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ELECTRIC DIPOLE MOMENTS OF ELEMENTARY PARTICLES IN STANDARD MODEL AND BEYOND

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UDK 530.1 M-16

ELECTRIC DIPOLE MOMENTS OF ELEMENTARY PARTICLES IN STANDARD MODEL AND BEYOND: Preprint ITEP 21-97/

E.Shabalin - M., 1997 - 8p.

The possible magnitudes of the electric dipole moments (EDM) of elementary particles originated by different sources of CP violation, such as the Kobayashi-Maskawa phase in Standard Model (SM), θ-term in QCD lagrangian, spontaneous CP breakdown in SM with extended Higgs sector and new phases appearing in SUSY, are considered.

Fig. - 7, ref. - 26 name.

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[1]Report at the International Conference "Rencontres de Moriond" (Electroweak Interactions and Unified Theories) Les Arcs, France, March 15-22, 1997.

The EDM of the charged system is a polar vector

$$\vec{D} = \int \vec{r}\rho(\vec{r})d^3r$$

where $\rho(\vec{r})$ is the charge density. Its interaction with the electric field $H \sim \vec{D}\vec{E}$ is P–and T invariant.

As for an elementary particle, the only vector which can be associated with it in its rest frame – is its spin, and interaction $H' \sim \vec{\sigma}\vec{E}$ is P– and T–noninvariant. It can be simply established taking into account that the transformation properties of $\vec{\sigma}$ and angular momentum

$$\vec{\ell} = m\frac{d\vec{r}}{dt} \times \vec{r}$$

are the same. Then

$$T(\vec{\sigma}) = -\vec{\sigma}, \qquad P(\vec{\sigma}) = \vec{\sigma}.$$

The interaction $\vec{\sigma}\vec{E}$ does not contradict to CPT symmetry, it T non-invariance is compensated by CP violation of equal strength.

For a spin $\frac{1}{2}$ particle, the covariant form of such interaction is

$$L = i\, d(k^2)\bar{\psi}\left(p + \frac{k}{2}\right)\sigma_{\mu\nu}k_\nu\gamma_5\psi\left(p - \frac{k}{2}\right)A_\mu(k) \tag{1}$$

where $d(0)$ is EDM. And $d(0) \equiv d$ is the static property of a particle.

The imaginary unit "i" in eq.(1) is necessary to conserve CPT invariance. Consequently, EDM can arise in CPT – invariant theory only if some of the coupling constants are the complex ones.

In SM these are the elements

$$V_{cs}, \quad V_{cb}, \quad V_{ts}, \quad V_{tb} \tag{2}$$

of the Kobayashi-Maskawa matrix of the quark couplings to $W^{\pm}$–bosons. At one-loop level with one W boson, EDM is zero because $V_{ij}(V_{ij})^*$ is a real number. At two-loop level, as it is shown in Fig.1, the result is proportional to combination $V_{cd}V_{cs}^*V_{ts}V_{td}^*$ which is a complex number. And to decide how large is EDM of quark, it is necessary to consider a deference of the diagrams in Fig.1a and Fig.1b, substituting the regularized expressions for $\Gamma_{tc\gamma}^{Reg}(k,p)$ and $\Gamma_{ct\gamma}^{Reg}(k,p)$ [1]:

$$\begin{aligned}\Gamma_{tc\gamma}^{Reg}(k,p) &= (\hat{p}_t - m_t)\gamma_\mu(1-\gamma_5)(\hat{p}_c - m_c) \times \left(-\tfrac{2\kappa Q_c}{M_W^4}\right) + \\ &+ i\,\epsilon_{\mu\sigma\tau\eta}k_\sigma p_\tau\gamma_\eta(1+\gamma_5) \times \left(\tfrac{\kappa(Q_c - 3Q_s)}{2M_W^4}\right) + O(k^2).\end{aligned} \tag{3}$$

$\Gamma^{Reg}_{ct\gamma}(k,p)$ differs from this expression by rearranging the factors $(\hat{p}_t - m_t)$ and $(\hat{p}_c - m_c)$. Being inserted into the diagram in Fig.1a the first term in eq. (3) forms the construction

$$\gamma_\alpha(1+\gamma_5)\frac{1}{\hat{p}_t - m_t}(\hat{p}_t - m_t)\gamma_\mu(1-\gamma_5)(\hat{p}_c - m_c)\frac{1}{\hat{p}_c - m_c}\gamma_\beta(1+\gamma_5)$$

in which the individual properties of the internal quarks disappear. The same is true for Fig.1b. Therefore, a contribution of the first term in eq. (3) disappers in $M_1 - M_2$.

