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ON THE EXPERIMENTAL LIMITS ON THE CP-ODD THREE-GLUON INTERACTION

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On the Experimental Limits on the CP-Odd Three-Gluon Interaction

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ABSTRACT

The limits on the coefficient at three-gluon operator in the CP-odd effective Lagrangian are found. They follow from the results of the search of the neutron electric dipole moment. The limits following from the experimental results on the *T*-odd effects in atoms prove to be considerably much weaker ones.

Recently Weinberg [1] has argued that the dominant contribution to the neutron electric dipole moment (EDM) d_n is due to the CP-odd three-gluon operator

$$O=\frac{-1}{6}f^{ikl}\,G^i_{\mu\nu}\,G^k_{\lambda\rho}\,G^l_{\rho\sigma}\,\varepsilon^{\mu\nu\lambda\sigma}, \qquad (1)$$

where $G^i_{\mu\nu}$ is the gluon field strength tensor, $\varepsilon^{0123}=+1$. This operator arises in the effective Lagrangian with some coefficient C hereafter written as $G_F k_g/\sqrt{2}$, k_g being dimensionless quantity. Let us extract the limits on k_g from the results of the experiments on d_n. The contribution of O to d_n should be found for that. The contributions of CP-odd quark and quark-gluon operators of dimensions 5, 6 to d_n were estimated in [2]. The estimate for O has been made by Weinberg [1] in the framework of dimensional analysis and chiral Lagrangian [3]. Now we reconsider this estimate using the method of [2] using the principle of quark-hadron duality and introducing the nonzero vacuum expectation values (VEV's) of the field products [4]. Our result is in agreement with that of Weinberg. We also estimate the effect of three-gluon operator on the CP-violating nuclear interaction. Corresponding restriction on k_g from the atomic experiments turns out to be a three orders weaker than that following from the experiments on the neutron EDM.

The quark-hadron duality reduces calculation of the hadronic matrix elements of different operators to calculation of the correlator of these operators and of hadronic currents in the deep Euclidean region. Now the following correlator is of interest:

$$T(p^2)=\int \exp(ipx)\, iky\, d^4x\, d^4y\, d^4z\,,$$
$$\langle 0|\, T\{\eta(x)\, J_\mu(y)\, iCO(z)\, \bar\eta(0)\}\, |0\rangle A^\mu\,. \qquad (2)$$

Here $\eta=(d^a C\gamma_\mu d^b)\gamma^\mu u^c \varepsilon^{abc}$ is the neutron current ($C=\gamma_0\gamma_2$ is the charge conjugation matrix), A_μ is the amplitude of the electromagnetic potential, J_μ is the electromagnetic quark current (the linear part of the exponent *iky* is left in (2) which is needed to form the electromagnetic field strength tensor $F_{\mu\nu}$). The correlator (2) is examined at $-p^2=Q^2\gg\mu^2$, $\mu\simeq 1$ GeV is a typical hadron scale. In this region the correlator is given by the sum of the perturbative loop of Fig. 1 and the nonperturbative contribution of VEV's (see, e. g.,

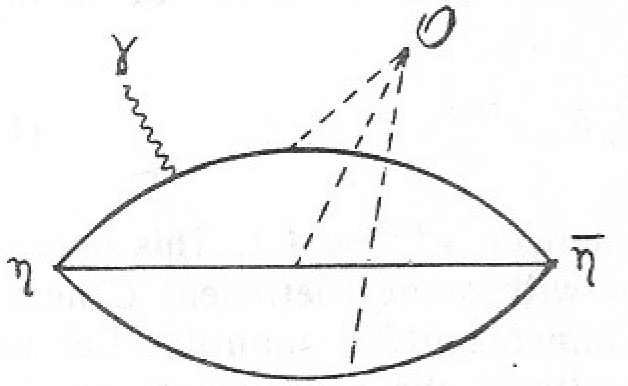

Fig. 1. Perturbative loop for the correlator (2). The solid line denotes quark, the dotted line denotes gluon and the wavy one—photon γ.

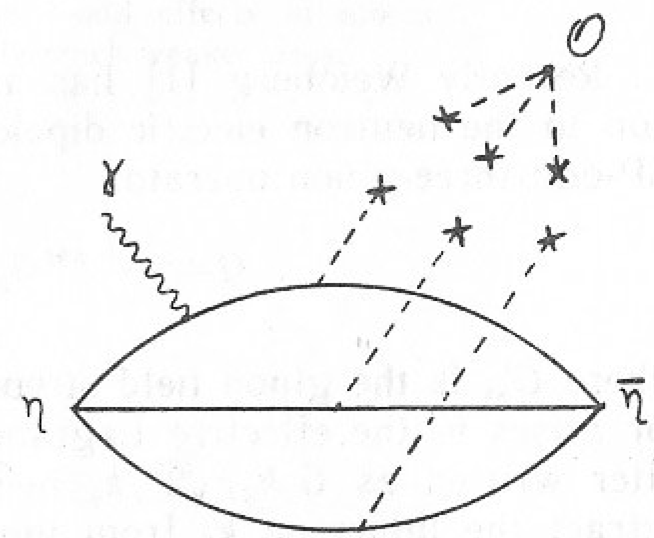

Fig. 2. Nonperturbative diagram for the correlator (2) relevant to the vertex *CO* at large distance. Crosses denote the nonperturbative fields (the gluon fields in the given case).

