A possible relation between leptogenesis and PMNS phases

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The CP phase relevant in the leptogenesis is related to the PMNS phase in case only one CP phase appears in the full theory. The weak CP phase is introduced by spontaneous CP violation at a high energy scale toward realizing the successful Kobayashi-Maskawa electroweak CP violation. This phase is in a complex vacuum expectation value of a standard model singlet field. Here, we find the new W boson exchange diagrams for leptogenesis. Assuming that the lightest (intermediate scale) Majorana lepton N_0 dominates the lepton asymmetry, the lepton asymmetry and the PMNS phases are related.

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I. INTRODUCTION

The origin of the baryon asymmetry of the Universe (BAU) has been a longstanding theoretical issue [1]. Among Sakharov's three conditions, the first (baryon number violating interaction) and the second (C and CP violating interaction) are the key problems in particle physics. The third non-equilibrium condition is conveniently introduced by some heavy particle decay producing $\Delta B \neq 0$, by making its decoupling temperature lower than the Hubble expansion rate in the evolving Universe. Along this line, there already exist several theoretical models to generate the BAU [2–6]. Among the three conditions, thus the needed CP phase for the BAU is the key issue in many theories on the baryogenesis.

At the level of the Standard Model (SM) of particle physics, there are two CP phases, one in the quark sector the Cabibbo-Kobayashi-Maskawa (CKM) phase $\delta_{\rm CKM}$ [7, 8] and the other in the lepton sector the Pontecorvo-Maki-Nakagawa-Sakada(PMNS) phase $\delta_{\rm PMNS}$ [9]. In a family unified grand unified theory (GUT), these two phases can be related if only one phase appears in the full theory [10]. From the early time on, it has been an interesting issue to investigate a possibility of relating the baryon asymmetry with the SM phase(s) $\delta_{\rm CKM}$ or/and $\delta_{\rm PMNS}$. The first obvious investigation was looking for a possibility of $\delta_{\rm CKM}$ whether it works for the BAU or not. But, it has been known that $\delta_{\rm CKM}$ is not enough for the baryon number generation suggested in GUTs [11]. With supersymmetry, superpartners of quarks (squarks) carry baryon number. Squarks decaying in the early Universe, during or after the reheating event that followed cosmic inflation, can generate ΔB with an appropriate CP phase $\delta_{\rm B}$, known as the Affleck-Dine (AD) mechanism [4]. This phase appearing in the squark sector is independent from $\delta_{\rm CKM}$. In the electroweak baryogeneses (EWBG), employing sphaleron processes to have $\Delta B \neq 0$ [3], the required CP and C violation is occuring at the boundary of two phases (of SU(2)×U(1) preserving and SU(2)×U(1) breaking vacua) [12]. Successful EWBG requires a first-order electroweak phase transition between these two phases. In the SM, the required first order phase transion corresponds to the Brout-Englert-Higgs (BEH) boson mass less than 70 GeV [13], which is already ruled out by the discovery of the BEH boson at 125 GeV. Even if the phase transition were made to be of the first-order, the CP violation induced by $\delta_{\rm CKM}$ is known to be insufficient to generate an enough chiral asymmetries [14]. Therefore, the phases in the AD and EWBG cannot be used for a relation between BAU and the key CP phases of the SM.

The sphaleron process is effective during the electroweak phase transition. The corresponding effective interaction is to change the chiralities of SU(2) doublets,[1] typically by an interaction with nine quark– and three lepton–doublet external lines. This process violates both baryon(B) and lepton(L) numbers, but conserves baryon minus lepton number ($B-L$). If baryon number generation at a GUT scale occurred with the conserved $B-L$ as in the SU(5) GUT, all baryon numbers combine with the lepton number to make $\Delta B = \Delta L = 0$ during the electroweak phase

[1] Change of chiralities is needed for ΔB from sphaleron related processes.

transition. Therefore, baryogenesis or leptogenesis above the electroweak scale must have occurred with $B-L$ violating interaction(s). If any GUT is responsible for this, the GUT must be beyond SU(5). One good GUT example is SO(10) GUT where $\Delta B \neq 0$ interaction, while violating gauged $B-L$, is possible. In fact, the required interaction in SO(10) conserves gauged $B-L$, because the ranks of SO(10) and SM are 5 and 4, respectively, and the gauged $B-L$ must be broken at a GUT scale. Therefore, the leptogenesis [5] can be realized in SO(10) GUT also. A non-GUT example is the SM singlet fermion genesis, *i.e.* the original leptogenesis [5], where the process $\Delta(B+L) = \Delta L$ is constructed. Generation of ΔB by $B-L$ violating interactions by heavy quarks was suggested as 'Q genesis' [6]. Since the neutrino masses can be related with the heavy Majorana neutrino masses, here we focus on the leptonenesis idea.

