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CP violation and Leptogenesis in Minimal Seesaw Model

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We propose a highly predictive framework of minimal seesaw model where leptogenesis can originate from leptonic CP violating phases measureable in low energy experiments. We examine the implication of current neutrino data on leptogenesis realized in the scheme we consider. We also discuss how neutrinoless double beta decay can be correlated with leptogenesis.

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1. Introduction

While CP is violated in quark sector, it is a mistery if CP is violated in lepton sector. Thanks to the various neutrino oscillation experiments performed for about two decades, we could determine three neutrino mixing angles in the neutrino mixing matrix. The only unknown parameters in the neutrino mixing matrix are a Dirac type CP phase and two more possible Majorana phases if neutrinos are Majorana particles. The not-so-small mixing angle θ_{13} measured from reactor experiments opens up new window to search for CP violation through neutrino oscillation experiments. While the Dirac type CP phase is measureable through neutrino oscillation experiments, the Majarana CP phases can be probed through lepton number violating processes such as neutrinoless double beta decay. Establishing leptonic CP violation (LCPV) is one of the most challenging tasks in future neutrino experiments [1]. Recent measurements from T2K and MINOS indicate a preference on CP violation with 1.5π of Dirac-type CP phase at 1σ C.L. [2, 3]. Concerned with leptonic CP violation, an important question would be how the low energy leptonic CP violation impacts on resolving some problems in particle physics and cosmology.

The origin of baryon asymmetry observed from astrophysical and cosmological observations is one of the unsolved problems in particle physics and cosmology. Since the standard model (SM) of particle physics fails to account for the amount of baryon asymmetry observed, we must rely on new physics beyond the SM to explain it. Among various attempts for the origin of baryon asymmetry, leptogenesis proposed by Fukugida and Yanagida [4] has been attracted much attention mainly because it is realized in the context of seesaw model that was invented for explaining why neutrino masses are tiny compared to other fermions. To realize leptogenesis, new source of CP violation is demanded, and thus it would be interesting to investigate whether low energy CP phases in the neutrino mixing matrix can be responsible for leptogenesis or not.

The purpose of this talk is to examine how leptogenesis can be related to the low energy CP violation by determining the parameters as many as possible from available low energy experimental results and cosmological observations. It is likely that there is no conection between low energy CP violation and leptogenesis via canonical seesaw model with three heavy right-handed neutrinos without any specific assumptions because of many unknown parameters. In order to make a quantitative analysis of the connection between low energy leptonic CP violation and leptogenesis, we consider a *minimal* CP violating seesaw model (MSM) which has two heavy Majorana neutrinos and three light left-handed neutrinos [5]. The MSM is consistent with recent data of neutrino oscillations, more constrained and predictive compared with the general seesaw models with three heavy right-handed neutrinos [6]. For our purpose, we assume that 3×2 Dirac Yukawa matrix contains a texture zero which gives rise to a connection between low energy and high energy parameters. We will show how leptogenesis can depend on low energy CP phases. In addition to the low energy CP phases, leptogenesis is sensitive to the lighter Majorana neutrino mass M_1 for a scenario with hirarchical heavy Majorana masses. Imposing the recent observation of matter-antimatter asymmetry, we can get some bounds on M_1 for the scenario of the hierachical Majorana mass spectrum. We will also show how the amplitude of neutrinoless double beta decay is predicted for the allowed region of parameter space obtained from baryogenesis. Finally, we will present the potential implication of the best fit value of Dirac CP phase $\delta_{\rm CP} \sim 1.5\pi$ on the MSM.

