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Leptogenesis in neutrino textures with two zeros

Satoru Kaneko, Makoto Katsumata and Morimitsu Tanimoto

Department of Physics, Niigata University
Ikarashi 2-8050, 950-2181 Niigata, Japan
E-mail: kaneko@muse.sc.niigata-u.ac.jp, katumata@muse.sc.niigata-u.ac.jp, tanimoto@muse.sc.niigata-u.ac.jp

Abstract: The leptogenesis is studied in the neutrino textures with two zeros, which reduce the number of independent phases of the CP violation. The phenomenologically favored neutrino textures with two zeros are decomposed into the Dirac neutrino mass matrix and the right-handed Majorana one in the see-saw mechanism. Putting the condition to suppress the $\mu \to e\gamma$ decay enough, the texture zeros of the Dirac neutrino mass matrix are fixed in the framework of the MSSM with right-handed neutrinos. These textures have only one CP violating phase. The magnitude of each entry of the Dirac mass matrix is determined in order to explain the baryon asymmetry of the universe by solving the Boltzmann equations. The relation between the leptogenesis and the low energy CP violation is presented in these textures.

Keywords: Baryogenesis, Neutrino Physics, CP violation.

Contents

1. Introduction

In these years empirical understanding of the mass and mixing of neutrinos have been advanced [1, 2, 3]. The KamLAND experiment selected the neutrino mixing solution that is responsible for the solar neutrino problem nearly uniquely [4], only large mixing angle solution. We have now good understanding concerning the neutrino mass difference squared ($\Delta m^2_{\rm atm}$, $\Delta m^2_{\rm sun}$) and flavor mixings of neutrinos ($\sin^2 2\theta_{\rm atm}$, $\tan^2\theta_{\rm sun}$) [5].

The texture zeros of the neutrino mass matrix have been discussed to explain these data [6]. Recently, Frampton, Glashow and Marfatia [7] found acceptable textures of the neutrino mass matrix with two independent vanishing entries in the basis where the charged lepton mass matrix is diagonal. They have been examined in detail phenomenologically [8]–[11]. These textures can be decomposed into the Dirac and the right-handed Majorana neutrino mass matrix with zeros in the see-saw mechanism [12]. The texture zeros of neutrino reduce the number of independent phases of the CP violation.[1]

In this paper, we study the leptogenesis [13] based on these textures. The leptogenesis is an important candidate to explain the observed baryon asymmetry of the universe. The CP violation required for the leptogenesis stems from phases in both Dirac and Majorana mass matrices, whereas the CP violation in the neutrino oscillations [14] can be described by the Dirac phase in the neutrino mixing matrix [15]. Therefore, once the texture of the Dirac neutrino mass matrix and right-handed Majorana neutrino mass matrix are given, the leptogenesis is linked with the low energy CP violation in the neutrino oscillations [16]–[21].

We have decomposed the acceptable textures of the neutrino mass matrix [7] into the Dirac neutrino mass matrix and the right-handed Majorana one [22]. Putting the condition

[1] In general, the number of independent CP violating phases are six for three generations without a left-handed Majorana mass term.

to suppress the $\mu \to e\gamma$ decay enough, we fix the textures of the Dirac neutrino mass matrix, which have only one CP violating phase. The magnitude of each entry of the Dirac mass matrix is determined in order to explain the baryon asymmetry of the universe by solving the Boltzmann equations.

We have already discussed the textures of the Dirac neutrinos only for the special case[2] in the previous work [23], in which the rough approximate dilution factor was used. In this paper, we fix the texture in the framework of the minimal supersymmetric standard model (MSSM) with right-handed neutrinos (RN) by solving the Boltzmann equations numerically. The relation between the leptogenesis and the low energy CP violation is presented in these textures.

The texture zeros of the Dirac neutrino mass matrix are presented in section 2. The CP violating phases and magnitude of matrix elements are discussed in section 3. In section 4, the CP asymmetry in the leptogenesis and the low energy CP violation are discussed for the selected textures. Numerical results are given in section 5. Section 6 is devoted to the summary.

2. Texture zeros of dirac neutrino mass matrix

Let us start with decomposing the textures presented by Frampton, Glashow and Marfatia [7] into the Dirac neutrino mass matrix and the right-handed Majorana neutrino one [22].

There are seven acceptable textures with two independent zeros for the effective neutrino mass matrix M_ν [7]. Among them, the textures A_1 and A_2 in ref. [7], which correspond to the hierarchical neutrino mass spectrum, are strongly favored by the phenomenological analyses [8, 9, 10, 11]. Therefore, we discuss these two textures in this paper. The neutrino mass matrix M_ν are written for A_1 and A_2 as follows:

$$\mathrm{A}_1 : \mathbf{M}_\nu = \begin{pmatrix} \mathbf{0} & \mathbf{0} & \times \\ \mathbf{0} & \times & \times \\ \times & \times & \times \end{pmatrix} \simeq m_0 \begin{pmatrix} 0 & 0 & \lambda \\ 0 & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}, \quad \mathrm{A}_2 : \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \times \\ \mathbf{0} & \times & \times \end{pmatrix} \simeq m_0 \begin{pmatrix} 0 & \lambda & 0 \\ \lambda & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}, \tag{2.1}$$

with $\lambda \simeq 0.22$ in the basis of the diagonal charged lepton mass matrix, and m_0 is the scale of the neutrino mass.