In the leptogenesis scheme with two BEH doublets, the lepton asymmetry arises from the decay of a heavy Majorana neutrino, producing light leptons by

$$N \to \ell_i + H_u, \tag{1}$$

where ℓ_i is the i-th lepton doublet and H_u is the up-type BEH doublet. In the present paper, we introduce just one pair of BEH doublets H_u with the electroweak hypercharge $Y = \frac{1}{2}$ and H_d with $Y = -\frac{1}{2}$. Then, the weak CP phase is required to descend down from high energy scale by a complex vacuum expectation value (VEV). To relate different phases, we assume that only one SM singlet field X develops a CP phase $\delta_{\rm X}$. Thus, all Yukawa couplings and the other VEVs are real. In this case, possible diagrams relevant for the process (1) up to one loops are shown in Fig. 1. In this case, we show that the asymmetry in the leptogenesis is related with the PMNS phase.

II. LEPTOGENESIS

The process (1) can include the phase $\delta_{\rm X}$ by the interference terms. To relate the leptogenesis phase $\delta_{\rm L}$ to the SM phase(s), one needs a families-unified GUT toward a calculable theory on the physically measurable phases. In the anti-SU(7) [15], indeed $\delta_{\rm PMNS}$ and $\delta_{\rm CKM}$ are shown to be related [10]. In this paper, we now investigate another relation between the phases, *i.e.* between $\delta_{\rm L}$ with $\delta_{\rm CKM}$ and/or $\delta_{\rm PMNS}$. In other words, the lepton asymmetry $\epsilon_{\rm L}$ is expressible in terms of $\delta_{\rm PMNS}$. There exists an earlier attempt on this issue [16], where however a theory-based calculation was not available.

Toward a calculable theory for phases, we introduce only one Froggatt-Nielsen(FN) fields [17] X developing a complex VEV, $\langle X\rangle = x\, e^{i\delta_{\rm X}}$ [18, 19]. The Yukawa coupling matrix of the doublet H_u include powers of X such that some symmetry behind the Yukawa couplings is satisfied. To simplify the discussion, let us assume that the heavy Majorana neutrinos have a mass hierarchy and let the lightest heavy Majorana neutrino N_0 dominates in the leptogenesis calculation. The mass matrix for the three light neutrinos and N_0 can be written as

$$\begin{array}{c|c} & \begin{array}{cccc} \ell_1 & \ell_2 & \ell_3 & N_0 \end{array} \\ \hline \begin{array}{c} \ell_1 \\ \ell_2 \\ \ell_3 \\ N_0 \end{array} & \begin{pmatrix} 0 & 0 & 0 & f^1_{N_0} H_u X^{n_1} R^{x_1} \\ 0 & 0 & 0 & f^2_{N_0} H_u X^{n_2} R^{x_2} \\ 0 & 0 & 0 & f^3_{N_0} H_u X^{n_3} R^{x_3} \\ f^1_{N_0} H_u X^{n_1} R^{x_1} & f^2_{N_0} H_u X^{n_2} R^{x_2} & f^3_{N_0} H_u X^{n_3} R^{x_3} & M_0 \end{pmatrix} \end{array} \tag{2}$$

where the powers of X and R are determined by the symmetry under consideration. In (2), we introduced two singlets X and R among which only X develops a complex VEV. We suppressed two rows and two columns of heavier Majorana neutrinos N_1 and N_2. These extra rows and columns are needed for all three light neutrinos to obtain non-zero masses. With the N_0 domination in the leptogenesis, Eq. (2) is sufficient for calculating the lepton asymmetry $\epsilon_{\rm L}$ (hence baryon asymmetry also). For the discussion on neutrino masses, the effects of heavier Majorana neutrinos N_1 and N_2 must be included.

