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ORIGINAL PAPER

Low-energy CP violation and leptogenesis in a minimal seesaw model

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Abstract

We investigate whether CP phases in the neutrino mixing matrix can be the source of the CP violation necessary to achieve leptogenesis. In general, low-energy CP violation in the neutrino sector is not directly linked to leptogenesis, but we show that the low-energy leptonic CP violation can give rise to the CP asymmetry required for leptogenesis in a minimal seesaw model where the Dirac neutrino mass matrix contains one-zero texture. Performing numerical analyses based on the current results of the global fit to neutrino data and the measurement of baryon asymmetry, we study how the CP phases in the neutrino mixing matrix can be constrained and show how lepton asymmetry is sensitive to two heavy Majorana neutrino masses as well as CP phases. From the constraints on the neutrino parameters, the values of the effective neutrino mass contributing to the amplitude of neutrinoless double beta decay are predicted.

Keywords CP violation · Leptogenesis · Minimal seesaw model

1 Introduction

Thanks to the enormous number of neutrino experiments, we have been able to determine three neutrino mixing angles in neutrino mixing matrix. The remaining unknown parameters in the neutrino mixing matrix are CP violating phases. Thus, establishing leptonic CP violation (LCPV) is one of the most challenging tasks for future neutrino experiments [1]. Although we do not yet have compelling evidence for LCPV, the current global fit to available neutrino data indicates nontrivial values for the Dirac-type CP phase [2]. Recent measurements from T2K and MINOS indicate a preference for CP violation (CVP) with around 1.5π for the Dirac-type CP phase at 1σ confidence level (C.L.) [3–6]. Much attention has been paid to the prediction of the Dirac-type LCPV phase with regards to some observables [7–27]. Recently, it has been shown [28–30] that Dirac-type leptonic CP phase can be particularly predictable in terms of two neutrino mixing angles in the standard parameterization of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) mixing matrix [31–35]. If neutrinos are Majorana particles, the PMNS mixing matrix will contain two more CP phases, in general. Those Majorana CP phases are not measurable through neutrino oscillations, but can be probed through neutrinoless double beta decay [36].

Baryogenesis through leptogenesis demands new source of CPV in lepton sectors [37]. From the perspective of leptogenesis, examining whether the low-energy leptonic CP phases can be sources of the CPV required for successful leptogenesis in the type-I seesaw framework is worthwhile. As will be shown later, in general, the low-energy CP phases are not directly related with leptogenesis, which is obvious from the description of the Dirac neutrino mass matrix in terms of the neutrino mixing matrix, an orthogonal matrix and diagonal mass matrices of light and heavy Majorana neutrinos in the type-I seesaw mechanism, which is the so-called Casas–Ibarra parametrization [38]. From the parameterization, one can see that the CPV necessary to achieve leptogenesis depends only on the CP phases in the orthogonal matrix, which are totally unknown.

In this work, we propose a scenario in which the orthogonal matrix in the Casas–Ibarra parameterization can be presented in terms of the entries in the PMNS mixing matrix and two neutrino masses. The model we consider is the so-called minimal seesaw model with two heavy Majorana neutrinos [39–43]. In the minimal seesaw model, one of the light neutrino masses should be zero and only one Dirac and one Majorana phase generically survive, so the model is very predictive because of the small number of independent parameters compared with the canonical seesaw model

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with three heavy Majorana neutrinos [44–51]. Inspired by the idea of the calculability of the quark mixing angles in terms of the quark masses suggested by Weinberg a long time ago [52], we introduce one-zero texture in the Dirac neutrino mass matrix and then show how the CP phases in the PMNS mixing matrix can be the source of CPV in leptogenesis. Carrying out numerical analyses based on the current results of the global fit to neutrino data, we show how the unknown parameters are constrained by confronting our predictions with the measurement for baryon asymmetry. From the constraints on the parameters, we also predict the so-called effective light neutrino mass which contributes to the amplitude of neutrinoless double beta decay [36] .

