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Leptogenesis in $E_6 \times U(1)_A$ SUSY GUT model

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We study the thermal leptogenesis in the $E_6 \times U(1)_A$ SUSY GUT model in which realistic masses and mixings of quarks and leptons can be realized. We show that the sufficient baryon number can be produced by the leptogenesis in the model, in which the mass parameter of the lightest right-handed neutrino is predicted to be smaller than 10^8 GeV. The essential point is that the mass of the lightest right-handed neutrino can be enhanced in the model because it has a lot of mass terms whose mass parameters are predicted to be the same order of magnitude which is smaller than 10^8 GeV. We show that O(10) enhancement for the lightest right-handed neutrino mass is sufficient for the observed baryon asymmetry. Note that such mass enhancements do not change the predictions of neutrino masses and mixings at the low energy scale in the E_6 model which has six right-handed neutrinos. In the calculation, we include the effects of supersymmetry and flavor in final states of the right-handed neutrino decay. We show that the effect of supersymmetry is quite important even in the strong washout regime when the effect of flavor is included. This is because the washout effects on the asymmetries both of the muon and the electron become weaker than that of the tau asymmetry. This proceeding is based on Ref. [1].

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1. Introduction

The E_6 supersymmetric (SUSY) grand unified theory (GUT) model is one of the promising candidate of the extended model of the standard model (SM). The various hierarchies of quark and lepton masses and mixings can be naturally understood in $SU(5)$ unification if we assume that the **10** fields of $SU(5)$ induce stronger hierarchy in Yukawa couplings than the $\bar{\mathbf{5}}$ fields of $SU(5)$. One of the most important advantages of the E_6 unification [2] is that the above assumption can be naturally derived [3].

In this scenario, by introducing the anomalous $U(1)_A$ gauge symmetry [4], the doublet-triplet splitting problem [5] can be solved under a natural assumption that all the interactions are introduced with $O(1)$ coefficients [6, 7, 8]. Because of this natural assumption, the coefficients of the terms and the vacuum expectation values (VEVs) of the GUT Higgs can be determined only by the symmetry of the theory. The coefficients of the interaction XYZ are determined [9, 10] except the $O(1)$ coefficients by the total anomalous $U(1)_A$ charge $x+y+z$ as

$$\begin{array}{ll} \lambda^{x+y+z}XYZ & (x+y+z \geq 0) \\ 0 & (x+y+z < 0), \end{array} \tag{1.1}$$

where x, y, and z are the $U(1)_A$ charges of the fields X, Y, and Z, respectively. Here λ is the ratio of the Fayet-Illiopoulos parameter ξ to the cutoff Λ, and in this paper we take $\lambda \sim 0.22$ as a typical value[1]. Under the natural assumption, we can obtain the realistic Yukawa couplings in E_6 GUT [3]. The VEVs of the operators O are also determined by their total anomalous $U(1)_A$ charges o as

$$\langle O \rangle = \begin{cases} 0 & (o > 0) \\ \lambda^{-o} & (o \leq 0) \end{cases}. \tag{1.2}$$

In this paper, we often use a unit in which the cutoff Λ is taken to be 1. Because of the natural assumption, all the mass spectrum of superheavy particles and the VEVs of GUT Higgs are determined only by the symmetry of the theory.

If the E_6 GUT describes our world, it must be consistent with the cosmology. In this work, we discuss the leptogenesis [11] in this scenario. One of the important things in E_6 unification for the leptogenesis is that the fundamental representation **27**, which is decomposed in the $E_6 \supset SO(10) \times U(1)_{V'}$ notation (and in the $[SO(10) \supset SU(5) \times U(1)_V]$ notation) as

$$\mathbf{27} = \mathbf{16}_1[\mathbf{10}_1 + \bar{\mathbf{5}}_{-3} + \mathbf{1}_5] + \mathbf{10}_{-2}[\mathbf{5}_{-2} + \bar{\mathbf{5}}'_2] + \mathbf{1}'_4[\mathbf{1}'_0], \tag{1.3}$$