2. Leptogenesis and neutrinoless double beta decay in MSM

Let us begin our study by considering the leptonic sector of the MSM. In a basis where both heavy Majorana and charged lepton mass matrices are real and diagonal, the Lagrangian is given by [5]:

$$\mathscr{L} = -\overline{l_{iL}} m_{l_i} l_{iR} - \overline{\nu_{Li}} m_{Dij} N_{Rj} - \frac{1}{2}\overline{(N_{Rj})^c} M_j N_{Rj}, \tag{2.1}$$

where $i = 1,2,3,\ j = 1,2$ and the Dirac mass term m_D is a 3×2 complex matrix. Here, we remark that the Dirac mass matrix m_D contains $3N-3$ unremovable CP phases if we take N singlet heavy Majoran neutrinos in this basis. Thus, one can easily see that at least two singlet heavy Majorana neutrinos are required to break CP symmetry in the seesaw model with three lepton $SU(2)$ doublets. From the seesaw mechanism, the effective light neutrino mass matrix is given by $m_{eff} = m_D \frac{1}{M} m_D^T$, where $M = \text{Diag.}[M_1, M_2]$. The neutrino mass matrix, m_{eff}, is diagonalized by 3×3 PMNS mixing matrix U_{PMNS}, [7] and then the following relation holds,

$$m_{eff} = U^*_{\text{PMNS}} m^D_\nu U^\dagger_{\text{PMNS}}, \tag{2.2}$$

where $m^D_\nu = \text{Diag}[m_1, m_2, m_3]$. It is obvious that one of three light neutrino masses is zero in minimal seesaw model. For normal hierarchical neutrino mass spectrum (NH), $m_1 = 0$, whereas $m_3 = 0$ for inverted hierarchical one (IH). Then, m_{eff} can be written in terms of the entries of U_{PMNS} and light neutrino masses as

$$(m_{eff})_{ij} = \begin{cases} U^*_{i2}U^*_{j2}m_2 + U^*_{i3}U^*_{j3}m_3, & \text{for NH} \\ U^*_{i1}U^*_{j1}m_1 + U^*_{i2}U^*_{j2}m_2, & \text{for IH} \end{cases} \tag{2.3}$$

where U_{ij} denotes the (i,j) entry of U_{PMNS}.

Parameterizing 3×2 matrix m_D as follows:

$$m_D = \begin{pmatrix} \sqrt{M_1}a_1 & \sqrt{M_2}b_1 \\ \sqrt{M_1}a_2 & \sqrt{M_2}b_2 \\ \sqrt{M_1}a_3 & \sqrt{M_2}b_3 \end{pmatrix}, \tag{2.4}$$

we can write down m_{eff} as $(m_{eff})_{ij} = a_i a_j + b_i b_j$. From the seesaw mechanism, it holds that [8]

$$m_D \frac{1}{\sqrt{M}} O^T = U^*_{\text{PMNS}} \sqrt{m^D_\nu}, \tag{2.5}$$

where $\sqrt{m^D_\nu} = \text{Diag.}[0, \sqrt{m_2}, \sqrt{m_3}](NH)$, $1/\sqrt{M} = \text{Diag.}[1/\sqrt{M_1}, 1/\sqrt{M_2}]$ and O is 2×2 complex orthogonal matrix that is totally unknown. Note that one of two Majorana phases in U_{PMNS} is reduced because one of three neutrino masses is zero. Parameterizing O in terms of two complex parameters x and y as follows;

$$O = \begin{pmatrix} x & y \\ -y & x \end{pmatrix}, \tag{2.6}$$

we can write down the parameters $a_i, b_i (i = 1,2,3)$ in terms of low energy neutrino parameters U_{ij} and m_i as follows:

$$\text{For NH}: \quad a_i = \sqrt{m_2}U^*_{i2}x + \sqrt{m_3}U^*_{i3}y, \quad b_i = \sqrt{m_2}U^*_{i2}(-y) + \sqrt{m_3}U^*_{i3}x, \tag{2.7}$$

$$\text{For IH}: \quad a_i = \sqrt{m_1}U^*_{i1}x + \sqrt{m_2}U^*_{i2}y, \quad b_i = \sqrt{m_1}U^*_{i1}(-y) + \sqrt{m_2}U^*_{i2}x, \tag{2.8}$$