This paper is organized as follows: In Sect. 2, we investigate whether low-energy leptonic CP phases can give rise to the CP asymmetry in leptogenesis. In Sect. 3, we briefly review the minimal seesaw model and show how two CP phases in the PMNS mixing matrix are directly related to leptogenesis. In Sect. 4, we present the results of the constraints on the parameter space from a numerical analysis and the prediction of the effective neutrino mass contributing to the amplitude of neutrinoless double beta decay. We finally conclude in Sect. 5.

2 CP phases in the PMNS mixing matrix and leptogenesis

One of the important questions concerning leptogenesis is "Are the CP phases in the PMNS mixing matrix responsible for leptogenesis?". To get the answer to this question, we examine how leptogenesis in the type-I seesaw model depends on the neutrino parameters. The Lagrangian for the lepton sector of the type-I seesaw model is given by [39–41]

$$-\mathcal{L} = Y_{li}\overline{l_{Li}}\phi^0 l_{Rj} + Y_{\nu ij}\overline{\nu_{Li}}\phi^0 N_{Rj} + \frac{1}{2}\overline{(N_R)^c}_i M_j N_{Rj}, \tag{1}$$

where $i, j = 1, 2, 3$, and Y_ν is a 3×3 complex matrix. l_{Li}, l_{Ri}, ν_{Li}, and N_{Ri} stand for left-handed, right-handed charged leptons, left-handed neutrino and right-handed Majorana neutrino, respectively. For our purpose, we take a basis for which heavy Majorana neutrino mass matrix M is diagonal and the charged lepton Yukawa matrix Y_l is real and diagonal.

From the seesaw mechanism [53–57], the effective light neutrino mass matrix is given by

$$m_{\rm eff} = Y_\nu \frac{1}{M} Y_\nu^T v^2, \tag{2}$$

where $v =< \phi^0 >$ is the vacuum expectation value of Higgs scalar. The effective neutrino mass matrix $m_{\rm eff}$ can be diagonalized by using the PMNS mixing matrix given as follows [34, 35]:

$$\begin{aligned} U_{\rm PMNS} =& UP_\beta \\ =& \begin{pmatrix} c_{12}c_{13} & -s_{12}c_{13} & -s_{13}e^{i\delta_D} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{-i\delta_D} & c_{12}c_{23} + s_{12}s_{23}s_{13}e^{-i\delta_D} & -s_{23}c_{13} \\ s_{12}s_{23} + c_{12}c_{23}s_{13}e^{-i\delta_D} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{-i\delta_D} & c_{23}c_{13} \end{pmatrix} P_\beta, \end{aligned} \tag{3}$$

where P_β is 3×3 phase matrix given by Diag. $[e^{i\beta_1}, e^{i\beta_2}, e^{i\beta_3}]$. Among the three phases in P_β, one is removable, in general. Then, the following relation holds:

$$m_{\rm eff} = U^*_{\rm PMNS} m^D_\nu U^\dagger_{\rm PMNS}, \tag{4}$$

where m^D_ν is a diagonal neutrino mass matrix presented by Diag. $[m_1, m_2, m_3]$.

Leptogenesis realized in the type-I seesaw model requires CPV in the decay of a heavy Majorana neutrino into a left-handed lepton and the Higgs scalar, which originates from the nontrivial CP phases in the Yukawa matrix Y_ν. The lepton asymmetry ε_i is given explicitly as [58–60]

$$\varepsilon_i = \frac{\sum_j[\Gamma(N_i \to l_j\phi^*) - \Gamma(N_i \to \bar{l}_j\phi)]}{\sum_j[\Gamma(N_i \to l_j\phi^*) + \Gamma(N_i \to \bar{l}_j\phi)]} = \frac{1}{8\pi}\frac{\sum_{j\neq i} \mathrm{Im}\,[(Y_\nu{}^\dagger Y_\nu)_{ij}]^2}{(Y_\nu{}^\dagger Y_\nu)_{ii}} g(x), \tag{5}$$

where $g(x) = \sqrt{x}[1/(1-x) + 1 - (1+x)\ln((1+x)/x)]$, with $x = |M_i^2/M_j^2|$. It is well known that the Dirac neutrino Yukawa matrix can be presented using the Casas–Ibarra parameterization as follows [38]:

$$Y_\nu = \frac{1}{v} U^*_{\rm PMNS}\sqrt{m^D_\nu} O \sqrt{M}, \tag{6}$$

where $\sqrt{m^D_\nu} =$ Diag. $[\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}]$, $\sqrt{M} =$ Diag. $[\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}]$ and O is a 3×3 complex orthogonal matrix that is totally unknown. Putting Eq. (6) into Eq. (5), one can easily see that ε_i depends not on $U_{\rm PMNS}$ but on the complex orthogonal matrix O. The result shows that the CPV required for canonical leptogenesis originates not from the CP phases in $U_{\rm PMNS}$, but from new CP phases contained in O. Thus, the measurement of CPV through low-energy experiments, such as neutrino oscillations and neutrinoless double beta decay, may not be direct hint for canonical leptogenesis. However, that is not always true. Rather, leptogenesis can be realized with CP phases in $U_{\rm PMNS}$ in a specific model. In this work, we will show that the CP phases in $U_{\rm PMNS}$ are the source of the CPV necessary to achieve leptogenesis in a minimal seesaw model with one-zero texture in the Dirac neutrino mass matrix.

3 Minimal seesaw model

The minimal seesaw model (MSM) is an extension of the standard model (SM) with two heavy right-handed Majorana neutrinos [39–43]. The Lagrangian for the lepton sector of the MSM after electroweak symmetry breaking is given by [39–43]

$$-\mathcal{L} = \overline{l_{iL}} m_{l_i} l_{iR} + \overline{\nu_{Li}} m_{Dij} N_{Rj} + \frac{1}{2}\overline{(N_{Rj})^c} M_j N_{Rj}, \quad (7)$$

where $i = 1, 2, 3,\ j = 1, 2$ and the Dirac neutrino mass term m_D is a 3×2 complex matrix. Here, we take a basis for which heavy Majorana neutrino mass matrix M is diagonal, and the charged lepton mass matrix m_l is real and diagonal. Since the generic $n \times n$ Dirac neutrino mass matrix contains $3n - 3$ unremovable CP phases if n singlet heavy Majorana neutrinos are introduced in this basis, at least two singlet heavy Majorana neutrinos are necessary to break CP symmetry [42, 43]. That is why we call this the MSM.

The effective light neutrino mass matrix obtained from the seesaw mechanism is given by

$$m_{\mathrm{eff}} = m_D \frac{1}{M} m_D^T, \quad (8)$$

where $1/M =$ Diag. $[1/M_1, 1/M_2]$. We can diagonalize m_{eff} using U_{PMNS}. Obviously one of the three light neutrino masses is zero in the MSM. For the normal hierarchy (NH) of the neutrino mass spectrum, $m_1 = 0$ whereas $m_3 = 0$ for the inverted hierarchy (IH). Thus, the lighter neutrino mass is a solar neutrino oscillation scale $\sqrt{\Delta m^2_{\mathrm{sol}}}$ whereas the heavier neutrino mass is an atmospheric neutrino oscillation scale $\sqrt{\Delta m^2_{\mathrm{atm}}}$. Thanks to this fact, only one phase in P_β, which is denoted as δ_M, is unremovable. Explicitly, $(m_{\mathrm{eff}})_{ij}$ can be written in terms of the entries of U_{PMNS} and the light neutrino masses as follows:

$$(m_{\mathrm{eff}})_{ij} = \begin{cases} (U^*_{\mathrm{PMNS}})_{i2}(U^*_{\mathrm{PMNS}})_{j2} m_2 + (U^*_{\mathrm{PMNS}})_{i3}(U^*_{\mathrm{PMNS}})_{j3} m_3, & \text{for NH} \\ (U^*_{\mathrm{PMNS}})_{i1}(U^*_{\mathrm{PMNS}})_{j1} m_1 + (U^*_{\mathrm{PMNS}})_{i2}(U^*_{\mathrm{PMNS}})_{j2} m_2, & \text{for IH}\,. \end{cases} \quad (9)$$

