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QCD corrections to neutron electric dipole moment from dimension-six four-quark operators

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ABSTRACT

In this Letter, the renormalization-group equations for the (flavor-conserving) CP-violating interaction are derived up to the dimension six, including all the four-quark operators, at one-loop level. We apply them to the models with the neutral scalar boson or the color-octet scalar boson which have CP-violating Yukawa interactions with quarks, and discuss the neutron electric dipole moment in these models.

1. Introduction

The electric dipole moment (EDM) for neutrons is sensitive to CP violation in physics beyond the standard model (SM) around TeV scale. This is because, while the CP phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix is $O(1)$, the CKM contribution to the neutron EDM is too much suppressed [1] to be observed in near future. (The recent evaluation of the CKM contribution to the neutron EDM is given in Ref. [2].) The naturalness problem in the Higgs-boson mass term in the SM might require new physics at TeV scale, and many extensions of the SM generically have CP-violating interactions. The supersymmetric standard model, which is the leading candidate for the TeV-scale physics, is severely constrained from the EDM measurements [3].

The (flavor-conserving) CP-violating effective operators at parton level up to the dimension six are the QCD theta term, the EDMs and the chromoelectric dipole moments (CEDMs) of quarks, the Weinberg's three-gluon operator [4] and the four-quark operators. In the evaluation of the neutron EDM, the CP-violating four-quark operators tend to be ignored since the four-light-quark operators suffer from chiral suppression in many models. However, the four-quark operators including heavier ones, such as bottom/top quarks, may give sizable contributions to the neutron EDM. The EDMs, CEDMs, and the three-gluon operator are radiatively generated from the four-quark operators by integrating out heavy quarks.

In the multi-Higgs models, the Barr–Zee diagrams are known to give the sizable contribution to the neutron EDM [5]. In the Barr–Zee diagrams the heavy-quark loops are connected to light-quark external lines by the neutral scalar boson exchange so that the CEDMs for light quarks are generated at two-loop level at $O(\alpha_s)$. However, it is not clear which renormalization scale should be chosen for α_s. In addition, the contributions from the Barr–Zee diagrams at two-loop level to the quark EDMs vanish at $O(\alpha_s)$. However, it is still unclear that the higher-order corrections to the quark EDMs are negligible in the neutron EDM evaluation.

In this Letter, in order to answer those questions, we derive the renormalization-group equations (RGEs) for the Wilson coefficients for the CP-violating effective operators up to the dimension six at one-loop level, including operator mixing. The RGEs for the EDMs and CEDMs for quarks and the three-gluon operator have been derived in Refs. [6–8]. The next-leading order corrections to them are also partially included [9]. We include the four-quark operators in the calculation at the leading order. Using the derived RGEs, we evaluate

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the EDMs and CEDMs for light quarks and the three-gluon operators induced by the neutral scalar boson exchange including the QCD correction. We also discuss the four-quark operators induced by the color-octet scalar boson.

This Letter is organized as follows. In the next section, we review the neutron EDM evaluation from the parton-level effective Lagrangian at the hadron scale. In Section 3, we derive RGEs for the Wilson coefficients for the CP-violating effective operators up to the dimension six at one-loop level. In Section 4, we show the effect of the running α_s on the evaluation of the Wilson coefficients, assuming the neutral scalar boson exchange induces the CP-violating effective operators. In Section 5, another example of the application of the RGEs is shown, assuming the effective operators induced by a color-octet scalar boson. Section 6 is devoted to conclusion.

2. Neutron EDMs

First, we review about evaluations of the neutron EDM from the low-energy effective Lagrangian at parton level. The CP-violating interaction at parton level around the hadron scale ($\mu_H = 1$ GeV) is given by

$$\mathcal{L}_{\rm CPV} = \theta\frac{\alpha_s}{8\pi}G^A_{\mu\nu}\widetilde{G}^{A\mu\nu} - \frac{i}{2}\sum_{q=u,d,s} d_q\bar{q}(F\cdot\sigma)\gamma_5 q - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q\bar{q}g_s(G\cdot\sigma)\gamma_5 q + \frac{1}{3}wf_{ABC}G^A_{\mu\nu}\tilde{G}^{B\nu\lambda}G^{C\mu}_{\lambda}. \tag{1}$$

