Resonant Leptogenesis in B-L Model with modular symmetry

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- Flavor Symmetry

Resonant Leptogenesis

Baryon Asymmetry

There are baryon asymmetry in universe.

$$5.8\ 10^{-10} < \frac{n_b - n_{\bar{b}}}{n_\gamma} < 6.5\ 10^{-10}$$

The origin of baryon asymmetry is mystery.

Sakharov's condition

The baryon asymmetry can be dynamically generated ('baryogenesis') provided that

1. B violation
2. C and CP violation
3. Out of thermal equilibrium

Baryogenesis in SM

Electroweak baryogenesis

- B violation

  sphaleron process

- C and CP violation

  CKM matrix

- Out of thermal equilibrium

  1^{st} order phase transition

Can electroweak baryogenesis in SM produce a sufficiently large asymmetry?

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⬇

NO!

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NO!

The SM fails on two aspects:

1. The Higgs sector does not give a strongly first order PT.

Requirement: $m_H < 70GeV$ LHC: $m_H = 125\ GeV$

2. CP Violation in CKM is not enough.

Requirement: $Y_B \sim 10^{-10}$ CKM: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-20}$

Baryogenesis Via Leptogenesis

SM + right-handed Majorana neutrinos

- B violation

  L violation by majorana neutrinos decay

  Sphaleron process

- C and CP violation

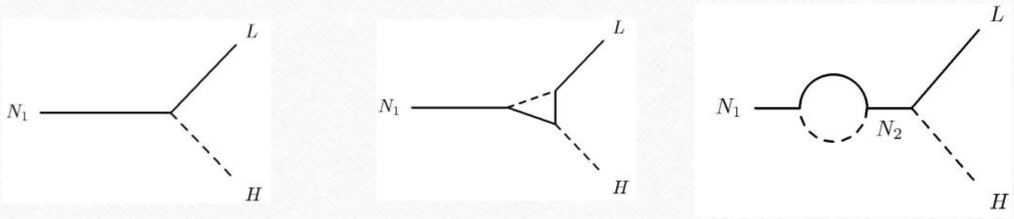
  Neutrino mixing matrix (complex)

- Out of thermal equilibrium

  Out of equilibrium decay of right-handed neutrino

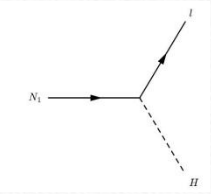
Baryogenesis Via Leptogenesis

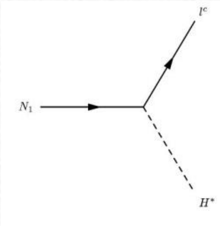
- L asymmetry is generated due to CP asymmetry that arises through interference of tree level and one-loop diagrams.



- Sphaleron process converts L asymmetry into B asymmetry.

CP Asymmetry





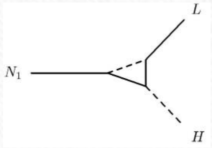
Right-handed Majorana neutrino can decay into lepton and anti-lepton.

$$\epsilon_1 \equiv \frac{\sum_j \left[\Gamma\left(N_1 \to \ell_j h\right) - \Gamma\left(N_1 \to \ell_j^C h^*\right)\right]}{\sum_j \left[\Gamma\left(N_1 \to \ell_j h\right) + \Gamma\left(N_1 \to \ell_j^C h^*\right)\right]}$$

$$= -\sum_{j=2,3} \frac{M_1}{M_j}\frac{\Gamma_j}{M_j}\left(\frac{V_j}{2} + S_j\right)\frac{\mathrm{Im}\left[(Y_D^2)_{1j}^2\right]}{\left|Y_D^2\right|_{11}\left|Y_D^2\right|_{jj}}$$

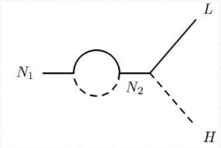
$$\frac{\Gamma_j}{M_j} = \frac{\left|Y_D^2\right|_{jj}}{8\pi}$$

Vertex contribution



$$V_j = 2\frac{M_j^2}{M_1^2}\left[\left(1 + \frac{M_j^2}{M_1^2}\right)\log\left(1 + \frac{M_1^2}{M_j^2}\right) - 1\right]$$