In principle these textures are given at the low energy scale because the experimental data are used to determine zeros, however, the structure of zeros in the mass matrix is not changed by the one-loop renormalization group equations of the MSSM [24]. Therefore, we discuss the see-saw realization in these textures at the right-handed Majorana neutrino $(N_1,\ N_2,\ N_3)$ scale:

$$\mathbf{M}_\nu = \mathbf{m_D}\ \mathbf{M_R}^{-1}\ \mathbf{m_D}^{\mathrm{T}}\,, \tag{2.2}$$

where $\mathbf{m_D}$ and $\mathbf{M_R}$ are the mass matrices for the Dirac neutrino masses and the right-handed Majorana neutrino ones, respectively. As far as we exclude the possibility that zeros are originated from cancellations among coefficients in the see-saw mechanism, the

[2] This case corresponds to $m = 4$, $n = 2$, $x = 2$, $y = 2$, $z = 2$ and $w = 1$ in this paper.

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see-saw realization of these seven textures are not trivial. Then, these zeros should come from zeros of the Dirac neutrino mass matrix and the right-handed Majorana neutrino one. These results are summarized in the ref. [22].

Once the right-handed Majorana neutrino mass matrix is specified, the Dirac neutrino ones are selected to reproduce the textures in eq. (2.1). In order to study the leptogenesis, the diagonal basis of the right-handed Majorana neutrino mass matrix is favored. However, there is no solution for acceptable textures unless we consider cancellations between matrix elements of the Dirac and Majorana ones. Therefore, we take a following texture for the right-handed Majorana neutrinos with three independent parameters:

$$\mathbf{M_R} = \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \times \end{pmatrix}, \tag{2.3}$$

where $\times' s$ denote non-zero entries. It should be noted that specifying the texture of the right-handed Majorana neutrinos is a choice of weak basis. Furthermore we can take the matrix in eq. (2.3) to be real. Then, the CP violating phases appear only in the Dirac neutrino mass matrix. In this case, we have six Dirac neutrino mass matrices, which reproduce the texture A_1 in eq. (2.1):

$$\begin{aligned} \mathbf{m_D} = & \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \mathbf{0} & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \times & \mathbf{0} \end{pmatrix}, \\ & \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \\ \times & \mathbf{0} & \mathbf{0} \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \times \\ \times & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \times \\ \times & \mathbf{0} & \times \end{pmatrix}, \end{aligned} \tag{2.4}$$

where $\times' s$ denote complex numbers. For the texture A_2 in eq. (2.1), we obtain

$$\begin{aligned} \mathbf{m_D} = & \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \times \\ \mathbf{0} & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \times \\ \mathbf{0} & \mathbf{0} & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \times & \mathbf{0} \\ \mathbf{0} & \times & \times \end{pmatrix}, \\ & \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \mathbf{0} & \times \\ \mathbf{0} & \times & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \mathbf{0} & \times \\ \mathbf{0} & \mathbf{0} & \times \end{pmatrix}, \begin{pmatrix} \mathbf{0} & \times & \mathbf{0} \\ \times & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \times & \times \end{pmatrix}. \end{aligned} \tag{2.5}$$

We can select the texture by the lepton flavor violation (LFV). Many authors have studied the LFV in the MSSM+RN assuming the relevant neutrino mass matrix [25]–[28]. In the MSSM with soft breaking terms, there exist lepton flavor violating terms such as off-diagonal elements of slepton mass matrices and trilinear couplings (A-term). It is noticed that large neutrino Yukawa couplings and large lepton mixings generate the large LFV in the left-handed slepton masses. For example, the decay rate of $\mu \to e\gamma$ can be approximated as follows:

$$\Gamma(\mu \to e\gamma) \simeq \frac{e^2}{16\pi} m_\mu^5 F \left| \frac{(6+2a_0^2)m_{S0}^2}{16\pi^2} (\mathbf{Y}_\nu \mathbf{Y}_\nu^\dagger)_{21} \ln \frac{M_X}{M_R} \right|^2 , \tag{2.6}$$

where the neutrino Yukawa coupling matrix $\mathbf{Y}_\nu$ is given as $\mathbf{Y}_\nu = \mathbf{m_D}/v_2$ (v_2 is a VEV of Higgs) at the right-handed mass scale M_R, and F is a function of masses and mixings for SUSY particles. In eq. (2.6), we assume the universal scalar mass (m_{S0}) for all scalars and the universal A-term ($A_f = a_0 m_{S0} Y_f$) at the GUT scale M_X. Therefore the branching ratio of $\mu \to e\gamma$ depends considerably on the texture of the Dirac neutrino mass matrix [28].

Many works have shown that this branching ratio is too large [28]. However, zeros in the Dirac neutrino mass matrix may suppress the branching ratio enough. The condition is that $(\mathbf{m_D m_D^\dagger})_{21}$ and $(\mathbf{m_D m_D^\dagger})_{31} \times (\mathbf{m_D m_D^\dagger})_{32}$ are tiny compared with other ones. Therefore we put the following conditions to select the texture zeros:

$$\left(\mathbf{m_D m_D^\dagger}\right)_{21} = 0\,, \qquad \left(\mathbf{m_D m_D^\dagger}\right)_{31} \times \left(\mathbf{m_D m_D^\dagger}\right)_{32} = 0\,. \tag{2.7}$$

Then, the branching ratio of $\mu \to e\gamma$ is safely predicted to be below the present experimental upper bound 1.2×10^{-11} [29] due to the texture zeros.[3] Actually, the case of the texture zeros was examined carefully in ref. [30].

