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

ABSTRACT

The leptogenesis is studied in the neutrino textures with two zeros, which reduce the number of independent phases of the CP violation. The phenomenological 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 Boltzman equations. The relation between the leptogenesis and the low energy CP violation is presented in these textures.
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 ($\Delta m^2_{\text{atm}}$, $\Delta m^2_{\text{sun}}$) and flavor mixings of neutrinos ($\sin^2 2\theta_{\text{atm}}$, $\tan^2 \theta_{\text{sun}}$) [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 with the diagonal charged lepton mass matrix. They have been examined in details phenomenologically [8, 9, 10, 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 neutrinos 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 the right-handed sector, whereas the CP violation in the neutrino oscillations [14] can be described by the phase in the left-handed neutrino mixing matrix [15]. Therefore, once the texture of the Dirac neutrino mass matrix is given, the leptogenesis links with the low energy CP violation in the neutrino oscillations [16, 17, 18, 19, 20, 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 to suppress the $\mu \rightarrow e\gamma$ 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,

---

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

2 This case corresponds to $m = 4$, $n = 2$, $x = 2$, $y = 2$, $z = 2$ and $w = 1$ 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 Boltzman 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 $M_\nu$ [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 textures of the $A_1$ and $A_2$ types are written:

$$A_1 : M_\nu = \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix} \simeq m_0 \begin{pmatrix} 0 & 0 & \lambda \\ 0 & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}, \quad A_2 : M_\nu = \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix} \simeq m_0 \begin{pmatrix} 0 & \lambda & 0 \\ \lambda & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix},$$

(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 put 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:

$$M_\nu = m_D M_R^{-1} m_D^T,$$

(2)

where $m_D$ and $M_R$ 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 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. (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:

\[
M_R = \begin{pmatrix}
0 & \times & 0 \\
\times & \times & 0 \\
0 & 0 & \times
\end{pmatrix},
\]  

(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. (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. (1):

\[
m_D = \begin{pmatrix}
0 & \times & 0 \\
0 & \times & \times \\
\times & \times & \times
\end{pmatrix}, \quad \begin{pmatrix}
0 & \times & 0 \\
\times & \times & \times \\
0 & \times & \times
\end{pmatrix}, \quad \begin{pmatrix}
0 & \times & 0 \\
\times & \times & \times \\
\times & \times & \times
\end{pmatrix},
\]

(4)

where \(\times\)'s denote complex numbers. For the texture \(A_2\) in eq. (1), we obtain

\[
m_D = \begin{pmatrix}
0 & \times & 0 \\
\times & \times & \times \\
0 & \times & \times
\end{pmatrix}, \quad \begin{pmatrix}
0 & \times & 0 \\
\times & \times & \times \\
0 & \times & \times
\end{pmatrix}, \quad \begin{pmatrix}
0 & \times & 0 \\
\times & \times & \times \\
0 & \times & \times
\end{pmatrix},
\]

(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, 26, 27, 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 $\mu \rightarrow e\gamma$ can be approximated as follows:

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

where the neutrino Yukawa coupling matrix $Y_\nu$ is given as $Y_\nu = m_D/v_2$ ($v_2$ 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.(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 $\mu \rightarrow e\gamma$ depends considerably on the texture [28].

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

$$\begin{align*}
(m_D m_D^\dagger)_{21} &= 0, \\
(m_D m_D^\dagger)_{31} \times (m_D m_D^\dagger)_{32} &= 0.
\end{align*} \quad (7)$$

Then, the branching ratio of $\mu \rightarrow e\gamma$ is safely predicted to be below the present experimental upper bound $1.2 \times 10^{-11}$ [29] due to the texture zeros. 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.(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 $M_R$. 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 $\overline{m_D}$ in the new basis is given as follows:

$$\overline{m_D} = P_L m_D O_R, \quad (8)$$
where $P_L$ is a diagonal phase matrix and $O_R$ is the orthogonal matrix which diagonalizes $M_R$ as $O_R^T M_R O_R$. Since the phase matrix $P_L$ can remove one phase in each row of $m_D$, three phases disappear in $m_D$.

