Lepton electric dipole moments in supersymmetric type II seesaw model

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Abstract

We study the lepton electric dipole moments in the framework of the supersymmetric type II seesaw model where the exchange of heavy $SU(2)_W$ triplets generates small neutrino masses. We show that the CP violating phase of the bilinear soft supersymmetry breaking term associated with the $SU(2)_W$ triplets contributes to lepton electric dipole moments mainly through threshold corrections to the gaugino masses at the seesaw scale. As a consequence, the ratio of the electric dipole moments of the muon and the electron is the same as the ratio of their masses in a wide region of parameter space.
The electric dipole moments (EDMs) of leptons, nucleons and atoms are important probe for physics beyond the Standard Model. Until now, however, no EDMs has been observed experimentally and only upper limits of them have been obtained [1, 2]. It is known that the upper limits on EDMs strongly constrain CP violating parameters of the new physics sector. In particular, supersymmetric (SUSY) extensions of the Standard Model are the most promising candidates for the physics beyond the Standard Model. The minimal version of them are usually referred to as the Minimal Supersymmetric Standard Model (MSSM). In the framework of the MSSM, new sources of CP violation are introduced in terms of soft SUSY-breaking parameters and are severely constrained by the upper limits on EDMs [3].

Recent neutrino observations tell us the neutrinos have nonzero but tiny masses. The seesaw mechanism [4] is an attractive idea to explain their smallness, in which their masses are generated through the exchange of heavy fields. There are three types of seesaw models depending on the nature of the heavy fields. In the type I model, three generations of gauge singlet fermions (right-handed neutrinos) with large Majorana masses are introduced. The type II model [5] includes heavy SU(2)W triplets. Heavy SU(2)W triplet fermions are introduced in the type III model [6].

In the framework of SUSY seesaw models, newly introduced superpotential and soft SUSY breaking terms associated with the heavy fields may contain CP violating phases which contribute to the EDMs of leptons and quarks. Thus the current bounds and future measurements of the EDMs can provide us with information of physics at the seesaw scale. The lepton EDMs in the framework of the SUSY type I seesaw models have been studied by many authors [7, 8, 9]. In particular, Farzan [8] studied effects of the bilinear soft SUSY breaking terms (B terms) of heavy right-handed sneutrinos. It was shown that CP violating imaginary part of the B term contributes to trilinear coupling (A term) of slepton and Higgs fields through the threshold correction at the seesaw scale, and eventually generates lepton EDMs. A similar effect in the SUSY type II seesaw model was studied by Chun, Masiero, Rossi and Vempati [10], where the B term of heavy SU(2)W triplet fields contributes to the slepton A term in the same way as in the type I case. However, the B term affects not only the slepton A term but also the SU(2)W × U(1)_Y gaugino masses in the context of the type II seesaw model [11].

In this Letter, we study the effects of the triplet B term on lepton EDMs in the SUSY type II seesaw model taking account of the contribution from
the gaugino masses as well as that from the slepton $A$ term. We show that the former is more important than that from the latter. As a result, the ratio of muon EDM to electron EDM is given by $d_\mu/d_e \simeq m_\mu/m_e$ in a wide region of parameter space. In Ref. [10], where only the effect from the slepton is considered, it is argued that the lepton EDM ratios are determined by the neutrino parameters. Our result is different from that of Ref. [10] because the contribution from the gaugino masses turns out to be generally larger than that from the slepton $A$ term.

First, we briefly review the SUSY type II seesaw model. We follow the conventions of the SUSY Les Houches Accord [12] for the MSSM sector. The superpotential of the model is given by

$$W = \epsilon_{ab} \left( Y_{ij} H_1^a L_i^b \bar{E}_j + Y_{ij}^H H_1^a Q_i^b \bar{D}_j - Y_{ij}^U H_2^a Q_i^b \bar{U}_j - \mu H_1^a H_2^b \right)$$

$$+ \frac{1}{\sqrt{2}} Y_{ij}^L L_i^a T^{bc} L_j^c + \frac{1}{\sqrt{2}} \lambda_1 H_1^a T^{bc} H_1^c + \frac{1}{\sqrt{2}} \lambda_2 H_2^a T^{bc} H_2^c$$

