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Chromo-electric Dipole Moment of Light Quarks Through Two Loop Mechanism

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Abstract

We show that the leading contribution to the neutron electric dipole moment may arise from the chromo-electric dipole moment of the light quarks via a two loop mechanism of Barr and Zee.

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Recently, theoretical calculations of the neutron electric dipole moment in various models of CP violation have rekindled the interests of many theorists since Weinberg's discovery of the dimension 6 P-odd and T-odd purely gluonic operator[1], which has been identified as the chromo-electric dipole moment of the gluon itself[2]. Motivated by Weinberg's work, Barr and Zee[3] pointed out there is a new class of two loop diagrams which can lead to a large electric dipole moment of the electron. In the neutral Higgs boson exchange of Weinberg's three Higgs doublets model of CP violation, the Barr-Zee mechanism predicted a electric dipole moment of the electron which is eight orders of magnitude larger than the traditional one loop mechanism. In this letter, we wish to point out that the Barr-Zee mechanism also leads to a large chromo-electric moment of the light quarks and thus gives rise to a neutron electric dipole moment which is at least two orders of magnitude larger than the usual one loop mechanism. Either the neutral Higgs boson has to be very heavy or the complex CP violation phase has to be unnaturally small.

The CP violation due to a Higgs sector that obeys natural flavor conservation as proposed long time ago by Weinberg[4] is particularly interesting for low energy phenomenology because it is the only mechanism in which the mediator of the CP violating interaction can be much lighter than the weak gauge bosons. For the same reason it seems to be an easier mechanism to rule out. The charged Higgs sector is typically responsible for the observed CP violation in the Kaon system and thus more constrained. However it also contributes to the flavor conserving CP violating quantity like the neutron electric dipole moment, D_N. For a charged Higgs boson mass about $10GeV$, the one loop contribution is estimated to be $-9\times10^{-26}e-cm$ which is not too far from the experimental upper bound of $1.2 \times 10^{-25}e - cm$[5]. Such a light charged Higgs boson is no longer realistic. For a $100GeV$ charged Higgs boson, the one loop estimate of D_N is about $10^{-27}e - cm$. The neutral Higgs boson can also provide interesting CP violating effect. The most serious constraint is in fact provided by D_N. The naive estimate of its one loop contribution gives small result because it is suppressed by three powers of light quark mass. A more carefull analysis indicates that if one considers the neutral Higgs boson coupling to the nucleons instead of quarks the effect can be much larger. A recent estimate[6] gives $2 \times 10^{-26}(100GeV/M_{H^0})^2 e - cm$. The Barr and Zee's two loop mechanism provides another way to avoid the light quark mass suppression effect. It turns out the leading contribution to the two loop mechanism are the chromo-electric dipole moments (CEDMs) of the light quarks. This is anticipated because when the two photons in Fig.(1) of ref.[3] is replaced by gluons one gets an enhancement factor of α_s/α. However, note that the loop momenta in the two loop diagram are both of high mass scale, M (which is m_t for the most part). Therefore the CEDM is induced at the scale M. When the QCD renormalization group correction is taken into account, the scaling of the CEDM operators from the high mass scale (M) down to the hadronic scale (μ) give rise to a suppression effect of about one percent which we will discuss in more detail later on.

The calculation of the gluonic diagrams is very similar to the photonic ones in ref.[3]. In order to check their result we redo the calculation using some shortcuts. The t quark loop with two photons (or gluons) and a neutral Higgs boson in the external lines has been calculated many times before. A most recent summary of this result can be found in ref.[7] where both scalar and pseudoscalar amplitudes for the effective Higgs-photon-photon and Higgs-gluon-gluon vertices were given. Since the one loop amplitudes have already contained one power of external photon momentum, we can set the Higgs boson momentum and virtual photon momentum to be equal and the two loop result can be easily produced. For the photonic diagrams our result agrees with ref.[3]. For the gluonic diagrams, it gives rise to the CEDMs, $d^c_{u,d}$, for up and down quarks,

$$d^c_u = g_s f_u = 2m_u \frac{g_s^3}{(4\pi)^4}\sqrt{2}G_F \frac{\mathrm{Im}Z_0 - \mathrm{Im}\tilde{Z}_0}{\tan^2\beta}\left(f(z)+g(z)\right) \tag{1}$$

$$d^c_d = g_s f_d = 2m_d \frac{g_s^3}{(4\pi)^4}\sqrt{2}G_F \left[\mathrm{Im}Z_0(f(z)+g(z)) - \mathrm{Im}\tilde{Z}_0(f(z)-g(z))\right] \tag{2}$$