In Fig. 1, we show the relevant Feynman diagrams interfereing in the $N_0 \to \nu_i + H^0_u$ decay, which was discussed in [20–22]. Nonzero lepton numbers are created with one incoming and one outgoing lepton arrows, but two incoming lepton arrows and two outgoing lepton arrows conserve the lepton number. In the basis where N_0 and charged leptons are fixed, possible phases appear at the vertices with the red bullets in Fig. 1. Figure 1 (a) is the leading diagram with the smallest power in the $\langle X\rangle$ insertion, Fig. 1 (b) is the W exchange diagram, and Fig. 1 (c) is the wave function renormalization diagram of N_0, and Fig. 1 (d) is the heavy neutral lepton exchange diagram. Note that the directions of two arrows from $\langle X_{n_j}\rangle$'s appearing in Fig. 1 (c) and (d) are opposite, cancel the phases from $\langle X_{n_j}\rangle$'s, and hence Fig. 1 (c) and (d) can be neglected in the asymmetry calculation. We stress here again the choice of the basis where the charged leptons are already diagonalized. Most calculations on leptogenesis [20] use Fig. 1 (d) having the heavy Majorana lepton N_0 intermediate state, which can contribute only if there are two or more phases. In our case, we

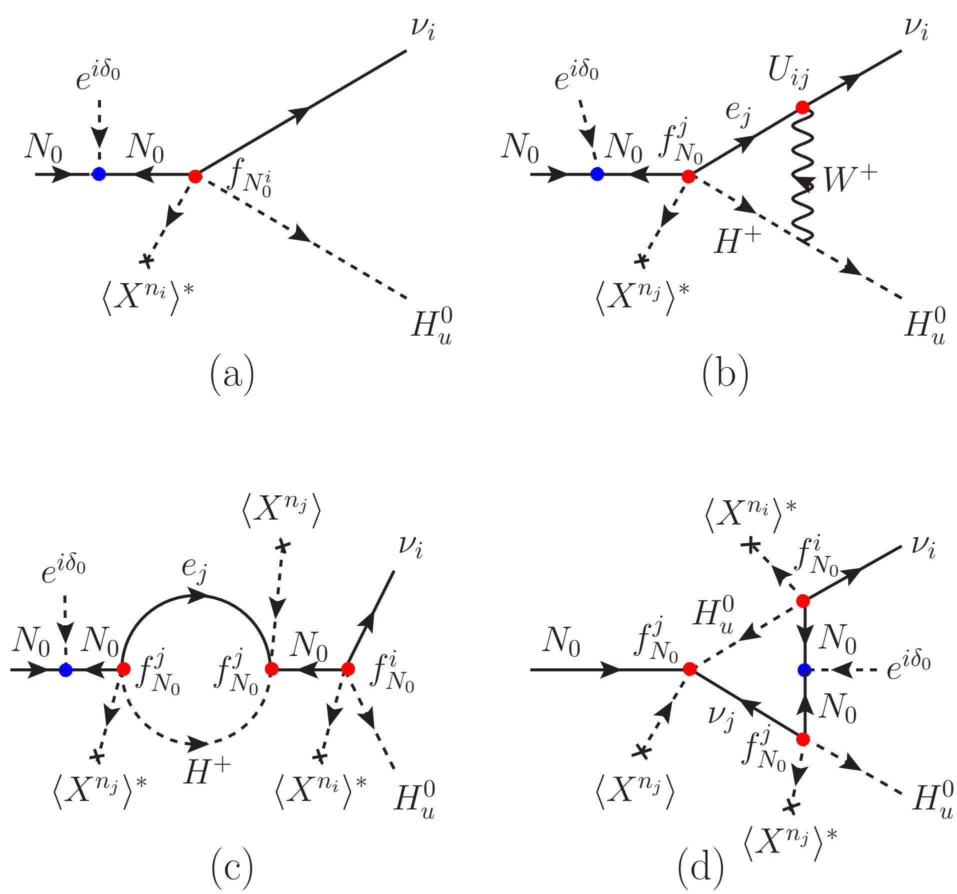

FIG. 1: The Feynman diagrams interfering in the N_0 decay: (a) the lowest order diagram, (b) the W exchange diagram, (c) the wave function renormalization diagram, and (d) the heavy neutral lepton exchange diagram. The lepton number violations are marked with blue dots. We can consider the charged lepton final states also with the replacement $U \to U^\dagger$ in (b) and appropriately changing other particles.

