A relation between CP violation of low energy and leptogenesis
G. C. Branco a, T. Morozumi b, B. M. Nobre a, and M. N. Rebelo a

aDepartamento de Fisica, Instituto Superior Tecnico, Av. Rovisco Pais, P-1049-001, Lisboa, Portugal
bGraduate School of Science, Hiroshima University, Higashi-Hiroshima, Japan, 739-8526,

We discuss how CP violation generating lepton number asymmetry can be related to CP violation in low energy.

1. Introduction

CP violation at low energy is observed in K and B system. In the future neutrino oscillation experiments, CP asymmetry of the neutrino oscillations \( P(\nu_i \rightarrow \nu_j) \neq P(\bar{\nu}_i \rightarrow \bar{\nu}_j) \) may be also measured. Our question is how low energy CP violation measurements are related to CP violation for Baryon number asymmetry. Fukugita and Yanagida proposed a scenario for Baryon number asymmetry based on the seesaw model.\[1\] In their scenario, heavy Majorana neutrinos decays give rise to lepton number asymmetry. The asymmetry is converted into Baryon number through spharelon process.\[2\] In this scenario, CP violating phases in the seesaw model contribute to both CP violation at low energy and CP violation for lepton number asymmetry. However, this correlation is not trivial. This is partly because there are six independent CP violating phases in the seesaw model and the low energy CP violating observables are just three phases of them. It can be shown that three of the six CP violating sources may contribute to the lepton number asymmetry.\[3\] We can ask the following question. If CP asymmetry of the neutrino oscillations \( P(\nu_i \rightarrow \nu_j) \neq P(\bar{\nu}_i \rightarrow \bar{\nu}_j) \) is measured, what does it mean about CP violation for leptogenesis. To answer to this question, we must first identify the number of the independent CP violating phases and find which of them contributes to leptogenesis and to neutrino oscillations. The plan of my talk is following. We first review the counting of CP phases in the minimal seesaw model and explicitly construct a parameterization. Then we identify the phases in leptogenesis and CP violation in low energy. Finally we give a specific scenario in which both CP violating phenomena has a correlation.

2. The number of independent CP violating phases in the minimal seesaw model

In the seesaw model, we have three sources for lepton mass terms; namely, Charged Lepton Yukawa couplings \( m_l \), neutrino Yukawa couplings, \( m_D \) and Majorana mass terms \( M_R \).

\[
\mathcal{L} = -[\bar{\nu} M_D N_R^0 + \frac{1}{2} N_R^0 \bar{N}_R^0 M_R N_R^0 + \bar{\nu} m_l \nu].
\]\(1\)

By using a suitable basis transformation, we can choose the basis in which \( m_l \) and \( M_R \) are real diagonal. In this basis all the CP violation is included into Dirac Yukawa term \( m_D \). \( m_D \) is \( n_g \times n_g \) complex matrix, this contains \( n_g^2 \) imaginary part. We can still absorb \( n_g \) phases. Therefore we obtain \( n_g^2 - n_g \) independent CP violating phases. For \( n_g = 3 \), we have six CP violation phases. These six CP violating sources are identified in weak basis invariant way.\[4\] The weak basis invariants are non-zero if CP is violated. The six weak basis invariants are given as:

\[
\begin{align*}
I_1 &= \text{Im} Tr[\bar{\nu} H M_R^* \bar{\nu}^* M_R], \\
I_2 &= \text{Im} Tr[\bar{\nu} H^2 M_R^* \bar{\nu}^* M_R], \\
I_3 &= \text{Im} Tr[\bar{\nu} H M_R^* M_R H], \\
I_4 &= \text{Im} Tr[\bar{\nu} H M_R^* \bar{\nu}^* M_R], \\
I_5 &= \text{Im} Tr[\bar{\nu} H^2 M_R^* \bar{\nu}^* M_R].
\end{align*}
\]
\[ I_6 = \text{Im} \text{Tr} [\tilde{H} H^T M_R^\dagger \tilde{h}^* M_R H], \]  
where \( \tilde{h} = m_D^\dagger m_D, \) \( H = M_R^\dagger M_R, \) and \( \tilde{h} = m_D^\dagger m_D m_D^\dagger. \)

3. CP violating phases for leptogenesis

CP violation for leptogenesis was computed in the base in which the heavy Majorana mass matrix \( M_R \) is real diagonal. The lepton number asymmetry from the heavy Majorana particles decay is proportional to the following combination.