The rest term in eq.(3) contains k_σ as the common factor and calculating $d(0)$ we can put $k = 0$ for a difference of momenta p_t and p_c, taking $p_t = p_c = p$.

Due to chiral factors in $W\bar{q}q$ vertices, the second term in eq.(3) produces the combination

$$\frac{\epsilon_{\mu\sigma\tau\eta}k_\sigma p_\tau}{(p_t^2 - m_t^2)(p_c^2 - m_c^2)}\gamma_\alpha(1+\gamma_5)\hat{p}_t\gamma_\eta(1+\gamma_5)\hat{p}_c\gamma_\beta(1+\gamma_5)$$

which is the same for Fig.1a and Fig.1b when $p_t = p_c = p$. Then, the second term in eq.(3) also does not contribute into $M_1 - M_2$. Two-loop diagrams with two $W^\pm$ do not produce EDM [2].

The situation changes, if the conditions of propagation of c- and t-quarks become different (see Fig.2). Then a possible magnitude of a quark EDM could reach a value

$$d_d \sim 2 \cdot 10^{-34} ecm \qquad [3] \tag{4}$$

The EDM of the neutron (EDMN) originated by d_q is estimated to be of the same order of magnitude. EDMN with allowance for exchange forces, as shown in Fig.3, could reach a value (see overview [4])

$$d_n(SM \quad \text{without} \quad \theta - term) \sim 10^{-32} ecm \tag{5}$$

<u>EDMN in SM with θ-term.</u>

A non-trivial topological structure of QCD vacuum allows, in principle, to add to QCD lagrangian the so-called θ-term [5] violating CP invariance.

$$L^{CP=-1}_{QCD} = -\theta\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} \tag{6}$$

Owing to triangle anomaly the effect of this term can be written in terms of quark fields [6]

$$L^\theta_q(CP=-1) = i\, m_0 \sum_j \bar{q}_j\gamma_5 q_j \tag{7}$$

where

$$m_0 = \theta \frac{m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s} \tag{8}$$

In presence of such term, a nucleon becomes a mixture of states of opposite parity

$$|n>=|N>+\sum_*(M^*-M)^{-1}|N^*><N^*|L_q^\theta|N>$$

where M and M^* are the masses of $\frac{1^+}{2}$ and $\frac{1^-}{2}$ states. Then

$$\vec{d_n} = 2\sum_*(M^*-M)^{-1}Re<N|\vec{d}|N^*><N^*|L_q^\theta|N> \tag{9}$$

where $\vec{d}$ is the dipole-moment operator allowed in $\frac{1^+}{2} \to \frac{1^-}{2}$ transition without CP violation. Baluni's result is

$$|d_n| \sim 2.7 \cdot 10^{-16}|\theta|\ ecm \tag{10}$$

A very close estimate was obtained by Crewther etal [7] considered the diagram in Fig.4 giving the largest contribution at $m_\pi \to 0$. L_q^θ produces CP-odd vertex $\tilde{g}_{\pi NN}\bar{N}\vec{\tau}N\vec{\pi}$ and resulting EDMN is estimated to be

$$|d_n| \sim 3.6 \cdot 10^{-16}|\theta|\ ecm \tag{11}$$

In the Skyrme model, the estimates are

$$|d_n| \approx \begin{cases} 1.2 \cdot 10^{-16}|\theta|\ ecm & [8] \\ 2 \cdot 10^{-16}|\theta|\ ecm & [9] \end{cases} \tag{12}$$

From $|d_n|^{exp} < 1.1 \cdot 10^{-25} ecm$, it follows that $|\theta| \leq 10^{-9}$.

