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IS THE MODEL OF SPONTANEOUS CP-VIOLATION IN THE HIGGS SECTOR CONSISTENT WITH EXPERIMENT?

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НОВОСИБИРСК

Is the Model of Spontaneous CP-violation in the Higgs Sector Consistent With Experiment

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Abstract

At natural values of parameters of the model dicussed, the contribution of the chromoelectric dipole moment of the s-quark to the neutron electric dipole moment (EDM) exceeds considerably the experimental upper limit for the neutron EDM. As strict bounds on the parameters of the model are derived from the atomic experiment with ^{199}Hg.

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1. The possibility of CP-violation being generated by the spontaneous symmetry breaking in the Higgs fields interaction was pointed out in [1]. A more realistic model based on this idea was suggested later [2] and contains at least three doublets of complex Higgs fields.

In the most ambitious approach one may try to ascribe to this mechanism the CP-odd effects observed in K-meson decays. In this case, however, not only the masses of charged Higgs bosons would be rather low [3, 4]. Various estimates for the neutron EDM in this version [5, 6, 7, 8] lead to the predictions:

$$d(n)/e \sim 10^{-24} - 10^{-23}\,\text{cm}, \tag{1}$$

well above the experimental upper limit [9, 10]:

$$d(n)/e \, < \, 7 \cdot 10^{-26}\,\text{cm}, \tag{2}$$

But then one can pass over to a more "natural" version of this model, with heavy Higgs bosons. Of course, in this case the model is responsible for only a small portion of CP-violation in kaon decays. It would be new physics, a new source of CP-violation, supplemental to that generating the effects already observed.

The dominant contribution to the dipole moments in this model is given by diagrams of the type 1 with a heavy particle (t-quark, W-boson or Higgs) propagating in the upper loop [11]. For the neutron dipole moment this approach is further elaborated upon in [12, 13, 14]. In particular, it is pointed out there that, in the model discussed, the neutron EDM is controlled by diagram 2 with the t-quark propagating in the upper loop, but both wavy lines corresponding to gluons. The effective operator generated by this diagram is

$$H_c = \frac{1}{2} d^c \, \bar{q} \gamma_5 \sigma_{\mu\nu} t^a q \, G^a_{\mu\nu} \tag{3}$$

where $t^a = \lambda^a/2$ are the generators of the colour $SU(3)$ group. The constant d^c in expression (3) is called the quark chromoelectric dipole moment (CEDM).

The value of the d-quark CEDM, as obtained directly from diagram 1, is [12, 13]

$$d^c = g_s \frac{G}{\sqrt{2}} m_d \frac{\alpha_s}{16\pi^3} \{ \mathrm{Im} Z_0 [f(z) + g(z)] - \mathrm{Im} \tilde{Z}_0 [f(z) - g(z)] \}. \tag{4}$$

In this expression g_s is the quark-gluon coupling constant, $\alpha_s = g_s^2/4\pi$, G is the Fermi weak interaction constant, m_d is the quark mass, $\mathrm{Im} Z_0$ and $\mathrm{Im} \tilde{Z}_0$ are CP-violating parameters of the model. Functions f and g describe the CEDM dependence on the ratio of the t-quark mass to the mass of the lightest neutral Higgs boson, $z = m_t^2/M^2_{H^0}$. At $z \sim 1$ both functions are close to unity. Their general z dependence is given in Refs. [11, 13]. An analogous expression was derived in Refs. [12, 13] for the u-quark CEDM.