Self-energy contribution



$$S_j = \frac{M_j^2 \Delta M_{1j}^2}{\left(\Delta M_{1j}^2\right)^2 + M_1^2 \Gamma_j^2}$$

$$\Delta M_{1j}^2 = M_j^2 - M_1^2$$

Hierarchical case

If right-handed neutrinos have a hierarchical mass spectrum ($M_{2,3} \gg M_1$), we can write a CP asymmetry parameter as

$$\epsilon_1 \sim \frac{3}{16\pi}\frac{m_\nu M_1}{v^2}\sin\delta \sim 10^{-6}\frac{m_\nu}{0.05eV}\frac{M_1}{10^{10}GeV}\sin\delta$$

The present Baryon asymmetry

$$Y_B \sim \kappa\frac{\epsilon_1}{g_*} \sim 10^{-10}$$

$g_* = \mathcal{O}(100)$ is the number of relativistic degrees of freedom.

In the SM $\kappa \sim 2\times 10^{-2}\left(\frac{0.05eV}{m_\nu}\right)^{1.1}$

Majorana mass bound

$$Y_B \sim 10^{-10}\left(\frac{0.05eV}{m_\nu}\right)^{0.1}\frac{M_1}{10^{10}GeV}\sin\delta \sim 10^{-10}$$

$$m_\nu \sim \sqrt{m_{atm}^2} \sim 0.05eV$$

The lightest Majorana mass is heavier than $10^{10}GeV$.

Resonant Leptogenesis

- The Majorana masses are heavier than $10^{10} GeV$, if the spectrum of Majorana masses has hierarchy.
- If the Majorana mass of right-handed neutrino is smaller than a few TeV, general leptogenesis can not work.

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Resonant-Leptogenesis

Resonant Leptogenesis

When two right-handed neutrinos have mass differences comparable to their decay widths $\left(M_2^2 - M_1^2 \sim M_1\Gamma_2\right)$, self-energy correction dominates.

$$\epsilon_1 \sim \frac{Im[Y^2]_{12}^2}{|Y^2|_{11}|Y^2|_{22}} \frac{M_1\Gamma_2\left(M_2^2 - M_1^2\right)}{\left(M_2^2 - M_1^2\right)^2 + M_1^2\Gamma_2^2}$$

$$\sim \frac{1}{2}\frac{Im[Y^2]_{12}^2}{|Y^2|_{11}|Y^2|_{22}}$$

ϵ_1 can be even O(1).

$M_1 \sim TeV$, $\quad \frac{M_2^2 - M_1^2}{M_1^2} \sim 10^{-12}$

Degenerate masses

$M_1 = M_2$ @ *High scale*

RG evolution

$$M_2^2 - M_1^2 \quad \propto \quad Y_\nu^\dagger Y_\nu \; (y v_{B-L})^2$$

$$\propto \Gamma M$$

Flavor symmetry

S_4 Modular symmetry

Flavor Symmetry

Model

3 Right-Handed Neutrinos ⇒ Resonant Leptogenesis

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Dark Matter candidate

U(1) B-L Gauge Symmetry ⇒ Thermal Production of Neutrinos

S_4 Modular Symmetry ⇒ Resonant Leptogenesis

Modular Symmetry

$$\tau \longrightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}\ , \quad \text{where} \;\; a, b, c, d \in \mathbb{Z} \;\; \text{and} \;\; ad - bc = 1, \;\; \text{Im}[\tau] > 0$$

Generators

$$S : \tau \longrightarrow -\frac{1}{\tau}\ , \qquad T : \tau \longrightarrow \tau + 1$$

$$S^2 = I, (ST)^3 = I$$

$$\Gamma(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2, \mathbb{Z})\ , \quad \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (\text{mod} N) \right\}$$

$$T^N = I$$

$$\Gamma(4) \approx S_4$$

S_4 symmetry

All permutations among four objects

$(x_1, x_2, x_3, x_4) \to (x_i, x_j, x_k, x_l)$

S:

$(x_1, x_2, x_3, x_4) \to (x_2, x_1, x_3, x_4)$

T:

$(x_1, x_2, x_3, x_4) \to (x_2, x_3, x_4, x_1)$

$S^2 = T^4 = (ST)^3 = 1$

Representations : 1, 1', 2, 3, 3'

S_4 modular symmetry

$S^2 = T^4 = (ST)^3 = 1$ $\Gamma_4 \approx S_4$

Representations : 1, 1', 2, 3, 3'

3(3') → 3 generations
2 → 2 degenerate masses

$\Gamma_2 \approx S_3 : 1, 1', 2$

$\Gamma_3 \approx A_4 : 1, 1', 1'', 3$

Minimum symmetry is S_4

Modular Symmetry

Modular form

$$f(\gamma\tau) = (c\tau + d)^k f(\tau)\ , \quad \gamma \in \Gamma(N)$$

k : Modular weight

$$a = d = -1, b = c = 0$$
$$f(\tau) = (-1)^k f(\tau)$$

Odd modular weight $\Rightarrow$ Vanish

Modular Weight	Representation
2	2, 3'
4	1, 2, 3, 3'
6	1, 1', 2, 3, 3'

Field

$$\phi^{(I)} \to (c\tau + d)^{-k_I} \rho^{(I)}(\gamma)\phi^{(I)},$$

$\rho^{(I)}(\gamma)$: Unitary representation matrix of S_4

Model

Yukawa

$$\mathcal{L}_Y = \alpha \bar{L}_L Y_{\mathbf{3}'}^{(2)} e_{R_e} H_d + \beta \bar{L}_L Y_{\mathbf{3}'}^{(2)} \ell_R H_d + \bar{L}_L \left(\gamma_1 Y_{\mathbf{3}}^{(4)} + \gamma_2 Y_{\mathbf{3}'}^{(4)} \right) N_R H_u + \delta \bar{N}_{R_1}^c Y_{\mathbf{1}}^{(6)} N_{R_1} \phi + y \bar{N}_R^c N_R \phi$$

