Non-thermal Leptogenesis in a simple 5D SO(10) GUT

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Abstract

We discuss the non-thermal leptogenesis in the scheme of 5D orbifold SO(10) GUT with the smooth hybrid inflation. With an unambiguously determined Dirac Yukawa couplings and an assumption for the neutrino mixing matrix of the tri-bimaximal form, we analyze baryon asymmetry of the universe via non-thermal leptogenesis in two typical cases for the light neutrino mass spectrum, the normal and inverted hierarchical cases. The resultant baryon asymmetry is obtained as a function of the lightest mass eigenvalue of the light neutrinos, and we find that a suitable amount of baryon asymmetry of the universe can be produced in the normal hierarchical case, while in the inverted hierarchical case the baryon asymmetry is too small to be consistent with the observation.

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The so-called renormalizable minimal SO(10) GUT model has been paid a particular attention, where two Higgs multiplets \(\{10 \oplus \overline{126}\}\) are utilized for the Yukawa couplings with matters \(\mathbf{16}_i\) \((i = 1, 2, 3\) is the generation index) \(\mathbf{1}, \mathbf{2}, \mathbf{3}\). A remarkable feature of the model is its high predictive power for the neutrino oscillation parameters, in reproducing charged fermion masses and mixing angles. The unambiguously determined Yukawa couplings play a crucial role for predictions of the model in other phenomena, such as the lepton flavor violation \[1\] and proton decay \[2\]. The Higgs superpotential of the model has been investigated and the explicit pattern of the SO(10) gauge symmetry to the standard model one has been shown \[3\]. On the other hand, the explicit representation of intermediate energy scales revealed in these papers gives rise to the deviation of gauge coupling unification \[4\]. Also the minimal SO(10) model likely predict too short proton lifetime and has some deviation from the precise measurements of the neutrino oscillation data \[5\] (see however \[6\]).

In order to remedy these problems, we have argued SO(10) GUT in the context of the orbifold GUT \[7\] and proposed a simple supersymmetric (SUSY) SO(10) model in 5D \[8\]. In this model, the SO(10) symmetry in 5D is broken by orbifold boundary conditions to the Pati-Salam (PS) symmetry SU(4)_C \(\times\) SU(2)_L \(\times\) SU(2)_R. All matter and Higgs multiplets reside only on a brane (PS brane) where the PS gauge symmetry is manifest, so that low energy effective description of this model is nothing but the PS model in 4D with a special set of matter and Higgs multiplets. At energies higher than the compactification scale, the Kaluza-Klein (KK) modes of the bulk SO(10) gauge multiplet are involved in the particle contents and in fact, the gauge coupling unification was shown to be successfully realized by incorporating the KK mode threshold corrections into the gauge coupling running \[9\]. The unification scale \(M_{\text{GUT}}\) and the compactification scale \(M_c\) which was set to be the same as the PS symmetry breaking scale \(v_{\text{PS}}\) was found to be \(M_{\text{GUT}} = 4.6 \times 10^{17}\) GeV and \(M_c = v_{\text{PS}} = 1.6 \times 10^{16}\) GeV, respectively.

More recently, it has been shown \[10\] that this orbifold GUT model is applicable to the smooth hybrid inflation \[11\]. Interestingly, this inflation model can fit the WMAP data \[12\] very well by utilizing the PS breaking scale \(v_{\text{PS}}\) and the gauge coupling unification scale predicted independently of cosmological considerations. Another cosmological issue, the dark matter candidate of the model has been investigated in \[13\]. In the paper, the sparticle mass spectrum is calculated in the context of the gaugino mediated supersymmetry breaking \[14\] which can be naturally incorporated in the model and it has shown that the neutralino LSP as the dark matter candidate can be realized when the compactification scale is taken to be slightly bigger than the PS symmetry breaking scale, while keeping the successful gauge coupling unification.

In the present paper, we apply our model to the leptogenesis scenario for creating the baryon asymmetry of the universe. In order to produce a suitable amount of the baryon asymmetry of the universe in the thermal leptogenesis scenario \[15\], the scale of right-handed (scalar) neutrino masses should be greater than \(10^9\) GeV \[16\] and hence the reheating temperature after inflation should also be beyond this scale. However, in supersymmetric models, the reheating temperature is severely constrained by Big Bang Nucleosynthesis (BBN) to be \(T_R < 10^6\) GeV \[17\] (gravitino problem \[18\]), and the conventional thermal leptogenesis scenario cannot work.
In this case, we consider the so-called non-thermal leptogenesis [20] in which the right-handed (scalar) neutrinos are non-thermally produced by the decay of inflaton and their decays can produce a suitable amount of baryon asymmetry of the universe even if the reheating temperature is low. We adopt the non-thermal leptogenesis to our hybrid inflation scenario [17] and show that the non-thermal leptogenesis is successful with a suitable choice of the model parameters which are consistent with the results in the previous works [16, 17, 20].