To investigate the CEDM contribution to the observable effects, we have to bring the expressions (3), (4) down from the scale of $M \sim 200$ GeV to the usual hadronic scale $m \sim 1$ GeV. In particular, to substitute for m_d the usual current mass value 7 MeV, we have to introduce the renormalization group (RG) factor

$$\left[\frac{\alpha_s(M)}{\alpha_s(m)} \right]^{12/23}.$$

Now, the QCD sum rule technique, used below to estimate the CEDM contribution to observable effects, is applied directly to the operators of the type

$$g_s \bar{q} \gamma_5 \sigma_{\mu\nu} t^a q \, G^a_{\mu\nu},$$

which include g_s explicitly. This brings one more RG factor [15]

$$\left[\frac{\alpha_s(M)}{\alpha_s(m)} \right]^{2/23}.$$

On the other hand, as distinct from Refs. [12, 13], we see no special reasons to bring the explicit α_s factor, entering the expression (4), down from the high-momenta scale M, where it is defined at least as well as at $m \sim 1$ GeV. The overall RG factor, introduced in this way into formula (4), is

$$\left[\frac{\alpha_s(M)}{\alpha_s(m)} \right]^{14/23}. \tag{5}$$

Now, assuming

$$\mathrm{Im} Z_0 [f(z) + g(z)] - \mathrm{Im} \tilde{Z}_0 [f(z) - g(z)] \sim 1,$$

we arrive at the following numerical estimate for the quark CEDM:

$$d^c \sim 3 \cdot 10^{-25} \text{ cm}. \tag{6}$$

2. However, the most serious problem is to find the CEDM contribution to the neutron dipole moment. Here our conclusions differ from those of Refs. [12, 13]. The simplest way [16] to estimate this contribution is to assume, just by dimensional reasons, that $d(n)/e$ is roughly equal to d^c (obviously, the electric charge e should be singled out of $d(n)$, being a parameter unrelated to the nucleon structure).

In a more elaborate approach [16], the neutron EDM is estimated in the chiral limit via diagram 3, according to Ref. [17]. For both u- and d-quarks, the contribution of operator (3) to the CP-odd $\pi N N$ constant $\bar{g}_{\pi NN}$ is transformed by the PCAC technique to the same expression:

$$< \pi^- p \,|\, g_s \bar{q} \gamma_5 \sigma_{\mu\nu} t^a q \, G^a_{\mu\nu} \,|\, n > = \frac{i}{f_\pi} < p \,|\, g_s \bar{u} \sigma_{\mu\nu} t^a d \, G^a_{\mu\nu} \,|\, n > . \tag{7}$$

We include the quark-gluon coupling constant g_s explicitly into the above relation since the corresponding estimate based on the QCD sum rules refers directly to the last matrix element. This estimate gives a value close to -1.5 GeV^2. For momenta ~ 1 GeV in this estimate, we take $g \approx 2$. Then the result for the neutron EDM is:

$$d(n)/e \sim 2 \cdot 10^{-25} \text{ cm}, \tag{8}$$

which exceeds the experimental upper limit (2).

Let us introduce the ratio of the neutron dipole moment, as induced by a CEDM, to d^c itself:

$$\rho = \frac{d(n)/e}{d^c(q)}. \tag{9}$$

Its value obtained in this approach, $\rho = 0.7$, is quite close indeed to unity. In our opinion, this good agreement with the above simple-minded result enhances the reliability of both estimates.

A quite essential contribution to the neutron EDM can be induced by the chromoelectric dipole moment $d^c(s)$ of the s-quark [14]. The gain in the magnitude of $d^c(s)$, as compared to the d-quark CEDM, is the large ratio of the quark masses, $m_s/m_d \approx 20$.

On the other hand, for the s-quark, the ratio

$$\rho_s = \frac{d(n)/e}{d^c(s)}. \tag{10}$$

should be much smaller than unity. Indeed, according to the QCD sum rule calculations of Ref. [8], it is about 0.1. One should mention that other estimates [5, 18] predict for the ratio (10) a value an order of magnitude smaller, and this smaller prediction was used in Ref. [14].

Then, how reliable is the estimate $\rho_s = 0.1$? There are strong indications now that the admixture of the $\bar{s}s$ pairs in nucleons is quite considerable. In particular, it refers to the spin content of a nucleon. And though these indications refer to operators different from $\bar{s}\gamma_5\sigma_{\mu\nu}\, t^a s\, G^a_{\mu\nu}$, they give serious reasons to believe that the estimate

$$\rho_s = 0.1 \tag{11}$$

is just a conservative one.