\[ \text{Im} [(m_D^\dagger m_D)_{ij}]^2 (i \neq j). \]  
This combination is independent of the left-handed rotation; \( m_D \rightarrow g_L m_D. \) Therefore it is convenient to use the following parametrization.

\[ m_D = U Y_\Delta, \]  
where \( U \) is a unitary matrix and \( Y_\Delta \) is a triangular matrix. The explicit parametrization for the unitary matrix is given as:

\[ U = U_{23} (\theta_{23})^\dagger U_{13} (\theta_{13})^\dagger \delta^\dagger U_{12} (\theta_{12})^\dagger \times \text{diag.}(1, \exp(i \alpha_1), \exp(i \alpha_2)). \]  
The triangular matrix is given as:

\[ Y_\Delta = \begin{pmatrix} Y_1 & 0 & 0 \\ Y_{21} & Y_2 & 0 \\ Y_{31} & Y_{32} & Y_3 \end{pmatrix}. \]  
Note that the diagonal elements \( Y_1, Y_2, \) and \( Y_3 \) are real. We can easily confirm the decomposition \( m_D = U Y_\Delta \) counts correctly the independent parameters of \( m_D. \) \( m_D \) (after removing three diagonal phases from the left) has 6 imaginary parameters and 9 real parameters. \( Y_\Delta \) has 3 imaginary parts and 6 real parts and \( U \) has 3 angles and 3 phases. Using the decomposition, we can write the CP violation relevant for leptogenesis as,

\[ \text{Im} [(m_D^\dagger m_D)_{ij}]^2 = \text{Im} [(Y_\Delta^\dagger Y_\Delta)_{ij}]^2, \quad i \neq j. \]  
Therefore, CP violation phases for leptogenesis are related to three phases, \( \arg Y_{ij} \) in \( Y_\Delta. \)

4. The correlation between CP violation at low energy and leptogenesis

Now we turn to CP violation in neutrino oscillation. The effective mass matrix for light Majorana neutrinos in the seesaw model is given as:

\[ m_{\text{eff}} = -m_D^\dagger M_R^\dagger M_R^T = -U Y_\Delta^\dagger M_R^T U^T. \]  
Here the MNS matrix \( K \) is determined as:

\[ -K^\dagger m_D^\dagger M_R^T K^* = d. \]  
where \( d = \text{diag.}(d_1, d_2, d_3), \) where \( d_1, d_2 \) and \( d_3 \) correspond to the three mass eigenvalues for light neutrinos. The low energy CP violation phases in \( K \) are one Kobayashi-Maskawa type phase \( \delta \) and two Majorana phases \( \alpha_1, \alpha_2. \) Our question is to what extent the CP violation phases in \( K \) is sensitive to \( \arg Y_{ij} \) which contribute to the leptogenesis. In general, the phases in \( K \) are complicated functions of all of the six phases \( (\delta', \alpha_1', \alpha_2', \arg Y_{1ij}). \) They also depend on heavy Majorana masses \( M_R = \text{diag.}(M_1, M_2, M_3) \) and \( [Y_{ij}]. \) To study the correlation between the low energy phases in \( K \) and phases for leptogenesis \( Y_\Delta, \) let us examine the equation for diagonalization of the effective Majorana mass matrix, \( m_{\text{eff}} = -m_D^\dagger M_R^T m_D^T \).

\[ -K^\dagger U (Y_\Delta^\dagger M_R^T Y_\Delta^T K^*) = d \]  
We can see that, in general, \( K \) depends on the \( Y_\Delta. \) Next we ask in what kind of situation, the correlation between a set of low energy phases \( (\delta, \alpha_1, \alpha_2) \) and CP violating phases for leptogenesis \( (\arg Y_{21}, \arg Y_{31}, \arg Y_{32}) \) is weak and/or strong. A key is the matrix \( Y_\Delta^\dagger M_R^{-1} Y_\Delta^T: \)