To present the paramaters a_i, b_i in terms of low energy variables U_{ij} and m_i, we consider a texture zero in m_D. Since m_D is a 3×2 matrix, there are 6 cases for a texture zero.
Case (1): If $b_i = 0$, then we get $x = \sqrt{\frac{m_2}{m_3}\frac{U^*_{i2}}{U^*_{i3}}}y$. Since $x^2+y^2 = 1$, for each cases, $x^2 = \frac{\eta_i}{1+\eta_i}, \quad y^2 = \frac{1}{1+\eta_i}$, with $\eta_i = \frac{m_2}{m_3}\left(\frac{U^*_{i2}}{U^*_{i3}}\right)^2$.
Case (2) : If $a_i = 0$, then we get $y = -\sqrt{\frac{m_2}{m_3}\frac{U^*_{i2}}{U^*_{i3}}}x$. Similar to case (1), we get $x^2 = \frac{1}{1+\eta_i}, \quad y^2 = \frac{\eta_i}{1+\eta_i}$,

Let us estimate lepton number asymmetry. The CP asymmetry required for leptogenesis is given by [9]

$$\varepsilon_1 = \frac{1}{8\pi v^2}\frac{\sum_{i\neq 1}\mathrm{Im}[(m_D^\dagger m_D)_{1i}]^2}{(m_D^\dagger m_D)_{11}}g(x), \tag{2.9}$$

where $g(x) = \sqrt{x}(1/(1-x)+1-(1+x)\ln((1+x)/x))$ with $x = M_2^2/M_1^2$ and $v = 246$ GeV. Depending on the neutrino mass spectrum, we consider two cases, one is normal hirarchy and the other inverted hierachy. The structures of the formulae are the same for both cases except for the subscript indices. We only present the formulae only for the NH case. The formulae for the IH case can be simply obtained by changing the subscript indices 2 and 3 into 1 and 2, respectively. For case (a),

$$\begin{aligned}\sum_{i\neq 1}\mathrm{Im}[(m_D^\dagger m_D)_{1i}]^2 &= M_1M_2(m_3^2-m_2^2)\frac{\mathrm{Im}(\eta_j)}{1+2\mathrm{Re}(\eta_j)+|\eta_j|^2}, \\ \varepsilon_1 &= \frac{M_2}{8\pi v^2}\frac{(m_3^2-m_2^2)}{(m_3+|\eta_j|m_2)}\frac{\mathrm{Im}(\eta_j)}{\sqrt{1+2\mathrm{Re}(\eta_j)+|\eta_j|^2}}g(x).\end{aligned} \tag{2.10}$$

where $j = 1,2,3$ denote $a_j = 0$. Similarily, For case (b),

$$\begin{aligned}\sum_{i\neq 1}\mathrm{Im}[(m_D^\dagger m_D)_{1i}]^2 &= M_1M_2(m_3^2-m_2^2)\frac{\mathrm{Im}(\eta_j^*)}{1+2\mathrm{Re}(\eta_j)+|\eta_j|^2}, \\ \varepsilon_1 &= \frac{M_2}{8\pi v^2}\frac{(m_3^2-m_2^2)}{(m_2+|\eta_j|m_3)}\frac{\mathrm{Im}(\eta_j^*)}{\sqrt{1+2\mathrm{Re}(\eta_j)+|\eta_j|^2}}g(x).\end{aligned} \tag{2.11}$$

where $j = 1,2,3$ denote $b_j = 0$.

Let us present how ε_1 depends on a Dirac CP phase δ_{CP} and a Majorana phase Φ. From eqs.(2.10, 2.11), we see that

$$\varepsilon_1 \propto \quad (\mathrm{NH})\begin{cases} \sin 2(\delta_{\mathrm{CP}}+\Phi) \ : a_1(b_1) = 0 \\ c_{12}^2c_{23}^2\sin 2\Phi - 2c_{12}s_{12}c_{23}s_{23}s_{13}\sin(\delta_{\mathrm{CP}}+2\Phi) \ : a_2 = 0 \\ c_{12}^2s_{23}^2\sin 2\Phi + 2c_{12}s_{12}c_{23}s_{23}s_{13}\sin(\delta_{\mathrm{CP}}+2\Phi) \ : a_3 = 0 \end{cases} \tag{2.12}$$

