

Lepton flavor mixing and Baryogenesis

Kyungsik Kang¹, Sin Kyu Kang² and Utpal Sarkar³

¹ *Department of Physics, Brown University, Providence, RI 02912, USA*

² *School of Physics, Korea Institute for Advanced Study, Seoul 130-012, Korea*

³ *Physical Research Laboratory, Ahmedabad 380 009, India*

Abstract

Recently a new general class of quark mass matrix ansatz has been proposed, which originates from some flavor symmetry. We extend that symmetry to the lepton sector and study the neutrino mass matrix and address the question of the baryon asymmetry of the universe in this model.

The question of flavor mixing and fermion masses can lead us to physics beyond the standard model, where several experimental results are present without any theoretical insight. As an attempt to derive relationship between the quark masses and flavor mixing hierarchies, mass matrix ansatz was suggested about two decades ago [1] These ansatz hopefully will emerge from some definite theoretical consideration.

Of the several ansatze of quark mass matrices, the canonical mass matrices of the Fritzsch-type have been generally taken to predict the entire Cabibbo-Kobayashi-Maskawa (CKM) matrix [2]. However, this ansatz is ruled out because it predicts a top quark mass to be no longer than 100 GeV [3]. Recently this form of mass matrices has been generalized to accommodate the large top quark mass while keeping the *calculability* of the ansatz [4]. It was shown that this generalized mass matrix could originate from breaking of the maximal permutation symmetry [5, 6].

In this letter we study the consequence of the breaking of the maximal permutation symmetry in the lepton sector. Since this symmetry acts on both the left- and the right-handed quark fields, when we generalize it to the lepton sector, it would be natural to include the right-handed neutrinos. Then the same symmetry could act on the left- and right-handed leptonic fields in the same way as in the quark sector. We shall assume that lepton number is broken at some intermediate scale when the right handed neutrinos get a Majorana mass. Then the usual Higgs doublets will combine the left-handed neutrinos to the right-handed neutrinos through the Dirac mass term, so that the left-handed neutrinos get a small see-saw Majorana mass [7]. There is no $SU(2)_L$ triplet Higgs scalar [8], which can break lepton number at some high scale and give a Majorana mass to the left-handed neutrinos. But, the maximal permutation symmetry will determine the form of the Majorana mass matrix for the right handed neutrinos and the Dirac neutrino mass matrix. From these matrices the see-saw mass matrix of the left-handed neutrinos will also be determined. With these neutrino mass matrices of the left-handed and the right-handed Majorana particles we shall study the possibility of generating a lepton asymmetry of the universe which will get converted to a baryon asymmetry of the universe before the electroweak phase transition [9, 10, 11].

Let us begin by introducing the general form of the Fritzsch-type mass matrix in which a nonvanishing (2,2) element is introduced to accommodate a large top quark mass[4]. This mass matrix form is achieved by breaking the

democratic flavor symmetry $S(3)_L \times S(3)_R \rightarrow S(2)_L \times S(2)_R \rightarrow S(1)_L \times S(1)_R$. The resulting quark mass matrix takes the form,

$$M_q = \begin{pmatrix} 0 & A & 0 \\ A & D & B \\ 0 & B & C \end{pmatrix}. \quad (1)$$

Although this matrix contains four independent parameters even in the case of real parameters, one can make additional ansatz to relate D to B in general so as to maintain the *calculability* [4].

We shall now assume that the same flavor symmetry is also true in the lepton sector. In the $S(3)_L \times S(3)_R$ symmetric limit the charged lepton mass matrix has the form in the democratic basis:

$$\frac{a}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}, \quad (2)$$

which will lead to the largest contribution in the mass eigenstate basis. By making unitary transformation of the mass matrix Eq.(2) with the help of

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix}, \quad (3)$$

one can obtain the diagonal mass matrix with only a nonvanishing (3,3) element $m_{33} = a$. In order to account for the second generation masses, we break the $S(3)_L \times S(3)_R$ symmetry to $S(2)_L \times S(2)_R$. This can be achieved by adding the following matrix to Eq.(2):

$$\begin{pmatrix} 0 & 0 & b \\ 0 & 0 & b \\ b & b & c \end{pmatrix}. \quad (4)$$

Although different choice of the parameters b and c is general, in this paper we set for simplicity, $b = -c$, which renders the mass matrix diagonal after unitary transformation with Eq.(3). We then get the second largest mass given by $m_{22} = 2b$. Finally, the $S(1)_L \times S(1)_R$ symmetric mass matrix can be achieved by taking (1,2) and (2,1) elements to be nonzero ($= d$), which

can then be rotated to the diagonal form with $m_{11} = d$, $m_{22} = 2b + d$ and $m_{33} = a + c$.