\[
\begin{pmatrix}
\frac{Y_{21}^2}{M_2} & \frac{Y_{21}^2}{M_1} & \frac{Y_{21}^2}{M_3} \\
\frac{Y_{32}^2}{M_2} & \frac{Y_{32}^2}{M_1} + \frac{Y_{32}^2}{M_3} & \frac{Y_{32}^2}{M_1} + \frac{Y_{32}^2}{M_3} \\
\frac{Y_{31}^2}{M_3} & \frac{Y_{31}^2}{M_2} + \frac{Y_{31}^2}{M_3} & \frac{Y_{31}^2}{M_2} + \frac{Y_{31}^2}{M_3}
\end{pmatrix}
\]  
A) The case that the correlation is weak. If \( Y_\Delta^\dagger M_R^{-1} Y_\Delta^T \) are nearly diagonal, the neutrino mixings must be accounted by \( U. \) Therefore, in this case,

\[ K^\dagger U \sim 1 \rightarrow K \sim U(\alpha_i', \delta'). \]
3

Such situation may be realized if all \( Y_{ij} \) are the same order and \( M_1 \gg M_2 \gg M_3 \). If this is the case, the correlation between the low energy phase and CP violation for leptogenesis may be weak.\[1\]

B) The case that the correlation is strong.
If \( U \simeq 1 \) and the elements of \( Y_\Delta \) are nearly degenerate, we may except \( K \) directly depends on the phases of \( Y_\Delta \). The case study with hypothesis \( Y_1 = m_u, Y_2 = m_c, Y_3 = m_t \) and \( U = 1 \) is done. See \( [3] \). In this case, all the other parameters \( |Y_{21}|, |Y_{31}|, |Y_{32}| \) and \( M_1, M_2, M_3 \) arg\( Y_{21}, \) arg\( Y_{31}, \) arg\( Y_{32} \) can be determined from the low energy input \( d_1, d_2, d_3 \) (light neutrino masses) and MNS matrix: \( \theta_{12}, \theta_{13}, \theta_{23} \) and \( \alpha_1, \alpha_2, \delta \). It was shown that the hierarchy \( M_1 << M_2 << M_3 \) is required to obtain large mixing.

5. Conclusions
1. There are six independent CP violating phases in the seesaw model. Among them, three contribute to lepton number asymmetry.
2. In the basis where \( M_R \) and \( m_l \) are real diagonal, all CP violating sources can be put into Yukawa term \( m_D \).
3. A convenient parametrization of \( m_D \) is proposed: \( m_D = U Y_\Delta \). The phases in \( Y_\Delta \) exhausts the CP violation for lepton number asymmetry, while there are the other three phases in \( U \).
4. MNS matrix \( K \) is obtained from \(-K^\dagger(UY_\Delta \frac{1}{M_R} Y_\Delta^T U^T)K^* = d \). Therefore, in general, the CP violating phases in \( K \) are sensitive for leptogenesis.
5. The cases with the correlation and without the correlation are discussed qualitatively. In particular, the strong correlation occurs if \( U = 1 \). In this case, all the CP violating sources of the standard model come from \( Y_\Delta \) and low energy CP violation of neutrino sector can be related to leptogenesis phases. There are the other cases the correlation does exist.\[3\]

Acknowledgement
We would like to thank organizers of KEKTC5 and T. Endoh and A. Purwanto for discussion. The work of T. M. is supported by the Grant-in-Aid for scientific research No.13640290 from the Ministry of education, science and culture of Japan. The work of BMN was supported by Fundação para a Ciência e a Tecnologia (FCT) (Portugal) through fellowship SFRH/BD/995/2000; GCB, BMN and MNR received partial support from FCT from Project CERN/P/FIS/40134/2000, Project POCTI/36288/FIS/2000 and Project CERN/C/FIS/40139/2000. We thank the CERN Theory Division for hospitality during the preparation of Ref[4].

REFERENCES
1. T. Yanagida, in Proc. of the Workshop on the Unified Theory and Baryon Number in the Universe, ed. by O. Sawada and A. Sugamoto (KEK report 79-18, 1979), p.95, Tsukuba, Japan; M. Gell-Mann, P. Ramond and R. Slansky, in Supergravity, ed. by P. van Nieuwenhuizen and D. Z. Freedman (North Holland, Amsterdam, 1979), p.315; R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 44 (1980) 912.
2. M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45.
3. T. Endoh, T. Morozumi, T. Onogi and A. Purwanto, Phys. Rev. D 64 (2001) 013006.
4. G. Branco, T. Morozumi, B. Nobre and M. Rebelo, Nucl. Phys. B 617 (2001) 475.
5. G. C. Branco, L. Lavoura and M. N. Rebelo, Phys. Lett. B 180 (1986) 264.
6. Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28 (1962) 870.
7. J. Hashida, T. Morozumi and A. Purwanto, Prog. Theor. Phys. 101 (2000) 379 [Erratum-ibid. 103 (2000) 865] [hep-ph/9909208].
8. T. Endo, T. Morozumi, and A. Purwanto, "Numerical study on the correlation between CP violation in neutrino oscillations and baryogenesis" presented in KEKTC5, in these proceedings.
A relation between CP violation of low energy and leptogenesis