3. CP violating phases in dirac neutrino mass matrix

Key ingredients of the leptogenesis are the structure of CP violating phases and the magnitude of each entry for the Dirac neutrino mass matrices in eq. (2.4) since the right-handed Majorana neutrino mass matrix is taken to be real. Although the non-zero entries $\times$ in the Dirac neutrino mass matrix are complex, three phases are removed by the re-definition of the left-handed neutrino fields. There is no freedom of re-definition for the right-handed ones in the basis with real $\mathbf{M_R}$. Furthermore, we move to the diagonal basis of the right-handed Majorana neutrino mass matrix in order to calculate the magnitude of the leptogenesis. Then, the Dirac neutrino mass matrices $\overline{\mathbf{m}}_\mathbf{D}$ in the new basis is given as follows:

$$\overline{\mathbf{m}}_\mathbf{D} = \mathbf{P_L}\ \mathbf{m_D}\ \mathbf{O_R}\,, \tag{3.1}$$

where $\mathbf{P_L}$ is a diagonal phase matrix and $\mathbf{O_R}$ is the orthogonal matrix which diagonalizes $\mathbf{M_R}$ as $\mathbf{O_R^T M_R O_R}$. Since the phase matrix $\mathbf{P_L}$ can remove one phase in each row of $\mathbf{m_D}$, three phases disappear in $\overline{\mathbf{m}}_\mathbf{D}$.

By taking three eigenvalues of $\mathbf{M_R}$ as follows:[4]

$$M_1 = -\lambda^m M_0\,, \qquad M_2 = \lambda^n M_0\,, \qquad M_3 = M_0\,, \tag{3.2}$$

where m and n are positive integer with $m > n$, we obtain the orthogonal matrix $\mathbf{O_R}$ as

$$\mathbf{O_R} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}\,, \qquad \tan^2\theta = \lambda^{m-n}\,. \tag{3.3}$$

[3] In practice, looser conditions are given to suppress the branching ratio below the experimental upper bound as seen in ref. [30]. Since our principle is to suppress it by zeros, our conditions are strong ones.

[4] The minus sign of M_1 is necessary to reproduce $\mathbf{M_R}$. This minus sign is transfered to $\mathbf{m_D}$ by the right-handed diagonal phase matrix $diag(i, 1, 1)$.

For the texture A_1, only one texture satisfies conditions in eq. (2.7):

$$\mathrm{A}_1^{\mathrm{D}} : \mathbf{m_D} = m_{D0} \begin{pmatrix} 0 & a\lambda^x & 0 \\ 0 & 0 & b \\ c\lambda^z e^{i\rho} & 0 & f \end{pmatrix}, \tag{3.4}$$

where a, b, c, f are the real order one coefficients, x and z are positive integer, which should satisfy the following conditions:

$$x + z = \frac{m+n}{2} + 1\,, \qquad 2z \geq m\,, \qquad m > n\,, \tag{3.5}$$

in order to reproduce the texture A_1 in eq. (2.1). These conditions lead to the inequality:

$$\frac{m}{2} \leq z \leq \frac{n+m}{2} + 1 < m + 1\,. \tag{3.6}$$

Therefore, we obtain sets for $(m,\ z)$, where m starts from 3 since the hierarchy is assumed for the right-handed Majorana masses and $m + n$ is even, as follows:

$$(m=3,\ z=2,3)\,, \qquad (m=4,\ z=2,3,4)\,, \qquad (m=5,\ z=3,4,5)\,, \qquad \ldots\,. \tag{3.7}$$

We will discuss the best choice of m and z in the leptogenesis.

For the texture A_2, we find two textures of the Dirac neutrino mass matrix, which satisfy conditions in eq. (2.7). The first one is

$$\mathrm{A}_2^{\mathrm{D}}(1) : \mathbf{m_D} = m_{D0} \begin{pmatrix} 0 & a\lambda^x & 0 \\ b\lambda^y & 0 & ce^{i\rho} \\ 0 & 0 & f \end{pmatrix}, \tag{3.8}$$

where m, n, x and y satisfy the following conditions:

$$x + y = \frac{m+n}{2} + 1\,, \qquad 2y \geq m\,, \qquad m > n\,. \tag{3.9}$$

The second one is

$$\mathrm{A}_2^{\mathrm{D}}(2) : \mathbf{m_D} = m_{D0} \begin{pmatrix} 0 & a\lambda^x & 0 \\ b\lambda^y & 0 & 0 \\ 0 & d\lambda^w e^{i\rho} & f \end{pmatrix}, \tag{3.10}$$

where m, n, x, y and w satisfy the following conditions:

$$x + y = \frac{m+n}{2} + 1\,, \qquad y = \frac{m}{2}\,, \qquad y + w = \frac{m+n}{2}\,, \qquad m > n\,, \tag{3.11}$$

which lead to

$$x = 1 + \frac{n}{2}\,, \qquad y = \frac{m}{2}\,, \qquad w = \frac{n}{2}\,, \qquad m > n\,. \tag{3.12}$$

Thus, x, y and w are fixed if m and n are given in this case.

