Thermal Leptogenesis in $SO(10) \times U(1)_A$ GUT (Ongoing work)

SHIBATA Kei, N.MAEKAWA, M.YAMANAKA

Nagoya univ. E-lab D2

August 21, 2025

Introduction/Motivation

- There are some problems in SM.
  - Baryon asymmetry
  - Light neutrino mass
  - Dark matter
  - Strong CP problem etc.
- We focused on Right-Handed Neutrinos (RHNs) which can address two of these problems.
  - Leptogenesis $\rightarrow$ baryon asymmetry
  - Seesaw mechanism $\rightarrow$ neutrino masses
- It would be desirable to have a theory where RHNs arise naturally.
  - The $SO(10)$ Grand Unified Theory is a good candidate.

Table of Contents

Table of Contents

$SO(10)$ Grand Unified Theory(GUT)

- Advantage of $SO(10)$ GUT
  - Unify SM particles+ RHN N_i

$$\Psi_{\mathbf{16}} = \mathrm{SM}_{\mathbf{10},\overline{\mathbf{5}}} + \mathrm{RHN}_{\mathbf{1}} \tag{1}$$

  N_is are naturally introduced from this GUT. etc.

- Problems in minimal $SO(10)$GUT
  - Doublet-triplet splitting problem
  - GUT relation

$$y_{ij}\Psi_i\Psi_j H \quad \rightarrow \quad y = y_u = y_d = y_e^T = y_{\nu_D} \tag{2}$$

- Therefore, we need an extended theory to avoid these problems!

$SO(10) \times U(1)_A$GUT (natural GUT)

- Two methods are introduced to resolve these problems.
  - Adding new field Θ C.D.Frogatt, H.B.Nielsen (1979)
    - ★ $U(1)_A$ charge: $\theta = -1$
    - ★ VEV: $\langle \Theta \rangle = \lambda\Lambda \qquad (\lambda \sim 0.22)$

$$\left(\frac{\Theta}{\Lambda}\right)^{\psi_i+\psi_j+h} \Psi_i \Psi_j H \quad \rightarrow y_{ij} \sim \lambda^{\psi_i+\psi_j+h}$$

  - field $T_{\mathbf{10}} \rightarrow$ GUT relation is removed.

- $SO(10) \times U(1)_A$ GUT is consistent with experimental results.
  - neutrino yukawa y_{ν_D} and RHN mass $\overline{M}_i$ are determined by $U(1)_A$ symmetry.

$$y_{\nu_D} = \begin{pmatrix} \lambda^6 & \lambda^{5.5} & \lambda^5 \\ \lambda^5 & \lambda^{4.5} & \lambda^4 \\ \lambda^3 & \lambda^{2.5} & \lambda^2 \end{pmatrix}, \quad \begin{cases} \overline{M}_1 = & \Lambda_G \lambda^{12} \\ M_2 = & \Lambda_G \lambda^{10} \\ M_3 = & \Lambda_G \lambda^6 \end{cases} \tag{3}$$

Table of Contents

Thermal leptogenesis

- A mechanism to explain the baryon asymmetry of the universe M.Fukugita, T.Yanagida (1986)
  - Thermalizing RH neutrinos produce lepton numbers
  - Convert lepton number to baryon number (sphaleron process) F.R.Klinkhamer, N.S. Manton,(1984)
- In most cases, the $B-L$ asymmetry is assumed to be generated by N_1.
- Two key parameters: ϵ_i, K_i
  - CP asymmetry:$\epsilon_i \rightarrow B-L \propto \epsilon_1$

$$\epsilon_i := \frac{\Gamma(N_i \rightarrow \ell + H) - \Gamma(N_i \rightarrow \bar{\ell} + H^\dagger)}{\Gamma(N_i \rightarrow \ell + H) + \Gamma(N_i \rightarrow \bar{\ell} + H^\dagger)}$$

  - decay parameter: $K \rightarrow B-L$ is maximized at $K \sim 1$
    - ⋆ $1 \ll K \leftrightarrow$ strong wash-out, $1 \gg K \leftrightarrow$ weak wash-out

$$K_i := \frac{\Gamma_{N_i}(T=0)}{H(T=M_i)} \simeq \sqrt{\frac{45}{4\pi^3 g_*}} \frac{\left(y^\dagger_{\nu_D} y_{\nu_D}\right)_{ii}}{8\pi} \frac{M_{pl}}{M_i}$$