Vanishing terms

$\bar{L}_L N_{R_1} H_u$

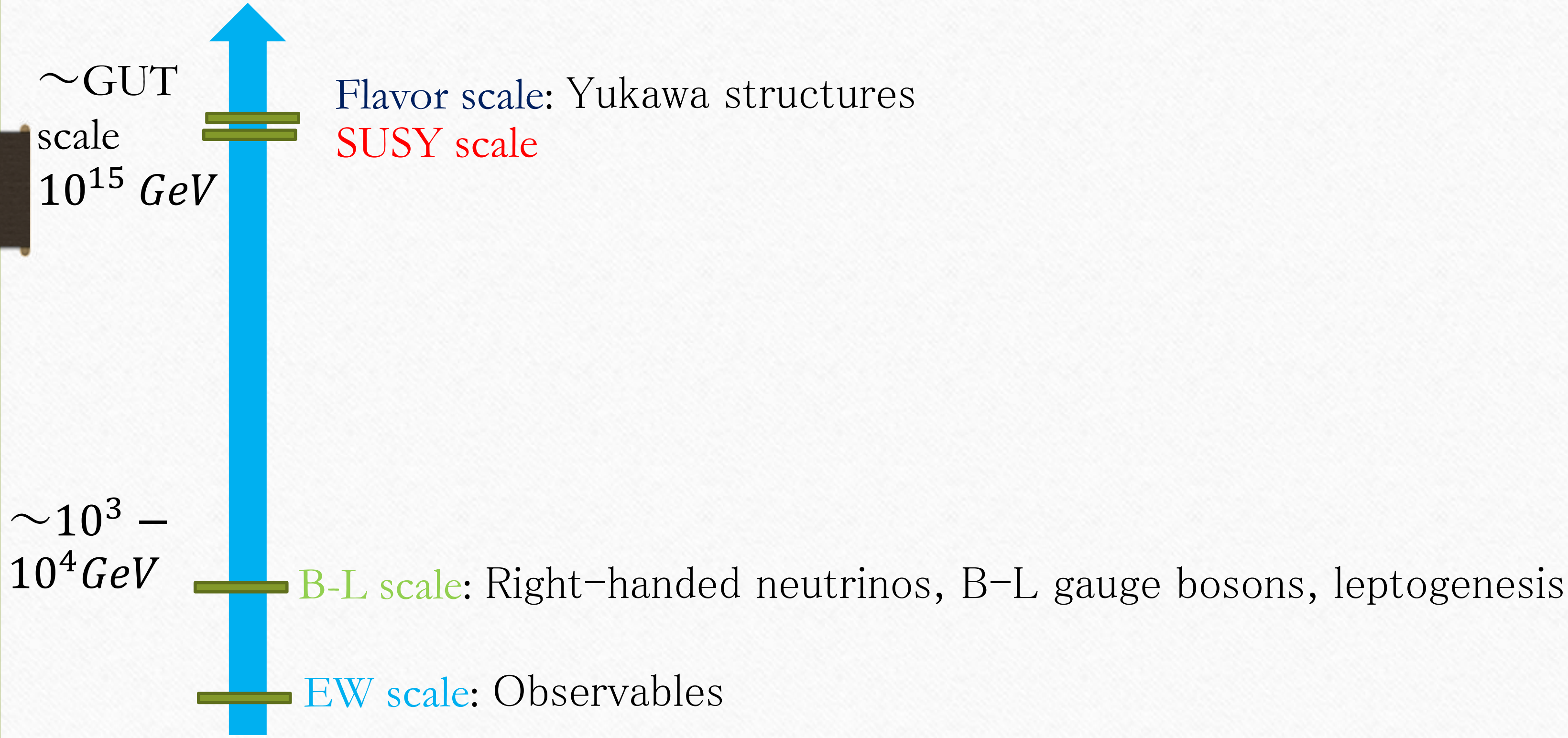
$\bar{N}_R^c N_{R_1} \phi$

→ Yukawa coupling with odd modular weight

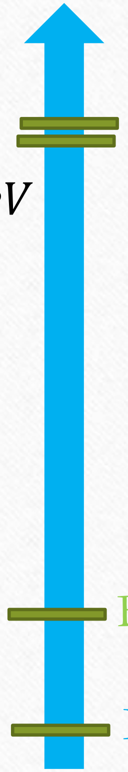
N_{R_1} is stable → Dark Matter Candidate

	Fermions					Bosons		
	$\bar{L}_L \equiv (\bar{L}_{L_e}, \bar{L}_{L_\mu}, \bar{L}_{L_\tau})^T$	e_{R_e}	$\ell_R \equiv (e_{R_\mu}, e_{R_\tau})^T$	N_{R_1}	$N_R \equiv (N_{R_2}, N_{R_3})^T$	H_u	H_d	ϕ
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{2}$	-1	-1	0	0	$-\frac{1}{2}$	$\frac{1}{2}$	0
$U(1)_{B-L}$	1	-1	-1	-1	-1	0	0	2
S_4	$\mathbf{3}'$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$-k$	-1	-1	-1	-3	0	-3	0	0

Supersymmetric B-L extended SM
with S_4 Modular symmetry



Supersymmetric B-L extended SM with S_4 Modular symmetry



~GUT scale $10^{15}\ GeV$

Flavor scale: Yukawa structures

SUSY scale

2HDM with $U(1)_{B-L}$ symmetry

RGE running

$\sim 10^3 - 10^4 GeV$

B-L scale: Right−handed neutrinos, B−L gauge bosons, leptogenesis

EW scale: Observables

Model

	Fermions					Bosons		
	$\bar{L}_L \equiv (\bar{L}_{L_e}, \bar{L}_{L_\mu}, \bar{L}_{L_\tau})^T$	e_{R_e}	$\ell_R \equiv (e_{R_\mu}, e_{R_\tau})^T$	N_{R_1}	$N_R \equiv (N_{R_2}, N_{R_3})^T$	H_u	H_d	ϕ
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{2}$	-1	-1	0	0	$-\frac{1}{2}$	$\frac{1}{2}$	0
$U(1)_{B-L}$	1	-1	-1	-1	-1	0	0	2
S_4	$\mathbf{3}'$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$-k$	-1	-1	-1	-3	0	-3	0	0