At this value of ρ_s the resulting contribution of the s-quark CEDM to the neutron dipole moment

$$d(n)/e = 6 \cdot 10^{-25}\,\text{cm} \tag{12}$$

is larger than the experimental upper limit (2) almost by an order of magnitude.

3. At last, let us compare the predictions of the model discussed with the result of the atomic experiment. The measurements of the EDM of the mercury isotope ^{199}Hg have resulted [19] in

$$d(^{199}\text{Hg})/e < 9 \cdot 10^{-28}\text{cm}. \tag{13}$$

According to calculations of Ref. [20], it corresponds to the upper limit on the d-quark CEDM

$$d^c < 2.4 \cdot 10^{-26}\text{cm} \tag{14}$$

The prediction (6) exceeds this upper limit by an order of magnitude.

Our analysis demonstrates that very special assumptions concerning the parameters of the model of spontaneous CP-violation in the Higgs sector (such as large mass M_{H^0} of the Higgs boson, small values of the CP-violating parameters $\mathrm{Im}Z_0$, $\mathrm{Im}\tilde{Z}^0$, etc) are necessary to reconcile the predictions of this model with the experimental upper limits on the electric dipole moments of neutron and ^{199}Hg.

Such fine tuning will change as well the prediction of the model for the electron EDM. It will make much smaller the accepted now prediction $d(e)/e \sim 10^{-27}$ cm [11, 21, 22], which is only an order of magnitude below the present experimental upper limit [23].

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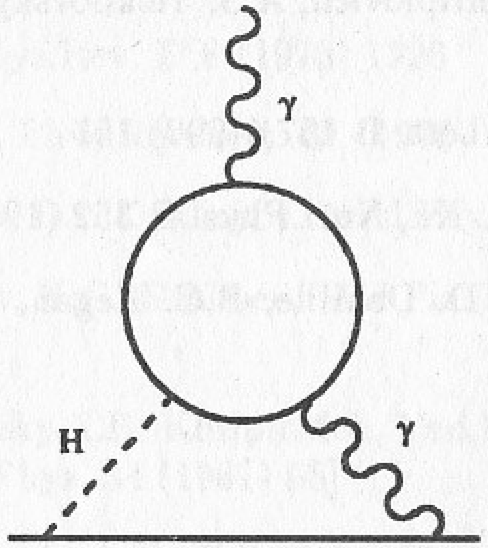

Fig.1. Two-loop contribution to an electric dipole moment.

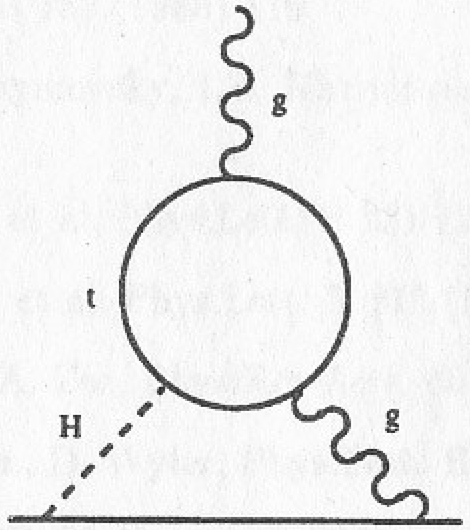

Fig.2. Two-loop contribution to the quark CEDM.

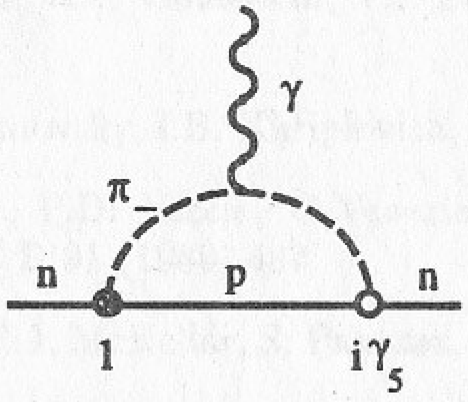

Fig.3. Chiral contribution to the neutron EDM.

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