We shall now work in the basis in which the charged lepton mass matrix is diagonal and real. For the $S(3)_L \times S(3)_R$ symmetry to be applicable we further consider that the model contains three right-handed neutrinos N_α , $\alpha = 1, 2, 3$ in addition to the usual left-handed neutrinos of three generations. Furthermore, since the right-handed neutrinos are singlets under the standard model gauge group they can get Majorana masses at the tree level, whereas the left-handed neutrinos can not get any tree level Majorana mass since there are no $SU(2)_L$ triplet Higgs scalar. The left-handed neutrinos then remain light and get a see-saw mass [7] due to their usual Dirac type coupling with the right-handed neutrinos. We can then write the neutrino mass matrix in the basis $[\nu_{iL} \ N_{\alpha R}]$ as,

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \quad (5)$$

where each of these elements are 3×3 matrices.

Assuming that the flavor symmetry under consideration comes from a transformation of the left- and the right-handed fields, the right-handed Majorana mass matrix will have a $S(3)_R \times S(3)_R$ symmetry to start with, which will then break to $S(2)_R \times S(2)_R$ and then to $S(1)_R \times S(1)_R$ in succession. The $S(3)_R \times S(3)_R$ symmetry gives a mass matrix of the form [12],

$$M_N = \begin{pmatrix} A & B & B \\ B & A & B \\ B & B & A \end{pmatrix} \quad (6)$$

in which we can choose $B = 0$ without loss of generality. Otherwise, we can keep the B and diagonalize it with the unitary matrix with the first row and the third row interchanged from Eq.(2) to a form proportional to a unit matrix $M_N = A \mathbf{I}$. Then the combination $N_1 + N_2 + N_3$ gets a mass, which we identify with the largest mass of the right-handed neutrino N_{eR} . Identification of the right-handed electron neutrino as the heaviest one is necessary to explain the large mixing between the left-handed μ and τ neutrinos, which is required to explain the atmospheric neutrino anomaly. We shall discuss this point in details at some later stage. In the same way, the $S(2)_R \times S(2)_R$ symmetry will contribute to the (2,2) diagonal elements by an amount C , and the

Table 1: Present experimental constraints on neutrino masses and mixing

Solar Neutrino [13] (Small angle MSW)	: $\Delta m^2 \sim (0.5 - 1) \times 10^{-5} eV^2$ $\sin^2 2\theta \sim 10^{-2} - 10^{-3}$
Atmospheric Neutrino [14]	: $\Delta m^2 \sim (0.5 - 6) \times 10^{-3} eV^2$ $\sin^2 2\theta > 0.82$
Neutrinoless Double Beta Decay [15]	: $m_{\nu_e} < 0.46 eV$
CHOOZ [16]	: $\Delta m_{eX}^2 < 10^{-3} eV^2$ (or $\sin^2 2\theta_{eX} < 0.2$)

corresponding state may be identified as the $N_{\mu R}$. Finally, the $S(1)_R \times S(1)_R$ symmetry will contribute only to the (3,3) element by an amount D . The resulting matrix in the basis $[N_{eR} \ N_{\mu R} \ N_{\tau R}]$ then becomes,

$$M_N = \text{diag}[A, \ C, \ D]. \quad (7)$$

We now assume that as in the quark sector the largest contribution to the left-handed neutrino mass comes in the $S(3)_R \times S(3)_R$ symmetric limit, then the heavy right-handed neutrinos follow an inverted hierarchical pattern $M_{N_e} \gg M_{N_\mu} \gg M_{N_\tau}$ and $N_{\tau R}$ becomes the lightest right-handed Majorana neutrino. As we shall demonstrate, this inverted hierarchical pattern can explain the present experimental results of the neutrino masses (which is given in table 1).

