



Electron electric dipole moment induced by octet-colored scalars

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Abstract

An appended sector of two octet-colored scalars, each an electroweak doublet, is an interesting extension of the simple two Higgs doublet model motivated by the minimal flavor violation. Their rich CP violating interaction gives rise to a sizable electron electric dipole moment, besides the quark electric dipole moment via the two-loop contribution of Barr–Zee mechanism.

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1. Introduction

The flavor diversity in the electroweak interaction continues to attract theoretical curiosity for new physics beyond the Standard Model. Pioneer work of Ref. [1] has shown a natural mechanism to suppress the unwanted neutral flavor changing process mediated by the Higgs exchange. Recent activities address the general structure of the minimal flavor violation (MFV) [2]. It is noticed that octet-colored scalars are able to respect MFV. The general Yukawa interaction is given by

$$\begin{aligned} \mathcal{L}_Y = & -\overline{Q}_L \mathbf{y}_d (\phi_d + \eta_d O_d^a T^a) d_R \\ & -\overline{Q}_L \mathbf{y}_u (\tilde{\phi}_u + \eta_u \tilde{O}_u^a T^a) u_R + \text{h.c.}, \end{aligned} \quad (1)$$

where Q_L refers to the three families of left-handed quark doublets, and d_R and u_R the three families of the up-type and down-type right-handed quark singlets. The new set of octet-colored scalars O_u and O_d couple to quarks in an analogous fashion of the usual Higgs ϕ_u and ϕ_d by the Yukawa coupling matrices \mathbf{y}_u and \mathbf{y}_d with additional proportional coefficients η_u and η_d , as well as the color generator T^a . All Higgs bosons $\phi_{u,d}$ and $O_{u,d}$ carry the weak hypercharge $Y = \frac{1}{2}$, in the convention $Q = T_3 + Y$. The usual conjugation operation $\tilde{\phi} = i\sigma_2\phi^*$ is adopted.

All interactions respect a Z_2 -symmetry, in which down-type fields ϕ_d , O_d , d_R are odd, $\phi_d \rightarrow -\phi_d$, $O_d \rightarrow -O_d$, $d_R \rightarrow -d_R$, but up-type fields ϕ_u , O_u , u_R are even. The symmetry is used to keep the desirable pattern of interaction that obeys the rule of the minimal flavor violation (MFV).

The complex coefficients η_u and η_d can produce CP violating vertices for the electric dipole moment (EDM) of the neutron. However the neutron EDM is masked with uncertainty of the hadronic matrix evaluations. It is interesting to ask the question of any contribution to the electron EDM, reached by ongoing and future experiments [3]. It turns out that one-loop or two-loop contributions to the electron EDM are absent if there is only one octet-colored scalar electroweak doublet. Nonetheless, in this article we show that with two of these octet-colored scalars, the electron EDM occurs through an amplitude $A \rightarrow O^+ O^-$ of the pseudoscalar neutral Higgs boson A into a pair of octet-colored charged scalars. Then, a CP even amplitude for $A \rightarrow \gamma\gamma$ appear even though A is CP-odd. As A and one of the photon touch down to an electron line, the electron EDM emerges via Barr–Zee [4] mechanism in an overall two-loop diagram, as shown in Fig. 1. In the past, the electron EDM via Barr–Zee two-loop mechanism has been exhaustively studied in scenarios of multi-Higgs doublets [5,6] (without octet-colored scalars) or supersymmetric particles [7,8]. Our current study uses similar bosonic contribution as in [7,9].

We have found that the present limit of the electron EDM has already restricted the parameter space of CP violation of the octet-colored scalars.

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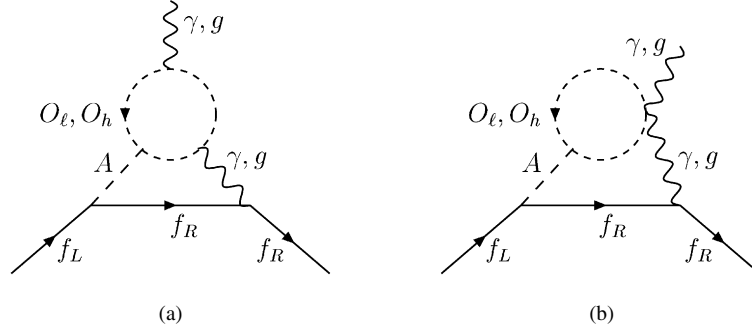


Fig. 1. Two-loop contributions to EDM and CDM by octet-colored scalars (mirror graphs are not displayed).