introduced only one phase and Fig. 1 (d) does not contribute because two directions of $\langle X^{n_j}\rangle$ are opposite. Since physics does not depend on the choice of basis, this conclusion that the phases appearing in Figs. 1 (c) and (d) are the same as that of Fig. 1 (a) will be true in any other basis as far as the N_0 domination in the leptogenesis is satisfied.

Earlier calculation [20–22] expressed the results in terms of the Yukawa coupling matrices with Figs. 1 (c) and (d), including those of all the heavy Majorana neutrino N's. While the radiative effects associated with the mass renormalization of N_0 in Fig. 1 (c) was studied before [20], here we first consider the effect with the vertex correction via the W boson of Figs. 1 (b). Thus, our Fig. 1 (b) is a novel one and leads to a fundamentally different result from these earlier calculations. With this set-up, it is a standard procedure to calculate the asymmetry $\epsilon_{\rm L}$, *i.e.* the difference of N_0 decays to the ℓ and $\bar\ell$,

$$\epsilon_{\rm L}^{N_0}(W) = \frac{\Gamma_{N_0\to\ell} - \Gamma_{N_0\to\bar\ell}}{\Gamma_{N_0\to\ell} + \Gamma_{N_0\to\bar\ell}}, \tag{3}$$

where $\ell(\bar\ell)$ is a (anti-)lepton. We have the following interference term from Figs. 1 (a) and (b),

$$\int \frac{d^4k}{(2\pi)^4}\,\mathcal{M}_{\rm (b)}\mathcal{M}^\dagger_{\rm (a)} = i\frac{f_i^* f_j U_{ij} g_2^2}{2\sqrt{2}} \times 2\int_0^1 dx \int_0^{1-x} dy\, \frac{d^4k}{(2\pi)^4}\,\frac{N}{D} \tag{4}$$

with

$$\begin{aligned} N &= {\rm Tr}\left[\left\{\bar u_i \gamma_\mu \mathcal{P}_L(\not{k} + m_{e_j})\mathcal{P}_R v_0\right\}\left\{\bar v_0 \mathcal{P}_L u_i\right\}\right](p_{\nu_i}+k)^\mu = -(P\cdot p_{\nu_i})k^2 - m^2_{\nu_i}(k\cdot P),\\ D &= \left[k^2 + 2k(yP + xp_{\nu_i}) + y(m_0^2 - m_H^2) + x(m^2_{\nu_i} - m_W^2) - (1-x-y)m^2_{e_j}\right]^3, \end{aligned} \tag{5}$$

where $\mathcal{P}_{L,R} = \frac{1\pm\gamma_5}{2}$, $\{u_i, v_0\}$ are spinors of left- and right-handed neutrinos, $P\cdot p_{\nu_i} \approx \frac{1}{2}(m_0^2 - m_H^2)$ with $\{P, m_0\}$ = four-momentum and mass of N_0, $\{p_{\nu_i}, m_{\nu_i}\}$ = four-momentum and mass of ν_i, m_{e_j} = mass of e_j, m_{H^+} = mass of H^+, and m_W = mass of W. In the limit $m_i, m_{\nu_j}, m_W \ll m_H^2 \ll m_0^2$, we will obtain the finite part of (4). We neglect the 125 GeV BEH boson, and keep only scalar particles H^+ and H^0 in the two Higgs doublet model. The Z and photon couplings are flavor diagonal and do not contribute. The logarithmically divergent part would contribute to the vertex renormalization. In the limit $m_{e_i}, m_{\nu_i}, m_W \to 0$, thus we obtain the following finite result

$$-\frac{f_i^* f_j U_{ij} g_2^2}{64\sqrt{2}\pi^2} m_0^2(1-\epsilon_{H^+}) \int_0^1 dx \int_0^{1-x} dy\ \frac{y^2 + xy(1-\epsilon_{H^+})}{y^2 - y(1-x)(1-\epsilon_{H^+})} \simeq -\frac{f_i^* f_j U_{ij} g_2^2}{64\sqrt{2}\pi^2} m_0^2 \left(\frac{1}{2} + \ln\frac{\epsilon_{H^+}}{1-\epsilon_{H^+}}\right), \quad (6)$$

where $\epsilon_{H^+} = m_{H^+}^2/m_0^2$.

