Communications in Physics, Vol. 21, No. 4 (2011), pp. 295-300

LEPTOGENESIS IN SUPERSYMMETRIC ECONOMICAL 3-3-1 MODEL

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Abstract. *We study a leptogenesis scenario in which the heavy Majorana neutrinos are produced non-thermally in inflaton decays in the supersymmetric economical* $\mathrm{SU}(3)_C \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_X$ *model with inflationary scenario. The lepton-number violating interactions among the inflaton and right-handed neutrinos appear at the one-loop level, and this is a reason for non-thermal leptogenesis scenario. The bound followed from the gravitino abundance and the cosmological constraint on neutrino mass/the neutrino oscillation data is:* $m_{\nu 3} \simeq \frac{0.05}{\delta_{eff}}$ *eV. By taking the reheating temperature as low as* $T_R = 10^6$ *GeV, we get a limit on the ratio of masses of the light heavies neutrino to those of the inflaton to be:* $\frac{M_{R1}}{M_\phi} = 0.87$.

I. INTRODUCTION

The recent experimental results confirm that neutrinos have tiny masses and oscillate [1], this implies that the standard model (SM) must be extended. Among the beyond-SM extensions, the models based on the $\mathrm{SU}(3)_C \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_X$ (3-3-1) gauge group [2, 3] have some intriguing features: First, they can give partial explanation of the generation number problem. Second, the third quark generation has to be different from the first two, so this leads to the possible explanation of why top quark is uncharacteristically heavy. An additional motivation to study this kind of the models is that they can also predict the electric charge quantization [4].

On the other hand, to explain the well-known matter-antimatter asymmetry, the baryogenesis plays an important role. In addition, primordial lepton asymmetry is converted to baryon asymmetry in the early universe through the "sphaleron" effects of electroweak gauge theories [5] if it is produced before the electroweak phase transition. Thus, the leptogenesis scenario [6] seems to be the most plausible mechanism for creating the cosmological baryon asymmetry.

II. NEUTRINO MASS IN SUPERSYMMETRIC 3-3-1 MODEL WITHOUT INFLATIONARY SCENARIO

II.1. Tree-level Dirac mass

At the tree-level, the neutrinos get masses from the term

$$-\lambda'_{ab} L_{aL} L_{bL} \rho + H.c, \tag{1}$$

which gives us

$$-\lambda'_{ab}(\nu^c_{aL}\nu_{bL} - \nu_{aL}\nu^c_{bL} + \overline{\nu^c_{aL}}\,\overline{\nu_{bL}} - \overline{\nu_{aL}}\,\overline{\nu^c_{bL}})\rho^0. \tag{2}$$

This mass term can now be rewritten in terms of a 6×6 matrix X_ν by defining the following column vector

$$(\psi^0_\nu)^T = \left(\begin{array}{cccccc} \nu_{1L} & \nu_{2L} & \nu_{3L} & \nu^c_{1L} & \nu^c_{2L} & \nu^c_{3L} \end{array} \right). \quad (3)$$

Now we can rewrite our mass term as

$$-L = \frac{1}{2}\left[(\psi^0_\nu)^T X_\nu \psi^0_\nu + H.c\right], \quad (4)$$

with

$$X_\nu = \frac{v}{\sqrt{2}} \left(\begin{array}{cccccc} 0 & 0 & 0 & 0 & G_{21} & G_{31} \\ 0 & 0 & 0 & G_{12} & 0 & G_{32} \\ 0 & 0 & 0 & G_{13} & G_{23} & 0 \\ 0 & G_{12} & G_{13} & 0 & 0 & 0 \\ G_{21} & 0 & G_{23} & 0 & 0 & 0 \\ G_{31} & G_{32} & 0 & 0 & 0 & 0 \end{array} \right) \equiv \left(\begin{array}{cc} 0 & M_D^T \\ M_D & 0 \end{array} \right)$$

where

$$G_{ab} = \left(\lambda'_{ab} - \lambda'_{ba}\right). \quad (5)$$

Due to the fact that $G_{ab} = -G_{ba}$, the mass pattern of this sector is $0,\ 0,\ m_\nu,\ m_\nu,\ m_\nu,\ m_\nu$, where $\sqrt{2}m_\nu = v\sqrt{G^2_{31} + G^2_{32} + G^2_{21}}$. Noting that this mass spectrum is the same as of the non-supersymmetric version and the mass spectrum is not realistic [7]. The most general neutrino mass spectrum is in the following form:

$$M_\nu = \left(\begin{array}{cc} M_L & M_D^T \\ M_D & M_R \end{array} \right), \quad (6)$$

where $M_{L,R}$ (vanish at the tree-level) and M_D get possible corrections.