As it is well known, it is not possible to explain the atmospheric neutrino anomaly [14], solar neutrino problem [13] and the LSND result [17] simultaneously in a three generation model, since the mass squared differences required in the three cases are widely different. One needs at least one more light sterile neutrino state which mixes with the ordinary neutrinos. On the other hand, such sterile neutrinos are severely constrained by the present limit on the nucleosynthesis bounds [11], which can hardly accommodate a fourth neutrino. So, in our analysis we consider only three light neutrinos

and thus do not try to accommodate the LSND result. There are three allowed regions of the parameter space for explaining the solar neutrino data [18], out of which we consider only the small angle MSW solution, which comes out naturally in this model.

The structure of the Dirac mass matrix in the neutrino sector will be similar to that of the quark sector and is given by,

$$m_D = \begin{pmatrix} 0 & x & 0 \\ x & t & y \\ 0 & y & z \end{pmatrix}. \quad (8)$$

However, the hierarchy in the different elements could, in general, be different. So, we try to determine the different parameters from experimental inputs, rather than justifying them from some theoretical reasonings.

At this point we can justify the requirement for the inverted hierarchy of the right-handed Majorana neutrino masses. Thanks to the largely hierarchical right-handed Majorana neutrino mass matrix, the main contribution to the left-handed Majorana masses comes from the lightest right-handed neutrinos in the see-saw mechanism. If N_{eR} becomes the lightest right-handed Majorana neutrino, then the largest element of the effective left-handed Majorana mass will be the $[\mu\mu]$ element only. On the other hand, the atmospheric neutrino anomaly requires a large mixing between ν_μ and ν_τ , which requires the $[\mu\tau]$ and $[\tau\mu]$ elements to be comparable or larger than the $[\mu\mu]$ element. Thus this cannot explain the large ν_μ and ν_τ mixing. If we assume that $N_{\tau R}$ is the lightest right-handed Majorana neutrino and y and z are of the same order of magnitude [20], then all the four elements $[\mu\mu]$, $[\mu\tau]$, $[\tau\mu]$ and $[\tau\tau]$ will be of the same order of magnitude, which ensures maximal mixing between ν_μ and ν_τ [21].

Along with the inverted hierarchy condition, $M_{N_e} \gg M_{N_\mu} \gg M_{N_\tau}$, we also assume that the elements of the Dirac mass matrix are not largely hierarchical. Then the largest contribution to the effective 3×3 mass matrix of the left-handed neutrinos will come from the see-saw contribution from M_{N_τ} and then the next leading contribution will come from M_{N_μ} . Then the effective 3×3 neutrino mass matrix can now be written as

$$m_\nu = m_D^T M_N^{-1} m_D$$

$$\simeq \begin{pmatrix} \frac{x^2}{M_{N\mu}} & \frac{xt}{M_{N\mu}} & \frac{xy}{M_{N\mu}} \\ \frac{xt}{M_{N\mu}} & \frac{y^2}{M_{N\tau}} & \frac{yz}{M_{N\tau}} \\ \frac{xy}{M_{N\mu}} & \frac{yz}{M_{N\tau}} & \frac{z^2}{M_{N\tau}} \end{pmatrix} \quad (9)$$

where we have ignored the next to leading terms of order $O(1/M_{N_e})$ and $O(1/M_{N\mu}^2)$. This means that the mass squared difference between ν_μ and ν_τ vanishes. So, for the nonvanishing mass squared difference we need to keep the higher order terms. However, to calculate the mixing matrix, we can ignore the next to leading terms without loss of generality.