Let us begin with a brief review of the orbifold SO(10) GUT proposed in Ref. [16]. The model is described in 5D and the 5th dimension is compactified on the orbifold $S^1/Z_2 \times Z'_2$ [11, 12, 14]. A circle $S^1$ with radius $R$ is divided by a $Z_2$ orbifold transformation $y \rightarrow -y$ ($y$ is the fifth dimensional coordinate $0 \leq y < 2\pi R$) and this segment is further divided by a $Z'_2$ transformation $y' \rightarrow -y'$ with $y' = y + \pi R/2$. There are two inequivalent orbifold fixed points at $y = 0$ and $y = \pi R/2$. Under this orbifold compactification, a general bulk wave function is classified with respect to its parities, $P = \pm$ and $P' = \pm$, under $Z_2$ and $Z'_2$, respectively.

Assigning suitable parities $(P, P')$ to the bulk SO(10) gauge multiplet [16], only the PS gauge multiplet has zero-mode and the bulk 5D N=1 SUSY SO(10) gauge symmetry is broken to 4D N=1 supersymmetric PS gauge symmetry. All vector multiplets has wave functions on the brane at $y = 0$, SO(10) gauge symmetry is respected there, while only the PS symmetry is on the brane at $y = \pi R/2$ (PS brane).

| brane at $y = \pi R/2$ |
|-------------------------|
| Matter Multiplets        |
| $\psi_i = F_{Li} \oplus F_{Ri}^c$ $(i = 1, 2, 3)$ |
| Higgs Multiplets         |
| $(1, 2, 2)_H, (1, 2, 2)'_H, (15, 1, 1)_H, (6, 1, 1)_H$ |
| $(4, 1, 2)_H, (\bar{4}, 1, 2)_H, (4, 2, 1)_H, (\bar{4}, 2, 1)_H$ |

Table 1: Particle contents on the PS brane. $F_{Li}$ and $F_{Ri}^c$ are matter multiplets of $i$-th generation in $(4, 2, 1)$ and $(\bar{4}, 1, 2)$ representations, respectively.

We place all the matter and Higgs multiplets on the PS brane, where only the PS symmetry is manifest, so that the particle contents are in the representation under the PS gauge symmetry, not necessary to be in SO(10) representation. For a different setup, see [27]. The matter and Higgs in our model is listed in Table 1. For later conveniences, let us introduce the following notations:

\[
\begin{align*}
H_1 &= (1, 2, 2)_H, \quad H_1' = (1, 2, 2)'_H, \\
H_6 &= (6, 1, 1)_H, \quad H_{15} = (15, 1, 1)_H, \\
H_L &= (4, 2, 1)_H, \quad \bar{H}_L = (\bar{4}, 2, 1)_H, \\
\phi &= (4, 1, 2)_H, \quad \bar{\phi} = (\bar{4}, 1, 2)_H.
\end{align*}
\]
Superpotential relevant for fermion masses is given by

\[ W_Y = Y^{ij} F_{Li} F^c_{Rj} H_1 + \frac{Y^{ij}}{M_5} F_{Li} F^c_{Rj} (H'_1 H_{15}) \]
\[ + \frac{Y^{ij}}{M_5} F^c_{Ri} F^c_{Rj} (\phi \bar{\phi}) , \]

where \( M_5 \) is the 5D Planck mass. The product, \( H'_1 H_{15} \), effectively works as \((15, 2, 2)_H\), while \( \phi \bar{\phi} \) effectively works as \((10, 1, 3)\), and is responsible for the right-handed Majorana neutrino masses. Assuming appropriate VEVs for Higgs multiplets, fermion mass matrices are obtained, which we parameterize as the following form [16]:

\[
\begin{align*}
M_u &= c_{10} M_{1,2,2} + c_{15} M_{15,2,2} , \\
M_d &= M_{1,2,2} + M_{15,2,2} , \\
M_D &= c_{10} M_{1,2,2} - 3c_{15} M_{15,2,2} , \\
M_e &= M_{1,2,2} - 3M_{15,2,2} , \\
M_R &= c_R M_{10,1,3} .
\end{align*}
\]

Here, \( M_u, M_d, M_D \) and \( M_e \) are the mass matrices of up and down type quarks, Dirac neutrino and charged lepton, respectively, while \( M_R \) is right-handed Majorana neutrino mass matrix.