From Eqs. (4) and (8), one can obtain the relation [38]

$$m_D \frac{1}{\sqrt{M}} O^T = U^*_{\mathrm{PMNS}} \sqrt{m^D_\nu}, \quad (10)$$

where O is a 2×2 complex orthogonal matrix that is totally unknown, and the zero column on the right-hand side of Eq. (10) due to a zero mass eigenvalue of m^D_ν is ignored. We parameterize O in terms of two complex variables x and y as follows:

$$O = \begin{pmatrix} x & y \\ -y & x \end{pmatrix}. \quad (11)$$

The construction of the neutrino mass matrix is necessary for model building, which, in turn, may unravel the underlying dynamics of the generation of neutrino masses, mixing and CPV. A long time ago, Weinberg proposed that the so-called "Cabibbo mixing angle", the mixing angle between the d-quark and the s-quark, could be predicted in terms of the ratio of two quark masses, m_d and m_s, at leading order by assuming that the mixing mass term $\bar{d}_L d_R$ in a weak basis is *zero* whereas the other mixing mass terms are nonzero [52]. Taking the *zeros* in the fermion mass matrix or fermion Yukawa matrix has been well known to make the mixing parameters predictive. In this context, the zero texture approach has been widely followed in the literature. In particular, the two-zero texture has been relatively more successful in both the flavor, as well as the non-flavor, basis [61–69]. Following this idea, we propose an ansatz that one entry of the Dirac neutrino mass matrix m_D is *zero*. As will be shown, the ansatz causes the CP phases in U_{PMNS} to become the source of the CPV required for leptogenesis. Without loss of generality, among the six possible entries in the Dirac neutrino mass matrix, we study only the case in which the (1,1) entry of m_D is zero. Zeros for the other entries do not alter the main conclusion in this work. Then, from Eq. (10), the requirement of $(m_D)_{11} = 0$ leads to the following relation,

$$y = \frac{(U_{\mathrm{PMNS}})_{12}\sqrt{m_2}}{(U_{\mathrm{PMNS}})_{13}\sqrt{m_3}} x. \quad (12)$$

Applying the orthogonality of the matrix O, we finally obtain

$$x^2 = \frac{(U_{\mathrm{PMNS}})^2_{13} m_3}{(U_{\mathrm{PMNS}})^2_{12} m_2 + (U_{\mathrm{PMNS}})^2_{13} m_3}, \quad (13)$$

$$y^2 = \frac{(U_{\mathrm{PMNS}})^2_{12} m_2}{(U_{\mathrm{PMNS}})^2_{12} m_2 + (U_{\mathrm{PMNS}})^2_{13} m_3}. \quad (14)$$

We see from Eqs. (13) and (14) that the orthogonal matrix can be parameterized using the PMNS mixing matrix and light neutrino masses, so leptogenesis in this scenario depends only on the CP phases measurable in low-energy experiments such as neutrino oscillations and neutrinoless double beta decay. In the end, the Dirac neutrino mass matrix in the weak basis can be written as

Table 1 Three neutrino mixing angles and the Dirac-type CP phase from the latest global fit to neutrino data at 1σ [2]

	best-fit $\pm$ 1σ NH	best-fit $\pm$ 1σ IH
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.575^{+0.017}_{-0.021}$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02240^{+0.00062}_{-0.00062}$
$\delta_D/^\circ$	195^{+51}_{-25}	286^{+27}_{-32}

Note that we only take the results of the global fit to the data without SK atmospheric data

$$m_D = \begin{pmatrix} (W_{12}x - W_{13}y)\sqrt{M_1} & (W_{12}y + W_{13}x)\sqrt{M_2} \\ (W_{22}x - W_{23}y)\sqrt{M_1} & (W_{22}y + W_{23}x)\sqrt{M_2} \\ (W_{32}x - W_{33}y)\sqrt{M_1} & (W_{32}y + W_{33}x)\sqrt{M_2} \end{pmatrix}, \tag{15}$$

where $W_{i2} = (U_{\rm PMNS})_{i2}\sqrt{m_2}$ and $W_{i3} = (U_{\rm PMNS})_{13}\sqrt{m_3}$. Inserting Eq. (15) into Eq. (5), we can predict the CP asymmetry ε_i in terms of three neutrino mixing angles; two CP phases in $U_{\rm PMNS}$; and two light neutrino masses m_1, m_2 and two heavy neutrino masses M_1, M_2. Among them, the two heavy neutrino masses and a Majorana type CP phase δ_M are totally unknown. For the Dirac type CP phase δ_D, although it has not yet been measured, a possible range derived from the recent result of the global fit analysis, which will be used to calculate ε_i in our numerical analysis, is known to exist. Since we consider that leptogenesis is generated by the decay of the lightest Majorana neutrino N_{R1} under the assumption $M_1 < M_2$, taking into account ε_1 in our study is sufficient.