$$(\mathrm{IH})\begin{cases} \sin 2\Phi \ : a_1(b_1) = 0 \\ c_{12}^2c_{23}^2\sin 2\Phi - 2c_{12}s_{12}c_{23}s_{23}s_{13}\sin(\delta_{\mathrm{CP}}+2\Phi) \ : a_2 = 0 \\ c_{12}^2s_{23}^2\sin 2\Phi + 2c_{12}s_{12}c_{23}s_{23}s_{13}\sin(\delta_{\mathrm{CP}}+2\Phi) \ : a_3 = 0 \end{cases} \tag{2.13}$$

Table 1: Three neutrino mixing parameters from the fit to global data after NOW 2014 conference [13].

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)	
	bfp$\pm$ 1σ	3σ range	bfp$\pm$ 1σ	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$
$\sin^2\theta_{13}$	$0.218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$

Due to complexity, we do not present dependence of the phases for the cases $b_2(b_3) = 0$. From the formulae, we see that the source of CP violation in leptogenesis realized in the scenario is CP phases in the neutrino mixing matrix. It is worhwhile to notice that ε_1 depends not on M_2 but on M_1 in the case of very hierachical heavy Majorana mass spectrum ($M_1 << M_2$), which leads us to a lower bound on M_1 for a given $\delta_{\rm CP}$.

The matter-antimatter asymmetry is presented by

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \kappa\frac{\varepsilon_1}{g_*}, \tag{2.14}$$

where $n_{B(\bar{B})}$and n_γ are baryon (anti-baryon) number density and photon number density, respectively. The parameters κ is so-called washout factor, which is studied in [10], and g_* is the number of relativistic particles after the decay of N_1 is decoupled [11].

Since the Majorana phase Φ affects neutrinoless double beta decay , it is related with leptogenesis. The amplitude of neutrinoless double beta decay is proportional to $|\sum_i U_{ei}^2 m_i|$, which is rewritten as [12]

$$|\sum_i U_{ei}^2 m_i| \equiv |< m_{ee} >| = \begin{cases} m_3 s_{13}^2 |1 + |\eta_1| e^{-2i(\Phi - \delta_{\rm CP})}| & \text{for NH} \\ m_2 c_{13}^2 c_{12}^2 |1 + |\eta_1| e^{-2i(\Phi - \delta_{\rm CP})}| & \text{for IH} \end{cases} \tag{2.15}$$

3. Numerical results

For our numerical analysis, we use the current experimental data for three neutrino mixing angles as inputs taken from Ref. [13], which is given by Table 1. For three neutrino mixing angles, we take their best fit values. The observed value of η_B is given by [14]

$$\eta_B = (8.65 \pm 0.085) \times 10^{-11}. \tag{3.1}$$

In the limit of $M_2 >> M_1$, the independent parameters of η_B are M_1, Φ and $\delta_{\rm CP}$. For our numerical analysis, we take $M_2 = 10^{16}$ GeV, which makes the limit very effective.

Fig. 1 shows how the parameter space (Φ, M_1) for NH cases with fixed values of $\delta_{\rm CP} = 1.4\pi$(blue), 1.5π(red), 1.6π(green) are allowed from (3.1). We see from Fig. 1 that a lower bound on M_1 can be obtained from (3.1) for a given $\delta_{\rm CP}$. The upper (lower) panels correspond to the cases $a_1(b_1) = 0, a_2(b_2) = 0, a_3(b_3) = 0$, respectively, from left to right.