The following two points should be remarked:

1. The combination of two mass matrices of \( M_{1,2,2} \) and \( M_{15,2,2} \) among \( M_u, M_d, M_D, \) and \( M_e \) in the PS symmetry is the same as that of \( M_{10} \) and \( M_{126} \) in the minimal SO(10) model (see [3] for notation) and, therefore, the procedure for fitting the realistic Dirac fermion mass matrices is the same as in the minimal SO(10) model.

On the other hand,

2. \( M_R \) is fully independent on the above four Dirac Fermion mass matrices in the PS group, whereas in the minimal SO(10) model it is described by \( M_{126} \) and not independent. This fact enables us to improve the precise data fitting on the neutrino oscillation parameters.

Now we discuss the smooth hybrid inflation model [18] in the context of the orbifold SO(10) GUT model. Introducing a singlet chiral superfield \( S \), we consider the superpotential

\[ W = \lambda S \left( -\mu^2 + \frac{(\tilde{\phi} \phi)^2}{M_5^2} \right) , \]

where \( \lambda \) is a dimensionless coefficient, \( \mu \) is a dimensionful parameter, and \( M_5 \) is the 5D Planck mass. SUSY vacuum conditions lead to non-zero VEVs for \( \langle \phi \rangle = \langle \tilde{\phi} \rangle = \sqrt{\mu M} \), by which the PS symmetry is broken down to the SM one, and thus

\[ v_{PS} = \sqrt{\mu M} . \]
It is theoretically natural to identify $M_5$ as the GUT scale, $M_5 \sim M_{\text{GUT}}$. From the analysis of the gauge coupling unification in the context of the 5D orbifold GUT [16], we found that $v_{\text{PS}} = 1.2 \times 10^{16}$ GeV and $M_{\text{GUT}} = 4.6 \times 10^{17}$ GeV. Independently of the analysis of the gauge coupling unification, it has shown in [17] that this smooth hybrid inflation model, where the inflation trajectory is approximately parameterized by the scalar component of $S$, can reproduce the WMAP data by $v_{\text{PS}} = 1.2 \times 10^{16}$ GeV and $M_5$ being the same order of magnitude as $M_{\text{GUT}}$.

Now we discuss the main topic of this paper: the non-thermal leptogenesis. The relevant part of the superpotential is

$$W = \lambda S \left( -\mu^2 + \frac{(\bar{\phi}\phi)^2}{M_5^2} \right) + \frac{Y_{ii}^{\nu R}}{M_5} F_{\bar{R}i}^c \bar{F}_{Ri}^c (\phi\phi),$$

where without loss of generality, we work on the mass diagonal basis of the right-handed neutrinos. The inflaton which is the scalar component of $S$ couples with the scalar right-handed neutrinos in the scalar potential,

$$V \supset \left| \frac{\partial W}{\partial \phi} \right|^2 = \left| \lambda S \frac{2\bar{\phi}(\bar{\phi}\phi)}{M_5^2} + 2\frac{Y_{ii}^{\nu R}}{M_5} \bar{F}_{\bar{R}i}^c \bar{F}_{Ri}^c \phi \right|^2.$$

Parameterizing the inflaton field $\sigma = \sqrt{2} \Re[S]$, the inflaton mass is found to be

$$m_{\sigma} = 2\sqrt{2} \lambda v_{\text{PS}}^2 M_5^2,$$

and the interaction between the inflaton and the scalar right-handed neutrinos

$$L_{\text{int}} = -\sqrt{2} \lambda \left( \frac{v_{\text{PS}}}{M_5} \right)^2 M_i \sigma \left( \bar{F}_{\bar{R}i}^c \bar{F}_{Ri}^c + \text{h.c.} \right),$$

where $M_i = 2Y_{ii}^{\nu R} (v_{\text{PS}}^2/M_5^2)$ is mass of the (scalar) right-handed neutrino of the $i$-th generation, and we set $M_1 \leq M_2 \leq M_3$ without loss of generality. The partial decay width of the inflaton into the $i$-th generation scalar right-handed neutrino, if kinematically allowed, given by

$$\Gamma(\sigma \to \bar{N}_i N_i) = \lambda^2 \frac{M_i^2}{2\pi m_{\sigma}} \left( \frac{v_{\text{PS}}}{M_5} \right)^4.$$

Here $\bar{N}_i$ denotes the scalar right-handed neutrino in the $i$-th generation. Since the inflaton and the superfields, $\phi$ and $\bar{\phi}$, have the same mass, the inflaton cannot decay into the superfields.

