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Leptogenesis in a perturbative SO(10) model

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Abstract: We consider a phenomenologically viable SO(10) grand unification model which allows perturbative calculations up to the Planck scale or the string scale. We use a set of Higgs superfields $\mathbf{10} + \overline{\mathbf{16}} + \mathbf{16} + \mathbf{45}$. In this framework, the data fitting of the charged fermion mass matrices is re-examined. This model can indeed reproduce the low-energy experimental data relating the charged fermion masses and mixings. As for the neutrino sector, we take the neutrino oscillation data as input data to construct right-handed Majorana neutrino mass matrix and get a prediction for the physics related to the right-handed neutrinos, e.g. the leptogenesis and for the proton decay. We propose two kinds of phenomenologically viable model, quoted as Model 1 and Model 2. We show that one of the models (Model 2) is consistent with all experimental constraints.

Keywords: Beyond Standard Model, Neutrino Physics, GUT.

Contents

1. Introduction

The supersymmetric (SUSY) grand unified theory (GUT) provides an attractive implication for the understandings of the low-energy physics. In fact, for instance, the anomaly cancellation between the several matter multiplets is automatic in the GUT based on a simple gauge group, since the matter multiplets are unified into a few multiplets, the experimental data supports the fact of unification of three gauge couplings at the GUT scale $M_{\rm G} \sim 2 \times 10^{16}$ [GeV] assuming the particle contents of the minimal supersymmetric standard model (MSSM) [1], and also the right-handed neutrino appeared naturally in the SO(10) GUT provides a natural explanation of the smallness of the neutrino masses through the seesaw mechanism [2]. While the SUSY GUT has several nice feature described above, it should be available up to a scale, several order of magnitude above the GUT scale in order to open up a window for really a GUT picture. In other words, we require to have perturbative description of the SUSY GUT up to a cutoff scale, say the Planck scale or the string scale. Once we adopt to have such a landscape, we can not include a large dimensional representations like $\overline{\mathbf{126}} + \mathbf{126}$ of SO(10) as a Higgs since it causes a strongly asymptotic non-free behavior. In addition, a free-field heterotic string theory can never give a $\overline{\mathbf{126}} + \mathbf{126}$ representations [3]. Thus we consider a model based on a set of Higgs with small dimensional representations and we explore the minimal choice of the Higgs superfields which can accommodate the low-energy experimental data. As for the neutrino sector, we take input the neutrino oscillation data and get a prediction for the physics related to the right-handed neutrinos, e.g. the leptogenesis, etc.

Here it needs some comments for the alternative approaches are in order. There could be another possibility which keep the coupling constant perturbative up to some cut-off scale (that could be the string scale or the Planck scale) by including the threshold corrections as shown in refs. [4]. Those approaches are also interesting as the masses of the colored Higgsinos can be raised enough to avoid too rapid proton decay without fine-tuning. However, at least, in this paper, we keep the simple unification picture within the framework of the MSSM particle content at low energy.

Now we think about SO(10) problems again. A very concrete problem we can ask and solve is the followings.

Is there an SO(10) model that has:

(1) Gauge couplings unification similar to MSSM RG analysis.

(2) Perturbative unification up to the string or the Planck scale.

(3) Fit all known phenomenology.

We think this is a very constrained requirement already. To demand perturbative unification up to the string or the Planck scale will require the model is pretty "minimal" for sure. There are two lines of minimal SO(10) model. One uses higher dimensional representation like $\overline{\mathbf{126}}$ and renormalizable [5–8], and the other does not use representations higher than **54** representation but non-renormalizable operators [9]. In order for satisfying the requirement (2) in the above list of questions, we investigate the allowed sets of Higgs superfields by considering their contributions to the beta function coefficient. In general, we have the RG equation for the unified gauge coupling $\alpha_{\rm G}$,

$$\frac{1}{\alpha_{\rm G}(\mu)} = \frac{1}{\alpha_{\rm G}(M_{\rm G})} - \frac{b}{2\pi}\log\left(\frac{\mu}{M_{\rm G}}\right). \tag{1.1}$$

When we set the condition that the coupling constant $\alpha_{\rm G}$ blows up at a scale $\mu = \Lambda$ we have the following condition,

$$\frac{1}{\alpha_{\rm G}(\Lambda)} \;=\; 0, \quad i.e.\ , \quad \frac{2\pi}{\alpha_{\rm G}(M_{\rm G})} \;=\; b\log\left(\frac{\Lambda}{M_{\rm G}}\right). \tag{1.2}$$

If we want to have a perturbative description up to the (reduced) Planck scale $\bar{M}_{\rm pl} = 2.4\times 10^{18}\,$GeV, we get the upper bound on the coefficient b as

$$b \;<\; 34. \tag{1.3}$$

In general, the coefficient b can be written as

$$b \;=\; \sum_{\text{chiral multiplet}} T(\mathbf{R}) - 3\times \underbrace{8}_{\text{vector multiplet}}. \tag{1.4}$$

When we extract the 3 generation matter contributions we have

$$b \;=\; \sum_{\text{Higgs multiplet}} T(\mathbf{R}) + 3\times 2 - 3\times 8. \tag{1.5}$$

So the maximal value for the sum of $T(\mathbf{R})$ is given by

$$\sum_{\text{Higgs multiplet}} T(\mathbf{R}) \;<\; 34-6+24 \;=\; 52. \tag{1.6}$$

IRREP	T($\mathbf{R}$)
10	1
16	2
45	8
54	12
120	28
126	35
210	56

Table 1: List of the Dynkin index for the SO(10) irreducible representations up to the **210** dimensional one

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For example, a set of Higgs multiplets $\left\{\mathbf{10} \oplus \mathbf{10}' \oplus \mathbf{16} \oplus \overline{\mathbf{16}} \oplus \mathbf{45}\right\}$ is allowable from perturbative argument,

$$\sum_{\text{Higgs multiplet}} T(\mathbf{R}) \;=\; \underbrace{1}_{\mathbf{10}\oplus\mathbf{10}'} \times 2 + \underbrace{2}_{\mathbf{16}\oplus\overline{\mathbf{16}}} \times 2 + \underbrace{8}_{\mathbf{45}} \;=\; 14 \;<\; 52. \tag{1.7}$$

In the former minimal SO(10) model including Higgs superpotential [10], the set of Higgs multiplets is given by $\mathbf{10} \oplus \overline{\mathbf{126}} \oplus \mathbf{126} \oplus \mathbf{210}$, thus, in this case, we have a very huge size of the beta function coefficient, $b \;=\; 109$. In this case, the cutoff scale obtained is very close to the GUT scale

$$\Lambda \,=\, M_{\mathrm{G}} \exp\left(\frac{2\pi}{b \times \alpha_{\mathrm{G}}(M_{\mathrm{G}})}\right) \;\simeq\; 4.2 \times M_{\mathrm{G}}. \tag{1.8}$$

So this model is severe but not excluded since we have nothing definite beyond M_G and even M_G itself. Its highly predictivity is deserved to study further. However, in this letter, we consider that the existence of the string or the Planck scale is an reality that one has to accept. So it is actually necessary to include that. It is much more important to see if one can get perturbative unification up to the string or the Planck scale even when higher dimensional operators are included. While there are *a priori* many choices for the Higgs superfields, the predictivity and the perturbativity may pick up some representations. And we explore the minimal choice of the Higgs superfields which can accommodate the low-energy experimental data. As for the neutrino sector, we take input the neutrino oscillation data and get a prediction for the mass matrix of the right-handed neutrinos.