In Fig. 2, we present the allowed region of parameter space (Φ, M_1) for the IH cases. In the plots, we fix $\delta_{\rm CP} = 1.5\pi$. In the left (right) panel, the blue, red and green regions correspond to

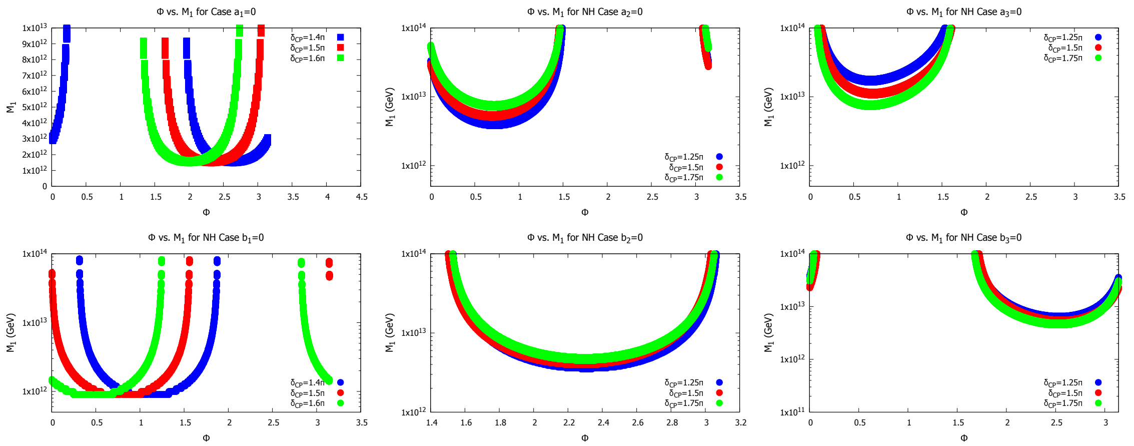

Figure 1: Allowed region of parameter space (M_1, Φ) for NH Cases with fixed values of $\delta_{\rm CP} = 1.4\pi(\text{blue}), 1.5\pi(\text{red}), 1.6\pi(\text{green})$.

$a_1(b_1) = 0, a_2(b_2) = 0, a_3(b_3) = 0$, respectively. We see that the case for $a_1(b_1) = 0$ leads to much lower bound on M_1 compared to the others.

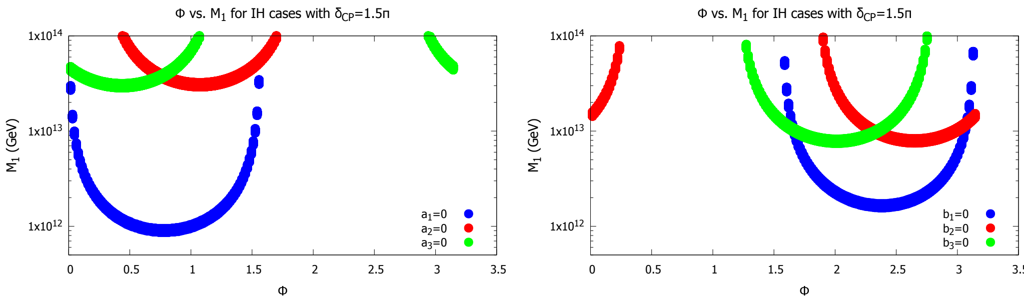

Figure 2: Allowed region of parameter space (Φ, M_1) for the IH cases for $\delta_{\rm CP} = 1.5\pi$. The blue, red and green regions correspond to $a_1 = 0, a_2 = 0, a_3 = 0$, respectively in left pannel and $b_1 = 0, b_2 = 0, b_3 = 0$, respectively in right pannel.

Fig. 3 shows how $| < m_{ee} > |$ is predicted in terms of Φ for the allowed region of parameter space presented in Fig. 1. for the NH cases. The blue, red and green regions correspond to $\delta_{\rm CP} = 1.4\pi(\text{blue}),\ 1.5\pi(\text{red}),\ 1.6\pi(\text{green})$, respectively. The upper (lower) panels correspond to the cases $a_1(b_1) = 0, a_2(b_2) = 0, a_3(b_3) = 0$, respectively, from left to right.