We can also consider the charged lepton final states in Figs. 1 (a) and (b), in which case the PMNS matrix is $U^\dagger$ instead of U. Thus, $\epsilon_{\rm L}^{N_0}(W)$ has an expression

$$\epsilon_{\rm L}^{N_0}(W) \approx \frac{\alpha_{\rm em}}{8\sqrt{2}\pi \sin^2\theta_W} \frac{1}{\sum_i |f_i|^2}\ {\rm Im}\sum_{i,j} f_i^* f_j \left[U_{ij}\left(\frac{1}{2} + \ln\frac{\epsilon_{H^+}}{1-\epsilon_{H^+}}\right) + U_{ij}^\dagger\left(\frac{1}{2} + \ln\frac{\epsilon_{H^0}}{1-\epsilon_{H^0}}\right)\right]. \quad (7)$$

For concreteness, we use the PMNS matrix U_{ij}, in the vertex diagram of Fig. 1 (b), presented in [10, 23] together with Majorana phases $\delta_{a,b,c}$,

$$U = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -c_2 s_1 & e^{-i\delta_{\rm PMNS}} s_2 s_3 + c_1 c_2 c_3 & -e^{-i\delta_{\rm PMNS}} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta_{\rm PMNS}} s_1 s_2 & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta_{\rm PMNS}} & c_2 c_3 + c_1 s_2 s_3 e^{i\delta_{\rm PMNS}} \end{pmatrix}_{\rm KS} \begin{pmatrix} e^{i\delta_a} & 0 & 0 \\ 0 & e^{i\delta_b} & 0 \\ 0 & 0 & e^{i\delta_c} \end{pmatrix}_{\rm Maj}, \quad (8)$$

where only two phases out of three phases $e^{i\delta_{a,b,c}}$ are independent. One out of three $e^{i\delta_{a,b,c}}$, one can be set to 1, which will be chosen for the dominently coupled neutrino of N_0. The first factor of Eq. (7) is about 10^{-3} and we need a huge suppression from the other factors to obtain a number $\epsilon_{\rm L}^{N_0}(W) = O(10^{-9})$.

III. DISCRETE SYMMETRY $\mathbf{Z}_N$

The coupling matrix (2) results from some symmetry. For example, in Table I we present quantum numbers of some U(1) symmetry, where ℓ_i are the lepton doublets containing three neutrinos, N's are heavy neutrinos, and X and R the SM singlets, with $\langle X\rangle = r\, e^{i\,\delta_{\rm X}}$ and $\langle R\rangle = R$. Here, we do not specify whether the U(1) is a gauge or global symmetry. Even if it is approximate with a global symmetry, the breaking term of U(1) by gravity effects can be made sufficiently small by some method. Even a fine tuning of O(10^{-2}) on the VEVs of R is acceptable in our level of discussion on relating $\delta_{\rm X}$ with $\delta_{\rm PMNS}$. A larger power r and R means a smaller coefficient due to the suppression by the Planck mass, $M_{\rm GUT}/M_{\rm P}$. Let us introduce a $\mathbf{Z}_N$ subgroup of U(1). Then, to give masses to N's, we need quantum numbers of N_i in Table I, *i.e.* $X^{n_i} = r^{n_i} e^{i\,n_i\delta_{\rm X}}$ and R^{x_i}, satisfying the following, for example [2]

$$-x_3 n_R - n_3 n_X - 1 = 0,\ \ -x_2 n_\Phi - n_2 n_X - 1 = \frac{N}{2},\ \ -x_1 n_\Phi - n_1 n_X - 1 = N. \quad (9)$$