In non-thermal leptogenesis, the inflaton decays into (scalar) right-handed neutrinos and then, the CP-violating decay of the neutrinos generates lepton asymmetry of the universe, which is finally converted into baryon asymmetry via the sphaleron processes. The resultant baryon asymmetry of the universe is evaluated as

$$\left( \frac{n_B}{s} \right) = -\frac{10}{31} \times \sum_i \left( \frac{n_{N_i}}{s} \right) \left( \frac{n_L}{n_{N_i}} \right) = -\frac{10}{31} \times \frac{3}{2} \sum_i \text{BR}(\sigma \to \bar{N}_i N_i) \left( \frac{T_R}{m_{\sigma}} \right) \epsilon_i,$$

where
Figure 1: The mass spectrum of the scalar right-handed neutrinos as a function of $m_0$ (solid lines) in the normal hierarchical case for the light neutrino mass spectrum. The dashed line represents $m_\sigma/2$.

where the sum is taken to be scalar right-handed neutrinos kinematically allowed, and the CP-violating parameter is given by

$$\epsilon_i = -\frac{1}{2\pi(Y_\nu^T Y_\nu^\dagger)_{ii}} \sum_{j\neq i} \text{Im} \left[(Y_\nu^T Y_\nu^\dagger)^2_{ij}\right] f(M^2_j/M^2_i)$$  \hspace{1cm} (12)

with the Dirac neutrino Yukawa coupling $Y_\nu$ and

$$f(x) \equiv \sqrt{x} \ln \left(\frac{1+x}{x}\right) + 2\sqrt{x} \frac{1}{x-1}. \hspace{1cm} (13)$$

Here we have assumed that masses of all scalar right-handed neutrinos are greater than the reheating temperature after inflation. This assumption is crucial because if a scalar right-handed neutrino is lighter than the reheating temperature, the scenario becomes thermal leptogenesis and the baryon asymmetry produced is not enough for a low reheating temperature.

For the prediction of the resultant baryon asymmetry, we need the information of the Dirac Yukawa coupling, the mass spectra of the scalar right-handed neutrinos and light neutrinos, and the neutrino mixing matrix. Through the seesaw mechanism \[29\], the light neutrino mass matrix is given by

$$m_\nu = Y^T_\nu M^{-1}_R Y_\nu v^2_u = U_{MNS}D_\nu U_{MNS}^T$$  \hspace{1cm} (14)

in the basis where the mass matrix of charged lepton is diagonal. Here $v_u$ is the VEV of the up-type Higgs doublet, $M_R$ is the mass matrix of the right-handed neutrinos, and $D_\nu$ is the
diagonal mass matrix of light neutrinos. In this paper, we consider two typical cases for the light neutrino mass spectrum and describe $D_\nu$ in terms of the lightest mass eigenvalue $m_0$ and the mass squared differences:

$$D_\nu = \text{diag}(m_0, \sqrt{\Delta m_{12}^2 + m_0^2}, \sqrt{\Delta m_{13}^2 + m_0^2})$$

(15)

for the normal hierarchical case, and

$$D_\nu = \text{diag}\left(\sqrt{\Delta m_{13}^2 + m_0^2}, \sqrt{\Delta m_{12}^2 + \Delta m_{13}^2 + m_0^2}, m_0\right)$$

(16)

for the inverted hierarchical case. Here we adopted the neutrino oscillation data [30]:

$$\Delta m_{12}^2 = 7.59 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{13}^2 = 2.43 \times 10^{-3} \text{ eV}^2$$

(17)

In addition, we assume the mixing matrix of the so-called tri-bimaximal form [31]

$$U_{MNS} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \end{pmatrix},$$

(18)

which is in very good agreement with the current best fit values of the neutrino oscillation data [30]. As we mentioned above, the data fit for the realistic Dirac mass matrices of the present model is the same as in the minimal SO(10) model, and as an example, we here use
Figure 3: The resultant baryon asymmetry produced via non-thermal leptogenesis as a function of $m_0$ (solid line) in the normal hierarchical case. The dashed line represents the observed value $Y_B = 0.87 \times 10^{-10}$.

...
λ = 0.02. For these parameters fixed, Fig. 1 shows the mass spectrum of the scalar right-handed neutrinos as a function of \( m_0 \), together with \( m_\sigma/2 \), in the normal hierarchical case. For \( m_0 \lesssim 0.1 \text{ eV} \), the inflaton decays into only a pairs of the scalar right-handed neutrinos in the first generation.