4. Leptogenesis and low energy cp violation

Once the textures are fixed, we can discuss the leptogenesis numerically. Summing up the one-loop vertex and self-energy corrections, the lepton number asymmetry (CP asymmetry) for the lightest heavy Majorana neutrino (N_1) decays into $l^{\mp}\phi^{\pm}$ in the MSSM+RN [17] is given by

$$\epsilon_1 = \frac{\Gamma_1 - \overline{\Gamma_1}}{\Gamma_1 + \overline{\Gamma_1}} = -\frac{1}{8\pi v_2^2} \frac{1}{(\overline{\mathbf{m}}_{\mathbf{D}}{}^{\dagger}\overline{\mathbf{m}}_{\mathbf{D}})_{11}} \sum_j \mathrm{Im}\left[(\overline{\mathbf{m}}_{\mathbf{D}}{}^{\dagger}\overline{\mathbf{m}}_{\mathbf{D}})^2_{1j}\right]\left[f\left(\frac{M_j^2}{M_1^2}\right) + g\left(\frac{M_j^2}{M_1^2}\right)\right],$$

$$f(x) = \frac{2\sqrt{x}}{x-1}, \qquad g(x) = \sqrt{x}\ \ln\left(\frac{1+x}{x}\right), \tag{4.1}$$

where $M_1 < M_2,\ M_3$ is assumed, and $v_2 = v\sin\beta$ with $v = 174$GeV. In our analyses, we take $\sin\beta \simeq 1$. The lepton asymmetry Y_L is related to the CP asymmetry through the relation:

$$Y_L = \frac{n_L - n_{\overline{L}}}{s} = \kappa\,\frac{\epsilon_1}{g_*}\,, \tag{4.2}$$

where s denotes the entropy density, g_* is the effective number of relativistic degrees of freedom contributing to the entropy and κ is the so-called dilution factor which accounts for the washout processes (inverse decay and lepton number violating scattering). In the case of the MSSM+RN, one gets $g_* = 232.5$.

The produced lepton asymmetry Y_L is converted into a net baryon asymmetry Y_B through the $(B+L)$-violating sphaleron processes. One finds the relation [31]

$$Y_B = \xi\, Y_{B-L} = \frac{\xi}{\xi - 1} Y_L\,, \qquad \xi = \frac{8\ N_f + 4\ N_H}{22\ N_f + 13\ N_H}\,, \tag{4.3}$$

where N_f and N_H are the number of fermion families and complex Higgs doublets, respectively. Taking into account $N_f = 3$ and $N_H = 2$ in the MSSM, we get

$$Y_B = -\frac{5}{18}\,Y_L\,. \tag{4.4}$$

On the other hand, the low energy CP violation, which is a measurable in the long baseline neutrino oscillations [14], is given by the Jarlskog determinant J_{CP} [32], which is calculated by

$$\det[\mathbf{M}_\ell\mathbf{M}_\ell^\dagger, \mathbf{M}_\nu\mathbf{M}_\nu^\dagger] = -2iJ_{CP}(m_\tau^2 - m_\mu^2)(m_\mu^2 - m_e^2)(m_e^2 - m_\tau^2)(m_3^2 - m_2^2)(m_2^2 - m_1^2)(m_1^2 - m_3^2)\,, \tag{4.5}$$

where $\mathbf{M}_\ell$ is the diagonal charged lepton mass matrix, and m_1, m_2, m_3 are neutrino masses.

It is very interesting to investigate the link between the leptogenesis (ϵ_1) and the low energy CP violation (J_{CP}) in each texture. Let us begin with investigating the case A_1^D in eq. (3.4). In this texture, we get

$$\epsilon_1 \simeq -\frac{3m_{D0}^2}{8\pi v_2^2} \frac{\lambda^m + \lambda^n}{a^2\lambda^{m+2x} + c^2\lambda^{n+2z}} \frac{c^2 f^2 \lambda^{m+2z}}{1+\lambda^{m-n}} \sin 2\rho = -\frac{3m_{D0}^2}{8\pi v_2^2} \frac{c^2 f^2 \lambda^{m+2z}}{a^2\lambda^{2m-2z+2} + c^2\lambda^{2z}} \sin 2\rho\,,$$

$$J_{CP} = \frac{m_0^6 a^2 b^4 c^4 f^2}{(\Delta m_{\rm atm}^2)^2 \Delta m_{\rm sun}^2}\ \lambda^{-2m-n+2x+4z} \sin 2\rho = \frac{1}{64}\frac{\Delta m_{\rm atm}^2}{\Delta m_{\rm sun}^2} a^2 b^4 c^4 f^2 \lambda^{-m+2z+2} \sin 2\rho\,, \tag{4.6}$$

where we used $2m_0 \simeq \sqrt{\Delta m^2_{\rm atm}}$ because of $m_1,\ m_2 \ll m_3$ in our case.[5] The value of m^2_{D0} is estimated from $m_0 M_0$. The ϵ_1 of eq. (4.6) is classified by z. The first term of the denominator suppressed only in the case of $z = m/2$. Then, we have

$$
\begin{aligned}
\epsilon_1 &\simeq -\frac{3m^2_{D0}}{8\pi v_2^2} f^2 \lambda^m \sin 2\rho\,, \qquad (m = 2z)\,,\\
J_{CP} &= \frac{1}{64}\frac{\Delta m^2_{\rm atm}}{\Delta m^2_{\rm sun}}\; a^2 b^4 c^4 f^2 \lambda^2 \sin 2\rho\,.
\end{aligned}
\tag{4.7}
$$