By taking three eigenvalues of $M_R$ as follows $^3$:

$$M_1 = -\lambda^m M_0, \quad M_2 = \lambda^n M_0, \quad M_3 = M_0,$$

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

$$O_R = \begin{pmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \tan^2 \theta = \lambda^{m-n}.$$ (10)

For the texture $A_1$, only one texture satisfies conditions in eq.(7):

$$A_1^D : m_D = m_D^0 \begin{pmatrix} 0 & a\lambda^x & 0 \\ 0 & 0 & b \\ c\lambda^z e^{i\rho} & 0 & f \end{pmatrix},$$ (11)

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

$$x + z = \frac{m + n}{2} + 1, \quad 2z \geq m, \quad m > n,$$ (12)

in order to reproduce the texture $A_1$ in eq.(1). These conditions lead to the inequality:

$$\frac{m}{2} \leq z \leq \frac{n + m}{2} + 1 < m + 1.$$ (13)

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:

$$(m = 3, \quad z = 2, 3), \quad (m = 4, \quad z = 2, 3, 4), \quad (m = 5, \quad z = 3, 4, 5), \quad \cdots.$$ (14)

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.(7). The first one is

$$A_2^D (1) : m_D = m_D^0 \begin{pmatrix} 0 & a\lambda^x & 0 \\ b\lambda^y & 0 & c e^{i\rho} \\ 0 & 0 & f \end{pmatrix},$$ (15)

$^3$The minus sign of $M_1$ is necessary to reproduce $M_R$. This minus sign is transferred to $m_D$ by the right-handed diagonal phase matrix $\text{diag}(i, 1, 1)$. 
where \( m, n, x \) and \( y \) satisfy the following conditions:

\[
x + y = \frac{m + n}{2} + 1, \quad 2y \geq m, \quad m > n.
\]

The second one is

\[
A^D_2(2) : \quad m_D = m_{D0} \begin{pmatrix} 0 & a\lambda^x & 0 \\ b\lambda^y & 0 & 0 \\ 0 & d\lambda^w e^{i\rho} & f \end{pmatrix},
\]

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

\[
x + y = \frac{m + n}{2} + 1, \quad y = \frac{m}{2}, \quad y + w = \frac{m + n}{2}, \quad m > n,
\]

which lead to

\[
x = 1 + \frac{n}{2}, \quad y = \frac{m}{2}, \quad w = \frac{n}{2}, \quad m > n.
\]

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 \( l^\pm \phi^\pm \) in the MSSM+RN\[17\] is given by

\[
\epsilon_1 = \frac{\Gamma_1 - \Gamma_1^-}{\Gamma_1 + \Gamma_1^-} = -\frac{1}{8\pi v_2^2 (\langle m_D \rangle^2 m_D^T m_D)_{11}} \sum_j \text{Im}[(\langle m_D \rangle^T m_D)_{1j}^2] \left[ f \left( \frac{M_j^2}{M_1^2} \right) + g \left( \frac{M_j^2}{M_1^2} \right) \right],
\]

\[
f(x) = \frac{2\sqrt{x}}{x-1}, \quad g(x) = \sqrt{x} \ln \left( \frac{1+x}{x} \right),
\]

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

\[
Y_L = \frac{n_L - n_R}{s} = \kappa \frac{\epsilon_1}{g_*},
\]

where \( s \) denotes the entropy density, \( g_* \) is the effective number of relativistic degrees of freedom contributing to the entropy and \( \kappa \) 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]

\[
Y_B = \frac{\xi}{\xi - 1} Y_L , \quad \xi = \frac{8 N_f + 4 N_H}{22 N_f + 13 N_H} ,
\]

(22)

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

\[
Y_B = -\frac{5}{18} Y_L .
\]

(23)

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

\[
\det[M_\ell M_\ell^\dagger, M_\nu M_\nu^\dagger] = -2i J_{CP}(m_\tau^2 - m_\mu^2)(m_\mu^2 - m_e^2)(m_e^2 - m_\tau^2)(m_2^2 - m_1^2)(m_1^2 - m_3^2) ,
\]

(24)

where \( M_\ell \) is the diagonal charged lepton mass matrix, and \( m_1, m_2, m_3 \) are neutrino masses.