Yukawa

$$\mathcal{L}_Y = \alpha \bar{L}_L Y_{\mathbf{3}'}^{(2)} e_{R_e} H_d + \beta \bar{L}_L Y_{\mathbf{3}'}^{(2)} \ell_R H_d + \bar{L}_L \left(\gamma_1 Y_{\mathbf{3}}^{(4)} + \gamma_2 Y_{\mathbf{3}'}^{(4)}\right) N_R H_u + \delta \bar{N}_{R_1}^c Y_{\mathbf{1}}^{(6)} N_{R_1} \phi + y \bar{N}_R^c N_R \phi$$

Model

Boundary conditions

$$Y_M(m_0) = \begin{pmatrix} y & 0 \\ 0 & y \end{pmatrix}$$

m_0: Breaking scale of the flavor symmetry

$$Y_\nu(m_0) = \begin{pmatrix} \gamma_2 y_1' & -\gamma_1 y_1 \\ \frac{\sqrt{3}}{2}\gamma_1 y_2 - \frac{1}{2}\gamma_2 y_3' & \frac{1}{2}\gamma_1 y_3 + \frac{\sqrt{3}}{2}\gamma_2 y_2' \\ \frac{\sqrt{3}}{2}\gamma_1 y_3 - \frac{1}{2}\gamma_2 y_2' & \frac{1}{2}\gamma_1 y_2 + \frac{\sqrt{3}}{2}\gamma_2 y_3' \end{pmatrix}$$

$$Y_{\mathbf{3}}^{(4)} = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}, \quad Y_{\mathbf{3}'}^{(4)} = \begin{pmatrix} y_1' \\ y_2' \\ y_3' \end{pmatrix}$$

Renormalization group equations

$$16\pi^2 \mu \frac{dY_\nu^\dagger Y_\nu}{d\mu} = \frac{1}{2} Y_M Y_M^* Y_\nu^\dagger Y_\nu + \frac{1}{2} Y_\nu^\dagger Y_\nu Y_M Y_M^* + Y_\nu^\dagger Y_\nu (6y_t^2 - \frac{3}{2} g_1^2 - \frac{9}{2} g_2^2 - 12 g_{B-L}^2 - \frac{3}{2} g_{mix}^2 - 6 g_{B-L} g_{mix})$$

$$16\pi^2 \mu \frac{dY_M}{d\mu} = \underline{Y_M Y_\nu^\dagger Y_\nu + Y_\nu^\dagger Y_\nu Y_M} + Y_M Y_M^* Y_M + \frac{1}{2} Y_M Tr\left[Y_M Y_M^\dagger\right] - 6 g_{B-L}^2 Y_M$$

Mass difference

Off diagonal

Result

parameters	predictions	Observed values
Guage	Baryon number	
$v_{B-L} = 17\,TeV$	$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 5.93\ 10^{-10}$	$5.8\ 10^{-10} < \frac{n_b - n_{\bar{b}}}{n_\gamma} < 6.5\ 10^{-10}$ (95 % CL)
$g_{B-L} = 0.20$	Active neutrino	
Modular	$m_1 = 8.46\ 10^{-3}\ eV$	$8.26\ 10^{-3}\ eV < m_1 < 8.97\ 10^{-3}\ eV$ (3 σ)
$\tau = 0.25 + 2.5\,i$	$m_2 = 4.93\ 10^{-2}\ eV$	$4.93\ 10^{-2}\ eV < m_2 < 5.10\ 10^{-2}\ eV$ (3 σ)
Yukawa	Majorana neutrino	
$y = 0.5$	$M_1 = 7.79\,TeV$	
	$\frac{M_2^2 - M_1^2}{M_1^2} = 9.92\ 10^{-12}$	
	Gauge boson	
	$M_{z'} = 6.90\,TeV$	

Conclusions

- Resonant leptogenesis scenario in TeV scale B-L model
- S_4 Modular symmetry naturally realizes degenerate masses
- RG evolutions generate a splitting of Majorana masses
- CP asymmetry parameter is automatically enhanced by resonance
- Right amount of baryon number can be obtained

Future Work

- Search wide region
- Quark and Charged lepton sector