Let us try negative quantum numbers of n_R and n_X. Note that N_0, N_1 and N_2 have Majorana phases $n_1\delta, n_2\delta$ and $n_3\delta$, respectively. For $N = 4, n_R = -1$ and $n_X = -1$, we have $x_1 + n_1 = 5, x_2 + n_2 = 3$ and $x_3 + n_3 = 1$, which are the powers of a GUT scale VEVs. Then, the matrix element $(i4)$ of Eq. (2) is proportional to

$$\left(\frac{M_{\rm GUT}}{M_{\rm P}}\right)^{x_i+n_i} e^{-in_i\delta}. \quad (10)$$

	ℓ_1	ℓ_2	ℓ_3	N_0	N_1	N_2	H_u	X	R
Q	1	1	1	$-x_1n_\Phi - n_1n_X - 1$	$-x_2n_\Phi - n_2n_X - 1$	$-x_3n_\Phi - n_3n_X - 1$	0	n_X	n_R

TABLE I: Quantum numbers under some U(1).

[2] We use only positive powers as an overall powers of the real number such that the magnitude of every entry is less than 1, *i.e.* $-|n|$ is replaced by a positive number $N - |n|$.

IV. RELATION OF THE PHASES

Now we can relate the phases in our plan of spontaneous CP violation [26] with one complex VEV, *i.e.* the phase of $\langle X\rangle$. Following the argument of Ref. [10], we can conclude that there will be no observable lepton asymmetry if $\delta_{\rm X}=0$. Therefore, all the interference terms in Eq. (7) must have factors of the form $\sin(N_{ij}\delta_{\rm X})$ where N_{ij} is an integer. For example, consider the imaginary part of a specific term in Eq. (7) before taking the sum with i and j. From the product of (b) and (a)* of Fig. 1, we read one convenient term, *i.e.* for $i=3$ and $j=1$, which has the overall phase $e^{i[\delta_{\rm PMNS}+\delta_a-n_1\delta_{\rm X}+\delta_0]+i[n_3\delta_{\rm X}-\delta_0]}$ where $\delta_{\rm PMNS}$ and δ_a are defined in Eq. (8). The Majorana phase δ_0 is the phase of the heavy lepton sector, which does not appear in this phase expression with $i=3$ and $j=1$ if the lightest neutral heavy lepton dominates in the lepton asymmetry. The imaginary part of this term is

$$\sin[\delta_{\rm PMNS}+\delta_a-(n_1-n_3)\delta_{\rm X}]. \tag{11}$$

In Ref. [10], we argued that the observable phase $\delta_{\rm PMNS}$ in low energy experiments must be integer multiples of $\delta_{\rm X}$ since there will be no electroweak scale CP violation effects if $\delta_{\rm X}=0$ and π. Along this line, we argue that $\delta_{\rm PMNS}=n_P\delta_{\rm X}$ and $\delta_a=n_a\delta_{\rm X}$, which are sufficient for the physical requirement. In this case, Eq. (11) becomes $\sin[(n_P+n_a-n_1+n_3)\delta_{\rm X}]$. Now, consider the sum with i and j. We observe that all terms are of the form $Ae^{i(\pm n_P+\delta')}+Be^{i\delta'}$ where A and B are real numbers formed with real angles and $\delta'=n'\delta_{\rm X}=n_a\delta_{\rm X},n_b\delta_{\rm X}$, or $n_c\delta_{\rm X}$, viz. Eq. (8). It is of the form

$$\begin{aligned}
&\{A\cos[(\pm n_P+n')\delta_{\rm X}]+B\cos[n'\delta_{\rm X}]\}+i\,\{A\sin[(\pm n_P+n')\delta_{\rm X}]+B\sin[n'\delta_{\rm X}]\}\\
&=\sqrt{\{A\cos[(\pm n_P+n')\delta_{\rm X}]+B\cos[n'\delta_{\rm X}]\}^2+\{A\sin[(\pm n_P+n')\delta_{\rm X}]+B\sin[n'\delta_{\rm X}]\}^2}\;e^{i\delta_{ij}}\\
&\equiv a_{ij}\,e^{i\delta_{ij}}
\end{aligned} \tag{12}$$