2. Higgs potential and AOO coupling

As we know that if a CP-odd scalar couples to a conjugated pair of bosons, CP conservation is violated, just like the case in $K_L \rightarrow \pi\pi$. We are going to find such a coupling in the MFV scenario with two colorless doublet Higgs ϕ_u, ϕ_d , and two octet-colored Higgs O_u, O_d . Rotating the basis of colorless Higgs,

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \phi_u \\ \phi_d \end{pmatrix}, \quad (2)$$

$$\begin{pmatrix} \phi_u \\ \phi_d \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix},$$

we achieve that $\langle \phi_1 \rangle = 0$ as $\tan \beta = \langle \phi_u \rangle / \langle \phi_d \rangle$. The relevant vertices, allowed by the exact Z_2 , are

$$\mathcal{L} \supset \eta (\phi_u^\dagger \phi_d) (O_d^\dagger O_u) + \eta' (\phi_d^\dagger \phi_u) (O_d^\dagger O_u) + \text{h.c.} \quad (3)$$

We start with the first term

$$\begin{aligned} \eta (\phi_u^\dagger \phi_d) (O_d^\dagger O_u) &= \eta (\cos \beta \phi_1^\dagger + \sin \beta \phi_2^\dagger) \\ &\quad \times (-\sin \beta \phi_1 + \cos \beta \phi_2) O_d^\dagger O_u. \end{aligned} \quad (4)$$

We single out the pseudoscalar Higgs A from $\text{Im}(\phi_1)$, or $\phi_1 \rightarrow iA/\sqrt{2}$ with $\phi_2 \rightarrow v/\sqrt{2}$,

$$\begin{aligned} \mathcal{L} \supset \eta (\cos^2 \beta \phi_1^\dagger \phi_2 - \sin^2 \beta \phi_2^\dagger \phi_1) O_d^\dagger O_u + \text{h.c.} \\ \rightarrow -\frac{1}{2} \eta v i A O_d^\dagger O_u + \text{h.c.}, \end{aligned} \quad (5)$$

$$\begin{aligned} \mathcal{L} \supset -i \frac{1}{2} v A (\eta O_d^\dagger O_u - \eta^* O_u^\dagger O_d) \\ = i \frac{1}{2} v A (O_u^\dagger, O_d^\dagger) \begin{pmatrix} 0 & \eta^* \\ -\eta & 0 \end{pmatrix} \begin{pmatrix} O_u \\ O_d \end{pmatrix}. \end{aligned} \quad (6)$$

Including the η' coupling, we combine results and obtain

$$\mathcal{L} \supset i \frac{1}{2} v A (O_u^\dagger, O_d^\dagger) \begin{pmatrix} 0 & \eta^* - \eta'^* \\ \eta' - \eta & 0 \end{pmatrix} \begin{pmatrix} O_u \\ O_d \end{pmatrix}. \quad (7)$$

Now we look at the charged components of the color octets. The light and heavy mass states O_ℓ and O_h are given by the diagonalization of the mass matrix

$$\mathcal{L} \supset -(O_u^\dagger, O_d^\dagger) \begin{pmatrix} M_{uu}^2 & M_{ud}^2 \\ M_{du}^2 & M_{dd}^2 \end{pmatrix} \begin{pmatrix} O_u \\ O_d \end{pmatrix}, \quad (8)$$

where M_{uu}^2 and M_{dd}^2 are real, and the complex off-diagonal mass squared $M_{du}^2 = |M_{du}^2| e^{i\Delta}$,

$$-M_{du}^2 = (\eta' + \eta) v^2 \sin \beta \cos \beta. \quad (9)$$

We can absorb the phase ξ of $(\eta' - \eta) \equiv |\eta' - \eta| e^{i\xi}$ into the field O_u . Then AOO coupling matrix becomes real and anti-symmetric, but the remaining phase $\Delta - \xi$ in the off-diagonal mass squared is genuine and not removable. The unitary diagonalization transformation is usually complex,

$$\begin{pmatrix} O_u \\ O_d \end{pmatrix} = \begin{pmatrix} \cos \psi & \sin \psi e^{i\delta} \\ -\sin \psi e^{-i\delta} & \cos \psi \end{pmatrix} \begin{pmatrix} O_\ell \\ O_h \end{pmatrix}, \quad (10)$$

where the 2×2 unitary matrix is denoted as U .