$$+ M_T \text{tr}(T_1 T_2),$$

(1)

where $Q_i^a$, $L_i^a$, $\bar{E}_i$, $\bar{D}_i$, $\bar{U}_i$, $H_1^a$ and $H_2^a$ denote chiral supermultiplets in the MSSM with the suffixes $a, b, c = 1, 2$ and $i, j = 1, 2, 3$ being $SU(2)_W$ and generation indices, respectively. $T_1$ and $T_2$ are $SU(2)_W$ triplets with hypercharge 1 and $-1$, respectively. By rephasing and rotating the fields, we can take the basis that $Y_E$ is real and diagonal, $\lambda_2$ and $M_T$ are real, $\lambda_1$ is complex and $Y_T$ is a complex symmetric matrix. The relevant soft SUSY breaking terms are given by

$$\mathcal{L}^{\text{soft}} = -\epsilon_{ab} \left( A^H_{ij} H_1^a \tilde{L}_i^b \tilde{e}_{Rj}^* + A^D_{ij} H_1^a \tilde{Q}_i^b \tilde{d}_{Rj}^* - A^U_{ij} H_2^a \tilde{Q}_i^b \tilde{U}_{Rj}^* - B_H \mu H_1^a H_2^b \right)$$

$$+ \frac{1}{\sqrt{2}} A^H_{ij} \tilde{L}_i^a T^{bc} \tilde{L}_j^c + \frac{1}{\sqrt{2}} A^D_{ij} \tilde{Q}_i^a T^{bc} \tilde{H}_1^c + \frac{1}{\sqrt{2}} A^U_{ij} \tilde{Q}_i^a T^{bc} \tilde{H}_2^c + \text{h.c.} \right)$$

$$- \left( M_T B_T \text{tr}[T_1 T_2] + \text{h.c.} \right) + \frac{1}{2} \left( M_1 \tilde{b} \tilde{b} + M_2 \tilde{\nu} \tilde{\nu} + \text{h.c.} \right)$$

$$- (m_L^2)_{ij} \tilde{L}_i^a \tilde{L}_j^a + \cdots .$$

(2)

Here, $H_{1,2}^a$ and $T_{1,2}^{bc}$ denote scalar components of the chiral multiplets which are given by the same notations in (1). $\tilde{Q}_i^a$, $\tilde{L}_i^a$, $\tilde{e}_{Rj}^*$, $\tilde{d}_{Rj}^*$ and $\tilde{U}_{Rj}^*$ are scalar components of $Q_i^a$, $L_i^a$, $\bar{E}_i$, $\bar{D}_i$ and $\bar{U}_i$, respectively. $\tilde{b}$ and $\tilde{\nu}$ are $U(1)_Y$ and $SU(2)_W$ gaugino fields, respectively. To avoid large flavor changing neutral
current effects, we assume that the soft SUSY breaking mass terms are universal at a high energy scale $M_G = 2 \times 10^{16}$ GeV and that the $A$ terms are proportional to the corresponding Yukawa couplings ($A^{ij}_E = a_0 Y^{ij}_E$ etc.) at $M_G$. In the following, we denote the universal scalar mass by $m_0$ and the constant proportionality by $a_0$. We also assume that gaugino masses are universal at $M_G$ and are given by $m_{1/2}$.

Under these boundary conditions, there remain three CP violating phases that contribute to the EDMs: phases of $\mu$, $a_0$ and $B_T$. The phases of $m_{1/2}$ and $B_{H\mu}$ are rotated away without loss of generality. Different CP violating sources contribute to lepton EDMs in different ways. Effects of the phases of $\mu$ and $a_0$ have been studied in detail in the literature \[14\]. Here we study the effect of $B_T$ as a new source of CP violation and assume $\mu$ and $a_0$ to be real parameters.

