Towards the minimal seesaw model for the prediction of neutrino CP violaion

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Abstract

We discuss the minimal seesaw model for the Dirac CP violating phase of the lepton mixing matrix. We introduce two right-handed Majorana neutrinos and obtain several textures of the tri-maximal lepton mixing matrices. Moreover, we discuss the observed baryon asymmetry of the universe through the leptogenesis mechanism. As the result, we obtain the specific model which predicts the negative sign of maximal Dirac CP violating phase and normal hierarchy of neutrino masses.

1 Our minimal seesaw model

The remarkable developments in the neutrino oscillation experiments fuel our expectations for the future discovery of CP violation in the lepton sector. Indeed, recent T2K data strongly indicate the CP violation [1]. In order to discuss the theoretical aspects of the CP violation in the lepton sector, we investigate the minimal seesaw model via the CP violation and baryon asymmetry of the universe (BAU). Here, we briefly explain how to build our minimal seesaw model.

- The minimal seesaw model includes two heavy right-handed Majorana neutrinos and three left-handed neutrinos in Type I seesaw [2]. We take both the charged lepton and right-handed Majorana neutrino mass matrix M_R to be real diagonal. M_R and the Dirac neutrino mass matrix M_D are generally written as

$$M_R = -M_2 \begin{pmatrix} p^{-1} & 0 \\ 0 & 1 \end{pmatrix}, \quad M_D = \begin{pmatrix} a & d \\ b & e \\ c & f \end{pmatrix}, \quad p = M_2/M_1 \tag{1}$$

the neutrino mass matrix is obtained by the Type I seesaw:

$$M_\nu = -M_D M_R^{-1} M_D^T = \frac{1}{M_0} \begin{pmatrix} a^2p + d^2 & abp + de & acp + df \\ abp + de & b^2p + e^2 & bcp + ef \\ acp + df & bcp + ef & c^2p + f^2 \end{pmatrix}. \tag{2}$$

- We consider the lepton mixing matrix in the two frameworks of tri-maximal mixing, TM_1 and TM_2 which are derived from additional rotation of 2-3 and 1-3 plane to the tri-bi-maximal lepton mixing [3, 4] respectively. The following textures of Dirac neutrino mass matrices realize the tri-maximal lepton mixing:

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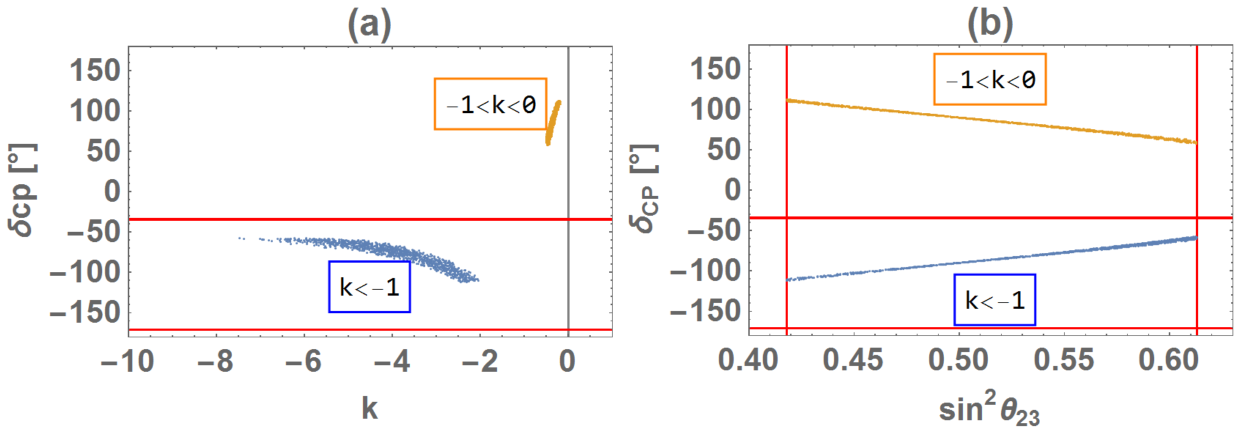

Figure 1: Predictions in case I, where the blue and orange dots denote the region of $k < -1$ and $-1 < k < 0$. The red lines for $\sin^2\theta_{23}$ and δ_{CP} denote the experimental bounds of 3σ (global analyses) and 2σ (T2K) ranges, respectively: (a) δ_{CP} versus k, (b) δ_{CP} versus $\sin^2\theta_{23}$.

$$M_D = \begin{pmatrix} \frac{b+c}{2} & \frac{e+f}{2} \\ b & e \\ c & f \end{pmatrix}, \quad \begin{pmatrix} -2b & \frac{e+f}{2} \\ b & e \\ b & f \end{pmatrix}, \quad \begin{pmatrix} b & -(e+f) \\ b & e \\ b & f \end{pmatrix}, \tag{3}$$

where they realize TM_1 for normal hierarchy (NH), TM_1 for inverted hierarchy (IH) and TM_2 for either NH or IH of neutrino masses respectively.