For other z's $(m/2 < z < m+1)$, the first term dominated the denominator in eq. (4.6). Then, we get

$$
\begin{aligned}
\epsilon_1 &\simeq -\frac{3m^2_{D0}}{8\pi v_2^2}\frac{c^2 f^2}{a^2}\lambda^{-m+4z-2} \sin 2\rho\,, \qquad \left(\frac{m}{2} < z < m+1\right)\\
J_{CP} &= \frac{1}{64}\frac{\Delta m^2_{\rm atm}}{\Delta m^2_{\rm sun}}\; a^2 b^4 c^4 f^2 \lambda^{-m+2z+2} \sin 2\rho\,,
\end{aligned}
\tag{4.8}
$$

where J_{CP} is smaller than λ^2.

The next case is given in the texture $A_2^D(1)$. The result is given by replacing z with y as follows:

$$
\begin{aligned}
\epsilon_1 &\simeq \frac{3m^2_{D0}}{8\pi v_2^2}\frac{\lambda^m+\lambda^n}{a^2\lambda^{m+2x}+b^2\lambda^{n+2y}}\frac{b^2c^2\lambda^{m+2y}}{1+\lambda^{m-n}}\sin 2\rho = \frac{3m^2_{D0}}{8\pi v_2^2}\frac{b^2c^2\lambda^{m+2y}}{a^2\lambda^{2m-2y+2}+b^2\lambda^{2y}}\sin 2\rho\,,\\
J_{CP} &= \frac{m_0^6 a^2 b^4 c^2 f^4}{(\Delta m^2_{\rm atm})^2 \Delta m^2_{\rm sun}}\;\lambda^{-2m-n+2x+4y}\sin 2\rho = \frac{1}{64}\frac{\Delta m^2_{\rm atm}}{\Delta m^2_{\rm sun}}\; a^2 b^4 c^2 f^4 \lambda^{-m+2y+2}\sin 2\rho\,.
\end{aligned}
\tag{4.9}
$$

Therefore, the numerical result is the same as the case in A_1^D except for the relative sign.

By putting eq. (3.12), we get for the case of the texture $A_2^D(2)$

$$
\begin{aligned}
\epsilon_1 &\simeq -\frac{3m^2_{D0}}{8\pi v_2^2}\frac{\lambda^m+\lambda^n}{a^2\lambda^{m+2x}+b^2\lambda^{n+2y}+d^2\lambda^{m+2w}}\frac{d^2 f^2\lambda^{2m+2w}}{\lambda^m+\lambda^n}\sin 2\rho\\
&\simeq -\frac{3m^2_{D0}}{8\pi v_2^2}\frac{d^2 f^2}{b^2+d^2}\lambda^m \sin 2\rho\,,\\
J_{CP} &= \frac{m_0^6 a^2 b^6 d^2 f^2}{(\Delta m^2_{\rm atm})^2 \Delta m^2_{\rm sun}}\;\lambda^{-3m-2n+2x+6y+2w}\sin 2\rho\\
&= \frac{1}{64}\frac{\Delta m^2_{\rm atm}}{\Delta m^2_{\rm sun}}\; a^2 b^6 d^2 f^2 \lambda^2 \sin 2\rho\,.
\end{aligned}
\tag{4.10}
$$

This case is the simplest one since ϵ_1 is given by only m and the magnitude of J_{CP} is λ^2.

5. Numerical results

In order to calculate the baryon asymmetry, we need the dilution factor that involves the integration of the Boltzmann equations [33].

[5] As is well known, the CP violation vanishes in the neutrino oscillation in the case of $\Delta m^2_{\rm sun} = 0$, which corresponds to the $\lambda = 0$ limit in our case.

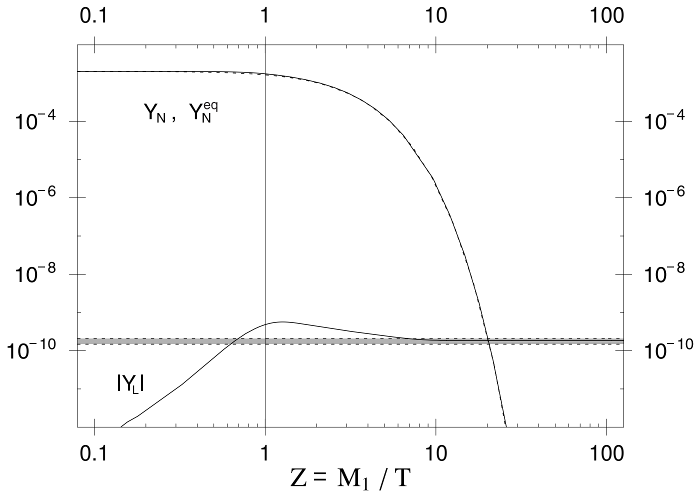

Figure 1: Time evolution of neutrino number density Y_{N_1}, and lepton asymmetry $|Y_L|$ for the texture A_1^D, where $M_0 = 10^{15}$GeV, $\sin 2\rho = 1/3$, $m = 6$, $n = 2$, $z = 3$ are taken. The equilibrium distribution $Y_{N_1}^{eq}$ is represented by a dashed line against $z = M_1/T$. The gray area shows the measured value for the lepton asymmetry.