On the other hand, the light neutrino masses, the mixing angles and the CP phases in $U_{\rm PMNS}$ may affect the amplitude of $\nu 0\beta\beta$, which is proportional to $|\sum_i U_{ei}^2 m_i|$ explicitly presented as follows [36]:

$$|\sum_i U_{ei}^2 m_i| \equiv M_{ee} = \begin{cases} \left|m_2 s_{12}^2 c_{13}^2 + m_3 s_{13}^2 e^{-2i(\delta_D+\delta_M)}\right|, & \text{for NH} \\ c_{13}^2\left|m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\delta_M}\right|, & \text{for IH}. \end{cases} \tag{16}$$

For NH, M_{ee} depends on both δ_D and δ_M whereas only δ_M contributes to M_{ee} for IH. Since s_{13}^2 is quite small, we expect the amplitude for IH to be much larger than that for NH.

In the next section, we numerically study how the unknown parameters in the MSM can be constrained by the measurement of the baryon asymmetry and the recent results of the global fit to neutrino data. Using constraints on the CP phases, we also show how the values of M_{ee} can be predicted.

4 Numerical results

We numerically analyze how the independent parameters discussed above are constrained. For our numerical analysis, we adopt the latest result for the three neutrino mixing angles and the Dirac-type CP phase δ_D as inputs taken from the global fit to neutrino data at the 1σ C.L. [2], which are explicitly presented in Table 1. For two light neutrino masses, we use the best fit results, $\Delta m_{21}^2 = 7.4\times10^{-5}$ eV^2 for the solar mass scale and $|\Delta m_{31(2)}^2| = 2.415\times10^{-3}$ eV^2 for the atmospheric mass scale.

The measured value of the ratio of the baryon asymmetry to the photon number density, η_B, is given by [70]

$$\eta_B = \frac{n_B - n_{\bar B}}{n_\gamma} = (8.65 \pm 0.085)\times10^{-11}, \tag{17}$$

where $n_{B(\bar B)}$ and n_γ are the baryon (anti-baryon) number density and the photon number density, respectively. Following Ref. [18], the asymmetry η_B can be explicitly given as

$$\eta_B = \frac{3}{4}\frac{a_{sph}}{f}\varepsilon_i \kappa_f(K_i) \quad K_i = \frac{\Gamma_D}{H(M_i)} \quad (i=1,2), \tag{18}$$

where we have taken the values of a_{sph} and f presented in Ref. [18] and

$$\begin{aligned} \Gamma_D &= \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi}M_1, \\ H(T) &= \sqrt{\frac{4\pi^3 g_*}{45}}\frac{T^2}{M_{pl}}, \\ z_B(K_i) &= 1 + \frac{1}{2}\ln\left(1 + \frac{\pi K_i^2}{1024}\left[\ln\left(\frac{3125\pi K_i}{1024}\right)\right]^5\right), \\ \kappa_f(K_i) &= \frac{2}{z_B(K_i)K_i}\left(1 - \exp\left\{-\frac{1}{2}z_B(K_i)K_i\right\}\right). \end{aligned} \tag{19}$$

The parameter κ_f is the so-called efficiency factor, which is studied in Refs. [21, 22], and g_* is the number of relativistic particles after the decay of N_{Ri} is decoupled [71]. In our numerical analysis, we use the analytic fits for κ_f explicitly presented in Ref. [18] without solving the complicated Boltzmann equations which are in good approximations to the actual solutions.