The tiny neutrino masses are generated through the exchange of the triplet fields, which is given by

$$ (m_\nu)_{ij} = \frac{\lambda_2}{M_T} \left( \frac{v_2}{\sqrt{2}} \right)^2 (Y_T)_{ij}. \quad (3) $$

$v_2$ is the vacuum expectation value of $H_2$ field. The matrix $m_\nu$ can be diagonalized by the Maki-Nakagawa-Sakata (MNS) matrix \[15\]:

$$ \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}) = m_{\nu}^{\text{diag}} = U_{\text{MNS}} m_\nu U_{\text{MNS}}^T, \quad (4) $$

where the matrix $U_{\text{MNS}}$ is defined as

$$ U_{\text{MNS}} = V \text{diag}(e^{-i\phi_2}, e^{-i\phi'_2}, 1), \quad (5) $$

where $\phi$ and $\phi'$ are CP violating Majorana phases and $V$ is given by

$$ V = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}. \quad (6) $$

We have abbreviated $\sin \theta_{ij}$ and $\cos \theta_{ij}$ as $s_{ij}$ and $c_{ij}$, respectively. Hereafter

\[1\] Strictly speaking, $M_G$ is not the “GUT scale” since the existences of the $T_1$ and $T_2$ spoil the gauge coupling unification. We take these boundary conditions for technical simplicity. A model with grand unification constructed by embedding $T_{1,2}$ into $SU(5)$ multiplets is considered in Refs. \[13\] \[11\].
we use the following parameters:

\[
\begin{align*}
\Delta m^2_{21} &= m^2_{\nu_2} - m^2_{\nu_1} = 8.0 \times 10^{-5} \text{eV}^2, \\
|\Delta m^2_{32}| &= |m^2_{\nu_3} - m^2_{\nu_2}| = 2.5 \times 10^{-3} \text{eV}^2, \\
\sin \theta_{12} &= 0.56, \quad \sin \theta_{23} = 0.71, \quad \sin \theta_{13} = 0.01, 
\end{align*}
\]

(7)

and assume that \( m_{\nu_1} \sim 0 \text{eV} \) which corresponds to the normal hierarchy of the neutrino masses. We take the values of \( \Delta m^2_{21} \), \( |\Delta m^2_{32}| \), \( \sin \theta_{12} \) and \( \sin \theta_{23} \) from Ref. [16]. Note here that \( Y^T Y_T \) can be written as follows,

\[
(Y^T Y_T)_{ij} \approx \left( \frac{0.01}{\lambda_2} \right)^2 \left( 1 + \tan^2 \beta \right)^2 \left( \frac{|M_T|}{10^{13} \text{GeV}} \right)^2 \left( \sum_k m^2_{\nu_k} U^k_{\text{MNS}} U^k_{\text{MNS}}^\ast \right) \left( \frac{10^{-3} \text{eV}^2}{10^{-13} \text{eV}^2} \right),
\]

(8)

where we have substituted \( 246 \text{ GeV} \) into the vacuum expectation value \( v = \sqrt{v_1^2 + v_2^2} \) and the \( \tan \beta \) is defined by the ratio of the vacuum expectation values of the two Higgs fields: \( \tan \beta = v_2/v_1 \). In the type II seesaw model, the Yukawa coupling \( Y_T \) is directly related to the neutrino masses and the MNS matrix in contrast to the type I seesaw model.

We calculate lepton EDMs in the SUSY type II seesaw model with use of the following procedure. We solve the renormalization group equations for the parameters in the SUSY type II seesaw model from \( M_G \) scale to \( M_T \) with the input parameters \( m_0, a_0 \) and \( m_{1/2} \) at \( M_G \)2. Next, at \( M_T \) scale, we calculate one-loop threshold corrections for the matching of the parameters in the SUSY type II seesaw model and those in the MSSM as an effective theory in the low energy scale. Then the renormalization group equations for the MSSM parameters are solved down to the electroweak scale to evaluate masses and mixing matrices of the SUSY particles. Finally we calculate the lepton EDMs with chargino-sneutrino and neutralino-charged slepton one-loop diagrams.

