ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

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PREPRINT 87-28

НОВОСИБИРСК

Neutron Electric Dipole Moment, T-Odd Nuclear Forces and Nature of CP-Violation

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ABSTRACT

Limits of the parameters of CP-violation in the system of light quarks are extracted from the experimental limits on the neutron electric dipole moment and T-odd effects in atoms. For a number of parameters the limits that follow from the neutron and atomic experiments turn out quite comparable.

1. INTRODUCTION

Thus far CP-violation was observed only in the neutral K-meson decays [1]. Although the searches for another manifestation of CP-violation — electric dipole moment (EDM) of the neutron are going on for many years, it has not been discovered up to now. However, the limits on the neutron EDM d_n obtained in these experiments have played very important role allowing one to exclude a number of the models of CP-violation. The result of the most accurate neutron experiment [2] is formulated by its authors as the limit at the 95% confidence level

$$|d_n/e| < 2.6\cdot 10^{-25}\,\mathrm{cm}\,. \qquad (1)$$

As for the searches for CP-violation in atoms and molecules, their results look much more modest. Being interpreted in terms of the limits on the proton or neutron EDMs these results are about 4 orders of magnitude weaker than those following from the neutron experiments.

However, as pointed out in Ref. [3], the gap in the physical significance between the neutron and atomic experiments is shortened essentially if one interprets the results of the latter as limits on the effective constant η of CP-odd nucleon-nucleon interaction (the definition of the constant η will be given below) rather than on the neutron or proton EDM. It was obtained in Ref. [4] from the most accurate measurement [5] of the ^{129}Xe atom EDM that

$$|\eta| < 0.5\,. \qquad (2)$$

In the present work the operators of the lowest dimensions 5 and 6 are constructed that can describe CP-violation in the system of light quarks and the limits on the corresponding effective constants are extracted from the results (1) and (2). For some constants these limits turn out quite comparable. Therefore, atomic and molecular experiments are the important tool for study of the possible mechanisms of CP-violation.

2. CP-ODD OPERATORS

We start from the enumeration of the CP-odd operators of interest. In the case of the dimension 5 they are as follows:

$$\frac{G}{\sqrt{2}} k_u^g m_p \bar{u} g \sigma_{\mu\nu} G_{\mu\nu}^a t^a \gamma_5 u = \frac{G}{\sqrt{2}} k_u^g m_p O_u^g \quad (3)$$

and

$$\frac{G}{\sqrt{2}} k_d^g m_p \bar{d} g \sigma_{\mu\nu} G_{\mu\nu}^a t^a \gamma_5 d = \frac{G}{\sqrt{2}} k_d^g m_p O_d^g . \quad (4)$$

Here $G_{\mu\nu}^a$ is the field strength of gluon, g is its coupling constant, $G=10^{-5}/m_p^2$ is the Fermi constant of weak interaction, m_p is the proton mass. Here and below k are just those dimensionless constants limits on which we are interested in.

Four-quark CP-odd operators of the dimension 6 are as follows:

$$\frac{G}{\sqrt{2}} k_q i(\bar{q}\gamma_5 q)(\bar{q} q) = \frac{G}{\sqrt{2}} k_q O_q , \quad q=u \text{ or } d; \quad (5)$$

$$\frac{G}{\sqrt{2}} k_q^c i(\bar{q}\gamma_5 t^a q)(\bar{q} t^a q) = \frac{G}{\sqrt{2}} k_q^c O_q^c ; \quad (6)$$

$$\frac{G}{\sqrt{2}} k_{q_1 q_2} i(\bar{q}_1 \gamma_5 q_1)(\bar{q}_2 q_2) = \frac{G}{\sqrt{2}} k_{q_1 q_2} O_{q_1 q_2} , \quad q_1, q_2 = u, d, \; q_1 \neq q_2 ; \quad (7)$$

$$\frac{G}{\sqrt{2}} k_{q_1 q_2}^c i(\bar{q}_1 \gamma_5 t^a q_1)(\bar{q}_2 t^a q_2) = \frac{G}{\sqrt{2}} k_{q_1 q_2}^c O_{q_1 q_2}^c , \quad q_1 \neq q_2 ; \quad (8)$$

$$\frac{G}{\sqrt{2}} k_t \frac{1}{2} \varepsilon_{\mu\nu\alpha\beta} (\bar{u} \sigma_{\mu\nu} u)(\bar{d} \sigma_{\alpha\beta} d) = \frac{G}{\sqrt{2}} k_t O_t ; \quad (9)$$

$$\frac{G}{\sqrt{2}} k_t^c \frac{1}{2} \varepsilon_{\mu\nu\alpha\beta} (\bar{u} \sigma_{\mu\nu} t^a u)(\bar{d} \sigma_{\alpha\beta} t^a d) = \frac{G}{\sqrt{2}} k_t^c O_t^c . \quad (10)$$

Note that in the case of identical quarks the tensor structures of the type (9), (10) are reduced by the Fierz transformation to the scalar ones (5), (6).

We define all the operators at the low normalization point $\mu=140$ MeV where $\alpha_s(\mu)\approx 1$.

