cases, lead to tremendous enhancement of CP-odd phenomena in the semileptonic decays of neutral mesons, observed long ago in the decays $K^0 \to \pi l\nu$.

Acknowledgements.

My interest to the problem of T-odd, Ṗ-even interactions originated to a large degree from the discussions with J.D.Bowman, D.A.Budker, R.S.Conti and H.Weidenmueller. On some theoretical points I had helpful discussions with V.L.Chernyak, M.G.Kozlov and A.R.Zhitnitsky. To all of them I owe my deep gratitude. To H.Weidenmueller I am grateful also for the kind invitation to and warm hospitality at the Max-Planck Institute of Nuclear Physics, Heidelberg, where this work was started.

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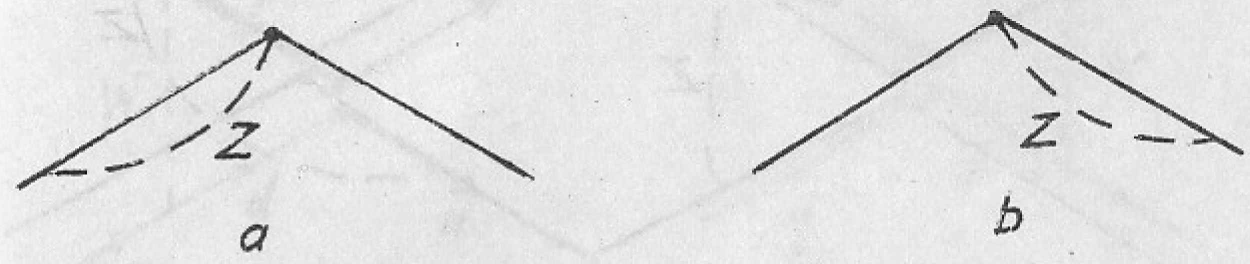