Fig. 4 shows how $| < m_{ee} > |$ is predicted in terms of Φ for the allowed region of parameter space presented in Fig. 2 for the IH cases. The meaning of color is the same as in Fig. 2. Since the blue region is overlapped with the other regions, it is hidden in the plots.

4. Conclusion

We have investigated if low energy CP phases appeared in the neutrino mixing matrix can be responsible for leptogenesis in MSM. By imposing a texture zero in m_D, we see that the entries

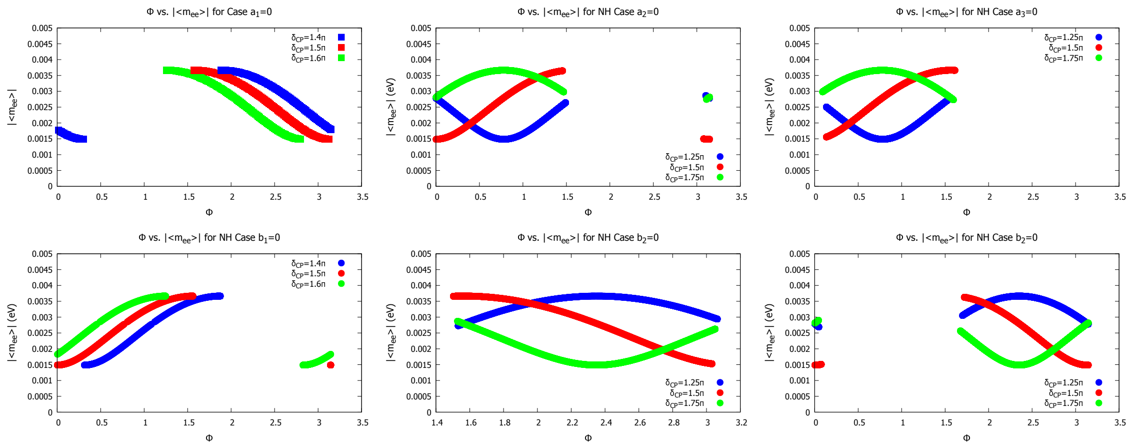

Figure 3: $|<m_{ee}>|$ *vs.* Φ for NH cases with fixed values of $\delta_{\rm CP} = 1.4\pi(\text{blue}), 1.5\pi(\text{red}), 1.6\pi(\text{green})$.

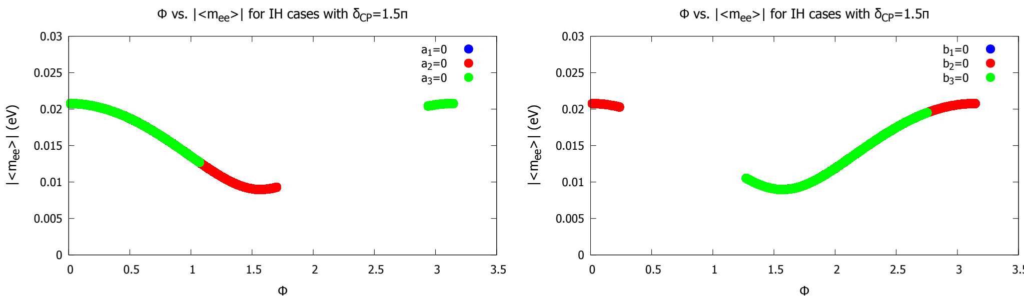

Figure 4: $|<m_{ee}>|$ *vs.* Φ for IH cases with a given values of $\delta_{\rm CP} = 1.5\pi$. The meaning of the colors is the same as in Fig. 2.

in m_D are presented in terms of low energy parameters and two heavy Majorana masses. In the limit of $M_2 >> M_1$, leptogenesis depends on two low energy CP phases and M_1. Imposing the experimental result of matter-antimatter asymmetry, we can get the allowed region of parameter space (Φ, M_1) for a fixed value of $\delta_{\rm CP}$. Lower bounds on M_1 are obtained. For the allowed region of the parameter space, we have estimated how $|<m_{ee}>|$ is predicted in terms of the phase Φ.

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