The reheating temperature as a function of \( m_0 \) is depicted in Fig. 2. The jump around \( m_0 \sim 0.1 \text{ eV} \) is because the decay channel of inflaton into the scalar right-handed neutrino in the second generation is opened up there and the reheating temperature becomes higher than \( M_1, T_R > M_1 \), so that we exclude the region \( m_0 \gtrsim 0.1 \text{ eV} \) in our analysis.

In Fig. 2, the reheating temperature exceeds its BBN bound \( T_R \lesssim 10^6 \). However, this bound is not applicable if the gravitino is heavy, \( m_3/2 \gtrsim 100 \text{ TeV} \), in which case gravitino in the early universe decays before BBN takes place. As has been investigated in [20], the gaugino mediated supersymmetry breaking is naturally incorporated in our 5D SO(10) GUT, where SUSY breaking is assumed to occur on the brane at \( y = 0 \) and the SO(10) gaugino residing in the bulk directly couples with the SUSY breaking sector,

\[
\mathcal{L} = c_g \delta(y) \int d^2 \theta \frac{X}{M_5^2} \text{tr} [\mathcal{W}^a \mathcal{W}_a];
\]

where \( X \) is a singlet chiral superfield which breaks SUSY by its F-component VEV \( (F_X) \), and \( c_g \) is a dimensionless constant. Then, the gaugino obtains the SUSY breaking soft mass,

\[
m_\lambda = c_g \frac{F_X}{M_5^2} M_c \simeq c_g \frac{F_X}{M_P} \left( \frac{M_5}{M_P} \right) \simeq c_g m_{3/2} \left( \frac{M_5}{M_P} \right),
\]

where the compactification scale \( M_c \) comes from the wave function normalization of the bulk gaugino, we have used the relation between the 4D and 5D Planck masses, \( M_P^2 \simeq M_5^2/M_c \) with the reduced Planck mass \( M_P = 2.4 \times 10^{18} \text{ GeV} \), and \( m_{3/2} \simeq F_X/M_P \) is gravitino mass. In this paper we adopt \( c_g \lesssim 0.1 \), so that \( m_{3/2} \gtrsim 100 \text{ TeV} \) for \( m_\lambda \sim 100 \text{ GeV} \).
Finally, in the normal hierarchical case for the light neutrino mass spectrum, we show the resultant baryon asymmetry of the universe generated via the non-thermal leptogenesis as a function of $m_0$ in Fig. 3, together with the currently observed value $[19]$:

$$Y_B = \frac{n_B}{s} = 0.87 \times 10^{-10}. \quad (24)$$

We find the observed value is reproduced for $m_0 \simeq 1.8 \times 10^{-3}$ eV.

We repeat the same analysis for the inverted hierarchical case. Fig. 4 shows the mass spectrum of the scalar right-handed neutrinos, and the reheating temperature is depicted in Fig. 5. The resultant baryon asymmetry is shown in Fig. 6 as a function of $m_0$. We find that in the inverted hierarchical case the baryon asymmetry produced in non-thermal leptogenesis is too small to be consistent with the observation.

In summary, we have studied the non-thermal leptogenesis in the scheme of 5D orbifold SO(10) GUT with the smooth hybrid inflation. With an unambiguously determined Dirac Yukawa couplings and an assumption for the neutrino mixing matrix of the tri-bimaximal form, we have analyzed the baryon asymmetry of the universe via non-thermal leptogenesis in two typical cases for the light neutrino mass spectrum, the normal and inverted hierarchical cases. The resultant baryon asymmetry is given as a function of the lightest mass eigenvalue of the light neutrinos $m_0$. In the normal hierarchical case, for $m_0 \simeq 1.8 \times 10^{-3}$ eV, the model predicts a suitable amount of the baryon asymmetry through non-thermal leptogenesis, while in the inverted hierarchical case, the predicted asymmetry is too small to be consistent with the observations. As can be seen from Eqs. (10) and (21), a mildly small $\lambda$ guarantees $M_1 \gg T_R$ and this is crucial for the realization of non-thermal leptogenesis where we can neglect wash-out processes.

Our 5D orbifold SO(10) GUT was originally constructed in order to remedy problems of the minimal SO(10) GUT in particle physics. It is very interesting that the parameters
Figure 6: The same as Fig. 3 but for the inverted hierarchical case.

determined from particle physics give the consistent observational values of WMAP coming from quite different origins of cosmology. Leptogenesis may be placed just in the midst of particle physics and cosmology among others and is very sensitive to the parameter of particle physics. Our theory is consistent with it, giving additional constraints on the lightest neutrino mass.

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