$$U^\dagger \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} U = \begin{pmatrix} -i \sin \delta \sin 2\psi & \cdots \\ \cdots & i \sin \delta \sin 2\psi \end{pmatrix}. \quad (11)$$

Note that diagonal entries arise due to the CP violating phase $\delta = \xi - \Delta$. Traceless is a consistent check. We denote $|\eta' - \eta| \equiv \lambda$. The relevant diagonal AOO interaction becomes

$$\mathcal{L} \supset \frac{1}{2} \lambda v \sin 2\psi \sin \delta A (O_\ell^\dagger O_\ell - O_h^\dagger O_h). \quad (12)$$

The interaction can produce the electron EDM via Barr-Zee mechanism with the charged octet Higgs O in the inner loop. Also note that if masses of eigenstates O_ℓ and O_h become equal, the CP violating effect disappears. Other quartic couplings not given in Eq. (3) do not generate the interaction between A and the O pair.

As the neutral pseudoscalar A is not constrained very much from LEP data, we can choose a light value, for example $m_A \sim M_Z$ about 100 GeV in our numerical analysis. The four degrees of freedom in the two real M_{uu}^2 and M_{dd}^2 and the complex M_{du}^2 can be replaced by the other four parameters, two masses m_{O_ℓ} and m_{O_h} of the light and heavy charged octet Higgs, and two angles ψ and δ . Our above derivation shows that the electron EDM depends directly upon the combination $\lambda \sin(2\psi) \sin(\delta)$. We understand that the product may have a more complicated dependence upon the original parameters in the Lagrangian, but our simpler expression makes the physics involved more transparent.

3. Barr-Zee amplitude

The CP violating short distance physics induces the effective vertex of the electric dipole d_f of the fermion f coupled with

the electromagnetic field strength $F_{\mu\nu}$,

$$\mathcal{L}_{\text{eff}} \supset -\frac{i}{2} d_f (\bar{f} \sigma^{\mu\nu} \gamma_5 f) F_{\mu\nu}. \tag{13}$$

The two-loop Barr–Zee diagram also involves the pseudoscalar coupling of A to fermions,

$$\mathcal{L} \supset -(1/v) [\tan \beta (m_e \bar{e} i \gamma_5 e + m_d \bar{d} i \gamma_5 d) + \cot \beta m_u \bar{u} i \gamma_5 u] A, \tag{14}$$

where the electron shares similar pattern of the Yukawa coupling as the down quark. Evaluating the Barr–Zee diagram, we obtain

$$\left(\frac{d_e}{e}\right) = -\frac{\alpha \lambda m_e}{8\pi^3 m_A^2} \tan \beta \sin(2\psi) \times \sin \delta \left[F\left(\frac{m_{O_\ell}^2}{m_A^2}\right) - F\left(\frac{m_{O_h}^2}{m_A^2}\right) \right]. \tag{15}$$

Eight color channels of O have been summed. The relevant function is defined by

$$F(z) = \int_0^1 \frac{x(1-x)}{z-x(1-x)} \log \frac{x(1-x)}{z}, \tag{16}$$

which has asymptotic behaviors,

$$F(z) \rightarrow \begin{cases} -0.344 & \text{as } z = 1, \\ -\frac{1}{6z} \ln z - \frac{5}{18z} & \text{for } z \gg 1, \\ (2 + \ln z) & \text{for } z \ll 1. \end{cases} \tag{17}$$