It is very interesting to investigate links between the leptogenesis (\( \epsilon_1 \)) and the low energy CP violation (\( J_{CP} \)) in each texture. Let us begin with investigating the case \( A_1^D \) in eq.(11). In this texture, we get

\[
\epsilon_1 \simeq -\frac{3 m_{D_0}^2}{8 \pi v_2} \frac{\lambda^m + \lambda^n}{a^2 \lambda^{m+2} + c^2 \lambda^{n+2} + 1 + \lambda^{m-n}} c f^2 \lambda^{m+2z} \sin 2 \rho = -\frac{3 m_{D_0}^2}{8 \pi v_2} \frac{c^2 f^2 \lambda^{m+2z}}{a^2 \lambda^{m+2z} + c^2 \lambda^{2z}} \sin 2 \rho ,
\]

(25)

\[
J_{CP} = \frac{1}{64} \frac{\Delta m_{atm}^2}{\Delta m_{sun}^2} a^2 b^4 c^4 f^2 \lambda^{-2m-n+2z+4} \sin 2 \rho = \frac{1}{64} \frac{\Delta m_{atm}^2}{\Delta m_{sun}^2} a^2 b^4 c^4 f^2 \lambda^{-m+2z} \sin 2 \rho ,
\]

(26)

where we used experimental values \( \Delta m_{atm}^2 \) and \( \Delta m_{sun}^2 \) assuming \( m_1 \ll m_2 \ll m_3 \). The value of \( m_{D_0}^2 \) is estimated from \( m_0 M_0 \). The \( \epsilon_1 \) is classified by \( z \). The first term of the denominator suppressed only in the case of \( z = m/2 \). Then, we have

\[
\epsilon_1 \simeq -\frac{3 m_{D_0}^2}{8 \pi v_2} f^2 \lambda^m \sin 2 \rho , \quad (m = 2z) ,
\]

\[
J_{CP} = \frac{1}{64} \frac{\Delta m_{atm}^2}{\Delta m_{sun}^2} a^2 b^4 c^4 f^2 \lambda^2 \sin 2 \rho .
\]

(27)

For other \( z 's \) \((m/2 < z < m + 1)\), the first term dominated the the denominator in eq.(25). Then, we get

\[
\epsilon_1 \simeq -\frac{3 m_{D_0}^2}{8 \pi v_2} c^2 f^2 \lambda^{-m+4z-2} \sin 2 \rho , \quad \left( \frac{m}{2} < z < m + 1 \right)
\]

\[
J_{CP} = \frac{1}{64} \frac{\Delta m_{atm}^2}{\Delta m_{sun}^2} a^2 b^4 c^4 f^2 \lambda^{-m+2z+2} \sin 2 \rho ,
\]

(28)

\[\text{As is well known, the CP violation vanishes in the neutrino oscillation in the case of } \Delta m_{sun}^2 = 0, \text{ which corresponds to the } \lambda = 0 \text{ limit in our case.}\]
where $J_{CP}$ is smaller than $\lambda^2$.