2. Fermion mass matrices

We can consider some possible choices for Higgs representations to be introduced in our SO(10) model. In any case, they should accomplish the following tasks: (1) it can break the SO(10) gauge symmetry down to the standard model one. (2) it can reproduce all the fermion mass matrices being realistic. For the task (1), we give some examples, $\mathbf{45} + \mathbf{54}$, $\mathbf{16} + \overline{\mathbf{16}} + \mathbf{45}$ etc. Considering the second task and the fact that top Yukawa coupling is of order one, it is necessary to introduce, at least, one **10** Higgs representation which can provide a renormalizable Yukawa coupling. Note that **126** Higgs representation is excluded by our criteria of the perturbative unification, since $\mathbf{126} + \overline{\mathbf{126}}$ contributes $b_{\rm Higgs} = 70$. Furthermore, in order to incorporate right-handed neutrino Majorana masses, we need $\overline{\mathbf{16}}$ Higgs, and consider the superpotential

$$W = \frac{1}{M} Y^{ij}_{\overline{16}} \mathbf{16}_i \mathbf{16}_j \overline{\mathbf{16}}_H \overline{\mathbf{16}}_H, \tag{2.1}$$

where M is the cutoff scale of our model, the Planck scale or the string scale, for example. In this paper, we consistently assume that only the singlet in $\overline{\mathbf{16}}_H$ ($\widetilde{\overline{\nu}}_H$) and $\mathbf{16}_H$ ($\widetilde{\nu}_H$) can achieve their VEVs and the doublets never get their VEVs. This assumption is essential to write down the GUT mass relations for the charged fermions. Then we may define our "minimal model" as the one which satisfies all the above requirements and contributes $b_{\rm Higgs}$ as small as possible. The most reasonable candidate is the choice with $\mathbf{10} + \mathbf{16} + \overline{\mathbf{16}} + \mathbf{45}$ Higgs multiplets.

With these Higgs multiplets, the superpotential relevant to the fermion mass matrices is given by (up to dimension 5 terms)

$$\begin{aligned} W \;=\; & Y^{ij}_{10} \mathbf{16}_i \mathbf{16}_j \mathbf{10}_H \;+\; \frac{1}{M} Y^{ij}_{45} \mathbf{16}_i \mathbf{16}_j \mathbf{10}_H \mathbf{45}_H & (2.2)\\ & + g_i \mathbf{16}_i \overline{\mathbf{16}}\, \mathbf{45}_H \;+\; h_i \mathbf{16}_i \mathbf{16}\, \mathbf{10}_H & (2.3)\\ & + \tilde{g}\, \mathbf{16}\, \overline{\mathbf{16}}\, \mathbf{45}_H \;+\; \tilde{h}\, \mathbf{16}\, \mathbf{16}\, \mathbf{10} \;+\; \tilde{f}\, \overline{\mathbf{16}}\, \overline{\mathbf{16}}\, \mathbf{10}_H & (2.4)\\ & + M_{10} \mathbf{10}_H^2 \;+\; M_{16} \mathbf{16}_H \overline{\mathbf{16}}_H \;+\; M_{45} \mathbf{45}_H^2 \;+\; \lambda \mathbf{16}_H \overline{\mathbf{16}}_H \mathbf{45}_H \;, & (2.5) \end{aligned}$$

where the Yukawa coupling matrices Y_{10} is symmetric, while Y_{45} is antisymmetric. Here, an extra vector like $\{\mathbf{16} + \overline{\mathbf{16}}\}$-multiplet with no subscript represents an extra matter multiplet, whose matter parity is assigned to be odd, so that the Yukawa coupling given in eqs. (2.2)–(2.5) becomes invariant under the matter parity.

Note that the $\mathbf{16}_i$ and $\mathbf{16}$ do mix with each other. So, in general, the Yukawa couplings can be written as

$$\begin{aligned} W &= \left(\mathbf{16}_i,\, \mathbf{16},\, \overline{\mathbf{16}} \right) \begin{pmatrix} Y_{ij} \mathbf{10}_H & (h_i/2)\, \mathbf{10}_H & (g_i/2)\, \mathbf{45}_H \\ (h_j/2)\, \mathbf{10}_H & \tilde{h} \mathbf{10}_H & (\tilde{g}/2)\, \mathbf{45}_H \\ (g_j/2)\, \mathbf{45}_H & (\tilde{g}/2)\, \mathbf{45}_H & \tilde{f} \mathbf{10}_H \end{pmatrix} \begin{pmatrix} \mathbf{16}_j \\ \mathbf{16} \\ \overline{\mathbf{16}} \end{pmatrix} \\ &= \left(\mathbf{16}_i,\, \mathbf{16},\, \overline{\mathbf{16}} \right) \begin{pmatrix} \mathcal{O}(M_W) & \mathcal{O}(M_W) & \mathcal{O}(M_{\rm G}) \\ \mathcal{O}(M_W) & \mathcal{O}(M_W) & \mathcal{O}(M_{\rm G}) \\ \mathcal{O}(M_{\rm G}) & \mathcal{O}(M_{\rm G}) & \mathcal{O}(M_W) \end{pmatrix} \begin{pmatrix} \mathbf{16}_j \\ \mathbf{16} \\ \overline{\mathbf{16}} \end{pmatrix}, \end{aligned} \tag{2.6}$$

where we provided the VEVs to the Higgs, $\langle \mathbf{10}_H \rangle \sim \mathcal{O}(M_W)$ and $\langle \mathbf{45}_H \rangle \sim \mathcal{O}(M_{\rm G})$ and this mass matrix has only one weak scale mass $\mathcal{O}(M_{\rm W})$ and the remaining two are of order the GUT scale $\mathcal{O}(M_{\rm G})$. Then three lighter modes in the multiplet $\mathbf{16}_\alpha = \left(\mathbf{16}_j,\, \mathbf{16},\, \overline{\mathbf{16}}\right)_\alpha$ ($\alpha = 1, 2, 3, 4, 5$) are identified with the **16**-multiplet including the usual quarks and leptons. The light modes ($\mathbf{16}'_i$) ($i = 1, 2, 3$) in the mass matrix of eq. (2.6), which contains the usual quarks and leptons can be written as the following linear combinations (up to some normalization factor):

$$\begin{aligned}\mathbf{16}'_1 &= -g\mathbf{16}_1 + g_1\mathbf{16}\ ,\\ \mathbf{16}'_2 &= -g_3\mathbf{16}_2 + g_1\mathbf{16}_3\ ,\\ \mathbf{16}'_3 &= -g_2\mathbf{16}_3 + g_1\mathbf{16}_2\ .\end{aligned} \tag{2.7}$$

The remaining two eigenstates become heavy of order $M_{\rm G}$, so the low energy effective theory can indeed become the MSSM without exotics. Then the extra vector-like matter $\overline{q}'_L \oplus q'_L$, $\overline{\ell}'_L \oplus \ell'_L$, *etc.* would decouple from the low-energy effectve field theory. After giving a VEV to the $\mathbf{45}_H$ Higgs multiplet, we have the dimension 5 neutrino mass operator eq. (2.1) and also the dimension 6 operator contributing to the charged fermion mass matrices

$$W = \frac{1}{M} Y_{16}^{ij}\mathbf{16}_i\mathbf{16}_j\overline{\mathbf{16}}_H\overline{\mathbf{16}}_H + \left(\frac{g_{\{i}h_{j\}}}{\tilde{g}M_{16}^2}\right)\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H\mathbf{45}_H^2. \tag{2.8}$$

In the followings, we consider two cases for the description of the charged fermion mass matrices. One is to consider the situation in which the second term in eq. (2.2) has larger contribution than eq. (2.8). Another one is the opposite case in which the dominant term is eq. (2.8) rather than the second term in eq. (2.2).

In the former case, eq. (2.2) corresponds to the Dirac mass matrices of quarks and leptons. Note that this example is obviously unrealistic since it predicts the Kobayashi-Maskawa matrix being unity. This is because the Higgs doublets in eq. (2.2) is the same, and as result the up-type quark mass matrix is proportional to the down-type quark mass matrix. One way to avoid this problem is to introduce new $\mathbf{10}$ Higgs and a symmetry which allow the superpotential such as

$$W \;=\; Y_{10}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_1 \;+\; \frac{1}{M} Y_{45}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_2\mathbf{45}_H, \tag{2.9}$$

where $\mathbf{10}_1$ and $\mathbf{10}_2$ are two Higgs multiplets of $\mathbf{10}$ representation. Since $\mathbf{10}\times\mathbf{45} \supset \mathbf{10}+\mathbf{120}+\mathbf{320}$, this system is effectively the same as the one with $\mathbf{10}+\mathbf{120}$ Higgs multiplets.