The Boltzmann equations for the N_1 number densities and the N_{B-L} asymmetry is given as:

$$\begin{aligned}
\frac{dN_1}{dz} &= -\left(\frac{\Gamma_D}{Hz} + \frac{\Gamma_S}{Hz}\right)(N_1 - N_1^{eq}) \,, \\
\frac{dN_{B-L}}{dz} &= -\epsilon_1 \frac{\Gamma_D}{Hz}(N_1 - N_1^{eq}) - \frac{\Gamma_W}{Hz} N_{B-L} \,, \qquad z = \frac{M_1}{T} \,,
\end{aligned} \tag{5.1}$$

where H is Hubble parameter at $z = 1$, and Γ_D, Γ_S and Γ_W account for the decay and inverse decay process, the scattering processes, the total washout processes, respectively. In our numerical calculation, we take only the process involving the interaction with the top quark for $\Delta L = 1$ scattering processes Γ_S since this process is dominant one.

In figure 1, we show the evolution of neutrino number density Y_{N_1}, $Y_{N_1}^{eq}$ and the lepton asymmetry $|Y_L|$ for the typical case of the texture A_1^D. The equilibrium distribution for N_1 is represented by a dashed line against z. In this calculation, $\sin 2\rho = 1/3$, $M_0 = 10^{15}$GeV, $m = 6$, $n = 2$, $z = 3$ are taken, and the coefficient f is 1. These parameters correspond to $M_1 \simeq 10^{11}$GeV. The gray area shows the measured value for the lepton asymmetry, which is derived from the new data of WMAP [34]:

$$\eta = 6.5^{+0.4}_{-0.3} \times 10^{-10} \ (1\ \sigma) \,. \tag{5.2}$$

This value corresponds to

$$Y_B = (7.9 \sim 11) \times 10^{-11} \ (3\ \sigma) \,. \tag{5.3}$$

The generated asymmetry is consistent with the observed one as seen in figure 1.

In figure 2, we show the relation of the predicted J_{CP} and the baryon asymmetry $|Y_B|$ of the A_1^D texture in the case of $M_0 = 10^{15}$GeV, where 13 points are predictions for different m and z. The relative sign between J_{CP} and Y_B is minus as seen in eq. (4.6). The

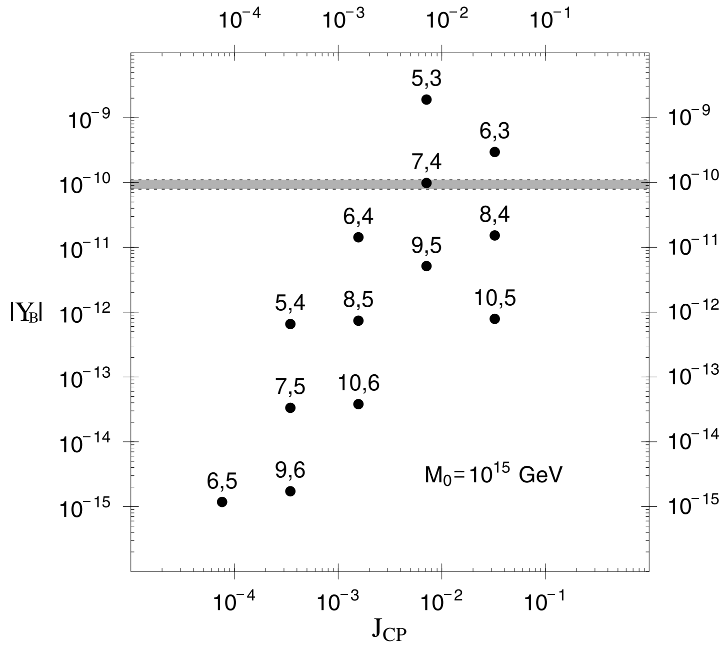

Figure 2: Relation of the predicted J_{CP} and the baryon asymmetry $|Y_B|$ of the texture A_1^D in the case of $M_0 = 10^{15}$GeV with $\sin 2\rho = 1$, where numbers above black points denote (m,z),respectively.

prediction in the case of $(m = 7,\ z = 4)$ is consistent with the observed baryon asymmetry taking $\sin 2\rho = 1$, while J_{CP} is 0.007. The cases of $(m = 5,\ z = 3)$ and $(m = 6,\ z = 3)$ give rather large asymmetry. In these cases, the prediction could be consistent with the observed baryon asymmetry by taking smaller $\sin 2\rho$. Then, J_{CP} is also reduced. It is noticed that the ambiguity of a factor $2 \sim 3$ should be taken into predictions since coefficients a, b, c, d and f are taken to be 1.

Figure 3 corresponds to the case of $M_0 = 10^{14}$GeV. The prediction in the cases of $(m = 5,\ z = 3)$ is consistent with the observed baryon asymmetry while J_{CP} is around 0.007. The cases of $(m = 4,\ z = 3)$ and $(m = 6,\ z = 3)$ may be consistent if we take account of the ambiguity of order one coefficients. In the case of $(m = 4,\ z = 2)$, the prediction could be consistent with the observed baryon asymmetry by taking smaller $\sin 2\rho$.