EDM of electron

In SM, the EDME is absent at 3-loop level [10]. It appears through the EDM of $W^\pm$ bosons

$$L^{CP=-1} = i[\lambda_1 W_\mu W_\nu + \lambda_2 W_{\mu\sigma} W_{\sigma\nu}]\tilde{F}_{\mu\nu} \tag{13}$$

According to estimates in ref.[11], $d_W \sim 8 \cdot 10^{-31} ecm$ and $d_e \sim 8 \cdot 10^{-41} ecm$. Experimentally [12], $d_e = (1.8 \pm 1.6)10^{-27} ecm$.

EDM in multi-Higgs-doublet theory

If a number of Higgs-doublets is more than two, the spontaneous CP violation can take place [13]. If the condition of absence of flavors-changing neutral Higgs bosons interaction is imposed, such a mechanism of CP violation requires not less than three Higgs doublets [14]. To illustrate a possibilities of such a theory, let's consider a special model proposed by Das and Kao (DK) for explanation, why t-quark is considerably heavier than the rest fermions. It occurs, if t-quark is the only fermion getting its mass from v.e.v. v_2 of the second doublet, and $v_2 \gg v_1$.

CP violation proceeds through the mixing between the scalar and pseudoscalar neutral Higgs bosons parametrized in the form

$$< H_1 A >_q = \frac{1}{2} \sin 2\beta \sum (Im Z_0)/(q^2 - m_0^2),$$

$$< H_2 A >_q = \frac{1}{2} \sum [\cos 2\beta \cdot Im Z_0 - Im \bar{Z}_0]/(q^2 - m_0^2) \qquad (14)$$

In such a model, the dominant contribution appears from the diagram in Fig.5 describing the so-called chromoelectric dipole moment of a quark and incorporating b-quark in the upper loop.

$$d_n/e = 6 \cdot 10^{-25} [f(m_b^2/m_H^2) + g(m_b^2/m_H^2)] tan^2\beta (I_m Z_0 + I_m \bar{Z}_0) \; cm \qquad (15)$$

where f and g are represented in refs. [15,16]. At $m_H = 70GeV$, a magnitude of the square bracket is ≈ 0.12. Then, the experimental limit on d_n says us that

$$|Im Z_0 + Im \bar{Z}_0| \leq (tan^2\beta)^{-1}, \quad \text{if} \quad m_H \approx 70GeV. \qquad (16)$$

It is considerably more restrictive limit than that found by Weinberg [17]. In more general models that the DK model, the EDMN can be close to its experimental limit too [16]. The interesting property of DK model is a possibility to relate EDMN and EDME (described by diagram in Fig.6). For $tan\beta \gg 1$ we obtain [18]

$$|d_e/d_n| \approx 2 \cdot 10^{-3} \quad \text{or} \quad d_e < 2 \cdot 10^{-28} ecm \qquad (17)$$

In the three-Higgs-doublet model by Weinberg [14], the EDMN could arise due to transition between charged Higgs bosons, as shown in Fig.7. Then [19,20]

$$d_d \sim \frac{e m_d m_c^2 \sin^2\theta_c}{24\pi^2} \left(\ln \frac{m_H^2}{m_c^2} \right) Im \frac{< H_2^+ H_1^{+*} >}{\lambda_2 \lambda_1^*} \qquad (18)$$

The last factor can be estimated from known limit on parameter ϵ' in $K \to 2\pi$ decay with the result [21]

$$Im \frac{< H_2^+ H^+ *_1 >}{\lambda_2 \lambda_1^*} \leq 0.8 \cdot 10^{-3} G_F / \left[m_K^2 \ln \left(\frac{m_H}{m_c} \right) \right] \qquad (19)$$

Then, taking into account the electromagnetic, chromoelectric interactions and assuming a presence of $1-2\%$ admixture of $\bar{s}s$ pairs in the neutron wave function [20], we come to conclusion that a mixing between charged Higgs bosons could produce EDMN

$$d_n \leq 8 \cdot 10^{-27} ecm \tag{20}$$

EDMs in SUSY

In SUSY generalization of SM, a necessity for many new particles opens the doors for appearance of new CP violating parameters. In particular, the gaugino Majorana masses, squrks masses and scalar trilinear interaction coupling can be complex ones. Then, in general, d_n and d_e could be close to their experimental limits [22–26]!