3. ESTIMATES

First of all consider the CP-odd nucleon-nucleon interaction constant. We shall take into account the π^0-exchange only. This mechanism stands out due to the large value of the strong πNN coupling constant $g_r=13.5$ and the smallness of the π-meson mass m_π. As for the derivative occuring at one of the vertices (here at the strong one) it arises inevitably in the case of a P-odd interaction and does not lead to a relative suppression of the corresponding contribution. Finally, a charged particle exchange is suppressed as compared with that of a neutral one in the shell model of nucleus [3, 4]. Thus, the π^0-exchange leads to the effective nucleon-nucleon interaction of the kind $\eta(G/\sqrt{2})i(\bar{N}\gamma_5 N)(\bar{N}' N')$ with dimensionless constant

$$\eta = \frac{\sqrt{2}}{G} \frac{\bar{g} g_r}{m_\pi^2} . \quad (11)$$

Here $\bar{g}$ is the CP-odd πNN coupling constant. In what follows we consider CP-violating interaction between neutron and proton: $N=n$, $N'=p$, since the limit (2) corresponds in fact just to the constant of such interaction [4].

The limits on the CP-odd interaction constants are most easily obtained for the operators composed of four identical quarks.

a) $i(\bar{u}\gamma_5 u)(\bar{u}u)$. Since there is only one valence u-quark in the neutron, this interaction contributes to the neutron EDM and to the CP-violating interaction of nucleons only through factorization [6]. Substituting for the product of quark fields $u\bar{u}$ its vacuum expectation value (VEV) in the external electromagnetic field $F_{\mu\nu}$

$$u\bar{u} \to -\frac{1}{24} \langle \bar{u} i \sigma_{\mu\nu} u \rangle_F i \sigma_{\mu\nu} = -\frac{e\chi}{36} \langle \bar{u} u \rangle i \sigma_{\mu\nu} F_{\mu\nu} \quad (12)$$

($\chi=6$ GeV^{-2} is the vacuum magnetic susceptibility [7—9]) we get the value of the neutron EDM:

$$d_n = -\frac{1}{36} k_u d. \tag{13}$$

Here

$$d = \frac{G}{\sqrt{2}} \frac{e\chi}{\pi^2} a = 9\cdot 10^{-20} e\cdot\text{cm}, \tag{14}$$

$a = -(2\pi)^2 \langle \bar{q} q \rangle \approx 0.55\ \text{GeV}^3$, e is the proton charge. We assume for estimates that $\langle n | \bar{q} \sigma_{\mu\nu} \gamma_5 q | n \rangle \approx \bar{n} \sigma_{\mu\nu} \gamma_5 n$.

Turn now to the CP-odd constant η of nucleon-nucleon interaction. There are two factorized contributions to the matrix element $\langle N\pi^0 | H | N \rangle$. We can pick either $\bar{u}\gamma_5 u$, or pseudoscalar part of the quark fields product $u\bar{u}$ out for π^0-meson:

$$\langle \pi^0 | u\bar{u} | 0 \rangle = -\frac{1}{12} \langle \pi^0 | \bar{u} \gamma_5 u | 0 \rangle \gamma_5.$$

So we get

$$\eta = \frac{5}{6\sqrt{2}} k_u g_r \frac{f_\pi}{m_u + m_d} \varkappa_u, \tag{15}$$

where $f_\pi = 130$ MeV is the pion decay constant and $m_u + m_d = 11$ MeV is the sum of the light quarks masses. For the constants $\varkappa_q = \langle p | \bar{q} q | p \rangle / 2m_p$ we take the values $\varkappa_u = 6$, $\varkappa_d = 5$ according to [10—12].

b) $i(\bar{u}\gamma_5 t^a u)(\bar{u} t^a u)$. When calculating the EDM the only difference from the previous case consists in the colour factor $t^a t^a = 4/3$:

$$d_n = -\frac{1}{27} k_u^c d. \tag{16}$$

The constant η is here

$$\eta = -\frac{\sqrt{2}}{9} k_u^c g_r \frac{f_\pi}{m_u + m_d} \varkappa_u. \tag{17}$$

c) $i(\bar{d}\gamma_5 d)(\bar{d} d)$. The factorized contribution to the neutron EDM is calculated as in the case (a):

$$d_n^f = \frac{1}{72} k_d d. \tag{18}$$

Unlike the previous cases, in this interaction two valence d-quarks can take part. Corresponding contribution to the neutron EDM we call the «four-quark» one. It can be estimated by means of QCD sum rules (SR) [13]. Omitting here the details of calculation (its crucial points are outlined in the Appendix) we present the final result for the EDM:

$$d_n = \frac{1}{72} k_d \left(1 + 2.4 \frac{a^2}{\beta^2}\right) d. \tag{19}$$

Here $\beta^2 \approx 1\ \text{GeV}^6$ is the nucleon residue into current [7, 14]. Note that the natural scale of normalization for the SR is about 1 GeV. So we have taken into account strong interaction at small distances leading to the renormalization and mixing of the operators O_d and O_d^c initially chosen at 140 MeV. In the case considered the four-quark contribution accounts for about 40% of the EDM value.