The \( B_T \) term contributes to the threshold corrections only at the \( M_T \) scale where the triplet fields \( T_{1,2} \) are integrated out. There are two main contributions from \( B_T \): threshold corrections to the \( A \) terms and those to the gaugino masses. The threshold correction to the slepton \( A \) term, denoted by \( \delta A_E \), is generated through the diagrams shown in Fig. [1] Keeping auxiliary

\[1\text{The renormalization group equations that we have used agree with the relevant part of those given in Ref. [17].}\]
fields as independent fields \[9\], we can easily calculate the correction \(\delta A_E\):

\[
\delta A_E = \frac{3}{16\pi^2} B_T(Y_T Y_T^\dagger + |\lambda_1|^2)Y_E. \quad (9)
\]

Since \(T_1\) and \(T_2\) fields have \(SU(2)_W \times U(1)_Y\) gauge charges, threshold corrections to the electroweak gaugino masses \(M_{1,2}\) are generated. One-loop correction terms proportional to \(B_T\) are induced by the diagram shown in Fig. 2. We obtain the threshold corrections \(\delta M_1\) and \(\delta M_2\) as

\[
\delta M_1 = -\frac{6}{16\pi^2} g'^2 B_T, \quad (10)
\]
\[
\delta M_2 = -\frac{4}{16\pi^2} g^2 B_T. \quad (11)
\]

CP violating imaginary part of \(B_T\) contributes to the lepton EDMs through these threshold corrections.

Figure 2: One-loop Feynman diagram which gives threshold corrections to the gaugino masses.
Figure 3: One-loop diagrams contributing to lepton EDMs.

Let us examine the effects from $\delta A_E$ and $\delta M_{1,2}$ on the lepton EDMs. Lepton EDMs are induced by the one-loop diagrams shown in Fig. 3. Contributions of $B_T$ through the neutralino-charged slepton diagram (Fig. 3(a)) are schematically given by

$$d_i \text{Im} A_E \sim \frac{eg^2}{(16\pi^2)^2 M^4_{\text{SUSY}}} \text{Re} M_i [(Y_T Y_T^\dagger)_i] + |\lambda_1|^2 \text{Im} B_T,$$

$$d_i \text{Im} M_1 \sim \frac{eg^2}{(16\pi^2)^2 M^4_{\text{SUSY}}} m_{e_i} (\mu g^2 \tan \beta) \text{Im} B_T,$$

where $d_i \text{Im} A_E$ and $d_i \text{Im} M_1$ are contributions of $\delta A_E$ and $\delta M_1$, respectively. $M_{\text{SUSY}}$ means a typical scale of SUSY particle masses in the loop. Contribution of $B_T$ in the chargino-sneutrino diagram (Fig. 3(b)) through $\delta M_2$ is given by

$$d_i \text{Im} M_2 \sim \frac{eg^2}{(16\pi^2)^2 M^4_{\text{SUSY}}} m_{e_i} (\mu g^2 \tan \beta) \text{Im} B_T.$$

We can see that the flavor dependence of the lepton EDMs induced by $d_i \text{Im} A_E$ and $d_i \text{Im} M_1$ in Eqs. 12 and 13 and the term proportional to $|\lambda_1|^2$ in Eq. 12 comes only from the lepton mass in the overall factor. On the other hand, the term proportional to $(Y_T Y_T^\dagger)_i$ in Eq. 12 has extra lepton flavor dependence determined by the neutrino masses and mixings. Therefore, if the contribution from $(Y_T Y_T^\dagger)_i$ dominates, the ratios of the lepton EDMs differ significantly from the corresponding lepton mass ratios. Otherwise, the lepton EDM ratios are approximately equal to the lepton mass ratios. In Ref. [10], it is argued that the ratios of EDMs are given by

$$\frac{d_i}{d_j} \sim \frac{m_{e_i}}{m_{e_j}} \frac{(Y_T Y_T^\dagger)_ii}{(Y_T Y_T^\dagger)jj},$$
taking the contribution from Eq. (12) into account with the assumption $|\lambda_1|^2 \ll Y_T Y_T^\dagger$. If this relation is valid, we obtain $d_\mu/d_e \sim 10^4$ and $d_\tau/d_\mu \sim 17$ substituting the neutrino parameters shown in Eq. (7) for the normal hierarchy of neutrino masses. However, since the contributions from Eq. (13) and Eq. (14) are missing in Ref. [10], we calculate lepton EDMs including all the contributions in the following.