Conclusion

A discovery of EDMN and EDME with the magnitudes not far from their present experimental limits looks quite possible from the theoretical point of view. It will mean that the Nature is more complicated than represented by SM!

Figures

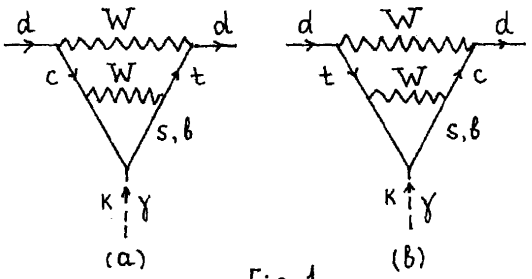

Fig. 1

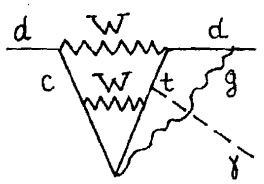

Fig. 2

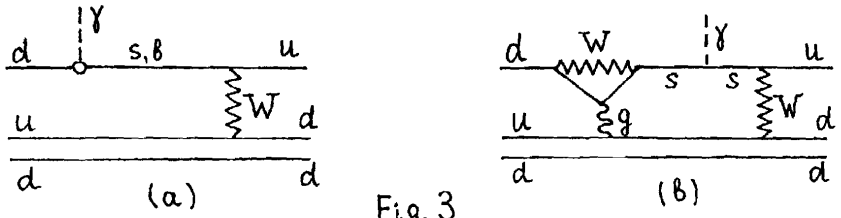

Fig. 3

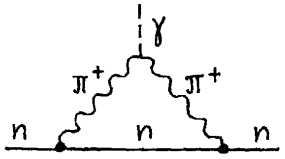

Fig. 4

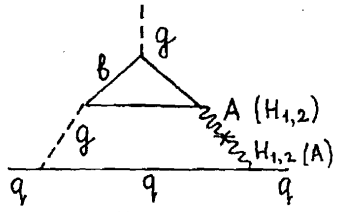

Fig. 5

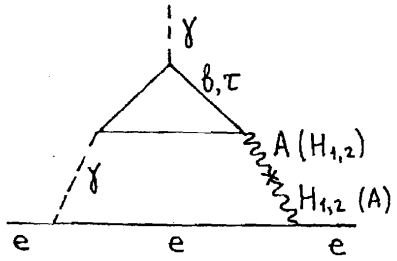

Fig. 6

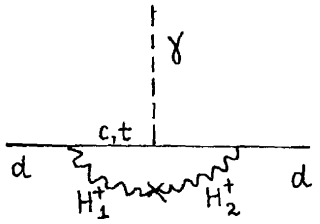

Fig. 7

Figure captions

Fig.1 Two-loop contribution to EDM of d-quark.

Fig.2 Three-loop contribution to EDM of d-quark with one intermediate gluon (g).

Fig.3 Diagrams contributing to EDM of the neutron with allowance for exchange forces.

Fig.4 Diagram giving the largest contribution in limit $m_\pi \to 0$ to EDMN arising due to CP–odd part of $\pi\bar{N}N$ vertex originated by θ-term in QCD lagrangian.

Fig.5 Diagram giving the largest contribution to d_q in the model of Das-Kao [15] at $tan\beta \gg 1$.

Fig.6 Diagram giving the largest contribution to d_e in the model of ref.[15].

Fig.7 Contribution ot EDM of quark arising due to mixing of charged Higgs bosons in the Weinberg's model of CP violation.

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Е.П.Шабалин

Электрические дипольные моменты элементарных частиц в Стандартной Модели и вне ее.

Подписано к печати I2.05.97 Формат 60x90 I/I6 Офсетн.печ.
Усл.-печ.л.0,5. Уч.-изд.л.0,3. Тираж 90 экз. Заказ 2I.
Индекс 3649

Отпечатано в ИТЭФ, II7259,Москва, Б.Черемушкинская, 25