which has the phase $\delta_{ij}=\arctan\left(\{A\sin[(\pm n_P+n')\delta_{\rm X}]+B\sin[n'\delta_{\rm X}]\}/\{A\cos[(\pm n_P+n')\delta_{\rm X}]+B\cos[n'\delta_{\rm X}]\}\right)$. Thus, every term has the vanishing phase if $\delta_{\rm X}=0$ and π. Thus, the sum in Eq. (11) gives 0 if $\delta_{\rm X}=0$ and π. Even at this stage, we have obtained an important conclusion: the phases in the heavy lepton sector does not appear. For further relations, we must use a specific model relating n_P,n',n_i, and n_j, as we used the flipped-SU(5) model in relating $\delta_{\rm PMNS}$ and $\delta_{\rm CKM}$ [10]. Thus, the asymmetry takes a form,

$$\epsilon_{\rm L}^{N_0}(W)\approx\frac{\alpha_{\rm em}}{8\sqrt{2}\pi\sin^2\theta_W}\sum_{i,j}\mathcal{A}_{ij}\sin[(\pm n_P+n'-n_i+n_j)\delta_{\rm X}], \tag{13}$$

where $\mathcal{A}_{ij}$ are a_{ij} times appropriate ratio of Yukawa couplings. If $\sin(\pm n_P+n'-n_i+n_j)\delta_{\rm X}$ vanish except for sufficiently small $\mathcal{A}_{ij}$'s, we can obtain a needed suppression. Note that there are only two independent n' as commented before, below Eq. (8).

V. CONCLUSION

By introducing only one CP phase by a complex VEV of a SM singlet field X and assuming the lightest Majorana neutrino domination in the lepton asymmetry, we directly introduced the PMNS phase $\delta_{\rm PMNS}$ in the lepton asymmetry calculation in the early Universe. The CP phase is introduced by spontaneous mechanism at a high energy scale along the Froggatt-Nielsen method. We noted the domination of the asymmetry by the W boson exchange diagram, which is a novel suggestion useful for relating the high and low energy physics.

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[1] A. D. Sakharov, *Violation of CP Invariance, C asymmetry, and baryon asymmetry of the Universe*, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32 [JETP Lett. **5**, 24 (1967)]; Sov.Phys.Usp. 34 (1991) 392-393, Usp.Fiz.Nauk 161 (1991) 61-64 [doi:10.1070/PU1991v034n05ABEH002497].