In the latter case, the system is completely equivalent to the minimal SO(10) model which uses $\mathbf{10}+\overline{\mathbf{126}}$ Higgses w.r.t. the charged fermion sector since $\mathbf{10}\times\mathbf{45}^2 \supset \mathbf{126}+\overline{\mathbf{126}}$. In this case we need only one $\mathbf{10}$ multiplet to reproduce realistic fermion mass matrices.

Model 1. In the following notation, we use $\mathbf{120}$ Higgs, for simplicity. This model has been studied in [11], in detail, and we give a very brief review of this model.

The Yukawa couplings relevant to the Dirac mass matrices are given by

$$W = Y_{10}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H + Y_{120}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{120}_H, \tag{2.10}$$

where Y_{10} and Y_{120} are symmetric and anti-symmetric, respectively. Number of free parameters in the Yukawa matrices is found to be $3+3\times2=9$ in total. Both of the Higgs multiplets $\mathbf{10}_H$ and $\mathbf{120}_H$ include a pair of Higgs doublets in the MSSM decomposition.

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At low-energy after the GUT symmetry breaking, the superpotential leads to[1]

$$\begin{aligned} W &= (Y_{10}^{ij} H_{10}^u + Y_{120}^{ij} H_{120}^u) u_i^c q_j + (Y_{10}^{ij} H_{10}^d + Y_{120}^{ij} H_{120}^d) d_i^c q_j \\ &\quad + (Y_{10}^{ij} H_{10}^u - 3Y_{120}^{ij} H_{120}^u) N_i \ell_j + (Y_{10}^{ij} H_{10}^d - 3Y_{120}^{ij} H_{120}^d) e_i^c \ell_j, \end{aligned} \tag{2.11}$$

where H_{10} and H_{120} correspond to the Higgs doublets in **10** an **120** Higgses, which originate $\mathbf{10}_1$ and $\mathbf{10}_2$ in the original superpotential eq. (2.9). The factor 3 in the lepton sector is the results from the VEV of **45** Higgs in the $B - L$ direction. Providing VEVs for all the Higgs doublets, the Dirac mass matrices are obtained as

$$W_{mass} = M_u^{ij} u_i^c q_j + M_d^{ij} d_i^c q_j + M_D^{ij} N_i \ell_j + M_e^{ij} e_i^c \ell_j, \tag{2.12}$$

where

$$\begin{aligned} M_u &= c_{10} M_{10} + c_{120} M_{120}, \\ M_d &= M_{10} + M_{120}, \\ M_D &= c_{10} M_{10} - 3c_{120} M_{120}, \\ M_e &= M_{10} - 3M_{120}. \end{aligned} \tag{2.13}$$

Here $c_{10} = \langle H_{10}^u \rangle / \langle H_{10}^d \rangle$ and $c_{120} = \langle H_{120}^u \rangle / \langle H_{120}^d \rangle$ are complex parameters in general. Now number of free parameters in terms of mass matrices are found to be $3 + 3 \times 2 + 2 \times 2 = 13$. This relation leads to a relation among the mass matrices of up- and down-type quarks and charged lepton such as

$$M_e = c_d \left(M_d + \kappa M_u \right), \tag{2.14}$$

where

$$\begin{aligned} c_d &= -\frac{3c_{10} + c_{120}}{c_{10} - c_{120}}, \\ \kappa &= -\frac{4}{3c_{10} + c_{120}}. \end{aligned} \tag{2.15}$$

Note that this GUT relation holds at the GUT scale. By the same methods in [7], we will solve the relation and find mass matrices compatible to the low-energy data of the fermion mass matrices.

Without loss of generality, we can begin with the basis where M_u is real and diagonal, $M_u = D_u$. Here we assume M_d to be the hermitian matrix, and the number of parameters are reduced to $3 + 3 + 4 = 10$. Therefore it can be diagonalized by an unitary matrix, $M_d = V_{\mathrm{KM}} \, D_d \, V_{\mathrm{KM}}^\dagger$. Considering the basis-independent quantities, $\mathrm{tr}\,(M_e)$, $\mathrm{tr}\left(M_e^2\right)$ and $\det\,(M_e)$, and eliminating c_d, we obtain two independent equations,

$$\left(\frac{\mathrm{tr}(\widetilde{M_e})}{m_e + m_\mu + m_\tau} \right)^2 = \frac{\mathrm{tr}(\widetilde{M_e}^2)}{m_e^2 + m_\mu^2 + m_\tau^2}, \tag{2.16}$$

$$\left(\frac{\mathrm{tr}(\widetilde{M_e})}{m_e + m_\mu + m_\tau} \right)^3 = \frac{\det(\widetilde{M_e})}{m_e \, m_\mu \, m_\tau}, \tag{2.17}$$

[1] In general, there could be another contribution to the mass matrices from bi-doublet $(\mathbf{1}, \mathbf{2}, \mathbf{2}) \subset \mathbf{120}$ under $G_{422} = \mathrm{SU}(4) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$. In this paper, we assumed that it does not contribute to the fermion mass matrices, just for simplicity.

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where $\widetilde{M}_e \equiv V_{\rm KM}\, D_d\, V_{\rm KM}^\dagger + \kappa D_u$. With input data of six quark masses, three angles and one CP-phase in the CKM matrix and three charged lepton masses, we can solve the above equations and determine κ and c_d. The original basic mass matrices, M_{10} and M_{120}, are described by

$$
\begin{aligned}
M_{10} &= \frac{3+c_d}{4}\, V_{\rm KM}, D_d\, V_{\rm KM}^\dagger + \frac{c_d\,\kappa}{4}\, D_u, && (2.18)\\
M_{120} &= \frac{1-c_d}{4}\, V_{\rm KM}\, D_d\, V_{\rm KM}^\dagger - \frac{c_d\,\kappa}{4}\, D_u. && (2.19)
\end{aligned}
$$

Now M_{10} and M_{120} are completely determined with the solutions c_d and κ determined by the GUT relation.[2] It should be checked that Y_{120}^{ij} should be much smaller than one, since $Y_{120}^{ij} = Y_{45}^{ij}\langle \mathbf{45}\rangle/M$. In the next section, we will perform a numerical analysis by using the same method as [7].

Model 2. The Yukawa couplings relevant to the Dirac mass matrices are given by

$$
W = Y_{10}^{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H + Y_{126}^{ij}\mathbf{16}_i\mathbf{16}_j\overline{\mathbf{126}}_H, \qquad (2.20)
$$

where both Y_{10} and Y_{126} are symmetric, and the number of free parameters in the Yukawa matrices is found to be $3+6\times 2 = 15$ in total. In this model, the GUT relation is the same as the one in eq. (2.14). But in this case, the coefficients c_{10} and c_{126} are complex numbers, and then the analysis for finding a solution is somewhat restrictive. Notice that the right-handed neutrino Majorana mass matrix is completely free in this model as depicted in eq. (2.1), thus we can reproduce the neutrino oscillation data. But even in this case, since we know the neutrino Dirac mass matrix, we can get a prediction for the quantity relating the leptogenesis.

Now as in the same way in Model 1, considering the basis-independent quantities, $\mathrm{tr}[M_e^\dagger M_e]$, $\mathrm{tr}[(M_e^\dagger M_e)^2]$ and $\det[M_e^\dagger M_e]$, and eliminating $|c_d|$, we obtain two independent equations,

$$
\begin{aligned}
\left(\frac{\mathrm{tr}[\widetilde{M}_e^\dagger \widetilde{M}_e]}{m_e^2+m_\mu^2+m_\tau^2}\right)^2 &= \frac{\mathrm{tr}[(\widetilde{M}_e^\dagger \widetilde{M}_e)^2]}{m_e^4+m_\mu^4+m_\tau^4}, && (2.21)\\
\left(\frac{\mathrm{tr}[\widetilde{M}_e^\dagger \widetilde{M}_e]}{m_e^2+m_\mu^2+m_\tau^2}\right)^3 &= \frac{\det[\widetilde{M}_e^\dagger \widetilde{M}_e]}{m_e^2\, m_\mu^2\, m_\tau^2}, && (2.22)
\end{aligned}
$$

where $\widetilde{M}_e \equiv U^*\, D_d\, U^\dagger + \kappa D_u$. With input data of six quark masses, three angles and one CP-phase in the CKM matrix and three charged lepton masses, we can solve the above equations and determine κ and $|c_d|$, but five parameters, the phase of c_d [7] and the phases in U, except for the CKM phase are undetermined.[3] The original basic mass matrices, M_{10}

[2] Although the solution is found in [6], the GUT relation are applied at the electroweak scale. The analysis incorporating renormalization effects was done as in [7].