Since we are interested in the maximal mixing solution for ν_μ and ν_τ and the small mixing solution for ν_e and ν_μ , the neutrino mixing matrix can be parameterized by

$$\begin{aligned} U_\nu &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_2 & s_2 \\ 0 & -s_2 & c_2 \end{pmatrix} \cdot \begin{pmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ &= \begin{pmatrix} c_1 & s_1 & 0 \\ -\frac{s_1}{\sqrt{2}} & \frac{c_1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_1}{\sqrt{2}} & -\frac{c_1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \end{aligned} \quad (10)$$

where $c_1 = \cos\theta_1, c_2 = \sin\theta_2$ and we have taken $c_2 = s_2 = 1/\sqrt{2}$. Then, the favored solution for the solar and atmospheric neutrino anomaly leads to $c_1 \sim 1, s_1 \sim 0.05, m_2 \sim 3 \times 10^{-3}$ eV and $m_3 \sim 3 \times 10^{-2}$ eV. From these results, one can approximately estimate the neutrino mass matrix

$$m_\nu = U_\nu \cdot \text{diag}[m_1, -m_2, m_3] \cdot U_\nu^\dagger \quad (11)$$

$$\sim \begin{pmatrix} 10^{-6} & 10^{-4} & 10^{-4} \\ 10^{-4} & 1.5 \times 10^{-2} & 1.5 \times 10^{-2} \\ 10^{-4} & 1.5 \times 10^{-2} & 1.5 \times 10^{-2} \end{pmatrix} \quad (12)$$

In this case, by choosing y and z to be of the same order of magnitude we can ensure the maximal mixing between ν_μ and ν_τ . To be precise, the large mixing between ν_μ and ν_τ , as observed in the atmospheric neutrinos at SuperKamiokande(i.e., $\sin^2 2\theta > 0.82$), implies $0.64 < y/z < 1.56$. On the other hand, the ratio $x/y \sim x/t$ gives the mixing between ν_e and ν_μ and could be very small. For a reasonable choice, $x/y \sim x/t \sim 10^{-2}$, the solar

neutrino anomaly can be explained by the small angle MSW solution, which is one of the favored solutions for the solar neutrino anomaly [18].

In all the models for neutrino masses, another related question remains to be answered is the generation of the baryon asymmetry of the universe. The Majorana mass term of the right handed neutrinos introduces lepton number violation and hence $(B - L)$ violation. If this interaction is slower than the expansion rate of the universe when the right handed neutrinos decay (at $T = M_N$) and there is enough CP violation, this interaction can generate a lepton asymmetry of the universe. At finite temperature above the critical temperature of the electroweak phase transition sphaleron processes are in thermal equilibrium and $(B+L)$ number violating interactions are very fast [19]. This will then relate the lepton asymmetry or the $(B - L)$ asymmetry generated during the right handed neutrino decay to the baryon asymmetry of the universe before the electroweak phase transition. This remains to be the most interesting scenario for the understanding of the baryon number of the universe, which is referred to as leptogenesis [10, 22].

Since lepton number violation is the source of leptogenesis, it also depends on models of neutrino masses. It has recently been argued [23] that the see-saw mechanism of neutrino masses is the most preferred one for the generation of the baryon asymmetry of the universe in supersymmetric inflationary models. We shall now see if this could be implemented in the present scenario.

In the see-saw mechanism for neutrino masses the right-handed neutrino decay could generate a lepton asymmetry of the universe, which then gets converted to a baryon asymmetry of the universe. CP violation comes from an interference of the tree level diagrams with the self-energy type and vertex correction type diagrams [10, 22]. We start with the lagrangian

$$\mathcal{L} = M_i \overline{N_{iR}^c} N_{iR} + h_{\alpha i} \overline{\ell_{\alpha L}} \phi N_{iR} + h.c., \quad (13)$$

where $\ell_{\alpha L}$ are the light leptons, ϕ is the usual Higgs doublet of the standard model, $h_{\alpha i}$ are the complex Yukawa couplings and α is the generation index. We have chosen the Majorana mass matrix of the right-handed neutrino to be real and diagonal. Then the decay of the lightest neutrino $N_{\tau R}$ can generate a lepton asymmetry which can then generate a baryon asymmetry of the universe before the electroweak phase transition. The decay of the heavier neutrinos can also generate an asymmetry, but that asymmetry will be washed out before the lightest right-handed neutrino decay.