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

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

\begin{equation}
J_{CP} = \frac{1 \Delta m_{\text{atm}}^2}{64 \Delta m_{\text{sun}}^2} a^2 b^4 c^2 f^4 \lambda^{-2m-n+2x+4y} \sin 2\rho = \frac{1 \Delta m_{\text{atm}}^2}{64 \Delta m_{\text{sun}}^2} a^2 b^4 c^2 f^4 \lambda^{-m+2y+2} \sin 2\rho .
\end{equation}

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

By putting eq.(19), we get for the case of the texture $A_2^D(2)$

$$
\epsilon_1 \simeq - \frac{3m_{D0}^2}{8\pi v_2^2} \frac{\lambda^m + \lambda^n}{a^2 \lambda^{m+2x} + b^2 \lambda^{n+2y} + d^2 \lambda^{m+2w}} \frac{d^2 f^2 \lambda^{2m+2w}}{\lambda^m + \lambda^n} \sin 2\rho ,
$$

\begin{equation}
J_{CP} = \frac{1 \Delta m_{\text{atm}}^2}{64 \Delta m_{\text{sun}}^2} a^2 b^6 d^2 f^4 \lambda^{-3m-2w+6y+2w} \sin 2\rho
= \frac{1 \Delta m_{\text{atm}}^2}{64 \Delta m_{\text{sun}}^2} a^2 b^6 d^2 f^2 \lambda^2 \sin 2\rho .
\end{equation}

This case is the simplest one since $\epsilon_1$ is given by only $m$ and the magnitude of $J_{CP}$ is $\lambda^2$.

## 5 Numerical Results

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

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

$$
\frac{dN_1}{dz} = - \frac{\Gamma_D}{Hz} (N_1 - N_1^{eq}) ,
$$

$$
\frac{dN_{B-L}}{dz} = - \epsilon_1 \frac{\Gamma_D}{Hz} (N_1 - N_1^{eq}) - \frac{\Gamma_W}{Hz} N_{B-L} ,
$$

where $H$ is Hubble parameter at $z = 1$, and $\Gamma_D$, $\Gamma_S$ and $\Gamma_W$ account for the decay and inverse decay process, the scattering processes, the total washout processes, respectively. In our numerical calculation, we take into only the process involving the interaction with the top quark for $\Delta L = 1$ scattering processes $\Gamma_S$ since this process is dominant one.
Figure 1: Time evolution of neutrino number density \( Y_{N_1} \), and lepton asymmetry \( |Y_L| \) for the texture \( A_1^D \), where \( M_0 = 10^{15}\text{GeV}, \sin 2\rho = 1/3, m = 6, n = 2, z = 3 \) 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.

In Fig.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, \( \sin 2\rho = 1/3, M_0 = 10^{15}\text{GeV}, m = 6, n = 2, z = 3 \) are taken, and the coefficient \( f \) is 1. These parameters correspond to \( M_1 \simeq 10^{11}\text{GeV} \). The gray area shows the measured value for the lepton asymmetry, which is derived from the new data of WMAP [34]:

\[
\eta = 6.5^{+0.4}_{-0.3} \times 10^{-10} \ (1 \sigma) .
\]

This value corresponds to

\[
Y_B = (7.9 \sim 11) \times 10^{-11} \ (3 \sigma) .
\]

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

In Fig.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 \( M_0 = 10^{15}\text{GeV} \), 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.(25) and eq.(26). The
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 at most 0.01. It is noticed that the ambiguity of factor \(2 \sim 3\) should be taken into predictions since coefficients \(a, b, c, d\) and \(f\) are taken to be 1.