The case of $M_0 = 10^{13}$GeV is shown in figure 4. The prediction in the case of $(m = 4,\ z = 2)$ is consistent with the observed asymmetry. The predicted value of J_{CP} is 0.03. Since the predicted value may be multiplied by a factor $2 \sim 3$ due to the order one factor $c^2 f^2/a^2$, the case of $(m = 5,\ z = 3)$ could be consistent with the observed asymmetry. The case of $(m = 3,\ z = 2)$ is also consistent with the observed baryon asymmetry by taking smaller $\sin 2\rho$.

In order to show the M_1 dependence of $|Y_B|$, we combine predicted points of figures 2, 3, 4 into figure 5, where $|Y_B|$ is presented against M_1 for $M_0 = 10^{13},\ 10^{14},\ 10^{15}$GeV. The value of m in figures 2, 3, 4 is converted to the value of M_1. The values of z are not shown in figure 5 because we can find the value of z in figures 2, 3, 4. It is found that $M_1 = 10^{10} \sim 10^{11}$GeV is consistent with the observed asymmetry. This result is consistent with the lower bound of M_1 in ref. [35].

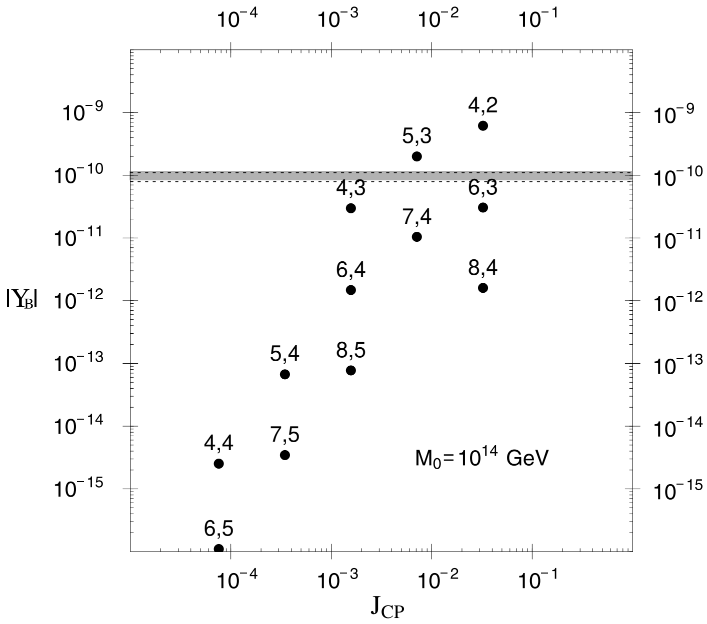

Figure 3: Relation of the predicted J_{CP} and the baryon asymmetry $|Y_B|$ of the texture A_1^D in the case of $M_0 = 10^{14}$GeV with $\sin 2\rho = 1$, where numbers above black points denote (m,z), respectively.

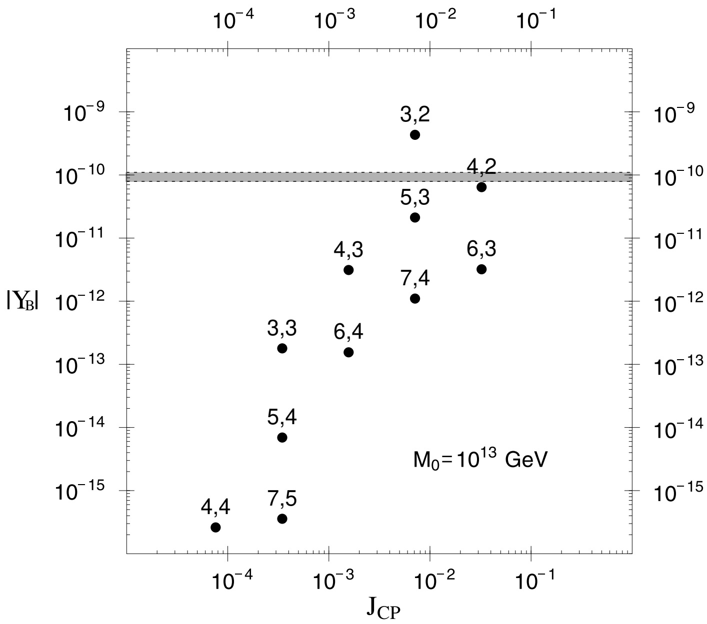

Figure 4: Relation of the predicted J_{CP} and the baryon asymmetry $|Y_B|$ of the texture A_1^D in the case of $M_0 = 10^{13}$GeV with $\sin 2\rho = 1$, where numbers above black points denote $(m,\ z)$, respectively.