Fig. 1

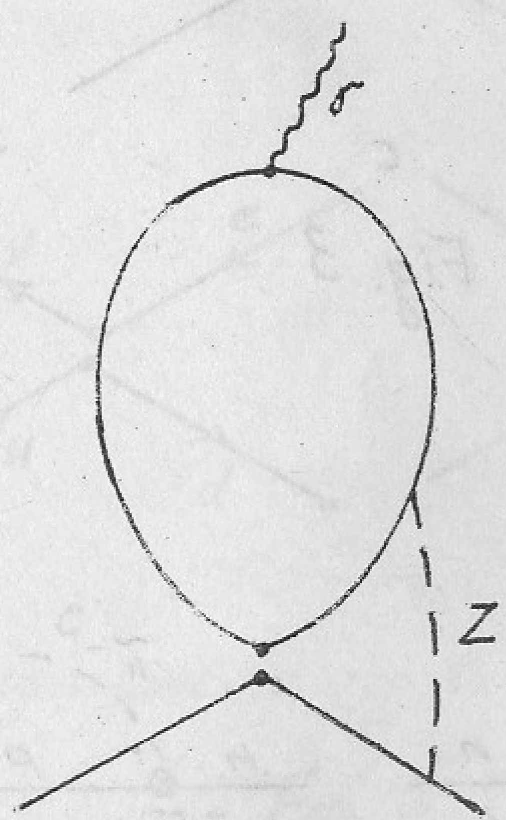

Fig. 2

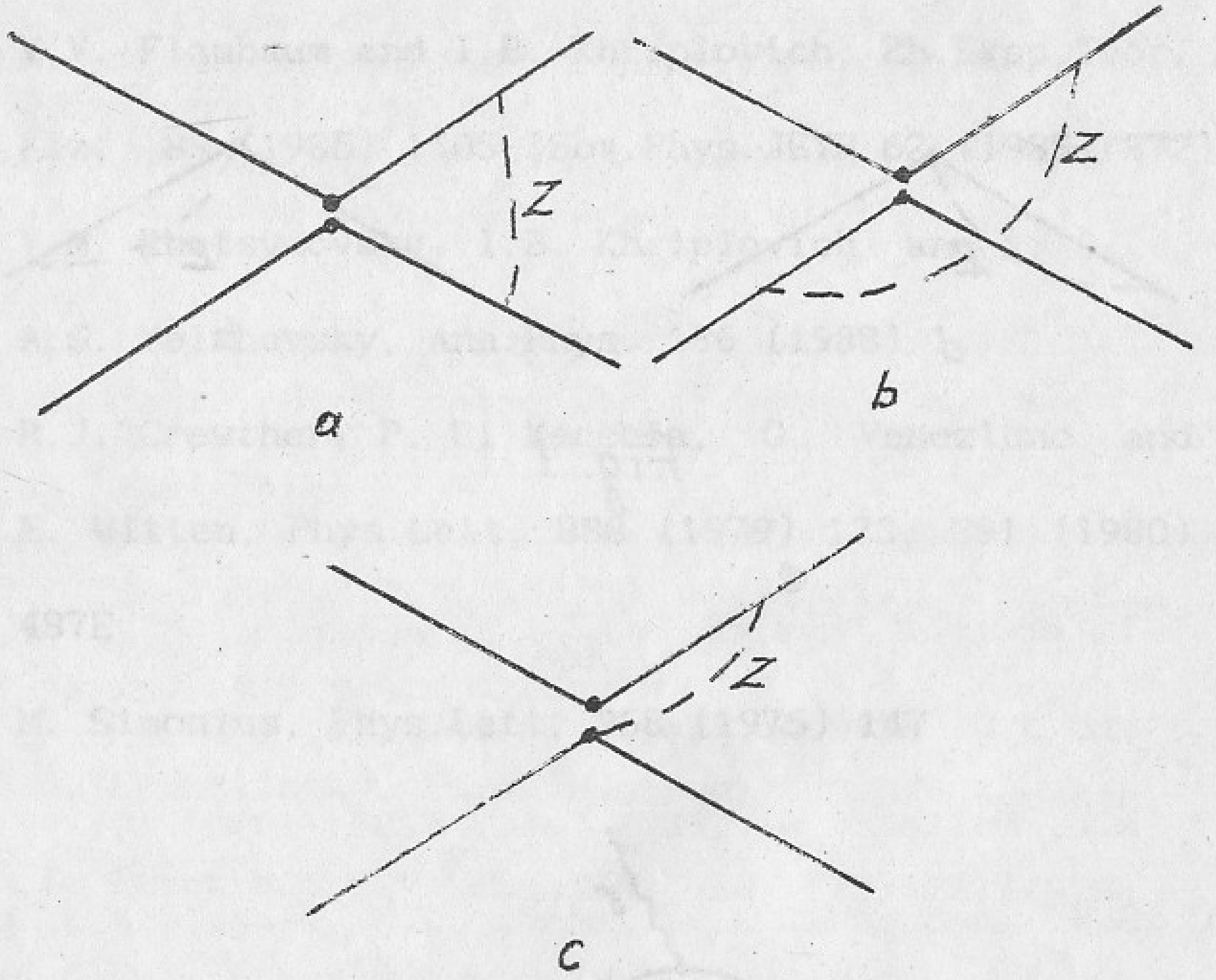

Fig. 3

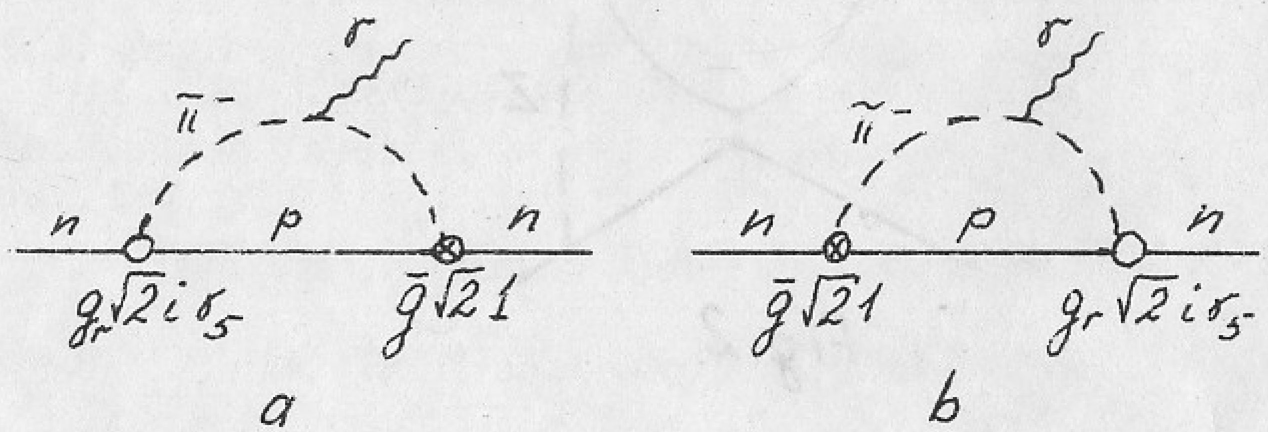

Fig. 4

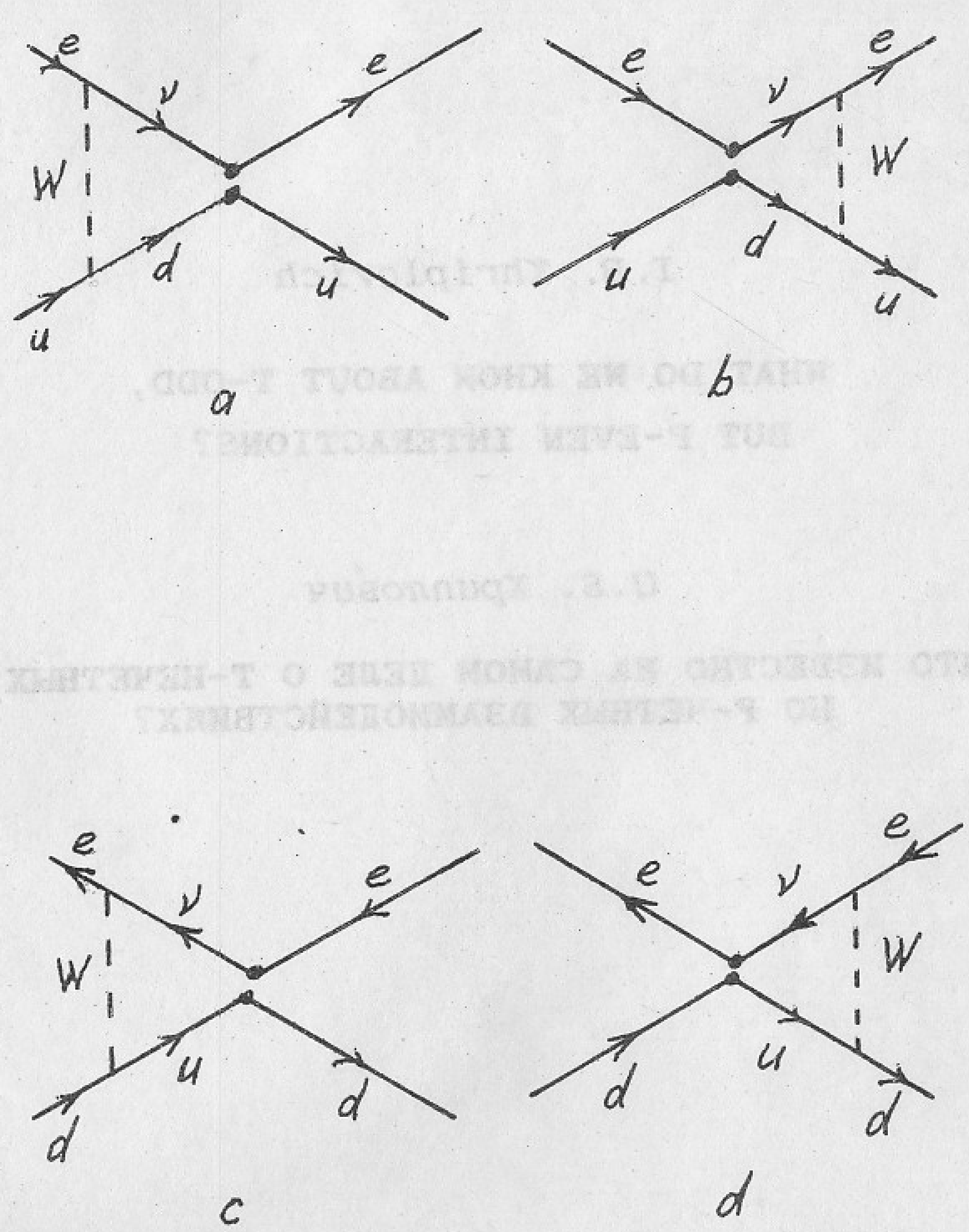

Fig. 5

I.B. Khriplovich

**WHAT DO WE KNOW ABOUT T-ODD,
BUT P-EVEN INTERACTIONS?**

И.Б. Хриплович

**ЧТО ИЗВЕСТНО НА САМОМ ДЕЛЕ О Т-НЕЧЕТНЫХ,
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Работа поступила - 11 июня 1990 г.

Ответственные за выпуск: С.Г.Попов

Подписано к печати 19.06. 1990 г. МН 08726
Формат бумаги 60×90 1/16
Усл. 1,0 п.л., 0,9 уч.-изд.л.
Тираж 220 экз. Бесплатно. Заказ 69.

Ротапринт ИЯФ СО АН СССР, г. Новосибирск 90.