G. C. Branco a, T. Morozumi b, B. M. Nobre a, and M. N. Rebelo a

aDepartamento de Fisica, Instituto Superior Tecnico, Av. Rovisco Pais, P-1049-001, Lisboa, Portugal

bGraduate School of Science, Hiroshima University, Higashi-Hiroshima, Japan, 739-8526,

We discuss how CP violation generating lepton number asymmetry can be related to CP violation in low energy.

1. Introduction

CP violation at low energy is observed in K and B system. In the future neutrino oscillation experiments, CP asymmetry of the neutrino oscillations $P(\nu_i \to \nu_j) \neq P(\bar{\nu}_i \to \bar{\nu}_j)$ may be also measured. Our question is how low energy CP violation measurements are related to CP violation for Baryon number asymmetry. Fukugita and Yanagida proposed a scenario for Baryon number asymmetry based on the seesaw model [1]. In their scenario, heavy Majorana neutrinos decays give rise to lepton number asymmetry. The asymmetry is converted into Baryon number through spharelon process. [2] In this scenario, CP violating phases in the seesaw model contribute to both CP violation at low energy and CP violation for lepton number asymmetry. However, this correlation is not trivial. This is partly because there are six independent CP violating phases in the seesaw model and the low energy CP violating observables are just three phases of them. It can be shown that three of the six CP violating sources may contribute to the lepton number asymmetry [3]. We can ask the following question. If CP asymmetry of the neutrino oscillations $P(\nu_i \to \nu_j) \neq P(\bar{\nu}_i \to \bar{\nu}_j)$ is measured, what does it mean about CP violation for leptogenesis? To answer to this question, we must first identify the number of the independent CP violating phases and find which of them contributes to leptogenesis and to neutrino oscillations. The plan of my talk is following. We first review the counting of CP phases in the minimal seesaw model and explicitly construct a parameterization. Then we identify the phases in leptogenesis and CP violation in low energy. Finally we give a specific scenario in which both CP violating phenomena has a correlation.

2. The number of independent CP violating phases in the minimal seesaw model

In the seesaw model, we have three sources for lepton mass terms; namely, Charged Lepton Yukawa couplings $m_l$, neutrino Yukawa couplings, $m_D$ and Majorana mass terms $M_R$.

$$\mathcal{L} = -\overline{[\nu_l^R]} m_D N^0_R + \frac{1}{2} N^0_R M_R N^0_R + \overline{l_l} m_l l_l. \quad (1)$$

By using a suitable basis transformation, we can choose the basis in which $m_l$ and $M_R$ are real diagonal. In this basis all the CP violation is included into Dirac Yukawa term $m_D$. $m_D$ is $n_g \times n_g$ complex matrix, this contains $n_g^2$ imaginary part. We can still absorb $n_g$ phases. Therefore we obtain $n_g^2 - n_g$ independent CP violating phases. For $n_g = 3$, we have six CP violation phases. These six CP violating sources are identified in weak basis invariant way [4]. The weak basis invariants are non-zero if CP is violated. The six weak basis invariants are given as:

$$I_1 = \text{ImTr}[\bar{\nu}_l H M_R^* h^* M_R],$$
$$I_2 = \text{ImTr}[\bar{\nu}_l H^2 M_{R^*} h^* M_R],$$
$$I_3 = \text{ImTr}[\bar{\nu}_l H^2 M_R^* h^* M_{R^*}],$$
$$I_4 = \text{ImTr}[\bar{\nu}_l H M_R^* h^* M_R],$$
$$I_5 = \text{ImTr}[\bar{\nu}_l H^2 M_R^* h^* M_{R^*}].$$
\[ I_6 = \text{Im} \text{Tr}[\hat{h} H^2 M R^+ \hat{h}^* M R H] \]  

where \( h = m_D^\dagger m_D \), \( H = M R^+ M R \), and \( \hat{h} = m_D^\dagger m_D \).