In the case of the texture $A_2^D(1)$, results are the same as the ones in the texture A_1^D apart from the relative sign between J_{CP} and Y_B, which is plus as seen in eq. (4.10). On the other hand, the case of the texture $A_2^D(2)$ is simple because the prediction depends

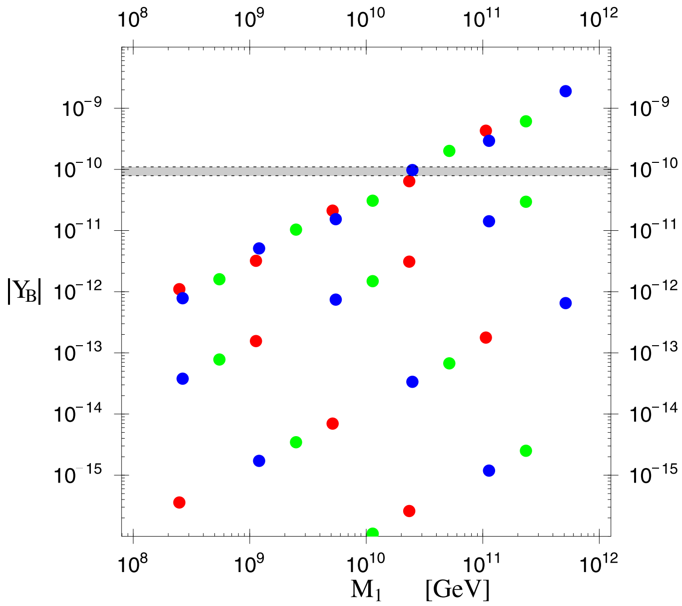

Figure 5: Combined results of the baryon asymmetry $|Y_B|$ versus M_1 in the texture A_1^D with $\sin 2\rho = 1$. The value of m is converted to M_1 while the values of z are not shown in this figure. Blue, green, red points correspond to $M_0 = 10^{15}$, 10^{14}, 10^{13}GeV, respectively.

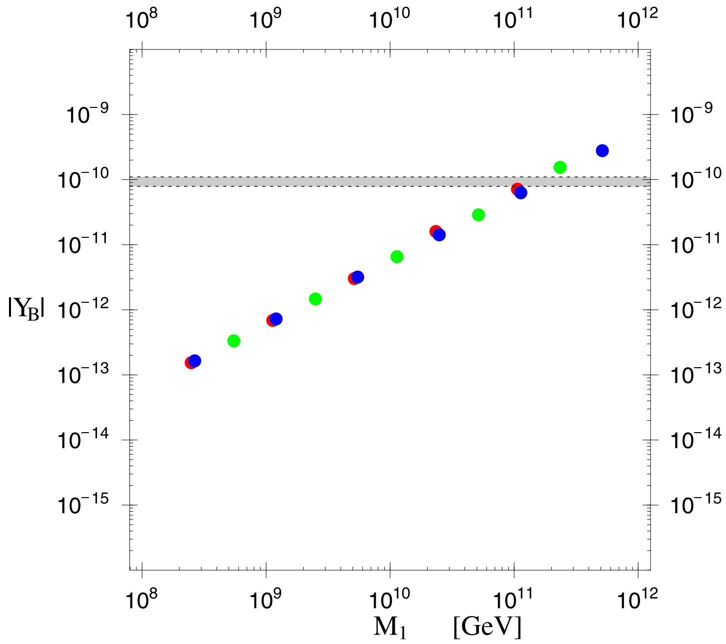

Figure 6: Baryon asymmetry $|Y_B|$ versus M_1 in the texture $A_2^D(2)$ for different m and M_0 by taking $\sin 2\rho = 1$. Blue, green, red points correspond to $M_0 = 10^{15}$, 10^{14}, 10^{13}GeV, respectively. Many predicted points overlap.

only on m and M_0, which are converted to M_1. We show the $|Y_B|$ versus M_1 in figure 6 for $M_0 = 10^{13}$, 10^{14}, 10^{15}GeV, while J_{CP} is λ^2 being independent of m. It is found that predictions almost depend on only M_1. It is found that $M_1 = 5 \times 10^{10} \sim 5 \times 10^{11}$GeV is consistent with the observed asymmetry. The typical Dirac neutrino mass matrices are given by $m = 6$ for $M_0 = 10^{15}$GeV, $m = 4$ for $M_0 = 10^{14}$GeV and $m = 3$ for $M_0 = 10^{13}$GeV.

6. Summary

The leptogenesis is studied in the texture zeros of neutrinos, which reduce the number of independent phases of the CP violation. The phenomenologically favored neutrino textures with two zeros are decomposed into the Dirac neutrino mass matrix and the right-handed Majorana one in the see-saw mechanism. Putting the condition to suppress the $\mu \to e\gamma$ decay enough, the Dirac neutrino textures are fixed in the framework of the MSSM with right-handed neutrinos. These textures have only one CP violating phase. The magnitude of each entry of the matrix is determined in order to explain the baryon asymmetry of the universe by solving the Boltzmann equations. We have typical ones, $(m = 7,\ z = 4)$ for $M_0 = 10^{15}$GeV, $(m = 5,\ z = 3)$ for $M_0 = 10^{14}$GeV and $(m = 4,\ z = 2)$ for $M_0 = 10^{13}$GeV. The relation between the baryon asymmetry and J_{CP} has been discussed in these textures. For the textures A_1^D and $A_2^D(2)$, the relative sign between the baryon asymmetry and J_{CP} is plus, while it is minus for the texture $A_2^D(1)$. Thus, it is very important to observe the relative sign to distinguish textures. It is also noticed that $M_1 = 10^{10} \sim 5 \times 10^{11}$GeV is required to reproduce the observed asymmetry, and J_{CP} is expected to be $0.007 \sim 0.03$. We expect the observation of J_{CP} in the future experiments.

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