Calculation of the factorized contribution to the constant η parallels the corresponding calculation for the operator O_u. The result is

$$\eta = -\frac{5}{6\sqrt{2}} k_d g_r \frac{f_\pi}{m_u + m_d} \varkappa_d. \tag{20}$$

The estimate by the SR method shows that the four-quark contribution to η is negligible.

d) $i(\bar{d}\gamma_5 t^a d)(\bar{d} t^a d)$. Calculations similar to the previous case give

$$d_n = \frac{1}{54} k_d^c \left(1 - 0.7 \frac{a^2}{\beta^2}\right) d. \tag{21}$$

(the four-quark contribution being about 30% of the total result),

$$\eta = \frac{\sqrt{2}}{9} k_d^c g_r \frac{f_\pi}{m_u + m_d} \varkappa_d. \tag{22}$$

Turn now to the operators composed of different quarks.

e) $i(\bar{q}_1\gamma_5 q_1)(\bar{q}_2 q_2)$. The neutron EDM is completely determined by the four-quark contribution. The SR estimate implies the calculation of the graphs shown in Fig. 1. A quality estimate (see Appendix) gives:

$$d_n = \pm \frac{1}{96} k_{q_1 q_2} \left(1 - \frac{2a^2}{3\beta^2}\right) \Delta_s d. \tag{23}$$

The upper sign corresponds to the operator O_{ud} , the lower one to the operator O_{du}. The difference of the operators O_{ud} and O_{du} is

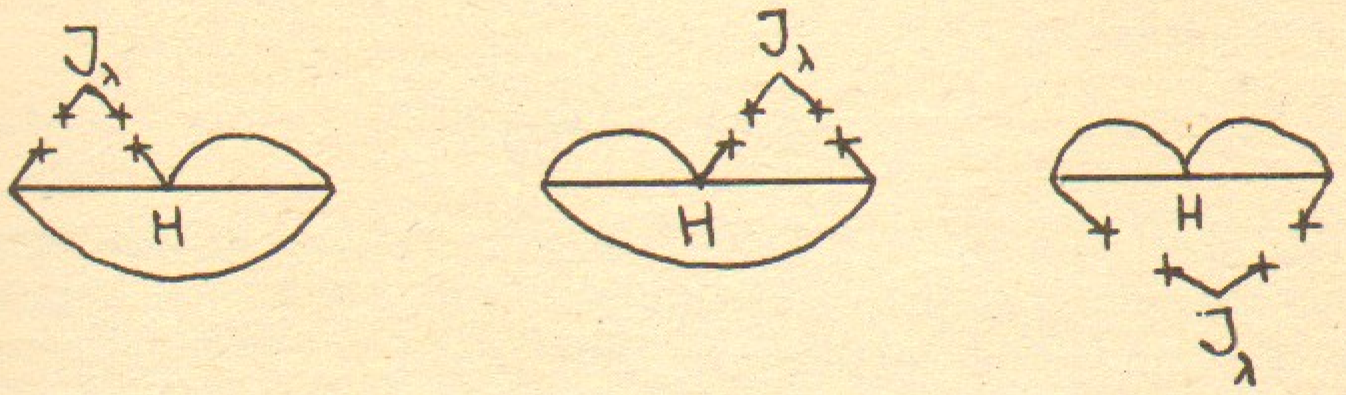

Fig. 1. Leading graphs for d_n if $H=\frac{G}{\sqrt{2}}k_{q_1q_2}O_{q_1q_2}$ and $\frac{G}{\sqrt{2}}k^c_{q_1q_2}O^c_{q_1q_2}$ (contribution of the VEV $\langle q\bar{q}\rangle_F$). Crosses mark vacuum fields. J_λ is the electromagnetic current of quarks.

renormalized multiplicatively. In this way the factor $\Delta_s = (\alpha_s(m_p)/\alpha_s(\mu))^{-8/9} = 3.3$ arises common for both operators. Note that the chiral estimate in the spirit of Ref. [15] leads to somewhat smaller value for d_n.

The constant η is given by the factorized contribution:

$$\eta = \pm \frac{1}{\sqrt{2}} k_{q_1q_2} g_r \frac{f_\pi}{m_u+m_d} \varkappa_{q_2}. \tag{24}$$

f) $i(\bar{q}_1\gamma_5 t^a q_1)(\bar{q}_2 t^a q_2)$. Here also there is no factorized contribution. The four-quark one differs from that in the case (e) by the

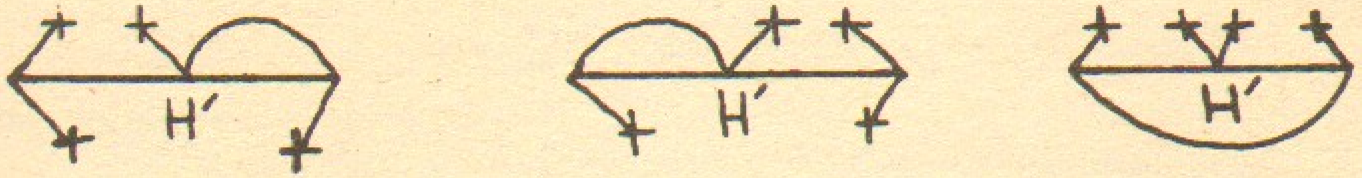

Fig. 2. Leading graphs for $\bar{g}$ in the case of operators (7), (8) (contribution of the VEV $\langle q\bar{q}\,q\bar{q}\rangle$). H' is defined in Appendix.