3. CP violating phases for leptogenesis

CP violation for leptogenesis was computed in the base in which the heavy Majorana mass matrix \( M R \) is real diagonal. The lepton number asymmetry from the heavy Majorana particles decay is proportional to the following combination:

\[ \text{Im}[(m_D^\dagger m_D)_{ij}]^2 (i \neq j). \]  

This combination is independent of the left-handed rotation; \( m_D \to gL m_D \). Therefore it is convenient to use the following parametrization.

\[ m_D = U Y_\Delta, \]  

where \( U \) is a unitary matrix and \( Y_\Delta \) is a triangular matrix. The explicit parametrization for the unitary matrix is given as:

\[ U = U_{23}(\theta_{23})' U_{13}(\theta_{13}, \delta') U_{12}(\theta_{12})' \times \text{diag}(1, \exp(i\alpha_1), \exp(i\alpha_2)). \]

The triangular matrix is given as:

\[ Y_\Delta = \begin{pmatrix} Y_1 & 0 & 0 \\ Y_{21} & Y_2 & 0 \\ Y_{31} & Y_{32} & Y_3 \end{pmatrix}. \]

Note that the diagonal elements \( Y_1, Y_2, \) and \( Y_3 \) are real. We can easily confirm the decomposition \( m_D = U Y_\Delta \) counts correctly the independent parameters of \( m_D \). \( m_D \) (after removing three diagonal phases from the left) has 6 imaginary parameters and 9 real parameters. \( Y_\Delta \) has 3 imaginary parts and 6 real parts and \( U \) has 3 angles and 3 phases. Using the decomposition, we can write the CP violation relevant for leptogenesis as,

\[ \text{Im}[(m_D^\dagger m_D)_{ij}]^2 = \text{Im}[(Y_\Delta^\dagger Y_\Delta)_{ij}]^2, \quad i \neq j. \]  

Therefore, CP violation phases for leptogenesis are related to three phases, \( \arg Y_{ij} \) in \( Y_\Delta \).

4. The correlation between CP violation at low energy and leptogenesis

Now we turn to CP violation in neutrino oscillation. The effective mass matrix for light Majorana neutrinos in the seesaw model is given as:

\[ m_{eff} = -m_D \frac{1}{M_R} m_D^T = -U Y_\Delta \frac{1}{M_R} Y_\Delta^T U^T. \]

Here the MNS matrix [6] \( K \) is determined as:

\[ -K^T \frac{1}{M_R} m_D^T K^* = d. \]

where \( d = \text{diag}(d_1, d_2, d_3) \), where \( d_1, d_2 \) and \( d_3 \) correspond to the three mass eigenvalues for light neutrinos. The low energy CP violation phases in \( K \) are one Kobayashi-Maskawa type phase \( \delta \) and two Majorana phases \( \alpha_1, \alpha_2 \). Our question is to what extent the CP violation phases in \( K \) is sensitive to \( \arg Y_{ij} \) which contribute to the leptogenesis. In general, the phases in \( K \) are complicated functions of all of the six phases \( (\delta', \alpha_1', \alpha_2', \arg(Y_\Delta)_{ij}) \). They also depend on heavy Majorana masses \( M_R = \text{diag}(M_1, M_2, M_3) \) and \( |Y_{ij}| \). To study the correlation between the low energy phases in \( K \) and phases for leptogenesis \( Y_\Delta \), let us examine the equation for diagonalization of the effective Majorana mass matrix, \( m_{eff} = -m_D\frac{1}{M_R} m_D^T \).

\[ -K^T U(Y_\Delta \frac{1}{M_R} Y_\Delta^T) U^T K^* = d \]

We can see that, in general, \( K \) depends on the \( Y_\Delta \). Next we ask in what kind of situation, the correlation between a set of low energy phases (\( \delta, \alpha_1, \alpha_2 \)) and CP violating phases for leptogenesis (\( \arg Y_{21}, \arg Y_{23}, \arg Y_{12} \)) is weak and/or strong. A key is the matrix \( Y_\Delta \frac{1}{M_R} Y_\Delta^T \):

\[ \left( \begin{array}{ccc} Y_{11}^2 M_1 & Y_{12} Y_{21} + Y_{13} Y_{31} & Y_{12} Y_{23} + Y_{13} Y_{32} \\ Y_{21} Y_{11} M_1 & Y_{22}^2 M_2 & Y_{22} Y_{23} + Y_{23} Y_{32} \\ Y_{31} Y_{11} M_1 & Y_{32} Y_{21} M_2 & Y_{33}^2 M_3 + Y_{32} Y_{23} M_2 + Y_{31} Y_{12} M_1 \end{array} \right) \]

(11)

A) The case that the correlation is weak.