includes two singlets $S(\mathbf{1'})$ and $N_R^c(\mathbf{1})$ under the SM gauge group, which can be the right-handed (RH) neutrinos. If we introduce three **27** for three generation quarks and leptons, we have six RH neutrinos. Since the masses and Yukawa couplings of the RH neutrinos are determined by the symmetry, we can examine whether the leptogenesis works well or not in this scenario. Naively, the leptogenesis in this scenario does not work because the lightest RH neutrino becomes lighter than 10^8 GeV, i.e., this scenario looks not to satisfy the Ibarra's upper bound [12] for the lightest RH neutrino which is 10^{8-9} GeV. Yukawa couplings are also easily estimated with the sum of the

[1]Even if we take the different value λ from the Cabibbo mixing angle, the results in this paper do not change so much because most of parameters including the $U(1)_A$ charges are fixed by observed values.

(effective) $U(1)_A$ charges of the up-type Higgs H_u and doublet-leptons l_i, $(\tilde{h}_u + \tilde{l}_1, \tilde{h}_u + \tilde{l}_2, \tilde{h}_u + \tilde{l}_3) = (0, -0.5, -1)$. The Yukawa couplings among l_i, S_1 and H_u become $(\lambda^{6.5}, \lambda^6, \lambda^{5.5})$. Then, we can estimate two important parameters for the leptogenesis as

$$K \equiv \Gamma_D / H \sim 40$$
$$\epsilon \equiv \frac{\Gamma(S_1 \to l + H_u) - \Gamma(S_1 \to \bar{l} + H_u^\dagger)}{\Gamma(S_1 \to l + H_u) + \Gamma(S_1 \to \bar{l} + H_u^\dagger)} \sim 5 \times 10^{-9}, \tag{1.4}$$

where Γ_D and H are the decay width of S_1 and the Hubble parameter at $T = M_{S_1}$, respectively. (In this paper we denote the lepton doublet fields with lowercase letter l in order to avoid the confusion with lepton asymmetry L in the following discussions.) Since the sufficient production of Baryon number requires $K \sim 1$ and $\epsilon \sim 10^{-7}$, this K is too large, and the ϵ is too small. The produced lepton number is estimated as

$$Y_L \equiv \frac{n_L}{s_0} \sim 10^{-13}, \tag{1.5}$$

which is about $O(1000)$ times smaller than the value $Y_L \sim 2.5 \times 10^{-10}$ which is required for the sufficient baryon number. Here, n_L and s_0 are the lepton number density and the entropy density today, and for simplicity, we neglect the SUSY contribution, which will be discussed later.

An important observation for leptogenesis in this scenario is that under fixed Yukawa couplings, $K \propto 1/M_{S_1}$ and $\epsilon \propto M_{S_1}$. Therefore, larger M_{S_1} results in larger baryon number. This observation is critical because in this scenario, the mass of S_1 tends to be larger than expected by the symmetry. There are two essential points in this scenario. One of them is that it has a plenty of terms which give mass to S_1. Each term gives the same order of mass to S_1 as expected by the symmetry, and the real mass can increase because of the large number of mass terms. The other point is that the predictions for the quark and lepton masses and mixings does not change so much even if the mass of S_1 becomes larger than expected by the symmetry. This is because the number of RH neutrino flavors becomes larger than three in E_6 unification. (In $SO(10)$ unification, it is not avoidable to change the predictions on neutrino sector if one of the RH neutrino masses is taken to be larger than expected by the symmetry.)

The question is how large enhancement of the mass is needed to obtain the sufficiently large baryon number. It is the main subject in this paper to answer this question.