colour factor $-2/3$ and the renormalization group factor $\Delta'_s = (\alpha_s(m_p)/\alpha_s(\mu))^{1/9} = 0.9$:

$$d_n = \mp \frac{1}{144} k^c_{q_1q_2} \left(1 - \frac{2a^2}{3\beta^2}\right) \Delta'_s d. \tag{25}$$

Unlike the previous case the factorized contribution to the constant η vanishes. Using the diagrams of Fig. 2 we get the value of the four-quark contribution:

$$\eta = \mp \frac{1}{54\sqrt{2}} k^c_{q_1q_2} g_r \frac{f_\pi}{m_u+m_d}. \tag{26}$$

g) $\frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}u)(\bar{d}\sigma_{\alpha\beta}d)$. The calculation of the factorized term is straightforward. The four-quark contribution in the SR method is dominated by the graphs shown in Fig. 3. The final answer reads:

$$d_n = -\frac{1}{6} k_t \left(1 + \frac{2a^2}{3\beta^2}\right) d. \tag{27}$$

When calculating the four-quark contribution we do not take into account the renormalization of operators. The point is that the renormalization group factors are close to unity and an account for them would be beyond the accuracy of our estimates.

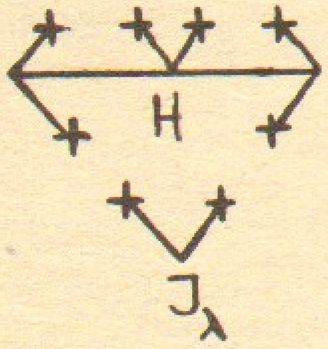

Fig. 3. Leading graph for d_n when $H=\frac{G}{\sqrt{2}}k_t O_t$ or $\frac{G}{\sqrt{2}}k^c_t O^c_t$ (contribution of the VEV $\langle q\bar{q}\,q\bar{q}\,q\bar{q}\rangle_F$).

Unfortunately, our techniques fails to give a reliable limit for the constant k_t from (2). Really, both factorized and four-quark contributions to the CP-odd $\pi^0 NN$ coupling constant vanish. However, we can calculate the factorized contribution to the CP-odd coupling of charged pions to nucleons:

$$\bar{g}' = -\frac{G}{\sqrt{2}} k_t \frac{f_\pi m_\pi^2}{m_u+m_d} \varkappa_{ud}. \tag{28}$$

The constant $\varkappa_{ud} = \langle p|\bar{u}d|n\rangle/2m_p$ is related to the SU(3) symmetry breaking in the baryon octet: $\varkappa_{ud} = (m_\Xi - m_\Sigma)/m_s \approx 1$ (m_Ξ, m_Σ and m_s

are the Ξ-, Σ-hyperon and s-quark masses). Since the CP-violating exchange by a charged meson is suppressed in the shell model of nucleus (3) we assume for a crude estimate that the limit on the corresponding nucleon-nucleon interaction constant

$$\eta' = \frac{2}{G}\,\frac{\tilde{g}' g_r}{m_\pi^2} \qquad (29)$$

is by an order of magnitude weaker than that for the π^0-meson exchange.

h) $\frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}(\bar{u}\,\sigma_{\mu\nu}\,t^a\,u)(\bar{d}\,\sigma_{\alpha\beta}\,t^a\,d)$. The neutron EDM is generated by the four-quark mechanism only and constitutes about

$$d_n = \frac{2}{27}\,k_t^c\,\frac{a^2}{\beta^2}\,d\,. \qquad (30)$$

Both factorized and four-quark contributions to the constant $\tilde{g}$ vanish again. The expression for $\tilde{g}'$ differs from (28) only by the factor 4/3. Thus, we assume the same limit for k_t^c as in the case before.

Fig. 4. Leading graphs for d_n when $H = \frac{G}{\sqrt{2}}\,k_q^g\,m_p\,O_q^g$ (contribution of the VEV $\langle q\bar{q}\,q\bar{q}\,G^a t^a\rangle_F$).

i) $m_p\bar{q}\,g\sigma_{\mu\nu}\,G^a_{\mu\nu}\,t^a\gamma_5 q$. Leading contribution to the neutron EDM is given by the graphs of Fig. 4. The result is

$$d_n = \frac{2\pi^2}{27}\,\frac{a m_p m_0^2}{\beta^2}\begin{pmatrix} k_u^g \\ -2k_d^g \end{pmatrix} d \qquad (31)$$

for $q = \begin{pmatrix} u \\ d \end{pmatrix}$. Here $m_0^2 = \dfrac{\langle i\bar{q}\,g\sigma_{\mu\nu}G^a_{\mu\nu}\,t^a\,q\rangle}{\langle\bar{q}q\rangle} \approx 0.8\,\mathrm{GeV}^2$ [14].