[3] In this paper, we ignore the additional phases in U except for the KM phase δ, and thus hereafter we denote U just as $V_{\rm KM}$.

and M_{126}, are described by

$$M_{10} = \frac{3+|c_d|e^{i\sigma}}{4} V_{\rm KM}^* D_d V_{\rm KM}^\dagger + \frac{|c_d|e^{i\sigma}\kappa}{4} D_u, \tag{2.23}$$

$$M_{126} = \frac{1-|c_d|e^{i\sigma}}{4} V_{\rm KM}^* D_d V_{\rm KM}^\dagger - \frac{|c_d|e^{i\sigma}\kappa}{4} D_u. \tag{2.24}$$

By giving a solution for $|c_d|$ and κ, we can determine all the Dirac mass matrix as a function of a phase σ. As a result, we can obtain a prediction for the leptogenesis parameters.

3. Numerical analysis and results

Now we are ready to perform all the numerical analysis. We first show the solution in Model 1. In the following analysis, we assume all the charged fermion mass matrices to be hermitian. We take input the absolute values of the fermion masses at M_Z as follows (in GeV) [12]:

$$\begin{aligned} m_u &= 0.00233, & m_c &= 0.677, & m_t &= 176, \\ m_d &= 0.00469, & m_s &= 0.0934, & m_b &= 3.00, \\ m_e &= 0.000487, & m_\mu &= 0.103, & m_\tau &= 1.76. \end{aligned} \tag{3.1}$$

Here the signs of the input fermion masses have taken as $(m_u, m_c, m_t) = (-,-,+)$ and $(m_d, m_s, m_b) = (-,-,+)$. And for the CKM mixing angles and a CP-violating phase in the "standard" parameterization, we input the center values measured by experiments as follows:

$$s_{12} = 0.2229, \quad s_{23} = 0.0412, \quad s_{13} = 0.0036, \quad \delta = \pi/3 \text{ [rad]}. \tag{3.2}$$

Since it is very difficult to search all the possible parameter region systematically, we present only reasonable results we found. In the following, we show our analysis in detail in the case $\tan\beta = 50$. After the RG running, we get the values at the GUT scale are use them as input parameters in order to solve the GUT relation of eq. (2.14).

Now for simplicity, we assume the matrices M_{10} and M_{120} in eq. (2.13) to be hermitie. Thus the coefficients c_d and κ are real parameters. Then we find a solution

$$\begin{aligned} c_d &= -11.1923, \\ \kappa &= -0.01433. \end{aligned} \tag{3.3}$$

This means we could reproduce the low-energy experimental data related to the charged fermion sector. As discussed in the previous section the Yukawa coupling matrices, Y_{10} and Y_{120}, are related to the corresponding mass matrices M_{10} and M_{120} such that

$$\begin{aligned} Y_{10} &= \frac{c_{10}}{\alpha^u v \sin\beta} M_{10}, \\ Y_{120} &= \frac{c_{120}}{\beta^u v \sin\beta} M_{120}. \end{aligned} \tag{3.4}$$

Here α^u and β^u are the Higgs doublet mixing parameters introduced in [13], which are restricted in the range $|\alpha^u|^2 + |\beta^u|^2 \le 1$. Although these parameters are irrelevant to fit the low-energy experimental data of the fermion mass matrices, there are theoretical lower bound on them in order for the resultant Yukawa coupling constant not to exceed the perturbative regime. Now we show one example of the Yukawa coupling matrices with fixed $\alpha^u = 0.707$,

$$Y_{10} = \begin{pmatrix} 0.00304 & 0.00644 & -0.00236 \\ 0.00644 & 0.0235 & -0.0502 \\ -0.00236 & -0.0502 & 0.761 \end{pmatrix}, \tag{3.5}$$

$$Y_{120} = \begin{pmatrix} 0 & -0.000170\,i & -0.00557\,i \\ 0.000170\,i & 0 & -0.0000226\,i \\ 0.00557\,i & 0.0000226\,i & 0 \end{pmatrix}. \tag{3.6}$$

For the proton decay analysis, we search for the parameters which cancel the proton decay rate, completely. In the followings, we restrict the region of the parameters in the range $(\alpha^u)^2 + (\beta^u)^2 = 1$ (we assume α^u and β^u real for simplicity). Then we actually find a solution that cancels the proton decay $p \to K^+\overline{\nu}$. The resultant 2×2 color-triplet mass matrix [13] has the following form:

$$M_C = M_{\rm G}\mathbf{I}_2 \times \begin{pmatrix} -0.0814 + 0.113\,i & -0.872 - 0.470\,i \\ 0.872 - 0.470\,i & -0.0814 - 0.113\,i \end{pmatrix}. \tag{3.7}$$

For about Model 2, we have already found a solution in [13]. Therefore we just present the result here

$$\begin{aligned} \kappa &= -0.00675 + 0.000309\,i\ , \\ |c_d| &= 5.99\ , \end{aligned} \tag{3.8}$$

with $\tan\beta = 2.5$.

4. Neutrino oscillation data

In our scheme adopted here, the right-handed neutrino mass matrix is left free from fitting the charged fermion data. We know the definite structure for the Dirac neutrino mass matrix. Therefore, by making use of the neutrino oscillation data, we can give a definite prediction for the right-handed neutrino mass matrix.

$$\begin{aligned} M_R &= M_D\, M_\nu^{-1}\, M_D^T \\ &= M_D\, U_{\rm MNS}^\dagger\, {\rm diag}(m_1^{-1}, m_2^{-1}, m_3^{-1})\, U_{\rm MNS}^*\, M_D^T. \end{aligned} \tag{4.1}$$

Here $U_{\rm MNS}$ is the Maki-Nakagawa-Sakata (MNS) lepton mixing matrix, and in the standard parametrization, it can be written as

$$U_{\rm MNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times {\rm diag}(1, e^{i\beta}, e^{i\gamma}), \tag{4.2}$$

where $s_{ij} := \sin\theta_{ij}$, $c_{ij} := \cos\theta_{ij}$, δ, β, γ are the Dirac phase and the Majorana phases, respectively. Now we take input the center values of a global analysis for the neutrino oscillation parameters after the recent KamLAND data [14].[4]

$$\begin{aligned}
\Delta m^2_{\oplus} &= \Delta m^2_{21} \;=\; 2.1\times 10^{-3}\ \text{eV}^2, \\
\sin^2\theta_{\oplus} &= 0.5, \\
\Delta m^2_{\odot} &= \left|\Delta m^2_{31}\right| \;=\; 8.3\times 10^{-5}\ \text{eV}^2, \\
\sin^2\theta_{\odot} &= 0.28, \\
|U_{e3}| &< 0.15.
\end{aligned} \tag{4.3}$$

Note that we can take both signs of Δm^2_{31}, $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$. The former is called "normal hierarchy" (NH), the latter is called "inverted hierarchy" (IH), and we study both cases. Writing the lightest neutrino mass eigenvalue as m_ℓ, we can write the mass eigenvalues as

$$\begin{aligned}
m_1 &= m_\ell, \\
m_2 &= \sqrt{m_\ell^2 + \Delta m^2_{\oplus}}, \\
m_3 &= \sqrt{m_\ell^2 + \Delta m^2_{\oplus} + \Delta m^2_{\odot}},
\end{aligned} \tag{4.4}$$

for the case of NH, and

$$\begin{aligned}
m_1 &= \sqrt{m_\ell^2 + \Delta m^2_{\oplus} + \Delta m^2_{\odot}}, \\
m_2 &= \sqrt{m_\ell^2 + \Delta m^2_{\oplus}}, \\
m_3 &= m_\ell,
\end{aligned} \tag{4.5}$$

for the case of IH.