2. Enhancement for the right-handed neutrino mass

The interactions which contribute to the masses of the RH neutrinos S_i and N^c_{Ri} $(i = 1, 2, 3)$ are $\Psi_i \Psi_i \bar{H}\bar{H}$ and $\Psi_i \Psi_i \bar{C}\bar{C}$, respectively. Here H (C) is a GUT Higgs which breaks E_6 into $SO(10)$ ($SO(10)$ into $SU(5)$). The total $U(1)_A$ charges of these interactions are (11, 9, 5) for S_i and (9, 7, 3) for N^c_{Ri}, while the masses expected by the symmetry are $(\lambda^{13}, \lambda^{11}, \lambda^7)$ and $(\lambda^{12}, \lambda^{10}, \lambda^6)$, respectively. This means that the enhancement factors η_{S_i} and $\eta_{N^c_{Ri}}$ for their masses are expected to be the largest for the lightest RH neutrino S_1, the second largest for the second and the third lightest neutrinos N^c_{R1} and S_2.

In this work, we do not count the total number of the independent interactions which give the mass term of these RH neutrinos. We discuss what happens when some of the RH neutrinos have larger masses than those expected by the symmetry. It is an important observation that each

RH neutrino gives the same order of the contribution to all components of the light neutrinos' mass matrix $M_\nu = Y^t_{\nu_D} M^{-1}_{\nu_R} Y_{\nu_D}\langle H_u\rangle^2$ if its mass is nothing but the value expected by the symmetry. Therefore, if one of the enhancement factors η_{S_i} and $\eta_{N^c_{Ri}}$ is around one, all components of M_ν becomes the values expected by the symmetry, and so are all components of the diagonalizing matrix.

The next important question is how large enhancement factor is needed for sufficient leptogenesis in this E_6 GUT model. In the next section, we try to answer this question.

3. Leptogenesis in the $E_6\times U(1)_A$ model

We calculate the lepton number in the $E_6\times U(1)_A$ model with the Dirac neutrino Yukawa couplings $Y_{\alpha i}$ ($\alpha = 1,2,\cdots,6, i = 1,2,3$) which are determined by the symmetry and the masses M_α for the mass eigenstate of the RH neutrinos N_α. What we would like to know is how large enhancement factors are required to obtain sufficiently large lepton number. In the calculation, it is important to include SUSY contributions and the effects of lepton flavor in the final state of the RH neutrino decay [13]. To quantitatively understand these effects, we consider following four cases:

- non-SUSY + non flavor
- non-SUSY + flavor
- SUSY + non flavor
- SUSY + flavor

Key ingredients for the leptogenesis are the CP asymmetry ϵ_{N_1} and the decay parameter $K\equiv \Gamma_{N_1}(T=0)/H(T=M_1)$ [14]. K is important because this parameter controls production rate of the RH neutrino, decoupling of RH neutrino from thermal equilibrium, and generation and washout of lepton asymmetry. The lepton asymmetry Y_L is essentially determined by the above two parameters as

$$Y_L \sim \epsilon^{\rm SM}_{N_1} C(K). \tag{3.1}$$

For $K>1$, $C(K)$ is a decreasing function of K. $K>1$ means that the RH neutrinos are still in the thermal equilibrium at $T=M_1$, and therefore, the number density of N_1 rapidly decreases when $T<M_1$. This reduces the final lepton asymmetry. For $K<1$, $C(K)$ is a increasing function of K. $K<1$ means that the RH neutrinos do not reach the thermal equilibrium at $T=M_1$, and therefore, the number of thermally produced RH neutrinos becomes smaller for smaller K. This reduces the final lepton asymmetry. For $K\sim 1$, the function $C(K)$ becomes maximal, and sufficient lepton asymmetry can be obtained.

To implement the flavor effect, we rearrange the decay parameter with the flavor projection, $K^0_i = Y_{1i}Y^*_{1i}/(YY^\dagger)_{11}$. In the $E_6\times U(1)_A$ scenario, flavor dependent decay parameters $K^{\rm SUSY}_i = K^0_i K^{\rm SUSY}$ are obtained as follows,

$$K^{\rm SUSY}_e = \frac{\Gamma^{\rm SUSY}_{N_1\to l_e H}(T=0)}{H(T=M_1)} \simeq 1.9\left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right), \tag{3.2}$$

$$K^{\rm SUSY}_\mu = \frac{\Gamma^{\rm SUSY}_{N_1\to l_\mu H}(T=0)}{H(T=M_1)} \simeq 8.8\left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right), \tag{3.3}$$

$$K_\tau^{\rm SUSY} = \frac{\Gamma^{\rm SUSY}_{N_1 \to l_\tau H}(T=0)}{H(T=M_1)} \simeq 40\left(\frac{5.7\times 10^7\,{\rm GeV}}{M_1}\right). \tag{3.4}$$