- We can discuss the BAU through the leptogenesis mechanism [5] in the decay of lighter right-handed neutrino M_1 only for the TM_1 with NH texture since only this texture produces the finite interference term between tree and 1 loop diagrams of the M_1 decay.

Therefore, we focus on the texture of TM_1 with NH in the following. In order to minimize our model, we impose zero in this texture. The following three types of Dirac neutrino mass matrices are possible.

$$M_D^{\mathrm{I}} = \begin{pmatrix} 0 & \frac{e+f}{2} \\ b & e \\ -b & f \end{pmatrix}, \quad M_D^{\mathrm{II}} = \begin{pmatrix} \frac{b}{2} & \frac{e+f}{2} \\ b & e \\ 0 & f \end{pmatrix}, \quad M_D^{\mathrm{III}} = \begin{pmatrix} \frac{c}{2} & \frac{e+f}{2} \\ 0 & e \\ c & f \end{pmatrix} \tag{4}$$

2 Numerical analysis

We discuss the correlation between the predicted CP violating phase δ_{CP} and the BAU through the leptogenesis. Our analysis about the leptogenesis mainly follows a simple framework [6] which is valid under the condition, $M_1 \ll M_2$ and $M_1 \ll 10^{14}$[GeV].

Here, we discuss the numerical results of TM_1 with NH. We use the recent neutrino oscillation data from NuFIT 3.2 (2018) [7] for the input data. According to this global experimental data, the numerical results from M_D^{II} and M_D^{III} are excluded from 3σ C.L.. Therefore, we only show the results of M_D^{I} in Figure 1. The results reflect the constraint from not only the recent neutrino oscillation data but also the observed BAU, $\eta_B \simeq [5.8, 6.6] \times 10^{-10}$ 95%C.L. [8]. These predictions are calculated in the case of $M_2 = 10^{14}$GeV. But the correlations in Figure 1 are independent of M_2. We note that the ratio of right-handed neutrino masses $p = M_2/M_1$ is allowed ,roughly speaking, within $p = [200 \sim 300]$ ($p = [2000 \sim 3000]$) for $M_2 = 10^{14}$[GeV] ($M_2 = 10^{15}$[GeV]).

Let's discuss the left panel of Figure 1. We show the $k = e/f$ dependence of the predicted δ_{CP} by inputting the observed BAU. It is remarked that δ_{CP} is predicted to be negative for $k < -1$ while it is positive for $-1 < k < 0$. The negative and maximal CP violation $\delta_{CP} \sim -\pi/2$ is realized around $k \sim -3$.

In the right panel of Figure 1, we show the predicted correlation between δ_{CP} versus $\sin^2\theta_{23}$. It indicates an important feature of this model: The maximal CP violation and mixing angle $(\delta_{CP}, \theta_{23}) = (-\pi/2, \pi/4)$ can be realized for $k < -1$ simultaneously, which is favored if we take account of the current data and future prospects.

3 Summary and discussions

We have studied the correlation between the CP violating phase δ_{CP} and the observed BAU in the minimal seesaw model, where two right-handed Majorana neutrinos are assumed. We have also taken the tri-maximal mixing pattern for the neutrino flavor (TM_1 or TM_2) in the diagonal basis of both the charged lepton and right-handed Majorana neutrino mass matrices. We have found the clear correlation between the CP violating phase δ_{CP} and BAU for TM_1 in NH of neutrino masses. The parameter k should be smaller than -1 in order to predict a negative δ_{CP}, which is indicated by the recent T2K data. It is emphasized that our Dirac neutrino mass matrix predicts the negative sign of δ_{CP} and the observed value of BAU as far as we take $k < -1$ under the condition, $M_1 \ll M_2$.

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The full references are available in [arXiv:1709.02136] and [arXiv:1711.03863].