Fig.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 $M_0 = 10^{13}\text{GeV}$ is shown in Fig.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 Fig.5, predictions of the baryon asymmetry $|Y_B|$ are presented against $M_1$ for $M_0 = 10^{13}, \ 10^{14}, \ 10^{15}\text{GeV}$. It is found that $M_1 = 10^{10} \sim 10^{11}\text{GeV}$ is consistent with the observed asymmetry. This result is consistent with the lower bound of $M_1$ in ref.[35]. 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.
Figure 4: Relation of the predicted $J_{CP}$ and the baryon asymmetry $|Y_B|$ of the texture $A_4^P$ in the case of $M_0 = 10^{13}$GeV with $\sin 2\rho = 1$, where numbers above black points denote $(m, z)$, respectively.
Figure 5: Baryon asymmetry $|Y_B|$ versus $M_1$ in the texture $A_1^{D}$ with $\sin 2\rho = 1$. Big, middle, small black points correspond to $M_0 = 10^{15}, 10^{14}, 10^{13}\text{GeV}$, 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 $\sin 2\rho = 1$. Big, middle, small black points correspond to $M_0 = 10^{15}, 10^{14}, 10^{13}\text{GeV}$, respectively. Many predicted points overlap.
between $J_{CP}$ and $Y_B$, which is plus as seen in eq.(30). On the other hand, the case of the texture $A_2^D(2)$ texture is simple because the prediction depends only on $m$ and $M_0$. We show the $|Y_B|$ versus $M_1$ in Fig.6 for $M_0 = 10^{13}$, $10^{14}$, $10^{15}$GeV, while $J_{CP}$ is $\lambda^2$ 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 phenomenological 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 $\mu \rightarrow e\gamma$ decay enough, the Dirac neutrino textures are fixed in the framework of the MSSM+RN. 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 Boltzman equations. The preferred Dirac mass matrix depends on $M_0$. 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.

This research is supported by the Grant-in-Aid for Science Research, Ministry of Education, Science and Culture, Japan (No.12047220).
References

[1] Super-Kamiokande Collaboration, Y. Fukuda et al, Phys. Rev. Lett. 81 (1998) 1562; ibid. 82 (1999) 2644; ibid. 82 (1999) 5194.

[2] Super-Kamiokande Collaboration, S. Fukuda et al. Phys. Rev. Lett. 86, 5651; 5656 (2001).

[3] SNO Collaboration: Q. R. Ahmad et al., Phys. Rev. Lett. 87 (2001) 071301; nucl-ex/0204008, 0204009.

[4] KamLAND Collaboration, K. Eguchi et al., Phys. Rev. Lett. 90 (2003) 021802.

[5] G. L. Fogli, E. Lisi, M. Marrone, D. Montanino, A. Palazzo and A.M. Rotunno, hep-ph/0212127;
J. N. Bahcall, M. C. Gonzalez-Garcia and C. Peña-Garay, JHEP 0302 (2003) 009;
M. Maltoni, T. Schwetz and J.W.F. Valle, hep-ph/0212129;
P.C. Holanda and A. Yu. Smirnov, hep-ph/0212270;
V. Barger and D. Marfatia, hep-ph/0212126.

[6] H. Nishiura, K. Matsuda and T. Fukuyama, Phys. Rev. D60 (1999) 013006;
S.K. Kang and C.S. Kim, Phys. Rev. D63 (2001) 113010;
B. R. Desai, D. P. Roy and A. R. Vaucher, hep-ph/0209035;
M. Bando and M. Obara, hep-ph/0212242, 0302034.

[7] P.H. Frampton, S.L. Glashow and D. Marfatia, Phys. Lett. B536 (2002) 79.

[8] Z. Xing, Phys. Lett. 530B (2002) 159.

[9] W. Guo and Z. Xing, hep-ph/0212142.

[10] R. Barbieri, T. Hambye and A. Romanino, hep-ph/0302118.

[11] M. Honda, S. Kaneko and M. Tanimoto, hep-ph/0303227.

[12] Gell-Mann, P. Ramond and R. Slansky, in Supergravity, Proceedings of the Workshop, Stony Brook, New York, 1979, edited by P. van Nieuwenhuizen and D. Freedmann, North-Holland, Amsterdam, 1979, p.315;
T. Yanagida, in *Proceedings of the Workshop on the Unified Theories and Baryon Number in the Universe*, Tsukuba, Japan, 1979, edited by O. Sawada and A. Sugamoto, KEK Report No. 79-18, Tsukuba, 1979, p.95.