In this model, it is known that the branching ratios of the lepton flavor violating (LFV) processes such as $l_i \to l_j \gamma$ decays can be large because of new source of lepton flavor mixing $Y_T$ [13]. Therefore, we calculate the branching ratios of $l_i \to l_j \gamma$ as well as the lepton EDMs. Since the $l_i \to l_j \gamma$ processes are induced by one-loop diagrams of charginos (neutralinos) and sleptons, the branching ratios $\text{Br}(l_i \to l_j \gamma)$ are proportional to $|(m_L^2)_{ij}|^2$. In the SUSY type II seesaw model, the off-diagonal elements of $m_L^2$ are mainly generated by the running between the $M_G$ and $M_T$ scales, which are roughly estimated as

\[ (m_L^2)_{ij} \sim -\frac{m_0^2}{16\pi^2} (Y_T^\dagger Y_T)_{ij} \ln \frac{M_G^2}{M_T^2}. \]

In the numerical calculations, this effect is implicitly included in the process of solving renormalization group equations. We also take account of threshold corrections at $M_T$, which turn out to be smaller than Eq. (16) by a factor of $\ln(M_G/M_T)$.

We show our numerical results of the branching ratio of $\mu \to e\gamma$, the EDMs of electron ($d_e$), muon ($d_\mu$) and tau ($d_\tau$), and the ratio of $d_\mu$ and $d_e$ as functions of $\lambda_2$ evaluated at $M_T$ scale for three cases of $M_T = 10^{12}$, $10^{13}$ and $10^{14}$ GeV in Fig. 4. We fix other input parameters as $\lambda_1 = 0$, $\tan \beta = 3$, $m_0 = m_{1/2} = 300$ GeV, $a_0 = 0$ GeV and $\text{Re}B_T = \text{Im}B_T = 100$ GeV. We take the Higgsino mass parameter $\mu$ as $\mu > 0$. In Figs. 4(a) and 4(b), current upper bounds of the branching ratio of $\mu \to e\gamma$, $\text{Br}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ [18] and the electron EDM $|d_e| < 1.6 \times 10^{-27}$ e cm [1] are shown, respectively. Since $Y_T$ is determined from $M_T$, $\lambda_2$ and the neutrino parameters (7) by Eq. (3), a large (small) $\lambda_2$ corresponds to small (large) $Y_T$ for a fixed $M_T$. The lower limit of $\lambda_2$ in each plot is determined by the conditions that $Y_T$ remains finite up to $M_G$ and the slepton masses squared are positive at the electroweak scale. The upper limit of $\lambda_2$ is set by the condition that $\lambda_2$ does not blow-up below $M_G$. We can see that the ratio $d_\mu/d_e$ is around 200 except for the lower end of $\lambda_2$ in each curve, but never becomes $10^4$ as predicted in Eq. (15). The reason why $d_\mu$ and $d_\mu/d_e$ grow at the smallest values of $\lambda_2$ is that the mass of the lightest slepton which couples to muon rather
Figure 4: (a) The branching ratio of $\mu \to e\gamma$, (b) the electron EDM, (c) the muon EDM, (d) the tau EDM and (e) the ratio of the muon EDM to the electron EDM as functions of $\lambda_2$ for $\lambda_1 = 0$, $\tan \beta = 3$, $m_0 = m_{1/2} = 300$ GeV, $a_0 = 0$ GeV and $\text{Re} B_T = \text{Im} B_T = 100$ GeV. Black and gray solid lines and dashed lines are for $M_T = 10^{12}, 10^{13}$ and $10^{14}$ GeV, respectively. The input value of $\lambda_{1,2}$ and $B_T$ are given at the scale $M_T$ while those of $m_0, m_{1/2}$ and $a_0$ are given at the scale $M_G$. 
than electron rapidly decreases due to the large $Y_T$ as shown in Fig. 5. This result implies that the contributions from $\delta M_{1,2}$ are much larger than that from $\delta A_E$ in the whole parameter region. As seen in Fig. 5(a), $\text{Br}(\mu \to e\gamma)$ exceeds the current experimental upper limit in the region where $d_{\mu}/d_e$ deviates from the lepton mass ratio $m_{\mu}/m_e$. This is because $\text{Br}(\mu \to e\gamma)$ is enhanced by the large splitting among the slepton masses due to the large $Y_T$. Consequently, after the experimental constraint on $\text{Br}(\mu \to e\gamma)$ is imposed, $d_{\tau}/d_e \approx m_{\mu}/m_e$ is satisfied in allowed parameter region. As for $d_{\tau}$, we obtain $d_{\tau}/d_{\mu} \approx m_{\tau}/m_{\mu} \approx 17$ in the whole parameter region. We also calculate the branching ratios of $\tau \to \mu\gamma$ and $\tau \to e\gamma$. We confirm that $\text{Br}(l_i \to l_j\gamma)$ are controlled by the neutrino parameters as discussed in Refs. [13, 10, 11], since the LFVs are determined by $Y_T$ in this model.