In this work, we first calculate η_B by scanning three neutrino mixing angles and δ_D for the range of 1σ C.L. from the results of the global fit and δ_M from 0 to 2π for fixed values of M_1 and M_2. Then, comparing the numerical results for η_B with the experimental results given by Eq. (17), we obtain allowed regions of parameter space. From our numerical analysis, we have found that leptogenesis works only for

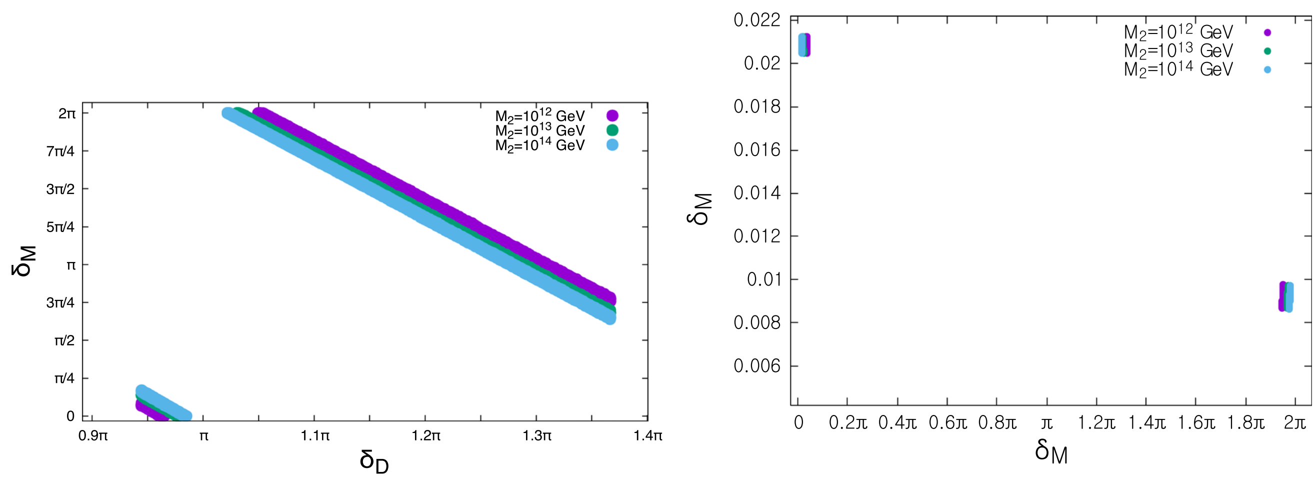

Fig. 1 Allowed region of parameter space (δ_D, δ_M). Left (Right) panel corresponds to $M_1 = 10^{10}$ ($M_2 = 10^{13}$) GeV. The purple, green and light blue regions correspond to $M_2 = 10^{12}$ GeV, 10^{13} GeV and 10^{14} GeV in the left panel and to $M_1 = 5 \times 10^{10}$ GeV, 10^{11} GeV and 10^{12} GeV in the right panel, respectively

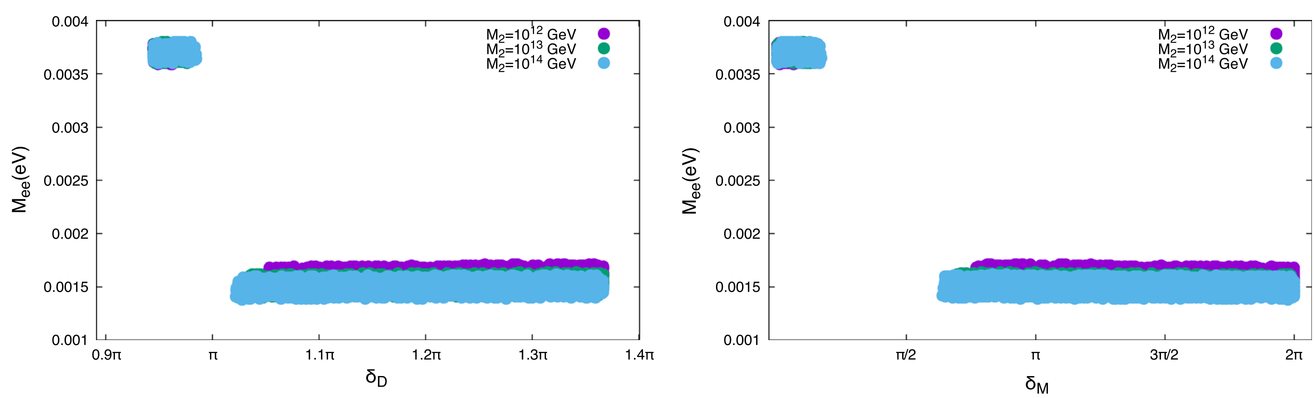

Fig. 2 Prediction of M_{ee} (eV) in terms of δ_D (left panel) and δ_M (right panel) for the allowed regions of parameters obtained in Fig. 1. The meanings of the colors are the same as in Fig. 1