Because we know the Dirac mass matrix M_D, by inputting the above neutrino oscillation data, we can predict the mass matrix of the right-handed neutrinos as a function of Majorana phases, β and γ. As a result, we can have a prediction on the phenomena relating the right-handed neutrinos, such as the leptogenesis, lepton flavor violating processes (LFV), etc.

Now we turn to the discussions about the baryon asymmetry of the universe based on the leptogenesis scenario [15]. In the leptogenesis scenario, lepton asymmetry is generated by the out-of-equilibrium decays of the right-handed neutrinos. The lepton asymmetry of the right-handed neutrino N_i is defined as

$$\epsilon_i = \frac{\Gamma(N_i \to \ell\, H) - \Gamma(N_i \to \ell^c\, H^\dagger)}{\Gamma(N_i \to \ell\, H) + \Gamma(N_i \to \ell^c\, H^\dagger)}. \tag{4.6}$$

At tree level, the decay width of N_i is given by

$$\Gamma_i = \frac{(M_D M_D^\dagger)_{ii}}{8\pi v^2 \sin^2\beta} M_i. \tag{4.7}$$

[4] Our convention is $\Delta m^2_{ij} = m_i^2 - m_j^2$.

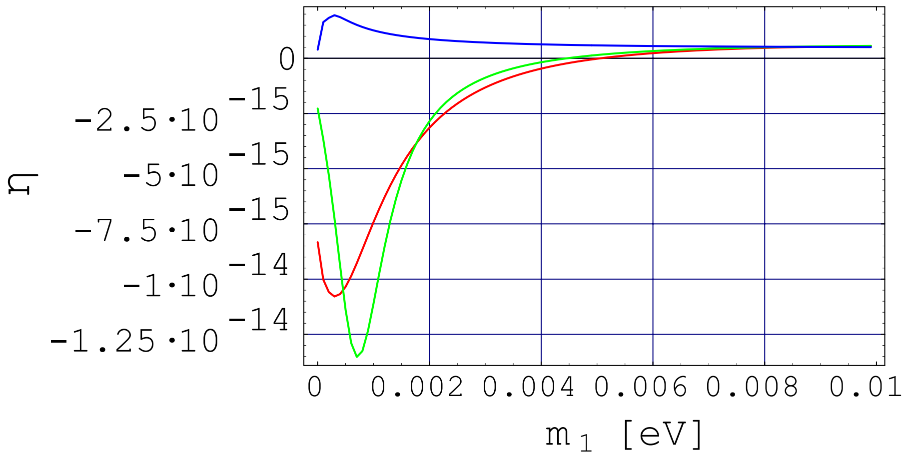

Figure 1: The baryon asymmetry of the universe η as a function of the lightest neutrino mass m_1 [eV] for Model 1. Three lines (red, blue, green) correspond to the values $\delta = \pi/4,\ \pi/2,\ \pi$, respectively. In this figure we have fixed $|U_{e3}| = 0.15$ and the Majorana phases β and γ as $\beta = \gamma = \pi/4$.

The CP asymmetry is produced for the first time on one-loop level as

$$\epsilon_i = -\frac{1}{8\pi v^2 \sin^2\beta}\frac{1}{(M_D M_D^\dagger)_{ii}}\sum_{j\neq i}\mathrm{Im}[(M_D M_D^\dagger)_{ij}^2]\left[f\left(\frac{M_j^2}{M_i^2}\right)+g_j\left(\frac{M_j^2}{M_i^2}\right)\right], \tag{4.8}$$

where $f(x)$ and $g_j(x)$ denote the one loop contribution from the vertex and the self-energy, respectively [16].

$$f(x) = \sqrt{x}\ \ln\left(\frac{1+x}{x}\right),\quad g_j(x) = \frac{(x-1)\sqrt{x}}{(x-1)^2+\left[(M_D M_D^\dagger)_{jj}/(8\pi v^2\sin^2\beta)\right]^2 x}. \tag{4.9}$$

Once we are able to know the values of the lepton asymmetry ϵ_i, we have to solve the Boltzmann equations in order to get the actual baryon asymmetry, $\eta = n_B/n_\gamma$. But we can use an approximate formula [17],

$$\eta \simeq 3\times 10^{-3}\left(\frac{10^{-3}\ \mathrm{eV}}{\tilde{m}_1}\right)\left[\log\left(\frac{\tilde{m}_1}{10^{-3}\ \mathrm{eV}}\right)\right]^{-0.6}\epsilon_1, \tag{4.10}$$

where

$$\tilde{m}_1 = \frac{(M_D M_D^\dagger)_{11}}{M_1}. \tag{4.11}$$

This formula is within a sufficiently good approximation for 10^{-2} [eV] $< \tilde{m}_1 < 10^3$ [eV].

Now we we show the results of the baryon asymmetry of the universe in case of NH, in figure 1, 2, and 3. The vertical axis represents the predicted baryon asymmetry of the universe η as a function of the lightest neutrino mass m_1 [eV] in figure 1, as a function of $|U_{e3}|$ in figure 2 and as a function of δ [rad] in figure 3. In figure 1, we have fixed

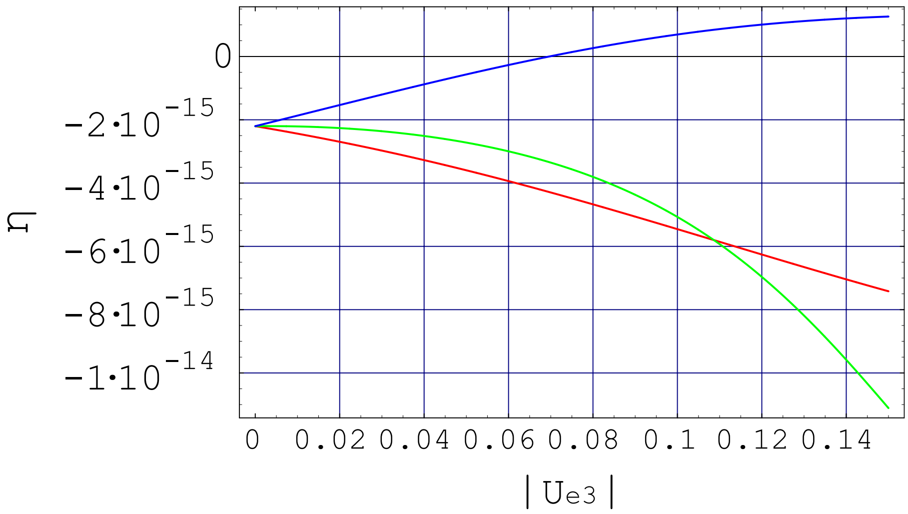

Figure 2: The baryon asymmetry of the universe η as a function of $|U_{e3}|$ for Model 1. Three lines (red, blue, green) correspond to the values $\delta = \pi/4,\ \pi/2,\ \pi$, respectively. In this figure, we have fixed $m_1 = 10^{-3}$ [eV] and the Majorana phases β and γ as $\beta = \gamma = \pi/4$.

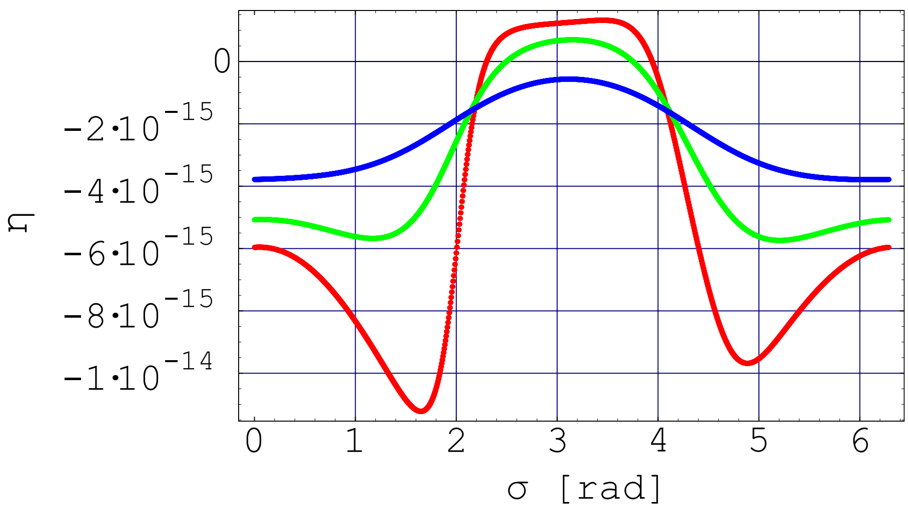

Figure 3: The baryon asymmetry of the universe η as a function of δ [rad] for Model 1. Three lines (red, blue, green) correspond to the values $|U_{e3}| = 0.15,\ 0.10,\ 0.05$, respectively. In this figure, we have fixed $m_1 = 10^{-3}$ [eV] and the Majorana phases β and γ as $\beta = \gamma = \pi/4$.