Fig 2). The diagram of Fig. 2 corresponds to the contribution of $O(z)$ at large distance z so that the effect of operator O is included in the definition of VEV's. Calculation of this diagram proceeds as if it were the diagram for the three-point correlator $\langle 0|T\{\eta J_\mu \bar\eta\}|0\rangle$ where the quark propagator should be considered in the external gluon field $G^i_{\mu\nu}$ [5]. In the Schwinger (fix-point) gauge $x^\mu A^i_\mu(x)=0$ [6], this propagator reads

$$-i\int \exp(ipx)\, d^4x \langle 0|\, T\{\psi(x)\, \bar\psi(0)\}\, |0\rangle = \frac{1}{\hat p} -$$

$$-\frac{p_\alpha}{p^4}\, g\tilde G_{\alpha\beta}\gamma_\beta\gamma_5 + \frac{2}{3}\, g\, \frac{1}{p^6}\,(p^2 D_\alpha G_{\alpha\beta}\gamma_\beta - \hat p D_\alpha G_{\alpha\beta} p_\beta -$$
$$- p_\gamma D_\gamma p_\alpha G_{\alpha\beta}\gamma_\beta - 3ip_\gamma D_\gamma p_\alpha \tilde G_{\alpha\beta}\gamma_\beta\gamma_5) + O(DDG) + O(G^2) + \dots\,, \qquad (3)$$
$$\tilde G^i_{\alpha\beta} = \frac{1}{2}\,\varepsilon_{\alpha\beta\gamma\delta}\, G^i_{\gamma\delta}\,.$$

The gluon field products of given dimension (*GDDG* and *GGG* in the case of Fig. 2) should be then averaged over vacuum, the interaction *CO* being taken into account in the first order in *C*. Thus we get the so-called «VEV's in the external field» or «induced VEV's» [7].

In the given case the considered VEV's are reduced by means of the equations of motion and of symmetry considerations to the induced VEV of the operator *O* itself i.e. to (the nonperturbative part of) the correlator

$$\langle O\rangle_{CO}=\int d^4z \langle 0|\, T\{\, iCO(z)\, O(0)\}\, |0\rangle \equiv K(0)\,,$$
$$K(q^2)=\int \exp(iqz)\, d^4z \langle 0|\, T\{\, iCO(z)\, O(0)\}\, |0\rangle\,. \qquad (4)$$

We adopt the order-in-magnitude estimate $K(0)\simeq K(-\mu^2)$ where $K(-\mu^2)$ can be found by the extrapolation of $K(-s)$ from the deep Euclidean region $s\gg\mu^2$ where this correlator is known. One of the diagrams for $K(-s)$ is shown in Fig. 3. It represents contribution of the four-gluon VEV $\langle GGGG\rangle$. Due to the factorization hypothesis [4] this VEV can be estimated as $\langle G^2\rangle^2$. Also let us associate the factor $(2\pi)^{-2}$ to each loop. The dimensional estimate of the diagram of Fig. 3 gives

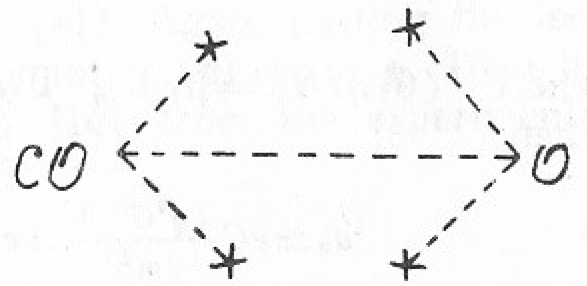

Fig. 3. The diagram for the correlator (4) relevant to the contribution of the VEV $\langle GGGG\rangle$.

$$\langle O\rangle_{CO} \simeq C\langle G^2\rangle^2 \qquad (5)$$

(another graphs for this correlator turn out to be smaller). This gives for the diagram of Fig. 2

$$T(-Q^2)^{\text{Fig. 2}} \simeq iC\frac{g^3 e}{(2\pi)^4}\langle G^2\rangle^2 \frac{1}{Q^4}\, q_\mu\gamma_\nu\gamma_5 F^{\mu\nu} + \dots\,, \qquad (6)$$

where the γ — matrix structure of interest $q_\mu\gamma_\nu\gamma_5F^{\mu\nu}$ is only retained; g is the QCD coupling constant, e is the positron charge. The contribution of Fig. 1 diagram

$$T(-Q^2)^{\text{Fig. 1}} \simeq iC\frac{g^3e}{(2\pi)^8}Q^4q_\mu\gamma_\nu\gamma_5F^{\mu\nu}+\dots, \tag{7}$$