Thermal leptogenesis with flavor effects

- Flavor effects must be considered in temperature $T \lesssim 10^{13}$GeV. C.S.Fong etal,(2010)
  - The temperature at which each interaction is thermalized differs for each flavor.
  - Flavored CP asymmetry and decay parameter are given by

$$\epsilon_{\alpha i} = \frac{\Gamma(N_i \to L_\alpha + H) - \Gamma(N_i \to \overline{L}_\alpha + H^\dagger)}{\Gamma(N_i \to L_\alpha + H) + \Gamma(N_i \to \overline{L}_\alpha + H^\dagger)}$$

$$\simeq -\frac{1}{8\pi}\frac{1}{(y_{\nu_D} y_{\nu_D}^\dagger)_{ii}} \sum_{j \neq i} \mathrm{Im}\left[y^*_{\nu_D\,\alpha i} y_{\nu_D\,\alpha j} (y^\dagger_{\nu_D} y_{\nu_D})_{ij}\right] f(M_j^2/M_i^2), \quad (4)$$

$$K_{\alpha i} \simeq \sqrt{\frac{45}{4\pi^3 g_*}} \frac{\left|y_{\nu_D\,\alpha i}\right|^2}{8\pi} \frac{M_{pl}}{M_i}. \quad (5)$$

- We calculate the $B - L$ asymmetry in this framework.
  - Considering 10^6GeV $\lesssim T \lesssim 10^{11}$GeV because $M_1 \sim 10^8$GeV, $M_2 \sim 10^{10}$GeV.

the relation of Y_{B-L} between M_1

- Both $\epsilon_{\alpha 1}$ and $K_{\alpha 1}$ depend on $\overline{M}_1$ → therefore Y_{B-L} depends on $\overline{M}_1$.
  - In $SO(10) \times U(1)_A$ GUT, M_1 has $O(1)$ coefficient → we set r_1 as $O(1)$ coefficient.
  - $M_1 := r_1 \overline{M}_1$ $(r_1 \geq 1)$ is fixed by consistency with cosmic observations.

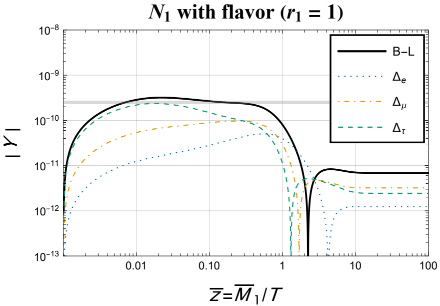


Fig 1: Y_{B-L} when $r_1 = 1$

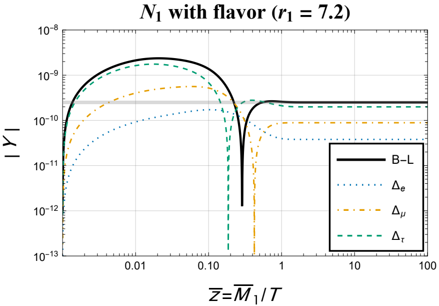


Fig 2: Y_{B-L} when $r_1 = 7.2$

Table of Contents

Results of this study

We worked on in this study

This study presents the first analysis of thermal leptogenesis in $SO(10) \times U(1)_A$ GUT.

Main Results

Result 1 Demonstrated the possibility of thermal leptogenesis in $SO(10)$ GUT.

Result 2 Calculated the contribution of N_2.

Result 1

- There is some bounds to the M_1.
  - lower bound to M_1 (Ibarra bound) S.Davidson, A.Ibarra (2002)
  - neutrino seesaw + $\sum m_\nu$

$$m_\nu = v_u^2 y_{\nu_D}^T M^{-1} y_{\nu_D}$$

- These bounds must be avoided.
  - In minmal SO(10), this is difficult.
  - Non-thermal leptogenesis can evade them.Asaka. T (2003) etc...
- $SO(10) \times U(1)_A$GUT can avoid these bounds
  - This presents the possibility of thermal leptogenesis in SO(10)GUT.

Result 2

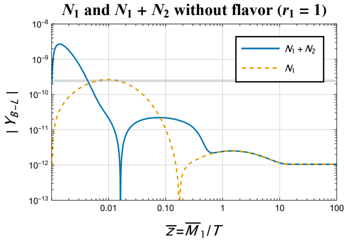
- Including N_2 contribution in leptogenesis.
- Under what conditions does the contribution from N_2 become relevant?
- "with flavor" case vs. "without flavor" case.

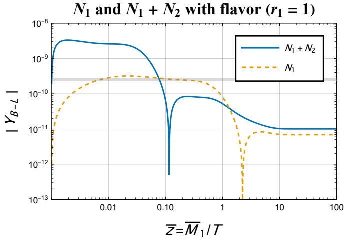
without flavor: all flavor have same $K_1 \sim 50$
strong wash-out
$\rightarrow$ no N_2 contribution