Due to the Majorana masses of the right-handed neutrinos, their decay violates lepton number,

$$N_{iR} \longrightarrow \ell_{\alpha L} + \phi^\dagger \quad (14)$$

$$\longrightarrow \ell_{\alpha L}^c + \phi. \quad (15)$$

CP violation comes from an interference of the tree level diagram for the decay of N_{iR} with the one loop diagrams shown in figure 1. There are two contributions coming from the interference of the tree diagram with the one loop vertex correction and another one with the one loop self energy diagram. When the masses of the heavy neutrinos are degenerate, there can be large contributions coming from an interference of the self energy diagrams. However, in the present case when the masses of the right handed neutrinos are hierarchical, the contribution coming from the two sources are equal. In this case the contributions from both the diagrams add up to give the total amount of CP violation. First, the heaviest right handed neutrino will decay and then the second heaviest, when it may or may not generate any lepton asymmetry. When the lightest one ($N_{\tau R}$) decays, it will first erase any pre-existing asymmetry and then generate the final lepton asymmetry, which is presented by

$$\begin{aligned} \epsilon_\tau &= \frac{\sum_\alpha \Gamma(N_{\tau R} \rightarrow \ell_{\alpha L} \phi^\dagger) - \sum_\alpha \Gamma(N_{\tau R} \rightarrow \ell_{\alpha L}^c \phi)}{\sum_\alpha \Gamma(N_{\tau R} \rightarrow \ell_{\alpha L} \phi^\dagger) + \sum_\alpha \Gamma(N_{\tau R} \rightarrow \ell_{\alpha L}^c \phi)} \\ &= \frac{3}{16\pi} \frac{\text{Im}[\sum_\alpha (h_{\alpha\tau}^* h_{\alpha i}) \sum_\beta (h_{\beta\tau}^* h_{\beta i})]}{\sum_\alpha |h_{\alpha\tau} h_{\alpha\tau}^*|^2} I\left(\frac{M_{N_\tau}^2}{M_{N_i}^2}\right), \end{aligned} \quad (16)$$

where $i = e, \mu$ and $I(x) = x^{1/2}[1 + (1+x)\ln(x/(1+x))]$.

Similar to the Jarlskog invariant for CP violation in the quark sector, in this case a different combination enters, which has its origin in the Majorana nature of the neutrino masses. The Majorana nature of the right handed neutrinos will imply that there are new Majorana phases which will contribute to the CP violation. In the basis we are working, where the right handed mass matrix is real and diagonal, all these Majorana phases has been transferred to the elements of m_D and the quantity $\sum_\alpha (h_{\alpha\tau}^* h_{\alpha i})$ becomes a rephasing invariant quantity. In the limit $x = 0$, this becomes equivalent to a two heavy neutrino scenario. In this case after considering the overall rephasing

there remains only one CP phase, which vanishes when $t = 0$. Thus, in the Fritzsch type of mass matrix, the CP violation for the generation of the a baryon asymmetry of the universe will be highly suppressed.

In terms of the elements of m_D , the amount of CP violation is given by,

$$\epsilon_\tau = \frac{3}{16\pi} \left[\frac{\text{Im}(y^*t + z^*y)^2}{(|y|^2 + |z|^2)} \left(\frac{M_{N_\tau}}{M_{N_\mu}} \right) + \frac{\text{Im}(y^*x)^2}{(|y|^2 + |z|^2)} \left(\frac{M_{N_\tau}}{M_{N_e}} \right) \right]. \quad (17)$$

We can now choose the overall phase so that z^*y is real. Then for $t = 0$, the first term vanishes and assuming that the CP phases are all similar the amount of CP violation gets suppressed by an amount, $\frac{xM_{N_e}}{yM_{N_\tau}} < 10^{-4}$.

With this additional suppression it will be impossible to explain the baryon asymmetry of the universe. Thus, for the generation of the lepton asymmetry of the universe, it is extremely important that we make the [2,2] element non-vanishing, which required to accommodate the heavy top quark mass in Fritzsch type (mass matrix) ansatz.