The combined factor $\lambda \tan \beta \sin(2\psi) \sin \delta$ can be of order of one. We illustrate the optimal choice of 1 with the understanding that a different choice can be easily scaled appropriately. Furthermore, a large combined factor is probably realized in case of a preferred large value of $\tan \beta$. The electron EDM is evaluated as the difference between two contributions from the light and heavy color octets O_ℓ and O_h . We illustrate in Fig. 2 the EDM component due to the light O_ℓ pretending $m_{O_h} \rightarrow \infty$ for given ψ and δ . The electron EDM contribution from the light octet is plotted versus m_A for various $m_O = 300, 500, 800, 1000$ GeV, assuming $\lambda \tan \beta \sin(2\psi) \sin \delta = 1$. The current experimental constraint [10] is shown by the horizontal double-line, which has already imposed a constraint on the parameter space of the model.

Similarly, we can obtain the quark EDM by rescaling parameters,

$$\left(\frac{d_{d,s}}{e}\right) = \begin{pmatrix} -\frac{1}{3} \\ -1 \end{pmatrix} \left(\frac{m_{d,s}}{m_e}\right),$$

$$\left(\frac{d_u}{e}\right) = \frac{1}{\tan^2 \beta} \begin{pmatrix} \frac{2}{3} \\ -1 \end{pmatrix} \left(\frac{m_u}{m_e}\right). \tag{18}$$

We can also work out [11] the associated color dipole moment (CDM) d_q^C of the quark q in the effective vertex by replacing color factors and couplings. On the other hand, Ref. [2] has

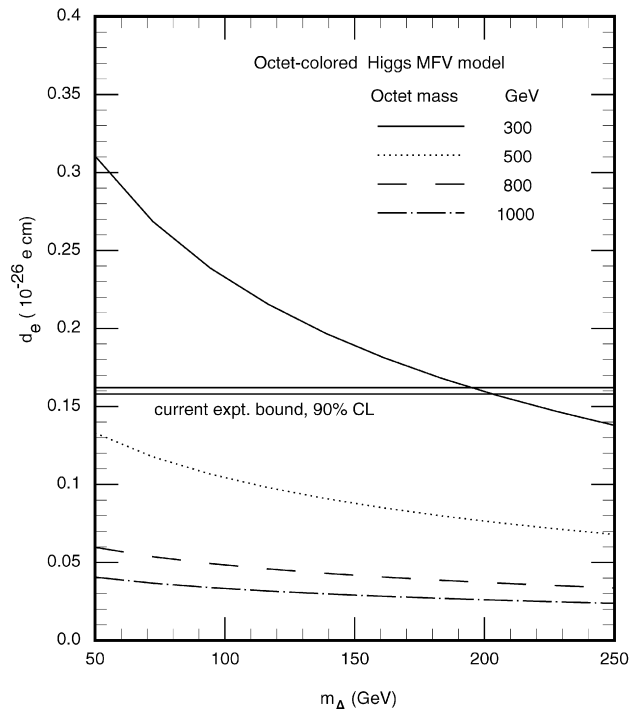


Fig. 2. Predicted electron EDM versus m_A for various $m_O = 300$ (solid), 500 (dotted), 800 (dashed), 1000 (dashed-dotted) GeV, with $\lambda \tan \beta \sin(2\psi) \sin \delta = 1$. The horizontal double-line is the present experimental upper bound.

studied the contribution of the color octet to the gluon dipole [12], known as the Weinberg operator [13], which is subjected to large renormalization suppression [14–16]. Due to the sophisticated hadron physics, we only have a qualitative relation between the neutron EDM and the CP violating coefficients, mainly based on naive dimensional analysis [17]. On the contrary, the electron EDM is well predicted because it is independent of the hadronic structure.

4. Conclusion

The octet-colored scalars if exist will be copiously produced [2,18–20] by LHC in coming years because of its strong interaction and its larger color representation. When their masses and couplings are determined, the electron EDM measurement is the key to disclose its nature of the CP violation. The flavor changing processes in Kaon and B systems involve the octet Yukawa coupling η_u which does not appear in our electron EDM study. The hadronic flavor physics has been studied in details by Manohar and Wise [2], who showed that the current measurements can be made compatible to the added octet Higgs sector. We demonstrate in this Letter that the electron EDM measurement is sensitive to an orthogonal set of CP parameters in the self coupling of octet-colored scalars.

Acknowledgements

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