The calculation of the CP-odd nucleon-nucleon constant by means of the standard current algebra gives

$$\eta = \pm\frac{5\sqrt{2}}{3}\,k_q^g\,g_r\,\frac{m_p}{f_\pi}\,\frac{m_0^2}{m_\pi^2}\,\varkappa_q\,, \qquad (32)$$

where the estimate of Ref. [16] is used for the matrix element of the operator $i\bar{q}\,g\sigma_{\mu\nu}G_{\mu\nu}t^a q$

$$\langle p|\,i\bar{q}\,g\,\sigma_{\mu\nu}\,G^a_{\mu\nu}\,t^a\,q\,|p\rangle \approx \frac{5}{3}\,m_0^2\,\langle p|\bar{q}q|p\rangle. \qquad (33)$$

The last relation is obtained by saturation of the matrix elements (33) with the lightest state O^{++}, gluonium. The factor 5/3 is the ratio of canonical dimensions for the operators $\bar{q}\,\sigma_{\mu\nu}\,G^a_{\mu\nu}\,t^a q$ and $\bar{q}q$ entering the low-energy theorems for gluoinum [16].

The obtained limits on the constants k are collected in the Table.

Limits on Phenomenological Constants k

	from (1), d_n	from (2), d (^{129}Xe)
$i(\bar{u}\gamma_5 u)(\bar{u}u)$	$2\cdot10^{-4}$	$1\cdot10^{-3}$
$i(\bar{u}\gamma_5 t^a u)(\bar{u}t^a u)$	$1.5\cdot10^{-4}$	$3.5\cdot10^{-3}$
$i(\bar{d}\gamma_5 d)(\bar{d}d)$	$2.5\cdot10^{-4}$	$1\cdot10^{-3}$
$i(\bar{d}\gamma_5 t^a d)(\bar{d}t^a d)$	$4\cdot10^{-4}$	$4\cdot10^{-3}$
$i(\bar{d}\gamma_5 d)(\bar{u}u)$	$2\cdot10^{-4}$ *)	$8\cdot10^{-4}$
$i(\bar{d}\gamma_5 t^a d)(\bar{u}t^a u)$	$1\cdot10^{-3}$ *)	$3\cdot10^{-1}$ *)
$\frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}u)(\bar{d}\sigma_{\alpha\beta}d)$	$3\cdot10^{-5}$	$4\cdot10^{-2}$ **)
$\frac{1}{2}\varepsilon_{\mu\nu\alpha\beta}(\bar{u}\sigma_{\mu\nu}t^a u)(\bar{d}\sigma_{\alpha\beta}t^a d)$	$2.5\cdot10^{-4}$	$4\cdot10^{-2}$ **)
$m_p\,\bar{u}\,g\,\sigma_{\mu\nu}\,G^a_{\mu\nu}\,t^a\gamma_5 u$	$2\cdot10^{-5}$ *)	$1\cdot10^{-5}$
$m_p\,\bar{d}\,g\,\sigma_{\mu\nu}\,G^a_{\mu\nu}\,t^a\gamma_5 d$	$1\cdot10^{-5}$ *)	$1\cdot10^{-5}$

*) The results obtained by the SR method. They are less accurate than the results, obtained by factorization.

**) Order-of-magnitude estimate, obtained in the approximation of charged pion exchange.

4. SOME MODELS

First consider the model with broken left-right symmetry [17]. One of the possible mechanisms of CP-violation in this model is the mixing of left- and right-handed W-bosons with the complex amplitude $M_L^2 \xi \exp(i\varphi)$ (M_L is the mass of standard, left-handed W-boson). The effective Hamiltonian describing the mixed W-boson exchange takes the form

$$H=\frac{4G}{\sqrt{2}} i\,\delta(\bar{u}_L \gamma_\mu d_L \bar{d}_R \gamma_\mu u_R - \bar{u}_R \gamma_\mu d_R \bar{d}_L \gamma_\mu u_L), \qquad (34)$$

where $\delta=(M_L^2/M_R^2)\xi \sin\varphi$ is the parameter limits on which we are searching for. By the Fierz transformation (34) is reduced to

$$H=\frac{4G}{\sqrt{2}}\delta\left(\frac{1}{3}(\tilde{O}_{ud}-\tilde{O}_{du})+2(\tilde{O}^c_{ud}-\tilde{O}^c_{du})\right). \qquad (35)$$

Here $\tilde{O}$, $\tilde{O}^c$ are the operators (7), (8) normalized at the momenta about M_L.