with flavor: $K_{1e} \sim 2, K_{1\mu} \sim 9, K_{1\tau} \sim 40$

weaker washout in e flavor

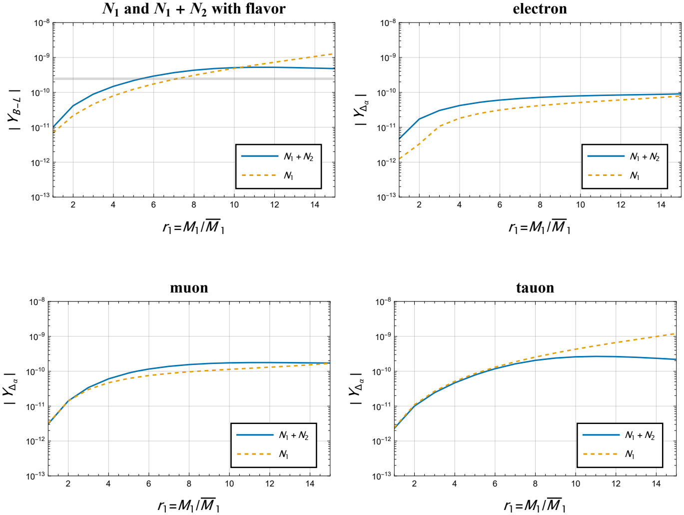
$\rightarrow$ N_2 contribution appears





- This contribution cannot be negligible in this model.

- The dependence of Y_{B-L} on r_1
- Lepton number of N_2 remain in electron flavor
  - weak wash-out in e flavor
    strong wash-out in μ, τ flavor
- For larger r_1, lepton number of $N_1 + N_2$ are decrease.
  - degenerate effect of M_1 and M_2?



- M_1 values consistent with cosmological observations.

$$r_1 := \frac{M_1}{\overline{M}_1} \simeq 7.2(N_1 \text{ only}) \to 5.4(N_1 + N_2)$$
$$M_1 \simeq 5.4\overline{M}_1 \simeq 1.39 \times 10^9 \text{GeV}$$

- Estimating the mass of the lightest LH neutrino from the seesaw mechanism.

$$m_{\nu_1} m_{\nu_2} m_{\nu_3} \propto \frac{1}{\overline{M}_1 M_2 M_3} \to \frac{1}{r_1 \overline{M}_1 M_2 M_3}$$
$$m_{\nu_1} \to \frac{m_{\nu_1}}{r_1}$$

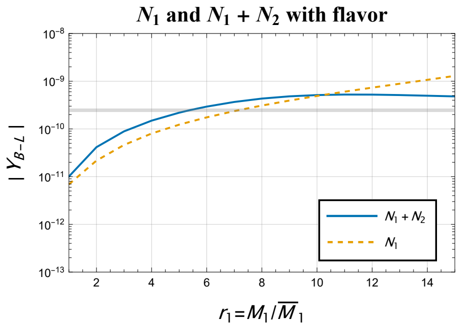


Fig 3: Relation between r_1 and Y_{B-L}

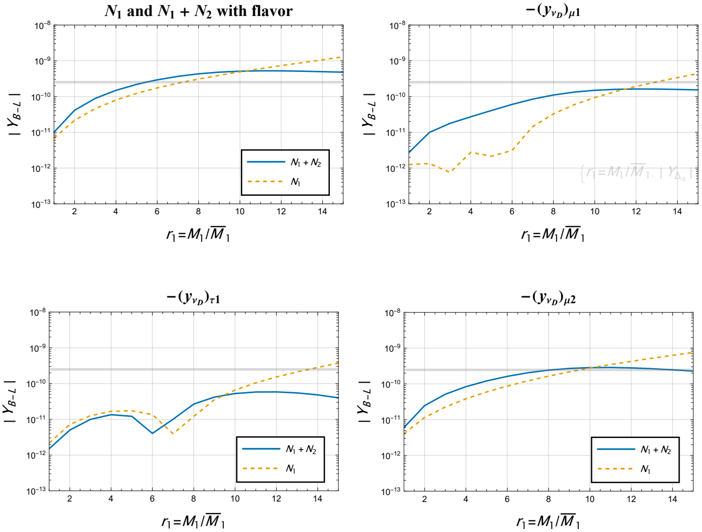
Summary

- First study of thermal leptogenesis with flavor effects in $SO(10) \times U(1)_A$ GUT
  - Demonstrated the possibility of thermal leptogenesis in $SO(10)$ GUT.
  - Clarified the contribution of N_2 in leptogenesis with flavor effects.
  - Estimated the mass of the lightest RH and LH neutrino via the seesaw mechanism.
    - ★ It is suppressed.$(1/r_1 \sim 0.19)$

Comments and future work

- $O(1)$ coefficients exist
  - Lepton number varies with $O(1)$ coefficient.
- We will examine the contribution of N_3.
  - We estimate the contribution to be small.
  - Other calculation methods are needed to deal with different equilibrium states.

Back Up


N_1 and $N_1 + N_2$ with flavor
$-(y_{\nu_D})_{\mu 1}$
$-(y_{\nu_D})_{\tau 1}$
$-(y_{\nu_D})_{\mu 2}$
$|Y_{B-L}|$
$r_1 = M_1/\overline{M}_1$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
2
4
6
8
10
12
14
$N_1 + N_2$
N_1
$\{r_1 = M_1/\overline{M}_1, |Y_{\Delta_\alpha}|\}$