Here, $F_{\mu\nu}$ and $G^A_{\mu\nu}$ ($A = 1$–8) are the electromagnetic and gluon field strength tensors, g_s is the strong coupling constant ($\alpha_s = g_s^2/4\pi$), $F\cdot\sigma \equiv F_{\mu\nu}\sigma^{\mu\nu}$, $G\cdot\sigma \equiv G^A_{\mu\nu}\sigma^{\mu\nu}T^A$, and $\tilde{G}^A_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{A\rho\sigma}$ with $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu,\gamma^\nu]$ and $\epsilon^{0123} = +1$. The matrix T^A denotes the generators in the $SU(3)_C$ algebra, and f^{ABC} is the structure constant. The first, second, third and forth terms in Eq. (1) are called the QCD θ term, the EDM and the CEDM for quarks, and the three-gluon operator, respectively. In this Letter, the covariant derivative is defined as $D_\mu = \partial_\mu - ieQ_qA_\mu - ig_sG^A_\mu T^A$, in which A_μ and G^A_μ are gauge fields for $U(1)_{EM}$ and $SU(3)_C$, respectively with Q_q, the QED charge ($(Q_u, Q_d, Q_s) = (2/3, -1/3, -1/3)$). In Eq. (1), we ignore the CP-violating four-quark operators, since their coefficients are often proportional to the light-quark masses in typical models, as mentioned in the Introduction.

The neutron EDM is evaluated from the low-energy interaction at parton level with the naive dimensional analysis, the chiral perturbation theory, and the QCD sum rules, though they are considered to have large uncertainties. The evaluation in term of the QCD sum rules is more systematic than the others, at least for the contributions from the QCD theta term, and the quark EDMs and CEDMs to the neutron EDM [10]. The recent evaluation of the neutron EDM with the QCD sum rules [11] is

$$d_n \simeq 2.9\times 10^{-17}\bar{\theta}[e\ \text{cm}] + 0.32d_d - 0.08d_u + e(+0.12\tilde{d}_d - 0.12\tilde{d}_u - 0.006\tilde{d}_s). \tag{2}$$

In the evaluation, the recent QCD lattice result is used for the low-energy constant λ_n, which is defined by $\langle 0|\eta_n(x)|N(\vec{p},s)\rangle = \lambda_n u_n(\vec{p},s)$ with $\eta_n(x)$ the neutron-interpolating field. If a value of λ_n evaluated with the QCD sum rules is used, the neutron EDM is enhanced by about five times compared with Eq. (2).

The contribution from the three-gluon operator might be comparable to the quark EDMs and CEDMs. The quark EDMs and CEDMs are proportional to the quark masses, while the three-gluon operator does not need to suffer from chirality suppression. However, the size of the contribution from the three-gluon operator depends on the methods of the evaluation. In Ref. [12] the authors compare the several evaluations and propose

$$d_n(w) \sim (10\text{–}30)\ \text{MeV}\times ew. \tag{3}$$

3. Operator bases and anomalous dimension matrix

We would like to introduce heavy quarks in the low-energy effective theory and evaluate their contributions to the neutron EDM. In this section, we show the one-loop RGEs for the Wilson coefficients for the CP-violating effective operators up to the dimension six, including heavy quarks.

First, we define the operator bases for the RGE analysis. The flavor-conserving effective operators for the CP violation in QCD are given up to the dimension six as

$$\mathcal{L}_{\rm CPV} = \sum_{i=1,2,4,5}\sum_q C^q_i(\mu)\mathcal{O}^q_i(\mu) + C_3(\mu)\mathcal{O}_3(\mu) + \sum_{i=1,2}\sum_{q'\neq q}\widetilde{C}^{q'q}_i(\mu)\widetilde{\mathcal{O}}^{q'q}_i(\mu) + \frac{1}{2}\sum_{i=3,4}\sum_{q'\neq q}\widetilde{C}^{q'q}_i(\mu)\widetilde{\mathcal{O}}^{q'q}_i(\mu), \tag{4}$$

where the sum of q runs not only light quarks but also heavy ones, and we ignore the QCD theta term since it is irrelevant to our discussion here.[1] The effective operators are defined as

$$\mathcal{O}^q_1 = -\frac{i}{2}m_q\bar{q}eQ_q(F\cdot\sigma)\gamma_5 q,$$
$$\mathcal{O}^q_2 = -\frac{i}{2}m_q\bar{q}g_s(G\cdot\sigma)\gamma_5 q,$$
$$\mathcal{O}_3 = -\frac{1}{6}g_s f^{ABC}\epsilon^{\mu\nu\rho\sigma}G^A_{\mu\lambda}G^{B\lambda}{}_{\nu}G^C_{\rho\sigma}, \tag{5}$$

and

[1] The QCD theta term does not contribute to the RGEs for other CP-violating terms. Furthermore, there may be contribution to the QCD theta term from other CP violation terms, while the QCD theta term vanishes dynamically if the Peccei–Quinn symmetry is invoked.