If \( Y_\Delta \frac{1}{M_R} Y_\Delta^T \) are nearly diagonal, the neutrino mixings must be accounted by \( U \). Therefore, in this case,

\[ K^T U \sim 1 \to K \sim U(\alpha_1', \delta'). \]  

(12)
Such situation may be realized if all $Y_{ij}$ are the same order and $M_1 >> M_2 >> M_3$. If this is the case, the correlation between the low energy phase and CP violation for leptogenesis may be weak.\[3\]

B) The case that the correlation is strong. If $U \approx 1$ and the elements of $Y_M Y_M^T$ are nearly degenerate, we may except $K$ directly depends on the phases of $Y_M$. The case study with hypothesis $Y_1 = m_\nu, Y_2 = m_\nu, Y_3 = m_\nu$ and $U = 1$ is done. See [8]. In this case, all the other parameters $|Y_{21}|, |Y_{31}|, |Y_{32}|$ are determined from the low energy input $d_1, d_2, d_3$ (light neutrino masses) and MNS matrix: $\theta_{12}, \theta_{13}, \theta_{23}$ and $\alpha_1, \alpha_2, \delta$. It was shown that the hierarchy $M_1 << M_2 << M_3$ is required to obtain large mixing.

5. Conclusions

1. There are six independent CP violating phases in the seesaw model. Among them, three contribute to lepton number asymmetry.

2. In the basis where $M_R$ and $m_\nu$ are real diagonal, all CP violating sources can be put into Yukawa term $m_D$.

3. A convenient parametrization of $m_D$ is proposed: $m_D = U Y_M$. The phases in $Y_M$ exhausts the CP violation for lepton number asymmetry, while there are the other three phases in $U$.

4. MNS matrix $K$ is obtained from $-K^T(U Y_M Y_M^T U^T)K^* = d$. Therefore, in general, the CP violating phases in $K$ are sensitive for leptogenesis.

5. The cases with the correlation and without the correlation are discussed qualitatively. In particular, the strong correlation occurs if $U = 1$. In this case, all the CP violating sources of the standard model come from $Y_M$ and low energy CP violation of neutrino sector can be related to leptogenesis phases. There are the other cases the correlation does exist.\[4\]

Acknowledgement

We would like to thank organizers of KEKTC5 and T. Endoh and A. Purwanto for discussion. The work of T. M. is supported by the Grant-in-Aid for scientific research No.13640290 from the Ministry of education, science and culture of Japan. The work of BMN was supported by Fundação para a Ciência e a Tecnologia (FCT) (Portugal) through fellowship SFRH/BD/995/2000; GCB, BMN and MNR received partial support from FCT from Project CERN/P/FIS/40134/2000, Project POCTI/36288/FIS/2000 and Project CERN/C/FIS/40139/2000. We thank the CERN Theory Division for hospitality during the preparation of Ref[4].

REFERENCES

1. T. Yanagida, in Proc. of the Workshop on the Unified Theory and Baryon Number in the Universe, ed. by O. Sawada and A. Sugamoto (KEK report 79-18, 1979), p.95, Tsukuba, Japan; M. Gell-Mann, P. Ramond and R. Slansky, in Supergravity, ed. by P. van Nieuwenhuizen and D. Z. Freedman (North Holland, Amsterdam, 1979), p.315; R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. 44 (1980) 912.

2. M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45.

3. T. Endoh, T. Morozumi, T. Onogi and A. Purwanto, Phys. Rev. D 64 (2001) 013006.

4. G. Branco, T. Morozumi, B. Nobre and M. Rebelo, Nucl. Phys. B 617 (2001) 475.

5. G. C. Branco, L. Lavoura and M. N. Rebelo, Phys. Lett. B 180 (1986) 264.

6. Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28 (1962) 870.

7. J. Hashida, T. Morozumi and A. Purwanto, Prog. Theor. Phys. 101 (2000) 379 [Erratum-ibid. 103 (2000) 865] [hep-ph/9909208].

8. T. Endo, T. Morozumi, and A. Purwanto, "Numerical study on the correlation between CP violation in neutrino oscillations and baryogenesis" presented in KEKTC5, in these proceedings.