II.2. The one-loop corrections to the Dirac and Majorana masses

The Yukawa couplings of the leptons and the relevant Higgs self-couplings are explicitly rewritten as follows:

$$\begin{aligned} L_Y^{lept} &= \lambda'_{ab}\nu_{aL}l_{bL}\rho_3^+ + \lambda'_{ab}\nu^c_{aR}l_{bL}\rho_1^+ + \gamma_{ab}\nu_{aL}l^c_R\rho_1'^- + \gamma_{ab}\nu^c_{aR}l^c_R\rho_3'^- + H.c., \\ L_H^{relv} &= \frac{g^2}{8}(\chi_i^\dagger\lambda^b_{ij}\chi_j - \chi_i'^\dagger\lambda^{*b}_{ij}\chi'_j + \rho_i^\dagger\lambda^b_{ij}\rho_j - \rho_i'^\dagger\lambda^{*b}_{ij}\rho'_j)^2 \\ &+ \frac{g'^2}{12}\left(-\frac{1}{3}\chi^\dagger\chi + \frac{1}{3}\chi'^\dagger\chi' + \frac{2}{3}\rho^\dagger\rho - \frac{2}{3}\rho'^\dagger\rho'\right)^2 \end{aligned} \quad (7)$$

In the limit $v, v', u, u' \ll w, w'$, the masses of the charged Higgs bosons get approximate values such as [8]: $m_{\rho_1'^-} \simeq m_W, m_{\rho_1^+} \simeq 0, m_{\rho_3^+} \simeq m_{\zeta_2} = 0, m_{\rho_3'^-} \simeq m_{\zeta_3} = 0$

With the couplings given in (7), the right- and left-handed neutrino mass matrices are given by

$$\begin{aligned} (M_L)_{ab} &\propto -(M_R)_{ab} = \sqrt{2}\frac{g^2}{16\pi^2}\lambda'_{ab}v\left[1 - \frac{m_a^2}{m^2_{\rho'^-}}\left(1 - \ln\frac{m_a^2}{m^2_{\rho_1'^-}}\right)\right] \\ &\simeq (M_D^{tree})_{ab} \propto v \end{aligned} \quad (8)$$

Thus, the one-loop correction leads to the relationship $M_L = -M_R$, which is similar to the case of non-supersymmetric economical 3-3-1 model [7]. These mass matrices are proportional to the value v but they are suppressed by an extra factor $\frac{g^2}{16\pi^2}$. Contribution to the mass matrix M_D of the form

$$\begin{aligned}(M_D^{rad})_{ab} &= \frac{g^2}{16\pi^2}\lambda'_{ab}v\left[1-\frac{m_a^2}{m^2_{\rho'^-}}\left(1-\ln\frac{m_a^2}{m^2_{\rho_1'^-}}\right)\right] \\ &\propto v. \end{aligned} \tag{9}$$

It is very interesting that the scale for one-loop correction to the Dirac masses is the same as that of the tree level. However, unlike the case of the tree level, the mass matrix given in (9) is non-antisymmetric in a and b. Hence, after including the one-loop correction to the Dirac neutrino mass, all three eigenvalues of the Dirac mass matrix are non-zero. On the other hand, the left and right handed neutrino mass matrices are gained at the one-loop correction. However, there is no larger hierarchy between M_L, M_R and M_D.

Below we shall show that, in the model with inflationary scenario, the type I seesaw mechanism can appear naturally.