Using (23) and (25) we find the expression for the EDM:

$$d_n=\delta\left(\frac{\Delta_s}{36}-\frac{\Delta'_s}{9}\right)\left(1-\frac{2a^2}{\tilde{\beta}^2}\right) d, \qquad (36)$$

where $\Delta_s=(\alpha_s(m_p)/\alpha_s(m_b))^{-24/25}(\alpha_s(m_b)/\alpha_s(M_L))^{-24/23}=0.4$ and $\Delta'_s=(\alpha_s(m_p)/\alpha_s(m_b))^{3/25}(\alpha_s(m_b)/\alpha_s(M_L))^{3/23}\approx 1.1$ are the renormalization factors accounting for the effect of hard gluons (remind that the SR are treated at the scale about 1 GeV). From (1) a limit on the parameter δ follows:

$$|\delta|<3\cdot 10^{-5}. \qquad (37)$$

Similarly, (24) and (26) lead to the following expression for η:

$$\eta=\frac{2\sqrt{2}}{3}\delta g_r \frac{f_\pi}{m_u+m_d}\left[(\varkappa_u+\varkappa_d)\Delta''_s-\frac{2}{9}\Delta'_s\right], \qquad (38)$$

where $\Delta''_s=(\alpha_s(\mu)/\alpha_s(m_p))^{-8/9}\Delta_s\simeq 0.13$. The limit from (2) is

$$|\delta|<2\cdot 10^{-3}. \qquad (39)$$

Note that the limit (37) excludes the model where the considered mechanism of CP-violation is the only one. In this case the parameter δ should exceed 10^{-3} to account for K^0-meson decays.

Dwell now on the predictions of the Kobayashi—Maskawa (KM) model for the quantities considered. The neutron EDM in this model is found in Ref. [18] to be

$$d_n \sim (2\div 4)\cdot 10^{-32} e\cdot\text{cm}. \qquad (40)$$

As for the T-odd nuclear forces the prediction of Ref. [3] for them was shown by I.B. Khriplovich and A.I. Vainshtein to be overestimated: the contribution of the K^0-meson exchange considered in Ref. [3] is cancelled by other diagrams.

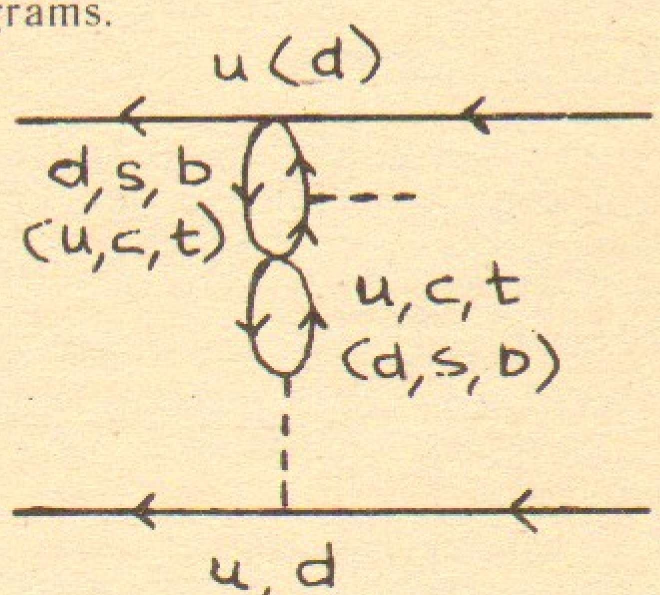

Fig. 5. The diagram leading to the effective operator (41).

The most effective mechanism generating T-odd nuclear forces in the KM model is perhaps the following one. Consider the graph of Fig. 5. The weak interaction of quarks is treated as a contact four-fermion one. The dashed lines denote gluons, the external gluon being connected to both sides of the upper loop. Similar graphs were considered in Ref. [19], where it was shown why they are singled out. Following the method of calculation of Ref. [19] one can easily obtain the expression for the effective operator thus arising:

$$\frac{G^2\alpha_s\tilde{\delta}}{24\pi^3} g G^a_{\mu\nu}\left\{\ln\frac{m_t^2}{m_c^2}\left[\frac{1}{3}\delta^{ab}\,\bar{u}\gamma_\mu(1+\gamma_5)u+d^{abc}\,\bar{u}\gamma_\mu(1+\gamma_5)t^c u\right]-\right.$$
$$\left.-\ln\frac{m_b^2}{m_s^2}\left[\frac{1}{3}\delta^{ab}\,\bar{d}\gamma_\mu(1+\gamma_5)d+d^{abc}\,\bar{d}\gamma_\mu(1+\gamma_5)t^c d\right]\right\}(\bar{u}\gamma_\nu t^a u+\bar{d}\gamma_\nu t^a d). \qquad (41)$$

Here $\tilde{\delta}=\sin\delta\, c_1c_2c_3s_1^2s_2s_3$, $c_i=\cos\theta_i$, $s_i=\sin\theta_i$, $\theta_{1,2,3}$ and δ are the angles of the standard KM matrix parametrization (see, e.g., [20]); m_t, m_c, m_b, m_s are the masses of t-, c-, b- and s-quarks; d^{abc} are the symmetric constants of SU(3) group. We shall use the fact that $\ln(m_t^2/m_c^2)$ and $\ln(m_b^2/m_s^2)$ are very close numerically.