where

$$f(z) = \frac{1}{2}z\int_0^1 dx \frac{1-2x(1-x)}{x(1-x)-z}\ln\frac{x(1-x)}{z} \tag{3}$$

$$g(z) = \frac{1}{2}z\int_0^1 dx \frac{1}{x(1-x)-z}\ln\frac{x(1-x)}{z}\ , \tag{4}$$

and z is $m_t^2/M_{H^0}^2$. As was first pointed out by Barr and Zee[3], this two loop mechanism provides only one power of light quark mass suppression. The quantities $\mathrm{Im}Z_0$ and $\mathrm{Im}\tilde{Z}_0$ parametrized the CP violating quantities in the neutral Higgs sector as defined in ref.[8]. The ratio of the vacuum expectation values of the Higgs bosons, v_2/v_1, is defined to be $\tan(\beta)$. Other notations are self-explanatory. $f(1)$ is about 0.8 and $g(1)$ is about 1.2. Large and small z limiting forms of $f(z)$ and $g(z)$ are given in ref.[3]. The general z dependence of these functions are given in Fig.(1). Unless z is very small, these two functions are of order unity.

The CEDM operators of the light quarks are induced at the heavy t quark or Higgs boson mass scale when these particles are integrated out in the effective theory. QCD renormalization effect brings us an extra factor

$$\left(\frac{g_s(M)}{g_s(\mu)}\right)^{\frac{74}{23}} \tag{5}$$

where we have assumed five flavors between the two scales M and μ. The strong coupling constant g_s in eqs.(1) and (2) has to be replaced by the running coupling $g_s(\mu)$. To estimate the resulting neutron electric dipole moment, we employ the valence quark model which gives

$$D_N = \frac{1}{3}e(\frac{4}{3}f_d + \frac{2}{3}f_u). \tag{6}$$

Therefore the two loop contributions to the neutron electric dipole moment due to the CP violating neutral Higgs boson exchange is

$$D_N = \frac{4}{9}\left(\frac{e}{(4\pi)^2}\right)\left(\frac{g_s(\mu)}{4\pi}\right)^2\left(\frac{g_s(M)}{g_s(\mu)}\right)^{\frac{74}{23}}\sqrt{2}G_F[(\mathrm{Im}Z_0 - \mathrm{Im}\tilde{Z}_0)(2m_d + \frac{m_u}{\tan^2\beta})f(z)$$
$$+(\mathrm{Im}Z_0(2m_d + \frac{m_u}{\tan^2\beta}) + \mathrm{Im}\tilde{Z}_0(2m_d - \frac{m_u}{\tan^2\beta}))g(z)] \tag{7}$$

To estimate its magnitude, assume the neutral Higgs boson to have about the same mass as the t quark and assume the CP violating quantities $\mathrm{Im}Z_0$ and $\mathrm{Im}\tilde{Z}_0$ to be of order unity. Take $M \sim 100GeV$, $g_s(M)/4\pi$ is about 0.1, and following Weinberg[1], use $g_s(\mu)/4\pi = 1/\sqrt{6}$. This gives D_N to be about $6.2 \times 10^{-26}(m_d/10MeV)e - cm$. Therefore even if we conservatively used the current quark masses the contribution is still larger than the one loop estimate quoted earlier under the same assumptions about the neutral Higgs boson mass and CP violating parameters. If the constituent quarks masses are used instead, one can boost up one to two orders of magnitude of the above estimation of D_N. Also, this is already about one order of magnitude larger than the neutral Higgs boson contribution through the two loop induced chromo-electric dipole moment of the gluon under the same assumptions[6, 10]. Barr and Zee[3] also calculated the electric dipole moments of the light quarks in the photonic two loop mechanism. The gluonic two loop contribution discussed here is actually larger than the photonic one. This gluonic two loop mechanism therefore provides the most stringent constraints on the CP violating parameters and/or the neutral Higgs boson mass. Of course, one should also keep in mind that the estimate of D_N is necessarily more uncertain than the photonic one due to the low energy hadronic physics. Using this mechanism, one can already rule out some of the models of CP violation which use the neutral Higgs bosons as the main source of CP violation. For example, the model of Geng and Ng in ref.[9] is ruled out by recent experiments[5] and this mechanism.

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Figure Caption

Fig. 1. The z dependence of the functions $f(z)$ (eq.(3)) and $g(z)$ (eq.(4)).

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