III. THE SEESAW MECHANISM IN SUPERSYMMETRIC ECONOMICAL 3-3-1 MODEL WITH INFLATIONARY SCENARIO

We have constructed a hybrid inflationary scheme based on a realistic supersymmetric 3-3-1 model by adding a singlet superfield $\widehat{\Phi}$ which plays the role of the inflation, namely the inflaton superfield [9]. Let us remind that the inflationary potential is given by

$$W_{inf}(\widehat{\Phi},\widehat{\chi},\widehat{\chi}') = \alpha\widehat{\Phi}\widehat{\chi}\widehat{\chi}' - \mu^2\widehat{\Phi}. \tag{10}$$

The superpotential related to the neutrino masses is

$$W_{neut} = \mu'_{0a}\widehat{L}_a\widehat{\chi}'\widehat{\phi} \tag{11}$$

Integrating out the superspace gives the relevant interaction Lagrangian for the one-loop correction to neutrino mass

$$L_{int} = \mu'_{0a}\nu_{aL}\widetilde{\phi}\chi_1'^0 + \mu'_{0a}\nu^c_{aR}\widetilde{\phi}\chi_3'^0 + H.c., \tag{12}$$

$$V^{rel.}_{Higgs} = \alpha^2(\chi\chi')^2 \tag{13}$$

Besides the relevant Higgs self-coupling given in Eq.(13), there is another Higgs potential contributing to the neutrino mass at the one-loop correction, namely

$$\begin{aligned} V_D &= \frac{g'^2}{12}\left(-\frac{1}{3}\chi^\dagger\chi + \frac{1}{3}\chi'^\dagger\chi' + \frac{2}{3}\rho^\dagger\rho - \frac{2}{3}\rho'^\dagger\rho'\right)^2 \\ &+ \frac{g^2}{8}(\chi_i^\dagger\lambda^b_{ij}\chi_j - \chi_i'^\dagger\lambda^{*b}_{ij}\chi'_j + \rho_i^\dagger\lambda^b_{ij}\rho_j - \rho_i'^\dagger\lambda^{*b}_{ij}\rho'_j)^2 \end{aligned} \tag{14}$$

with g', g are the gauge couplings of $U(1), SU(3)_L$ groups, respectively. Because of this, the g' coupling constant is the co-variant function of energy and the g coupling constant is the contra-variant function of energy. At the inflationary and preheating times, the g'

coupling constant is dominated and we will ignore the self Higgs coupling in the second line of Eq.(14). On the other hand, requiring that the nonadiabatic string contribution to the quadrupole to be less than 10%, the coupling α belongs to $10^{-4} \div 10^{-8}$ [9]. If we compare this value with that of g' coupling constant at the early time of universe, the values of α coupling is tiny enough to ignore the Higgs self-coupling given in Eq.(13). In short, at the inflationary and preheating times, the Lagrangian related to the one-loop correction to neutrino mass is given by

$$L_{int} = \mu'_{0a}\nu_{aL}\widetilde{\phi}\chi_1'^0 + \mu'_{0a}\nu^c_{aR}\widetilde{\phi}\chi_3'^0 + H.c. \tag{15}$$

$$V_D^{U(1)} = \frac{g'^2}{12}\left(-\frac{1}{3}\chi^\dagger\chi + \frac{1}{3}\chi'^\dagger\chi' + \frac{2}{3}\rho^\dagger\rho - \frac{2}{3}\rho'^\dagger\rho'\right)^2 \tag{16}$$

At the one-loop order, there is no correction to the mass matrix M_D but there is correction to the mass matrices M_L and M_R given

We assume the vacuum expectation values w, u, v are the same as w', u', v', respectively. The neutrino masses are the eigenvalues of the matrix:

$$\begin{pmatrix} M^{inf}_{Lab} & M^T_D \\ M_D & M^{inf}_{Rab} \end{pmatrix} \tag{17}$$

Because of the condition $w', w \gg u', u, v', v$ and $u', u \ll v', v$ and ($M_R \propto w^2, M_D \propto v^2, M_L \propto u^2$), we obtain a hierarchy in values of the elements of the neutrino mass [10]:

$$M^{inf}_{Rab} \gg M_D \gg M^{inf}_{Lab} \tag{18}$$

The heavy and light eigenvectors are found to be diagonalize the matrices

$$m_R = M^{inf}_{Rab};\ m_\nu = M_D M^{inf-1}_{Rab} M^T_D \tag{19}$$

The inflaton with mass around 10^{17} GeV plays the role of new physics in the economical models with inflationary scenario.