Factorizing the quark vacuum expectation value we reduce the πNN vertex discussed to the form

$$-\frac{7G^2\alpha_s\tilde{\delta}}{2^5 3^3 \pi^3} \ln\frac{m_t^2}{m_c^2} \langle \bar{q} q \rangle \langle \pi^0 N | g G^a_{\mu\nu} (\bar{u} \sigma_{\mu\nu} \gamma_5 t^a u - \bar{d} \sigma_{\mu\nu} \gamma_5 t^a d) | N \rangle. \tag{42}$$

Using the PCAC hypothesis and the relation (33) we find

$$\tilde{g} = -\frac{35\, G^2\alpha_s\tilde{\delta}}{2^{11/2} 3^4 \pi^2} \ln\frac{m_t^2}{m_c^2} m_0^2 m_\pi^2 \frac{f_\pi}{m_u + m_d} (\varkappa_u + \varkappa_d). \tag{43}$$

Correspondingly,

$$\eta = -\frac{35\, G\, \alpha_s\tilde{\delta}}{2^5 3^4 \pi^3} g_r \ln\frac{m_t^2}{m_c^2} m_0^2 \frac{f_\pi}{m_u + m_d} (\varkappa_u + \varkappa_d) \approx -5\cdot 10^{-10}. \tag{44}$$

Here we assume $\alpha_s \approx 0.2$, $\tilde{\delta} \approx 5\cdot 10^{-5}$. Similarly the contribution of interaction (41) to the neutron EDM can be found:

$$\Delta d_n = \frac{7\, G\, \alpha_s\tilde{\delta}}{2^{7/2} 3^6 \pi^3} \ln\frac{m_t^2}{m_c^2} m_0^2 \frac{a^2}{\bar{\beta}^2} d \approx 2\cdot 10^{-34}\, e\cdot\text{cm}. \tag{45}$$

It is considerably smaller than (40). Thus, prediction of the KM model for both the neutron EDM and T-odd nuclear forces are far away from the experimental results (1) and (2).

5. CONCLUSION

Returning to the effective operators (3) — (10) we would like to emphasize once more that in a number of cases the limits following from the measurement of the EDM of ^{129}Xe atom are comparable to the neutron experiment limits. The gain is due not only to the specific nuclear enhancement factor pointed out in Ref. [3] that allowed to extract quite meaningful limit (2) from the atomic experiment. The present consideration shows the important role of the factors arising at elementary particles level, such as the strong πNN constant $g_r = 13.5$; chiral enhancement factor $\sim m_q^{-1}$; numerically large scalar nucleon expectation values $\varkappa_q \approx 5$; the factor m_p/f_π.

In this connection we wish to draw attention to the fact that the searches for T-invariance violation in the nuclear transitions and in the neutron reactions even at the level of accuracy of P-violation experiments would be as informative as the neutron EDM searches

are. Remind that the limit (2) for the effective T-odd nucleon-nucleon interaction, actively used by us, is just at the level of the Fermi constant.

As far as atomic experiments are concerned it should be said that a considerable progress is expected in the near future in this field [5]. For example, the measurement of the ^{199}Hg atom EDM at the same level of accuracy as that attained for ^{129}Xe, due to larger charge of Hg nucleus would allow one to advance by an order of magnitude in the value of η and, therefore, of the constants k considered. In this case the atomic limits would get ahead for a lot of operators.

We wish, however, to point out the evident complementarity of atomic and neutron experiments: it can be seen from the Table that there are operators for which the neutron limits will remain leading ones for a long time.

Thus, the study of T-violation in atoms and molecules is by no means a mere exercise in atomic spectroscopy. It is an extremely important tool for the investigation of the fundamental properties of elementary particles.

The authors are grateful to V.V. Flambaum, O.P. Sushkov and A.R. Zhitnitsky for valuable discussions.

APPENDIX

In this Appendix of technical nature we discuss briefly the SR method used to evaluate the four-quark contribution to the neutron EDM and CP-odd πNN constant.

For this purpose we consider the correlators

$$T_\lambda = \int dx\, dy\, dz\, e^{iqx+iky} \langle 0 | T\{\eta(x) J_\lambda(y) H(z) \bar{\eta}(0)\} | 0 \rangle \tag{A1}$$

and

$$T = \int dx\, dy\, e^{iqx} \langle 0 | T\{\eta(x) H'(y) \bar{\eta}(0)\} | 0 \rangle \tag{A2}$$

for calculation of d_n and $\tilde{g}$ respectively. Here

$$J_\lambda = \frac{2}{3} \bar{u} \gamma_\lambda u - \frac{1}{3} \bar{d} \gamma_\lambda d$$

is the electromagnetic current, η is the nucleon current; we put

$\eta_p = \varepsilon^{abc}\gamma_\mu d^a (u^b C\gamma_\mu u^c)$ for a proton and $\eta_n = -\varepsilon^{abc}\gamma_\mu u^a (d^b C\gamma_\mu d^c)$ for a neutron [7], $H' = [A_0, H]$, $A_0 = u^+\gamma_5 u - d^+\gamma_5 d$. Phenomenologically T_λ and T are saturated by the transitions of interest, $n \to n\gamma$ and $n \xrightarrow{H'} n$:

$$T_\lambda = -\beta^2 \gamma_5 \frac{i}{\hat{q} - m_p} (-d_n) \sigma_{\lambda\rho} \gamma_5 k_\rho \frac{i}{\hat{q} - m_p} \gamma_5 + \begin{matrix}\text{higher states}\\ \text{contribution}\end{matrix} \tag{A3}$$

and

$$T = -\beta^2 \gamma_5 \frac{i}{\hat{q} - m_p} \tilde{g} \frac{i}{\hat{q} - m_p} \gamma_5 + \begin{matrix}\text{higher states}\\ \text{contribution}\end{matrix} . \tag{A4}$$