$|U_{e3}| = 0.15$ and the Majorana phases β and γ as $\beta = \gamma = \pi/4$. In figure 2, m_1 is fixed as $m_1 = 10^{-3}$ [eV] and the Majorana phases are the same as figure 1. For figure 1 and 2, three lines (red, blue, green) represent the values $\delta = \pi/4,\ \pi/2,\ \pi$, respectively. In figure 3, we have fixed $m_1 = 10^{-3}$ [eV] and the Majorana phases β and γ as $\beta = \gamma = \pi/4$

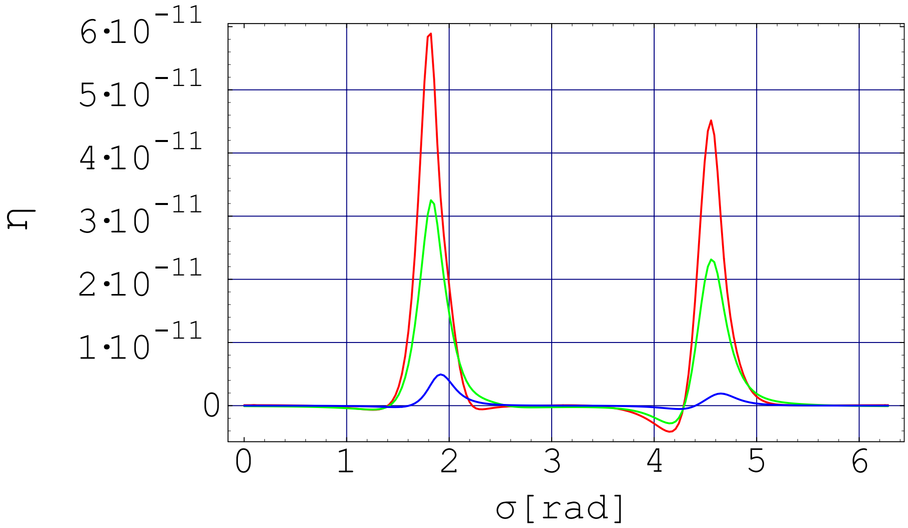

Figure 4: The baryon asymmetry of the universe η as a function of σ [rad] in Model 2. Three lines (red, blue, green) correspond to the values $\delta = \pi/4,\ \pi/2,\ \pi$, respectively. In this figure, we have fixed $m_1 = 10^{-3}$ [eV] and $|U_{e3}| = 0.15$, and the Majorana phases as $\beta = \gamma = \pi/4$.

but varied $|U_{e3}| = 0.15,\ 0.10,\ 0.05$, which correspond to the three lines (red, blue, green). These results show that Model 1 can not reproduce the observed baryon asymmetry in the standard leptogenesis scenario, though all possible values of free parameters have not been exhausted. But in strictly speaking, any (local) supersymmmetric models have a serious problem, so called, gravitino problem [18–20]. That says if we take a naïvely expected value for the garavitino mass $m_{3/2}$ of order the weak sacle $m_{3/2} \sim 100$ [GeV] the lifetime is shorter than 1 [sec], as a result the primordial gravitino dacays after the big-bang nucleosynthesis (BBN). Recently, the updated analysis for the hadronic decay of the gravitino shows that the reheating temperature is very strictly constrained as $T_R < 10^{6-8}$ [GeV] [20]. Therefore the results of our Model 1 for the baryon asymmetry of the universe should not taken so seriously.

On the other hand, in figure 4, 5, 6 and 7 we show the results of the baryon asymmetry of the universe in case of Model 2. The vertical axis represents the predicted baryon asymmetry of the universe η as a function of the CP-phase σ [rad]. In figure 4, we have fixed $m_1 = 10^{-3}$ [eV] and $|U_{e3}| = 0.15$, and Majorana phases β and γ as $\beta = \gamma = \pi/4$. In figure 5, we have adopted the same parameters as figure 4 except for the Majorana phases $\beta = \gamma = \pi/2$. Figure 6 is the zoomed up picture of the experimentally allowed parameters region of figure 5 for the Dirac CP-phase $\delta = \pi/4$. Figure 7 is the same diagram as figure 4 except for the Majorana phases $\beta = \gamma = \pi$. You can see that this model can reproduce the observed baryon asymmetry within the standard leptogenesis scenario.

Since Model 2 has passed the test for the leptogenesis, it is possible to go further steps, e.g. analysis of the proton lifetime $\tau(p \to K^+\bar{\nu})$ in a mode $p \to K^+\bar{\nu}$. The predicted values as a function of σ [rad] are depicted in figure 8. Though in general we can vary the param-

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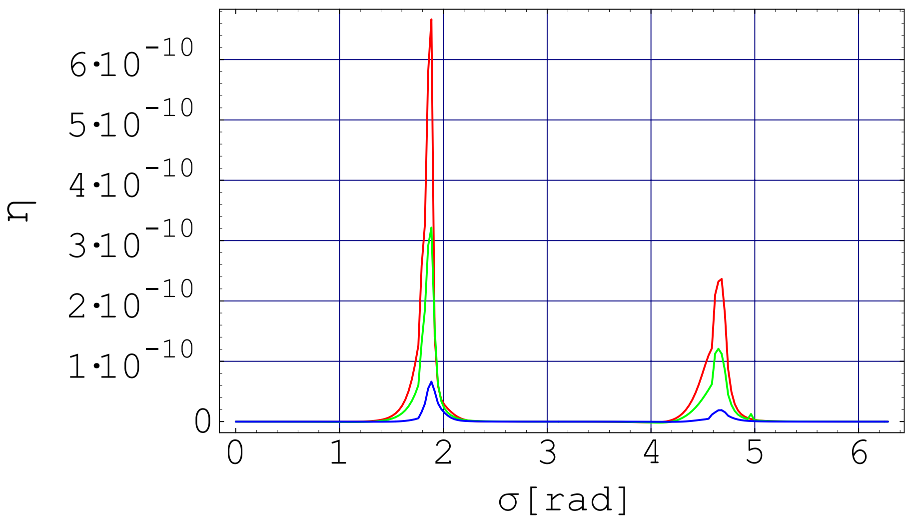

Figure 5: Same as figure 4, but for the Majorana phases $\beta = \gamma = \pi/2$.

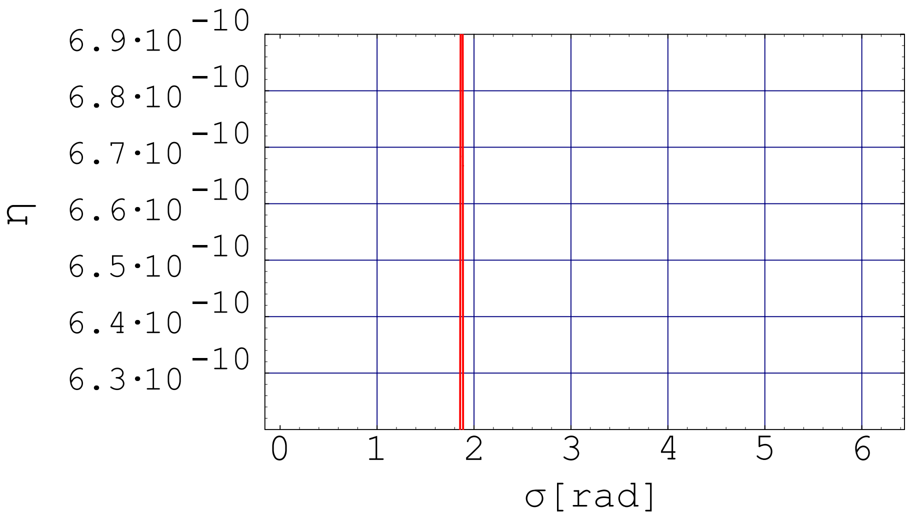

Figure 6: The experimentally allowed region in figure 5 are zoomed in for $\delta = \pi/4$.