Such large $K_\tau^{\rm SUSY}$ leads large production rate of RH neutrino. Relatively small $K_\mu^{\rm SUSY}$ and $K_e^{\rm SUSY}$ make the washout of lepton asymmetry to be weak. Hence the flavor effect can enhance the final lepton asymmetry with respect to the case where the flavor effects are ignored.

The flavor dependent CP asymmetry within the SM framework is defined as $\epsilon_{1i}^{\rm SM} = [\Gamma(N_1 \to l_i H) - \Gamma(N_1 \to \overline{l_i} H^\dagger)]/[\Gamma(N_1 \to l_i H) + \Gamma(N_1 \to \overline{l_i} H^\dagger)]$. The first non-zero contribution to the CP asymmetries come from interference between tree-level amplitude with the one-loop contributions, and it is calculated in a hierarchical limit in RH neutrino masses as $\epsilon_{1i}^{\rm SM} = -\left(1/8\pi(YY^\dagger)_{11}\right)\sum_{\beta\neq 1}^{6}$ $\Im\left\{Y_{\beta i}Y_{1i}^*\left[(3/2)\left(M_1/M_\beta\right)(YY^\dagger)_{\beta 1} + \left(M_1^2/M_\beta^2\right)\left(YY^\dagger\right)_{1\beta}\right]\right\}$ [15]. Note that, the E_6 GUT model has six RH neutrinos, and therefore, $\beta = 2, 3, \cdots, 6$. With the SUSY extension, SUSY particles also contribute, and each $\epsilon_{1i}^{\rm SM}$ is doubled. In the $E_6 \times U(1)_A$ scenario, $\epsilon_{1i}^{\rm SM}$ is obtained as

$$\epsilon_{1i}^{\rm SM} = 2\left(\frac{-1}{8\pi(YY^\dagger)_{11}}\Re\left\{Y_{6i}Y_{1i}^*\left[\frac{3}{2}\frac{M_1}{M_6}(YY^\dagger)_{61} + \frac{M_1^2}{M_6^2}(YY^\dagger)_{16}\right]\right\}\right). \tag{3.5}$$

We have adopted two assumptions. The first assumption is that the imaginary part of Yukawa couplings is equal to its real part. This assumption is reasonable because we regard all Yukawa couplings as complex numbers. The second assumption is on the overall factor 2 in Eq. (3.5). An important observation is that $\left(Y^\dagger Y\right)^2_{\beta 1}\left[Y^\dagger Y\right]^{-1}_{11} M_1/M_\beta \sim \lambda^{11}$ is not dependent on β. Therefore, we can expect an enhancement factor after summation of the index β, and we assume that the enhancement factor is two through all calculations in this paper.

Figure 1 shows the evolutions of total lepton asymmetry $|Y_{B-L}|$ and partial asymmetries of each lepton flavor $|Y_{\Delta_i}|$ for $M_1/M_1^0 = 16$. For the calculation, we use a dimensionless variable $z \equiv M_1/T$. Here $Y_a = n_a/s$ is the yield value for a particle species a, where n and s are number density and entropy density, respectively. The total lepton asymmetry is given by the sum of the asymmetry of each lepton flavor, $Y_{B-L} = Y_{\Delta_e} + Y_{\Delta_\mu} + Y_{\Delta_\tau}$, where $\Delta_i = B/3 - L_i$. We could confirm the successful baryon asymmetry in the SUSY+flavor case, namely, in a realistic situation of the $E_6 \times U(1)_A$ GUT model. It is sufficient to take the lightest RH neutrino mass $M_1 \sim 16 \times M_1^0 \sim 9\times 10^8$ GeV for the observed baryon asymmetry. It is important for this calculation that all components of neutrino Yukawa matrix are determined by the symmetry in the $E_6 \times U(1)_A$ GUT and we can integrate the flavor effects on the lepton asymmetry.