For the generation of a lepton asymmetry of the universe one more ingredient is necessary, namely, the out-of-equilibrium condition. Whether a system is in equilibrium or not can be understood by solving the Boltzmann equations. But a crude way to put the out-of-equilibrium condition is to say that the universe expands faster than the interaction rate [24]. This may be stated as

$$\Gamma_N < H = 1.7\sqrt{g_\star} \frac{T^2}{M_P} \quad (18)$$

where Γ_N is the interaction rate under discussion, $g_\star \sim 10^2$ is the effective number of degrees of freedom available at that temperature T , and M_P is the Planck scale.

In the case of right-handed neutrino decay, the asymmetry is generated when the lightest right handed neutrino decays. Before its decay, the pre-existing lepton asymmetry, if any, is washed out by its lepton number violating interactions. Just before the lightest right handed neutrino decays, it satisfies the out-of-equilibrium condition

$$\frac{|h_{\alpha 1}|^2}{16\pi} M_N < H \quad \text{at } T = M_N \quad (19)$$

if the masses of the heavy neutrinos are larger than $M_N > 10^7$ GeV. We consider that the reheating temperature is not too high so that after reheating

gravitinos are not produced in large numbers which can then overclose the universe [25]. This implies that for the lightest right-handed neutrinos to be produced after reheating, we must have $M_{N\tau} < 10^{10}$ GeV. This reduces the uncertainty in the scale of the heavy neutrinos to some extent. The explanation of the atmospheric neutrino anomaly, i.e., the mass of ν_τ to be around 10^{-2} then requires, $y, z, t \sim 0.1$ GeV for $M_{N\tau} \sim 10^8$ GeV. Taking the vacuum expectation value of the Higgs doublet field to be around 100 GeV, we get a lepton asymmetry of the universe to be around, $n_L \sim \frac{\epsilon}{g_*} \sim 10^{-8} \sin \delta$, where δ is the CP phase in the couplings of the Dirac neutrino mass matrix m_D . So, an CP violating phase of the order of $\sin \delta \sim 0.01$ can generate enough lepton asymmetry of the universe. During the period 10^{12} GeV $> T > 10^2$ GeV the sphaleron transitions will be very fast and this lepton asymmetry will get converted to a baryon asymmetry of the universe, $n_b \sim \frac{n_L}{s}$.

In summary, we extended a new general class of quark mass matrix ansatz to the leptonic sector to obtain the neutrino mass matrix. We showed that an interesting inverted hierarchical pattern for the heavy right-handed neutrinos can accommodate the atmospheric neutrino oscillation with the maximal $\nu_\mu \rightarrow \nu_\tau$ mixing and the small angle MSW solution of the solar neutrino deficit. It turned out that the baryon asymmetry of the universe comes out to be correct for this particular form of neutrino mass matrices.

Acknowledgments One of us (US) would like to thank the organisers of the journal club and the Korea Institute for Advanced Study for hospitality, where this work was initiated.