eters in the Higgs potential as possible, we pick up one solution satisfying the experimental constraint. In concrete, we used the 2×2 color-triplet Higgsino mass matrix [13] of the following form,

$$M_C = M_G \mathbf{I}_2 \times \begin{pmatrix} 1+i & 1+i \\ -1+i & -1-i \end{pmatrix}, \tag{4.12}$$

which corresponds to the parameters with $\theta = \varphi = \varphi' = \pi/4$ in the notation of ref. [13]. The horizontal line indicates the current experimental lower bound. Therefore,

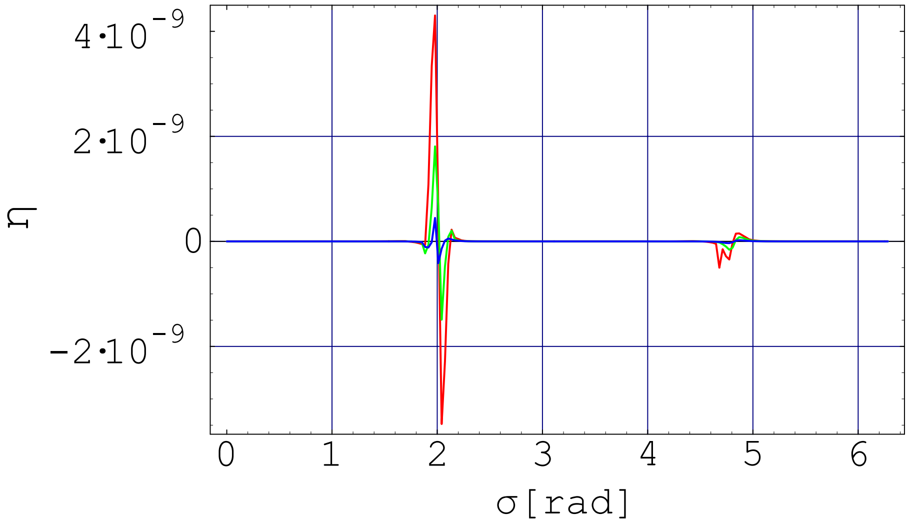

Figure 7: Same as figure 4, but for the Majorana phases $\beta = \gamma = \pi$.

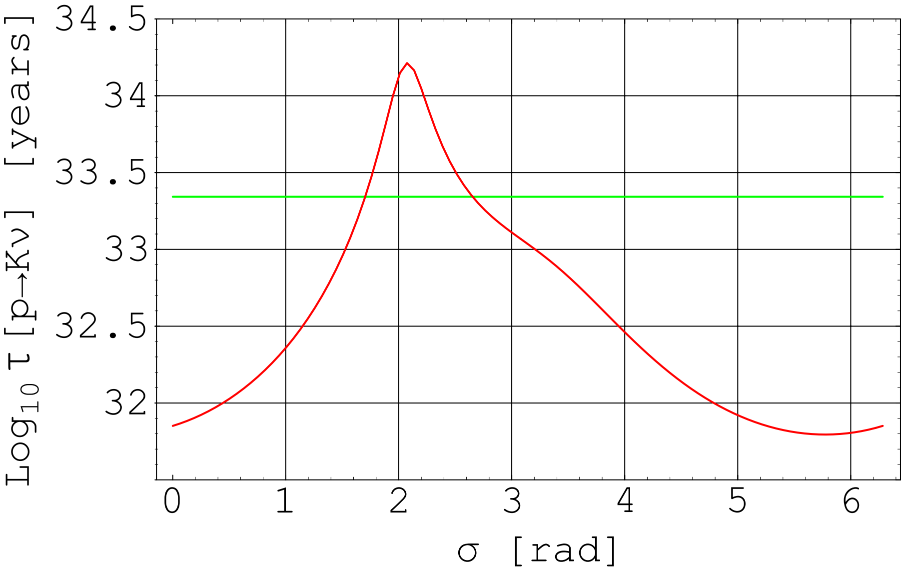

Figure 8: The proton lifetime $\tau(p \to K^+\bar{\nu})$ in a mode $p \to K^+\bar{\nu}$ as a function of σ [rad] for Model 2. Though in general we can vary the parameters in the Higgs potential as possible, we pick up one solution satisfying the experimental constraint. The horizontal line indicates the current experimental lower bound.

these results show that there exists a parameter region which simultaneously reproduces a required baryon asymmetry of the universe and satisfies the current experimental bound on the proton lifetime:

$$\eta|_{\text{exp.}} = (6.2 - 6.9) \times 10^{-10}, \tag{4.13}$$

$$\tau(p \to K^+\bar{\nu})|_{\text{exp.}} > 2.2 \times 10^{33} \text{ [years]}. \tag{4.14}$$

5. Conclusion

We have proposed a phenomenologically viable SO(10) grand unification model which use a set of Higgs superfields $\mathbf{10} + \overline{\mathbf{16}} + \mathbf{16} + \mathbf{45}$. In this framework, the data fitting of the charged fermion mass matrices have been re-examined. This model indeed can fit the low-energy experimental data relating the charged fermion masses and mixings. As for the neutrino sector, we have inputted the neutrino oscillation data to constrain right-handed Majorana neutrino mass matrix. Then the unknown parameters are used to fit the leptogenesis and for the proton decay. In such a framework, two models, Model 1 and Model 2, have been considered. The former is effectively equal to the model with the Yukawa couplings to the $\mathbf{10} + \mathbf{120}$ Higgses and the latter to the model with the Yukawa couplings to the $\mathbf{10} + \overline{\mathbf{126}}$ Higgses with respect to charged Fermions. It should be remarked in Model 2 that M_R has the different origin from that of the charged fermion mass matrices unlike the conventional minimal SO(10) model [6, 7]. Then it has been found that our model (Model 2) is consistent with all experimental constraints, especially, the required baryon asymmetry of the universe η can be produced, keeping in mind the proton lifetime constraint. Though Model 1 does not produce the sufficient baryon asymmetry of the universe within the standard framework of the leptogenesis, there is a serious problem in any SUSY models, so called, gravitino problem [18 − 20]. The decay products of the primodial gravitino destroy the produced baryon asymmetry of the universe and need further study to consider some extensions of the standad leptogensis scenario, such as Affleck-Dine scenario [21].

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References

[1] U. Amaldi, W. de Boer and H. Furstenau, *Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP*, *Phys. Lett.* **B 260** (1991) 447;
P. Langacker and M.-X. Luo, *Implications of precision electroweak experiments for $M(t)$, ρ_0, $\sin^2\Theta_W$ and grand unification*, *Phys. Rev.* **D 44** (1991) 817.

[2] T. Yanagida, *Horizontal symmetry and masses of neutrinos*, in Proceedings of the *Workshop on the Unified Theory and Baryon Number in the Universe*, O. Sawada and A. Sugamoto eds., KEK, Tsukuba Japan (1979);
P. Ramond, *The family group in grand unified theories*, invited talk at *Sanibel Symposium*, February 25–Mach 2, Palm Coast, Florida, U.S.A. (1979), CALT-68-709 [hep-ph/9809459];

R.N. Mohapatra and G. Senjanović, *Neutrino mass and spontaneous parity nonconservation*, *Phys. Rev. Lett.* **44** (1980) 912.

[3] K.R. Dienes and J. March-Russell, *Realizing higher level gauge symmetries in string theory: New embeddings for string GUTs*, *Nucl. Phys.* **B 479** (1996) 113 [hep-th/9604112];
K.R. Dienes, *New constraints on* SO(10) *model building from string theory*, *Nucl. Phys.* **B 488** (1997) 141 [hep-ph/9606467];
see also a review article, K.R. Dienes, *String theory and the path to unification: a review of recent developments*, *Phys. Rept.* **287** (1997) 447 [hep-th/9602045].