$M_1 > 5 \times 10^9$ GeV and that the results are almost independent of M_2 for $M_2 \gtrsim 100M_1$.[1] Thus, for the sake of simplicity, we keep $M_2 = 100M_1$ in our analysis.

4.1 Case of NH

Figure 1 shows the allowed region of parameter space (δ_D, δ_M) for a fixed $M_1 = 10^{10}$ GeV (left panel) and for a fixed $M_2 = 10^{13}$ GeV (right panel) in the case of NH of the neutrino mass spectrum. The purple, green and light blue regions correspond to $M_2 = 10^{12}$ GeV, 10^{13} GeV and 10^{14} GeV in the left panel and to $M_1 = 5 \times 10^{10}$ GeV, 10^{11} GeV and 10^{12} GeV in the right panel, respectively. The results show that small values of $\delta_M (< \pi/4)$ are allowed for $\delta_D < \pi$ and that δ_M decreases from 2π as δ_D increases in the range $\pi < \delta_D < 1.4\pi$. Comparing both panels, we see that leptogenesis in this scenario is more sensitive to M_1 than M_2. For a given δ_D, a smaller δ_M for $\delta_M > \pi$ and a larger one for $\delta_M < \pi$ are allowed as M_1 increases. We also see from Fig. 1 that some regions of δ_M are excluded, for instance, $\pi/4 < \delta_M < \pi/2$ for the cases of $M_2 = 10^{14}$ GeV (left panel) and $M_1 = 10^{11}$ GeV (right panel).

Figure 2 shows how the values of M_{ee} are predicted in terms of δ_D (left panel) and δ_M (right panel) for the allowed

[1] The lepton asymmetry can be resonantly enhanced when M_2 approaches M_1 for $M_2 < 100M_1$. The study for this case is beyond the scope of this work.

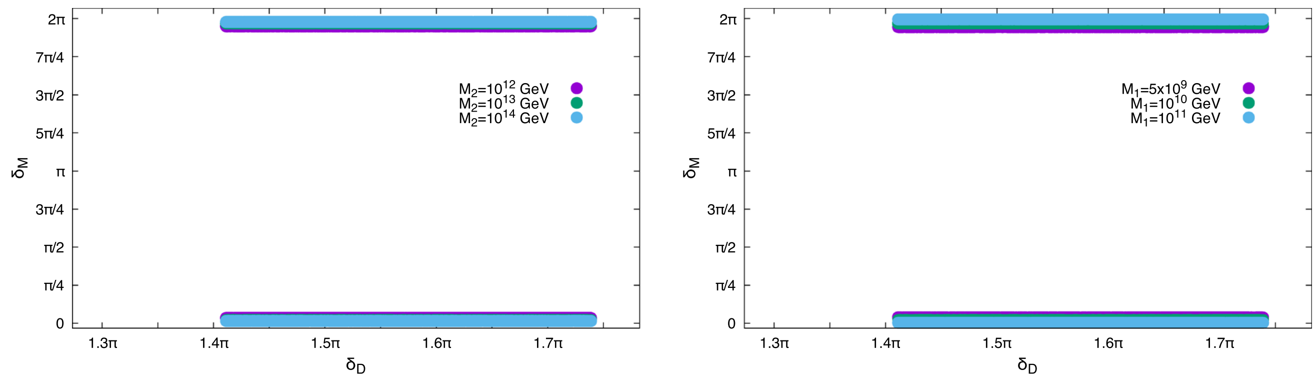

Fig. 3 Allowed region of parameter space (δ_D, δ_M). Left (Right) panel corresponds to $M_1 = 10^{10}$ ($M_2 = 10^{13}$) GeV. The purple, green and light blue regions correspond to $M_2 = 10^{12}$ GeV, 10^{13} GeV and 10^{14} GeV in the left panel and to $M_1 = 5 \times 10^{10}$ GeV, 10^{11} GeV and 10^{12} GeV in the right panel, respectively