References

- [1] S. Weinberg, in a Festschrift for I. I. Rabi, ed. L. Motz (N.Y. Academy of Sciences, N.Y. 1977); A. deRejula, H. Georgi, and S. L. Glashow, *Ann. Phys. (N.Y.)* **109**, 258 (1977); F. Wilczek and A. Zee, *Phys. Lett.* **B79**, 418 (1977); H. Georgi and D. V. Nanopoulos, *Nucl. Phys.* **B155**, 52 (1979).
- [2] A. C. Rothman and K. Kang, *Phys. Rev. Lett.* **43**, 1548 (1979); *Phys. Rev.* **D24**, 167 (1981); H. Fritzsch, *Phys. Lett.* **B73**, 317 (1978); *Nucl. Phys.* **B155**, 189 (1979).
- [3] K. Kang and S. Hadjithodoridis, *Phys. Lett.* **B193**, 504 (1987); K. Kang, J. Flanz, and E. Paschos, *Z. Phys. C* **55**, 75 (1992) See also H. Harari and Y. Nir, *Phys. Lett.* **B 195**, 586 (1987).
- [4] K. Kang and S. K. Kang, *Phys. Rev.* **D 56**, 1511 (1997); hep-ph/9802330.
- [5] H. Fritzsch and Z. z. Xing, *Phys. Lett.* **B 413**, 396 (1997); hep-ph/9904286; A. Mondragon, E. Rodriguez-Jauregui, *Phys. Rev.* **D 59**, 093009 (1999); hep-ph/9906429; D. Falcone, hep-ph/9905316; M. Randhawa, V. Bhatnagar, P.S. Gill, M. Gupta, hep-ph/9903428.
- [6] See also, S. L. Adler, *Phys. Rev.* **D 59**, 015012 (1999); hep-ph/9711393. P. S. Gill and M. Gupta, *Phys. Rev.* **D 56**, 3143 (1997); K. Kang, S. K. Kang, C. S. Kim and S. M. Kim, hep-ph/9808419.
- [7] M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, eds. P. van Nieuwenhuizen and D. Freedman, (North-Holland, 1979) p.315; T. Yanagida, in *Proc. Workshop on Unified Theories and Baryon Number in the Universe*, eds. A. Sawada and A. Sugamoto (KEK, 1979), p.95; R.N. Mohapatra and G. Senjanović, *Phys. Rev. Lett.* **44**, 912 (1980).
- [8] E. Ma and U. Sarkar, *Phys. Rev. Lett.* **80** (1998) 5716; U. Sarkar, *Phys. Rev.* **D 59** (1999) 031301; E. Ma, M. Raidal and U. Sarkar, hep-ph/9811240; *Eur. Phys. J.* **C8** (1999) 301.
- [9] E. W. Kolb and M. S. Turner, 1989, *The Early Universe* (Addison-Wesley, Reading, MA).

- [10] M. Fukugita and T. Yanagida, Phys. Lett. **B 174**, 45 (1986).
- [11] S. Yu. Khlebnikov and M.E. Shaposhnikov, Nucl. Phys. **B 308**, 885 (1988); J.A. Harvey and M.S. Turner, Phys. Rev. **D 42**, 3344 (1990).
- [12] K. Kang, S. K. Kang, J. E. Kim and P. Ko, Mod. Phys. Lett. **A 12**, 553 (1997); K. Kang and S. K. Kang, hep-ph/9802328; S. K. Kang and C. S. Kim, Phys. Rev. **D 59**, 091302 (1999); H. Fritzsch and Z. z. Xing, Phys. Lett. **B 372**, 265 (1996); hep-ph/9807234 ; Phys. Lett. **B 440**, 313 (1998); ; M. Tanimoto, hep-ph/9807517; M. Fukugita, M. Tanimoto and T. Yanagida, Phys. Rev. **D 57**, 4429 (1998).
- [13] Super-Kamiokande Collaboration : Y. Fukuda *et al*, Phys. Rev. Lett. **81**, 1158 (1998); Talk by Y. Suzuki at Neutrino'98, Takayama, Japan (1998).
- [14] Super-Kamiokande Collaboration : Y. Fukuda *et al*, Phys. Rev. Lett. **81** (1998)1562 ; hep-ex/9805006; Phys. Lett. **B433** (1998) 9; T. Kajita, hep-ex/9810001.
- [15] Heidelberg-Moscow Collaboration : H.V. Klapdor-Kleingrothaus, in Proc Lepton and Baryon number violatoin, Trento, April 1998; M. Günther et al, Phys. Rev. **D 55** (1997) 54; L. Baudis et al, Phys. Lett. **B 407** (1997) 219.
- [16] CHOOZ Collab., M. Apollonio *et. al*, hep-ex/9711002.
- [17] C. Athanassopoulos *et. al*, Phys. Rev. Lett. **75** (1995) 2650.
- [18] N. Hata and P. Langacker, Phys. Rev. **D56** (1997) 6107; J.N. Bahcall, P.J. Krastev and A.Yu. Smirnov, hep-ph/9807216.
- [19] V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, Phys. Lett. **B 155** (1985) 36.
- [20] E. Ma, D.P. Roy and U. Sarkar, Phys. Lett. **B444** (1998) 391; E. Ma and D.P. Roy, Phys. Rev. **D 59**, (1999) 097702.
- [21] R. Barbieri, L.J. Hall and A. Strumia, hep-ph/9808333.