[13] M. Fukugita and T. Yanagida. Phys. Lett. **B175** (1986) 45.

[14] M. Tanimoto, Phys. Rev. **D55** (1997) 322; Prog. Theor. Phys. **97** (1997) 901; Phys. Lett. **B435** (1998)373; Phys. Lett. **B462** (1999) 115;
J. Arafune and J. Sato, Phys. Rev. **D55** (1997)1653;
J. Arafune, M. Koike and J. Sato, Phys. Rev. **D56** (1997) 3093;
H. Minakata and H. Nunokawa, Phys. Lett. **B413** (1997) 369; Phys. Rev. **D57** (1998) 4403.
For recent proposal of the search for CP violation in neutrino oscillation, see Y. Itow et.al., hep-ex/0106019.

[15] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28** (1962) 870.

[16] M. Flanz, E. A. Paschos and U. Sarkar, Phys. Lett. **B345** (1995) 248;
L. Covi, E. Roulet and F. Vissani, Phys. Lett. **B 384** (1996) 169;
A. Pilaftsis, Phys. Rev. **D56** (1997) 5431.

[17] W. Buchmüller and M. Plümmacher, Phys. Lett. **B389** (1996) 73; *ibid.* **B431** (1998) 354;
Int. J. Mod. Phys. **A15** (2000) 5047.

[18] A. S. Joshipura, E. A. Paschos and W. Rodejohann, JHEP **0108** (2001) 029;
W. Buchmüller and D. Wyler, Phys. Lett. **B 521** (2001) 291;
J. Ellis and M. Raidal, hep-ph/0206174;
S. Davidson and A. Ibarra, Nucl. Phys. **B648** (2003) 345;
G. Branco, T. Morozumi, B. Nobre and M.N. Rebelo, Nucl. Phys. **B 617** (2001) 475;
G. Branco, R. González Felipe, F. R. Joaquim and M. N. Rebelo, Nucl. Phys. **B 640** (2002) 202;
G. Branco, R. González Felipe, F. R. Joaquim, I. Masina, M. N. Rebelo, and C. A. Savoy, hep-ph/0211001;
S. Pascoli, S. T. Petcov and C. E. Yaguna, hep-ph/0301095;
S. Pascoli, S. T. Petcov and W. Rodejohann, hep-ph/0302054; Kim Siyeon, hep-ph/0303077.
[19] D. Falcone, hep-ph/0204335;
   Z. Xing, hep-ph/0206245;
   M. Fujii, K. Hamaguti and T. Yanagida, Phys. Rev. D65 (2002) 115012;
   W. Rodejohann, Phys. Lett. B542 (2002) 100.

[20] P. Frampton, S. Glashow and T. Yanagida, Phys. Lett. B548 (2002) 119.

[21] T. Endoh, S. Kaneko, S. K. Kang, T. Morozumi and M. Tanimoto, hep-ph/0209020.

[22] A. Kageyama, S. Kaneko, N. Simoyama and M. Tanimoto, Phys. Lett. B538 (2002) 96.

[23] S. Kaneko and M. Tanimoto, Phys. Lett. B551 (2003) 127.

[24] P. H. Chankowski and Z. Pluciennik, Phys. Lett. B316 (1993) 312;
   K. S. Babu, C. N. Leung and J. Pantaleone, Phys. Lett. B319 (1993) 191;
   M. Tanimoto, Phys. Lett. 360B (1995) 41;
   P. H. Chankowski, W. Krolikowski and S. Pokorski, Phys. Lett. B473 (2000) 109;
   J. Ellis, G. K. Leontaris, S. Lola and D. V. Nanopoulos, Eur. Phys. J. C9 (1999) 389;
   J. Ellis and S. Lola, Phys. Lett. B458 (1999) 310;
   J. A. Casas, J. R. Espinosa, A. Ibarra and I. Navarro, Nucl. Phys. B556 (1999) 3; JHEP 9909 (1999) 015; Nucl. Phys. B569 (2000) 82;
   M. Carena, J. Ellis, S. Lola and C. E. M. Wagner, Eur. Phys. J. C12 (2000) 507;
   N. Haba, Y. Matsui, N. Okamura and M. Sugiura, Eur. Phys. J. C10 (1999) 677; Prog. Theor. Phys. 103 (2000) 145;
   N. Haba and N. Okamura, Eur. Phys. J. C14 (2000) 347;
   N. Haba, N. Okamura and M. Sugiura, Prog. Theor. Phys. 103 (2000) 367;
   S. Antusch, M. Drees, J. Kersten, M. Lindner and M. Ratz, Phys. Lett. B519 (2001) 238;
   B525 (2002) 130;
   S. Antusch and M. Ratz, JHEP 0207 (2002) 059.