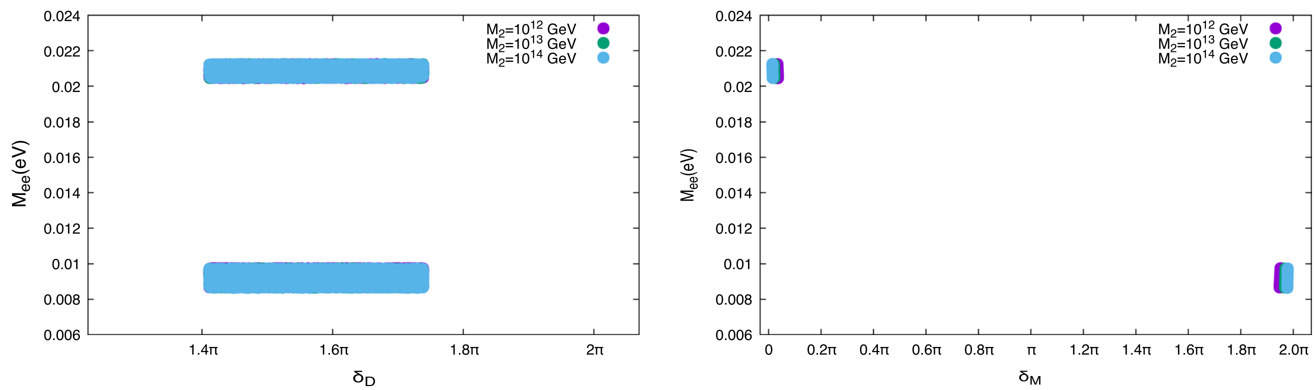

Fig. 4 Prediction of M_{ee} (eV) in terms of δ_D (left panel) and δ_M (right panel) for the allowed regions of parameters obtained in Fig. 3

regions of the parameters obtained in Fig. 1. As expected, M_{ee} is insensitive to M_1 and M_2. Since M_{ee} depends on a combination of δ_D and δ_M, as can be seen in Eq. (16), the shapes of the predicted regions in both panels are the same. Smaller values of $\delta_D(\delta_M)$ lead to larger values of M_{ee}.

4.2 Case of IH

In the case of IH, because $m_3 = 0$, δ_D affects neither leptogenesis nor the amplitude of neutrinoless double beta decay. In Fig. 3, we plot the allowed region of parameter space (δ_D, δ_M) for fixed $M_1 = 10^{10}$ GeV (left panel) and $M_2 = 10^{13}$ GeV (right panel). The meanings of the colors in the plots are the same as in Fig. 1. Figure 4 shows how the values of M_{ee} are predicted in terms of δ_D (left panel) and δ_M (right panel) for the allowed regions of parameters obtained in Fig. 3. In Figs. 3 and 4, we see that the allowed regions obtained from the constraint on ε_1 are independent of δ_D. Only the regions near $\delta_M = 0, 2\pi$ are allowed. In addition, the results are insensitive to the heavy Majorana neutrino masses. As expected, the predicted values of M_{ee} for IH are much larger than those for NH.

5 Conclusion

In this work, we have addressed whether the LCPV measurable through low-energy experiments such as neutrino oscillations and neutrinoless double beta decay can be responsible for the CP asymmetry necessary to achieve leptogenesis. In general, low-energy CPV is not directly linked to leptogenesis, but we have shown that the low-energy CP phases in U_{PMNS} can be the source of the CP asymmetry required for leptogenesis in the minimal seesaw model where the Dirac neutrino mass matrix contains one-zero texture. Performing numerical analyses based on the current results of the global fit to neutrino data at 1σ, we have obtained allowed regions of the two CP phases in U_{PMNS} by comparing our calculations with the measurement of baryon asymmetry, and we discuss how they depend on two heavy Majorana neutrino masses. From the constraints on the neutrino parameters, we have studied how the values of M_{ee}, which contributes to the amplitude of neutrinoless double beta decay, are predicted in terms of CP phases.

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