Figure 2 shows the enhancement factor dependence of total lepton asymmetry $|Y_{B-L}|$ for each case. In the case of SUSY+flavor, i.e., in a realistic situation of the $E_6 \times U(1)_A$ GUT model, the final lepton asymmetry is largely enhanced with respect to the case where the flavor effects are ignored. Thus, in order to predict and constrain the parameters in $E_6 \times U(1)_A$ GUT model from leptogenesis, it is necessary to implement both the SUSY and flavor effects. Before closing this section we would like to mention that the effect of supersymmetry is quite important even in the strong washout regime when the effect of flavor is included. This is because the washout effects on the asymmetries both of the muon and the electron become weaker than that of the tau asymmetry. It is first time that this important result is explicitly shown. We are investigating this important results in more generic cases.

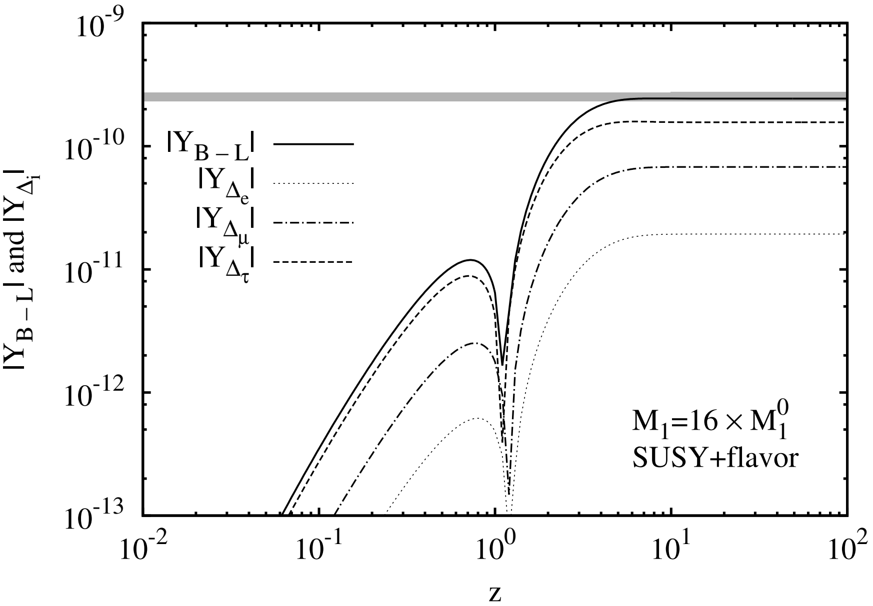

Figure 1: Evolutions of $|Y_{B-L}|$ and $|Y_{\Delta_i}|$ for $M_1 = 16 \times M_1^0$ in the SUSY+flavor case. Horizontal band corresponds to the observed baryon asymmetry. We take the simplified CP asymmetry $\epsilon_{1i}^{\rm SUSY} = 2 \times \epsilon_{1i}^{\rm SM}$ with the assumption $\Im[(Y^\dagger Y)_{61}] = \Re[(Y^\dagger Y)_{61}]$, where $\epsilon_{1i}^{\rm SM}$ is given by (3.5).