[2] M. Yoshimura, *Unified gauge theories and the baryon number of the Universe*, Phys. Rev. Lett. **41**, 281 (1978) [doi:10.1103/PhysRevLett.41.281].
[3] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, *On the anomalous electroweak baryon number nonconservation in the early Universe*, Phys. Lett. B **155**, 36 (1985) [doi:10.1016/0370-2693(85)91028-7].
[4] I. Affleck and M. Dine, *A new mechanism for baryogenesis*, Phys. Lett. B **249**, 361 (1985) [doi:10.1016/0550-3213(85)90021-5].
[5] M. Fukugita and M. Yanagida, *Baryogenesis without grand unification*, Phys. Lett. B **174**, 45 (1986) [doi:10.1016/0370-2693(86)91126-3].
[6] H. D. Kim, J. E. Kim, and T. Morozumi, *A new mechanism for baryogenesis living through electroweak era*, Phys. Lett. B **616**, 108 (2005) [arXiv:hep-ph/0409001].
[7] N. Cabibbo, *Unitary symmetry and leptonic decays*, Phys. Rev. Lett. **10**, 531 (1963).
[8] M. Kobayashi and T. Maskawa, *CP violation in the renormalizable theory of weak interaction*, Prog. Theor. Phys. **49**, 652 (1973).
[9] B. Pontecorvo, *Mesonium and anti-mesonium*, Phys. JETP **6** (1957) 429 [Zh. Eksp. Teor. Fiz. 33, 549 (1957)]; Z. Maki, M. Nakagawa and S. Sakata, *Remarks on the unified model of elementary particles*, Prog. Theor. Phys. **28**, 870 (1962).
[10] J.E. Kim and S. Nam, *Unifying CP violations of quark and lepton sectors*, doi:10.1140/epjc/s10052-015-3805-y [arXiv:1506.08491 [hep-ph]].
[11] S. M. Barr, G. Segré, and H. A. Weldon, *The magnitude of the cosmological baryon asymmetry*, Phys. Rev. D **20**, 2494 (1979) [doi: 10.1103/PhysRevD.20.2494].
[12] D. E. Mossissey and M. J. Ramsey-Musolf, *Electroweak baryogenesis*, New J. Phys. **14**, 125003 (2012) [arXiv:1206.2942[hep-ph]].
[13] K. Kajantie, M. Laine, K. Rummukainen, and M. E. Shaposhnikov, *The electroweak phase transition: A non-perturbative analysis*, Nucl. Phys. B **466**, 189 (1996) [arXiv:hep-lat/9510020].
[14] M. B. Gavela, P. Hernandez, J. Orlo, O, Pene, and C. Quimbay, *Standard Model CP-violation and baryon asymmetry Part II: Finite temperature*, Nucl. Phys. B **430**, 382 (1994) [arXiv:hep-ph/9406289].
[15] J.E. Kim, *Towards unity of families: anti-SU(7) from* $\mathbf{Z}_{12-I}$ *orbifold compactification*, JHEP **1506**, 114 (2015) [arXiv:1503.03104 [hep-ph]].
[16] S. Davidson and A. Ibarra, *Leptogenesis and low-energy phases*, Nucl. Phys. B **648**, 345 (2002) [arXiv: hep-ph/0206304].
[17] C.D. Froggatt and H.B. Nielsen, *Hierarchy of quark masses, Cabibbo angles and CP violation*, Nucl. Phys. B **147**, 277 (1979) [doi: 10.1016/0550-3213(79)90316-X].
[18] J.E. Kim, *The CKM matrix with maximal CP violation from Z(12) symmetry*, Phys. Lett. B **704**, 360 (2011) [arXiv:1109.0995 [hep-ph]].
[19] J.E. Kim, D.Y. Mo, and M-S. Seo, *The CKM matrix from anti-SU(7) unification of GUT families*, Phys. Lett. B **749**, 476 (2015) [arXiv:1506.08984 [hep-ph]].
[20] L. Covi, E. Roulet, and F. Vissani, *CP violating decays in leptogenesis scenarios*, Phys. Lett. B **384**, 169 (1996) [arXiv:hep-ph/9605319].
[21] M. Flanz, E.A. Paschos, and U. Sarkar, *Baryogenesis from a lepton asymmetric Universe*, Phys. Lett. B **345**, 248 (1995) and **382 382**, 447 (E) (1996) [arXiv:hep-ph/9411366].
[22] W. Buchmüller and M. Plümacher, *CP asymmetry in Majorana neutrino decays*, Phys. Lett. B **431**, 354 (1997) [arXiv:hep-ph/9710460].
[23] J.E. Kim and M-S. Seo, *Parametrization of the CKM matrix*, Phys. Rev. D **84**, 037303 (2011) [arXiv:1105.3304 [hep-ph]; J.E. Kim, D.Y. Mo, and S. Nam, *Final state interaction phases obtained by data from CP asymmetries*, J. Korean Phys. Soc. **66**, 894 (2015) [arXiv:1402.2978 [hep-ph]].
[24] S. M. Barr, *A new symmetry breaking pattern for SO(10) and proton decay*, Phys. Lett. B **112**, 219 (1982) [doi: 10.1016/0370-2693(82)90966-2]; J. P. Derendinger, J. E. Kim, and D. V. Nanopoulos, *Anti-SU(5)*, Phys. Lett. B **139**, 170 (1984) [doi:10.1016/0370-2693(84)91238-3]; I. Antoniadis, J. R. Ellis, J .S. Hagelin, and D. V. Nanopoulos, *The flipped SU(5)×U(1) string model revamped*, Phys. Lett. B **231**, 65 (1989) [doi: 10.1016/0370-2693(89)90115-9]; J. E. Kim and B. Kyae, *Flipped SU(5) from* $\mathbf{Z}_{12-I}$ *orbifold with Wilson line*, Nucl. Phys. B **770**, 47 (2007) [arXiv: hep-th/0608086].
[25] G. C. Branco, T. Morozumi, B. M. Nobre, and M. N. Rebelo, *A bridge between CP violation at low-energies and leptogenesis*, Nucl. Phys. B **617**, 475 (2001) [arXiv: hep-ph/0107164].
[26] T. D. Lee, *A theory of spontaneous T violation* , Phys. Rev. D **8**, 1226 (1973) [doi: 10.1103/PhysRevD.8.1226].