Here $\beta\gamma_5 n = \langle 0 | \eta_n | n \rangle$, $\tilde{g} = \langle n | H' | n \rangle / 2m_p$. On the other hand, T_λ and T can be found by means of operator expansion (in powers of q^{-2}) including the nonlocal VEVs [7, 21, 22]. Some diagrams for T_λ are presented in Figs 1, 3, 4, for T in Fig. 2. We pick out the γ-matrix structures $\hat{q}$ in T and $(q_\lambda \sigma_{\rho\nu} - q_\rho \sigma_{\lambda\nu})\gamma_5 q_\nu k_\rho$ in T_λ with the maximal power of momenta. Comparing phenomenological and theoretical expressions for a correlator we arrive at the SR of interest. Being Borel-transformed [7, 13] SR, e. g., for the neutron EDM, read

$$\tilde{\beta}^2 d_n e^{-m_p^2/M^2} + \begin{matrix}\text{higher states}\\ \text{contribution}\end{matrix} = \sum_n C_n M^{-2n} . \tag{A5}$$

Here M is the Borel parameter, C_n are the operator expansion coefficients, $\tilde{\beta} = (2\pi)^2 \beta$. Higher states contribution to (A5) can be transferred to the right-hand side and taken into account in a model-dependent way as a continuum [7, 13, 14, 21]. To this end we represent the RHS of (A5) in the form

$$\int_0^\infty \rho(s) e^{-s/M^2} ds \tag{A6}$$

and substitute $\rho(s)\theta(s_0 - s)$ for $\rho(s)$ in (A6), s_0 being a continuum threshold.

Throughout the paper the quality estimate is used. It is performed by putting $M \to \infty$ in the SR:

$$\tilde{\beta}^2 d_n = \int_0^{s_0} \rho(s) ds . \tag{A7}$$

For $\tilde{\beta}^2$ we have two expressions in terms of s_0 following from the nucleon mass SR [14]:

$$\tilde{\beta}^2 = \frac{s_0^3}{12} + \frac{2a^2}{3}, \tag{A8}$$

$$m\tilde{\beta}^2 = \frac{as_0^2}{2}. \tag{A9}$$

Using these expressions or putting $\tilde{\beta}^2$ equal to the definite numerical value we manage to cancel the s_0-dependence of d_n and $\tilde{g}$ and to express the answer in terms of known constants: VEVs, nucleon mass m_p and residue $\tilde{\beta}^2$.

To evaluate the neutron EDM we can restrict to the contribution of J_λ by means of the nonlocal VEVs of the type (12) (i. e. at large distances) since the constant χ describing this contribution is large numerically. As a result, the leading contribution to the SR for d_n comes from the VEVs $\langle q\bar{q} \rangle_F$ and $\langle q\bar{q} q\bar{q} q\bar{q} \rangle_F$, resulting from the breaking of quark lines. Multiquark VEVs are calculated by means of factorization, e. g.

$$\langle q\bar{q} q\bar{q} q\bar{q} \rangle_F \to \langle q\bar{q} q\bar{q} \rangle \langle q\bar{q} \rangle_F . \tag{A10}$$

Consider also the weak interaction at large distances parametrized by the VEVs of the type

$$\langle \dots \rangle_H = \int dx \langle 0 | T\{H(x) \dots\} | 0 \rangle . \tag{A11}$$

There is the pion pole term in (A11) since, generally speaking, $\langle \pi^0 | H | 0 \rangle \neq 0$. However, existence of the pion-to-vacuum transition would require a shift of the pion field in the effective chiral Lagrangian by a constant. This redefinition results in an additional term in H proportional to the interpolating pion field and chosen in such a way that the modified Hamiltonian no longer induces the transition $|\pi^0\rangle \to |0\rangle$. Thus, the effect of the VEVs like (A11) does not contain chiral enhancement factor. The terms in (A11) finite in the limit $m_\pi \to 0$ are unknown. Therefore, the account for VEVs $\langle \dots \rangle_H$ cannot be consistently performed. Estimates show, however, that the VEVs finite in the chiral limit and calculable (e. g. by means of the equations of motion) do not dominate and cannot substantially change our estimates.

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Neutron Electric Dipole Moment, T-Odd Nuclear Forces and Nature of CP-Violation

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Работа поступила 10 февраля 1987 г.
Подписано в печать 25.03 1987 г. МН 08662
Формат бумаги 60×90 1/16 Объем 1,5 печ.л., 1.2 уч.-изд.л.
Тираж 200 экз. Бесплатно. Заказ № 28

Набрано в автоматизированной системе на базе фотонаборного автомата ФА1000 и ЭВМ «Электроника» и отпечатано на ротапринте Института ядерной физики СО АН СССР,
Новосибирск, 630090, пр. академика Лаврентьева, 11.