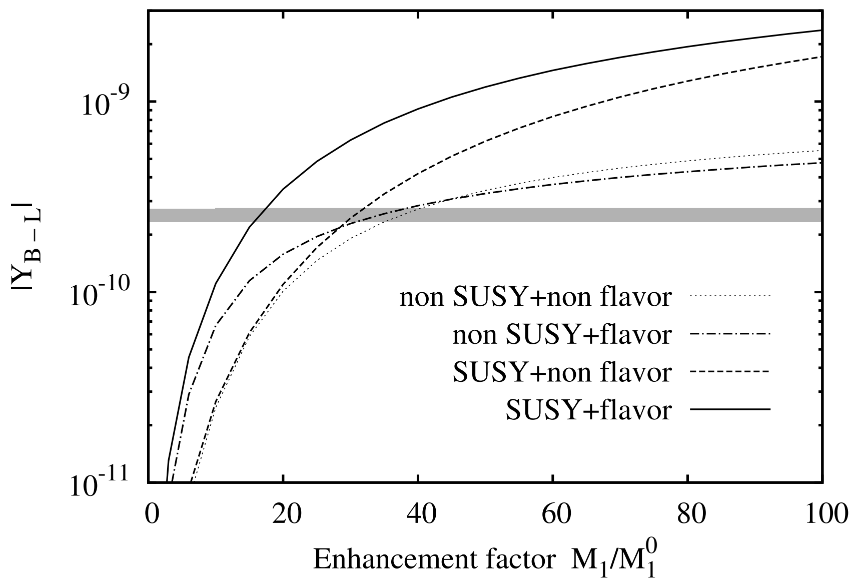

Figure 2: $\eta_1 \equiv M_1/M_1^0$ dependence of $|Y_{B-L}|$ in each case. Horizontal band corresponds to the observed baryon asymmetry in SUSY cases. M_1^0 is the "bare" Majorana mass in the absence of the $U(1)_A$ interactions. We take the simplified CP asymmetry $\epsilon_1^{\rm SM}$ (sum over i in Eq. (3.5)), $\epsilon_{1i}^{\rm SM}$ (3.5), $\epsilon_1^{\rm SUSY} = 2 \times \epsilon_1^{\rm SM}$, and $\epsilon_{1i}^{\rm SUSY} = 2 \times \epsilon_{1i}^{\rm SM}$ with the assumption $\Im[(Y^\dagger Y)_{61}] = \Re[(Y^\dagger Y)_{61}]$ for the calculation in each case, respectively. $K^{\rm SM}$ and $K^{\rm SUSY}$ can be written as $K^{\rm SM} \sim 37/\eta_1$ and $K^{\rm SUSY} \sim 51/\eta_1$, respectively.

4. Summary and Discussion

We have investigated the thermal leptogenesis in the $E_6 \times U(1)_A$ GUT model in which realistic quark and lepton masses and mixings are obtained and the doublet-triplet splitting problem is solved with natural assumption that all interactions including higher dimensional interactions are introduced with $O(1)$ coefficients.

We have shown that a key ingredient for successful leptogenesis is the enhancement of RH neutrino masses. The model can include a large number of higher dimensional interactions, and these interaction terms yield additional Majorana masses after developing the VEVs of negatively $U(1)_A$ charged fields. The enhancements of the RH neutrino masses enhance the CP asymmetry $\epsilon \propto M_1$ and make the decay parameter $K \propto 1/M_1$ smaller to be most efficient value $K \sim 1$. How large enhancement factor is required for the sufficient leptogenesis? To answer this question, we have calculated the lepton asymmetry including the effects of SUSY and flavor in the final state of the CP asymmetric decay. The result is that the enhancement factor $16-17$ is sufficient for the successful leptogenesis. About 300 mass terms are sufficient to obtain this enhancement factor, and this number looks not to be difficult to be obtained in the E_6 GUT model. It is important that such enhancement of the lightest RH neutrino mass does not change the neutrino physics at the low energy scale. This is because the $E_6 \times U(1)_A$ GUT has six RH neutrinos which induces the same order of the amplitude of all elements of the light neutrino mass matrix.

We have calculated the lepton asymmetry in the $E_6 \times U(1)_A$ model in following four cases: (i) non-SUSY+non-flavor (ii) non-SUSY+flavor (iii) SUSY+non-flavor (iv) SUSY+flavor. These calculations have shown that both the effects of lepton flavor and SUSY are important. It is known that in the strong washout regime lepton flavor effect becomes sizable, though SUSY contribution is not so large. We have shown that SUSY contribution becomes important even in the strong washout regime if lepton flavor effect is included. The essential point is that even in the strong regime $K^{\rm SM} > 1$, the washout effects of the muon and/or the electron can become weak, and therefore these lepton number abundances become sizable.

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