IV. NON-THERMAL LEPTOGENESIS VIA INFLATON DECAY

Let us consider the non-thermal leptongenesis scenario in our model. In the non-thermal leptongenesis scenario, the right handed neutrinos are produced through the direct non-thermal decay of the inflaton. In our scenario, there is no interaction term which describes that decay process at the tree level. However, the necessary interaction arises at the one-loop level. The relevant self Higgs and inflaton couplings is given by

$$L_{thermal} = \left|\frac{\partial W_{inf}}{\partial\chi}\right|^2 + \left|\frac{\partial W_{inf}}{\partial\chi'}\right|^2 = \alpha^2\left(|\chi|^2 + |\chi'|^2\right)\phi \tag{20}$$

From Lagrangian given in (15) and (20), the effective interaction relevant for the right handed neutrinos and inflaton at the one-loop correction is given in Fig. 1.

The effective Lagrangian for the process $\phi \to \nu_R\nu_R$ is given by

$$L_{\nu_R\nu_R\phi} = A_{eff}\phi\nu_R\nu_R + H.c \tag{21}$$

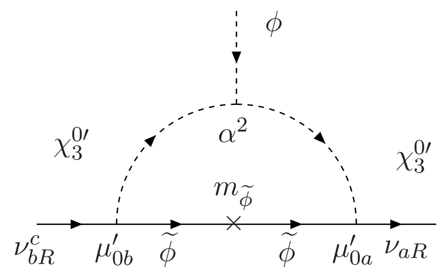

Fig. 1. Feynman diagram for the process $\phi \to \nu_R \nu_R$

where A_{eff} stands for effective coupling, which is obtained

$$A_{eff} \quad \propto \quad 54 \frac{M_R}{g'^2 w^2} \alpha^2 \tag{22}$$

The inflaton decay rate is given by

$$\Gamma(\phi \to \nu_R \nu_R) \simeq \frac{|A_{eff}|^2}{4\pi} m_\phi \tag{23}$$

with m_ϕ is the inflaton mass.

We assume that the inflaton ϕ decays dominantly into a pair of the lightest heavy Majorana neutrino, $\phi \to \nu_{R1}, \nu_{R1}$ and other decay modes including these into pair ν_{R2}, ν_{R3} are forbidden.

The lepton asymmetry is converted to the baryon asymmetry through the "sphaleron" effects which is given by

$$\frac{n_B}{s} = a \frac{n_L}{s} \tag{24}$$

with $a = -\frac{8}{23}$ in the MSSM. The ratio of the lepton number to entropy density after preheating is estimated to be [11]

$$\frac{n_B}{s} = -0.35 \times \frac{3}{2} B_r(\phi \to \nu_{R1}, \nu_{R1}) \frac{T_R}{M_\phi} \times \epsilon. \tag{25}$$

On the other hand, the ratio of the lepton number to entropy density after preheating can be written as

$$\frac{n_B}{s} \simeq 10^{-10} B_r(\phi \to \nu_{R1} \nu_{R1}) \left(\frac{T_R}{10^6 \text{ GeV}} \right) \left(\frac{M_{R1}}{M_\phi} \right) \left(\frac{\delta_{eff} m_{\nu 3}}{0.05 \text{ eV}} \right). \tag{26}$$

The cosmological constraint on the gravitino abundance gives a bound on the reheating temperature [12]: $T_R < 10^7$ GeV. Assuming that the reheating temperature is: $T_R = 10^6$ GeV and combining with the observed baryon number to entropy ratio, we get a constraint on the heaviest light neutrino as [10]:

$$m_{\nu 3} > 0.01 \text{ eV}. \tag{27}$$

V. CONCLUSIONS

In this paper, non-thermal leptogenesis in which the heavy Majorana neutrinos are produced through inflaton decays in the supersymmetric economical 3-3-1 model with inflationary scenario has been considered.

In the model with inflationary scenario, the lepton-number violating interactions among the inflaton and right-handed neutrinos appear at the one-loop level. Thus, it not only gives a solution for the above puzzle but also gives a chance for studying non-thermal leptogenesis scenario.

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Received 25 September 2010.