[25] F. Borzumati and A. Masiero, Phys. Rev. Lett. 57 (1986) 961.

[26] J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi and T. Yanagida, Phys. Lett. B357 (1995) 579;
   J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Rev. D53 (1996) 2442.
[27] J. Hisano, D. Nomura and T. Yanagida, Phys. Lett. B437 (1998) 351;
J. Hisano and D. Nomura, Phys. Rev. D59 (1999) 116005;
M.E. Gomez, G.K. Leontaris, S. Lola and J. D. Vergados, Phys. Rev. D59 (1999) 116009;
W. Buchmüller, D. Delepine and F. Vissani, Phys. Lett. B459 (1999) 171;
W. Buchmüller, D. Delepine and L.T. Handoko, Nucl. Phys. B576 (2000) 445;
J. Ellis, M.E. Gomez, G.K. Leontaris, S. Lola and D.V. Nanopoulos, Eur. Phys. J. C14 (2000) 319;
J. L. Feng, Y. Nir and Y. Shadmi, Phys. Rev. D61 (2000) 113005;
S. Baek, T. Goto, Y. Okada and K. Okumura, Phys. Rev. D63 (2001) 051701.

[28] J. Sato, K. Tobe, and T. Yanagida, Phys. Lett. B498 (2001) 189;
J. Sato and K. Tobe, Phys. Rev. D63 (2001) 116010;
S. Lavignac, I. Masina and C. A. Savoy, Phys. Lett. B520 (2001) 269;
J. A. Casas and A. Ibarra, Nucl. Phys. B618 (2001) 171;
A. Kageyama, S. Kaneko, N. Simoyama and M. Tanimoto, Phys. Lett. B527 (2002) 206;
Phys. Rev. D65 (2002) 096010.

[29] MEGA Collaboration, M. L. Brooks et al., Phys. Rev. Lett. 83 (1999) 1521.

[30] J. Ellis, J. Hisano, M. Raidal and Y. Shimizu, hep-ph/0206110.

[31] J. A. Harvey and M. S. Turner, Phys. Rev. D42 (1990) 3344;
S. Y. Khlebnikov and S. E. Shaposhnikov, Nucl. Phys. B308 (1998) 169.

[32] C. Jarlskog, Phys. Rev. Lett. 55 (1985) 1039.

[33] M. Luty, Phys. Rev. D45 (1992) 455;
M. Plüümacher, Z. Phys. C74 (1997) 549;
E. W. Kolb and M. S. Turner, The early universe, Redwood City, USA: Addison-Wesley (1990), (Frontiers in physics, 69);
M. Flanz and E. A. Paschos, Phys. Rev. D58 (1998) 113009;
A. Pilaftsis, Int. J. Mod. Phys. A14 (1999) 1811;
W. Buchmüller, P. Di Bari and M. Plüümacher, hep-ph/0302092.
[34] C. L. Bennett et al., astro-ph/0302207;
    D. N. Spergel et al., astro-ph/0302209;
    H. V. Peiris et al., astro-ph/0302225.

[35] S. Davidson and A. Ibarra, Phys. Lett. B535 (2002) 25.