- [22] P. Langacker, R. Peccei and T. Yanagida, *Mod. Phys. Lett.* **A 1**, 541 (1986); A. Acker, H. Kikuchi, E. Ma and U. Sarkar, *Phys. Rev.* **D 48**, 5006 (1993); M. Flanz, E.A. Paschos and U. Sarkar, *Phys. Lett.* **B 345**, 248 (1995); L. Covi, E. Roulet and F. Vissani, *Phys. Lett.* **B 384**, 169 (1996); M. Flanz, E.A. Paschos, U. Sarkar and J. Weiss, *Phys. Lett.* **B 389**, 693 (1996); W. Buchmuller and M. Plümacher, *Phys. Lett.* **B 389**, 73 (1996); *Phys. Lett.* **431**, 354 (1998); J. Faridani, S. Lola, P.J. O'Donnell and U. Sarkar, *Eur. Phys. J.* **C 7**, 543 (1999); A. Pilaftsis, *Phys. Rev.* **D 56**, 5431 (1997); *Nucl. Phys.* **B 504** (1997) 61.
- [23] D. Delepine and U. Sarkar, hep-ph/9811479; E. Ma, M. Raidal and U. Sarkar, hep-ph/9901406.
- [24] J.N. Fry, K.A. Olive and M.S. Turner, *Phys. Rev. Lett.* **45** (1980) 2074; *Phys. Rev.* **D 22** (1980) 2953; *Phys. Rev.* **D 22** (1980) 2977; E.W. Kolb and S. Wolfram, *Nucl. Phys.* **B 172** (1980) 224.
- [25] J. Ellis, G. B. Gelmini, J. L. Lopez, D. V. Nanopoulos and S. Sarkar, *Nucl. Phys.* **B373** (1992) 399; M. Boltz, W. Buchmuller and M. Plümacher, *Phys. Lett.* **B443** (1998) 209; D. J. H. Chung, E. W. Kolb and A. Riotto, hep-ph/9809453.

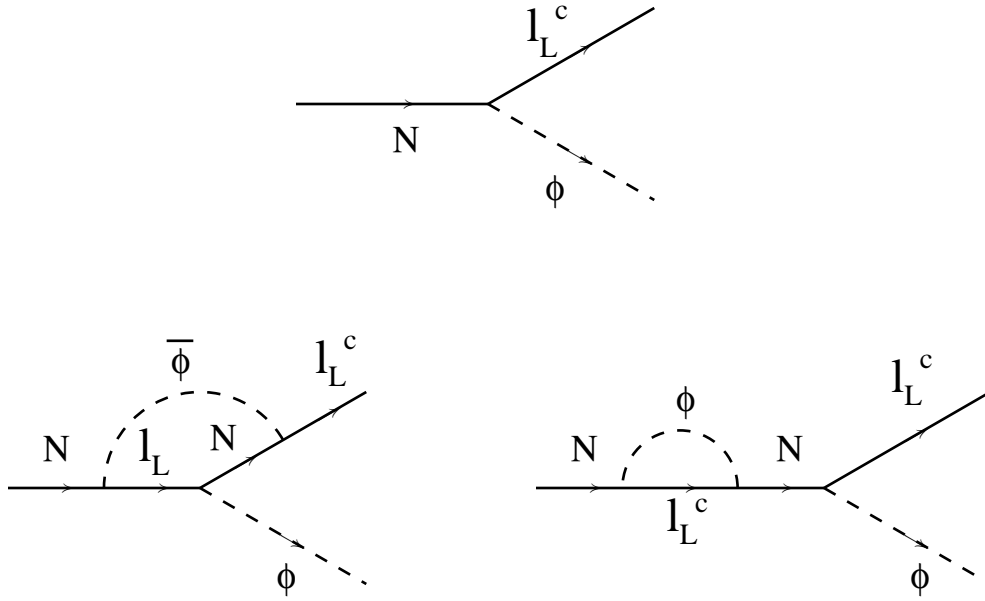


Figure 1: Tree level and one loop vertex and self energy diagrams for the generation of lepton asymmetry of the universe