[4] H.S. Goh, R.N. Mohapatra and S. Nasri, SO(10) *symmetry breaking and type-II seesaw*, *Phys. Rev.* **D 70** (2004) 075022 [hep-ph/0408139];
B. Dutta, Y. Mimura and R.N. Mohapatra, *Proton decay and flavor violating thresholds in* SO(10) *models*, *Phys. Rev. Lett.* **100** (2008) 181801 [arXiv:0712.1206].

[5] K.S. Babu and R.N. Mohapatra, *Predictive neutrino spectrum in minimal* SO(10) *grand unification*, *Phys. Rev. Lett.* **70** (1993) 2845 [hep-ph/9209215].

[6] K. Matsuda, Y. Koide and T. Fukuyama, *Can the* SO(10) *model with two Higgs doublets reproduce the observed fermion masses?*, *Phys. Rev.* **D 64** (2001) 053015 [hep-ph/0010026];
K. Matsuda, Y. Koide, T. Fukuyama and H. Nishiura, *How far can the* SO(10) *two Higgs model describe the observed neutrino masses and mixings?*, *Phys. Rev.* **D 65** (2002) 033008 [*Erratum ibid.* **65** (2002) 079904] [hep-ph/0108202].

[7] T. Fukuyama and N. Okada, *Neutrino oscillation data versus minimal supersymmetric* SO(10) *model*, *JHEP* **11** (2002) 011 [hep-ph/0205066].

[8] B. Bajc, G. Senjanović and F. Vissani, *b-τ unification and large atmospheric mixing: a case for non-canonical see-saw*, *Phys. Rev. Lett.* **90** (2003) 051802 [hep-ph/0210207];
H.S. Goh, R.N. Mohapatra, S. Nasri and S.-P. Ng, *Proton decay in a minimal SUSY* SO(10) *model for neutrino mixings*, *Phys. Lett.* **B 587** (2004) 105 [hep-ph/0311330];
B. Dutta, Y. Mimura and R.N. Mohapatra, *Neutrino masses and mixings in a predictive* SO(10) *model with CKM CP-violation*, *Phys. Lett.* **B 603** (2004) 35 [hep-ph/0406262].

[9] L.J. Hall, R. Rattazzi and U. Sarid, *The top quark mass in supersymmetric* SO(10) *unification*, *Phys. Rev.* **D 50** (1994) 7048 [hep-ph/9306309];
R. Rattazzi and U. Sarid, *The unified minimal supersymmetric model with large Yukawa couplings*, *Phys. Rev.* **D 53** (1996) 1553 [hep-ph/9505428];
G. Anderson, S. Raby, S. Dimopoulos, L.J. Hall and G.D. Starkman, *A systematic* SO(10) *operator analysis for fermion masses*, *Phys. Rev.* **D 49** (1994) 3660 [hep-ph/9308333];
L.J. Hall and S. Raby, *A complete supersymmetric* SO(10) *model*, *Phys. Rev.* **D 51** (1995) 6524 [hep-ph/9501298];
C.H. Albright, K.S. Babu and S.M. Barr, *A minimality condition and atmospheric neutrino oscillations*, *Phys. Rev. Lett.* **81** (1998) 1167 [hep-ph/9802314];
C.H. Albright and S.M. Barr, *Bimaximal mixing in an* SO(10) *minimal Higgs model*, *Phys. Lett.* **B 461** (1999) 218 [hep-ph/9906297]; *Explicit* SO(10) *supersymmetric grand unified model for the Higgs and Yukawa sectors*, *Phys. Rev. Lett.* **85** (2000) 244 [hep-ph/0002155]; *Construction of a minimal Higgs* SO(10) *SUSY GUT model*, *Phys. Rev.* **D 62** (2000) 093008 [hep-ph/0003251];
Q. Shafi and Z. Tavartkiladze, *Anomalous flavor* U(1)*: predictive texture for bi-maximal neutrino mixing*, *Phys. Lett.* **B 482** (2000) 145 [hep-ph/0002150];
K.S. Babu, J.C. Pati and F. Wilczek, *Fermion masses, neutrino oscillations and proton decay in the light of SuperKamiokande*, *Nucl. Phys.* **B 566** (2000) 33 [hep-ph/9812538].

[10] T. Fukuyama, A. Ilakovac, T. Kikuchi, S. Meljanac and N. Okada, *General formulation for proton decay rate in minimal supersymmetric* SO(10) *GUT*, *Eur. Phys. J.* **C 42** (2005) 191 [hep-ph/0401213]; SO(10) *group theory for the unified model building*, *J. Math. Phys.* **46** (2005) 033505 [hep-ph/0405300]; *Higgs masses in the minimal SUSY* SO(10) *GUT*, *Phys. Rev.* **D 72** (2005) 051701 [hep-ph/0412348].

[11] D. Chang, T. Fukuyama, Y.-Y. Keum, T. Kikuchi and N. Okada, *Perturbative* SO(10) *grand unification*, *Phys. Rev.* **D 71** (2005) 095002 [hep-ph/0412011].

[12] Particle Data Group collaboration, K. Hagiwara et al., *Review of particle physics*, *Phys. Rev.* **D 66** (2002) 010001.

[13] T. Fukuyama, A. Ilakovac, T. Kikuchi, S. Meljanac and N. Okada, *Detailed analysis of proton decay rate in the minimal supersymmetric* SO(10) *model*, *JHEP* **09** (2004) 052 [hep-ph/0406068].

[14] A. Bandyopadhyay, S. Choubey, S. Goswami, S.T. Petcov and D.P. Roy, *Update of the solar neutrino oscillation analysis with the* 766*-Ty KamLAND spectrum*, *Phys. Lett.* **B 608** (2005) 115 [hep-ph/0406328].

[15] M. Fukugita and T. Yanagida, *Baryogenesis without grand unification*, *Phys. Lett.* **B 174** (1986) 45.

[16] M. Flanz, E.A. Paschos and U. Sarkar, *Baryogenesis from a lepton asymmetric universe*, *Phys. Lett.* **B 345** (1995) 248 [*Erratum ibid.* **382** (1996) 447] [hep-ph/9411366];
L. Covi, E. Roulet and F. Vissani, *CP violating decays in leptogenesis scenarios*, *Phys. Lett.* **B 384** (1996) 169 [hep-ph/9605319];
W. Buchmüller and M. Plümacher, *CP asymmetry in Majorana neutrino decays*, *Phys. Lett.* **B 431** (1998) 354 [hep-ph/9710460].

[17] E.W. Kolb and M.S. Turner, *The early universe*, Addison-Wesley, U.S.A. (1990).

[18] S. Weinberg, *Cosmological constraints on the scale of supersymmetry breaking*, *Phys. Rev. Lett.* **48** (1982) 1303.

[19] M.Y. Khlopov and A.D. Linde, *Is it easy to save the gravitino?*, *Phys. Lett.* **B 138** (1984) 265;
I.V. Falomkin et al., *Low-energy* $\bar{p}$ He_4 *annihilation and problems of the modern cosmology, GUT and SUSY models*, *Nuovo Cim.* **A79** (1984) 193 [*Yad. Fiz.* **39** (1984) 990];
M.Yu. Khlopov, Yu.L. Levitan, E.V. Sedelnikov and I.M. Sobol, *Nonequilibrium cosmological nucleosynthesis of light elements: calculations by the Monte Carlo method*, *Phys. Atom. Nucl.* **57** (1994) 1393 [*Yad. Fiz.* **57** (1994) 1466].

[20] M. Kawasaki and T. Moroi, *Gravitino production in the inflationary universe and the effects on big bang nucleosynthesis*, *Prog. Theor. Phys.* **93** (1995) 879 [hep-ph/9403364];
M. Kawasaki, K. Kohri and T. Moroi, *Hadronic decay of late-decaying particles and big-bang nucleosynthesis*, *Phys. Lett.* **B 625** (2005) 7 [astro-ph/0402490]; *Big-bang nucleosynthesis and hadronic decay of long-lived massive particles*, *Phys. Rev.* **D 71** (2005) 083502 [astro-ph/0408426].

[21] I. Affleck and M. Dine, *A new mechanism for baryogenesis*, *Nucl. Phys.* **B 249** (1985) 361.