The gluon condensate $\langle g^2G^2\rangle \approx 0.5\ \text{GeV}^4$ [4]. Let us choose $\Lambda = 150$ MeV. Then $\alpha_s(1\ \text{GeV}) \approx 0.3$, $g(1\ \text{GeV}) \approx 2$, so that

$$\frac{T(-\mu^2)^{\text{Fig. 1}}}{T(-\mu^2)^{\text{Fig. 2}}} \simeq (2\pi)^{-4}\langle g^2G^2\rangle^{-2}\mu^8g^4 \simeq 0.1\,. \tag{8}$$

Thus the nonperturbative diagram of Fig. 2 dominates.

On the other hand let us consider the phenomenological expression for T taking into account only the lowest hadron states in the corresponding channels:

$$T(-Q^2)^{phen} \simeq \beta_n^2\gamma_5\frac{i}{\hat{q}-m}\times d_nF^{\mu\nu}\sigma_{\mu\nu}\gamma_5\frac{i}{\hat{q}-m}\times$$

$$\times(-\gamma_5) \overset{Q^2\to\infty}{\simeq} -4\beta_n^2d_n\frac{1}{Q^4}q_\mu\gamma_\nu\gamma_5F^{\mu\nu}+\dots, \tag{9}$$

where $\langle 0|\eta/N\rangle = \beta\gamma_5u_N$, $\bar{u}_Nu_N = 2m$, $\tilde{\beta}^2 = (2\pi)^4\beta^2 = 1.1\ \text{GeV}^6$ [8]. Then

$$d_n \simeq eC\frac{\langle g^2G^2\rangle^2}{gm\tilde{\beta}^2} \simeq eC\cdot 0.1\ \text{GeV} \simeq k_g\cdot 5\cdot 10^{-20}\,e\cdot\text{cm} \tag{10}$$

It agrees with the estimate of [1]: $d_n \simeq eCF_\pi/2 \approx eC\cdot 0.1$ GeV. The more conservative estimate follows if one adopts the loop factor being $(4\pi)^{-2}$ instead of $(2\pi)^{-2}$ (which often turns out to be more justified in practice). This gives a 16 times smaller d_n for given C. Using the experimental bound $|d_n| < 1.2\cdot 10^{-25}e\cdot\text{cm}$ [9] we get

$$|k_g| < 5\cdot 10^{-5}\,. \tag{11}$$

Now consider the limits on k_g following from the atomic experiments on the CP-odd nuclear forces. The usually dominating simplest mechanism for arising the latter is the pion exchange. But now the matrix element $\langle N\pi|O|N\rangle$ vanishes in the PCAC limit. Therefore another mechanisms are essential, say, the vector meson V

exchange. The CP-odd VNN coupling can be derived from the correlator

$$\int \exp(iqx)\,d^4xd^4yd^4z\langle 0|T\{\eta(x)\,V_\mu(y)\,iCO(z)\bar{\eta}(0)\}\,|0\rangle\,, \tag{12}$$

where V_μ is the vector current. This correlator can be calculated either from quark-gluon diagrams or saturating it by V-meson and nucleons in the corresponding channels. Analogously to (10) we find

$$g_{VNN} \simeq g_VC\frac{\langle g^2G^2\rangle^2}{g\tilde{\beta}^2}, \tag{13}$$

where $m_V^2g_V^{-1}$ is the V-meson residue into the vector current, $\langle 0|V_\mu|V\rangle = (m_V^2/g_V)\varepsilon_\mu$, ε_μ is the meson polarization. Presenting the effective CP-odd NN-interaction in the form

$$(\eta G_F/\sqrt{2})(\bar{N}i\gamma_5N)(\bar{N}'N') \tag{14}$$

we get the following estimate

$$\eta \simeq \frac{g_V^2\langle g^2G^2\rangle^2}{gm_V^2\tilde{\beta}^2}k_g \simeq 20k_g \tag{15}$$

(here we put $V=\rho$ and $4\pi^2/g_\rho^2 = 0.41$ [4]). Again putting the loop factor to be $(4\pi)^{-2}$ we get 16 times smaller value for η. Then the experimental limit $|\eta| < 0.5$ found in [10] from the experimental results on EDM of ^{199}Hg [11] gives

$$|k_g| < 5\cdot 10^{-2}\,. \tag{16}$$

The weakness of this restriction as compared to (11) is due to the absence of the pion pole in the NN-interaction caused by O.

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