In Fig. 6, we show the branching ratio of the $\mu \to e\gamma$ decay, $d_e$, $d_{\mu}$, $d_{\tau}$ and $d_{\mu}/d_e$ as functions of the lightest charged slepton mass $m_{\tilde{e}_1}$. We vary $m_0$ within $100 \text{ GeV} \leq m_0 \leq 1000 \text{ GeV}$ and fix other parameters as $\lambda_1 = 0$, $\lambda_2 = 0.03$, $M_T = 10^{12} \text{ GeV}$, $a_0 = 0 \text{ GeV}$, $\text{Re}B_T = \text{Im}B_T = 100 \text{ GeV}$. For $\tan \beta$ and $m_{1/2}$, we take the cases with $\tan \beta = 3$, $30$ and $m_{1/2} = 300, 600 \text{ GeV}$. We see that the relation $d_{\mu}/d_e \approx m_{\mu}/m_e$ holds in all cases.

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3 We confirmed that the same results are obtained in the case we drop the contribution from $\delta A_E$ by hand. In the case we drop the contribution from $\delta M_{1,2}$ by hand, we can reproduce the results of the Ref. [10].

4 We have also calculated SUSY contribution to the muon anomalous magnetic moment $a_{\mu} = (g_{\mu} - 2)/2$. Within the parameter space we have searched for, we obtain $0 \lesssim a_{\mu}(\text{SUSY}) \lesssim 40 \times 10^{-10}$ in the case of $\mu > 0$. This result is consistent with current experimental value [20].
Figure 6: (a) The branching ratio of $\mu \to e\gamma$, (b) the electron EDM, (c) the muon EDM, (d) the tau EDM and (e) the ratio of the muon EDM to the electron EDM as functions of the lightest charged slepton mass $m_{\tilde{e}_1}$ for $\lambda_1 = 0$, $\lambda_2 = 0.03$, $M_T = 10^{12}$ GeV, $a_0 = 0$ GeV and $\text{Re}B_T = \text{Im}B_T = 100$ GeV. Black and gray solid lines are for $(\tan \beta, m_{1/2}) = (3, 300 \text{ GeV})$ and $(3, 600 \text{ GeV})$, respectively, while black and gray dashed lines are for $(\tan \beta, m_{1/2}) = (30, 300 \text{ GeV})$ and $(30, 600 \text{ GeV})$, respectively.
In this Letter, we have studied leptonic EDMs in the SUSY type II seesaw model including all contributions generated by one-loop threshold corrections to SUSY breaking parameters at the seesaw scale through the bilinear soft SUSY breaking term of the $SU(2)_W$ triplet fields. We have shown that the ratios of the leptonic EDMs are given by those of the lepton masses in a good approximation for most of parameter space. We have presented numerical results for some specific cases, but this conclusion holds unless fine tuning of parameters is made. For instance, we have checked that the same conclusion is valid for the case of $\lambda_1 \neq 0$ or other types of neutrino mass hierarchy. We have also relaxed the relation $M_1 = M_2$ at the GUT scale and found that the ratios of the EDMs do not change even if we varied $M_1/M_2$ within the range $1/10 \leq M_1/M_2 \leq 10$. This result suggests that muon EDM is predicted to be 200 times larger than the electron EDM in the SUSY type II seesaw model, which is contrasted with the type I model where the relation is more complicated because the $B$ term phase contributions to the EDMs depend on neutrino Yukawa couplings. Since the upper bound of the electron EDM is at the level of $10^{-27} \text{e cm}$, planned dedicated experiments of the muon EDM search at the level of $10^{-24} - 10^{-25}$ are very important.

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