Leptogenesis in a TeV-scale Supersymmetric Left-Right Model with Inverse Seesaw

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Outline

1. Introduction to Leptogenesis
2. CP asymmetry
3. Departure from thermal equilibrium
4. Type-I seesaw case
5. Inverse Seesaw case
6. Summary
Matter-Antimatter Asymmetry

BBN + CMB data:

\[ \eta_B \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.2 \pm 0.15) \times 10^{-10} \]

Can be dynamically generated provided the Sakharov conditions (\(B, C\) and \(QP\), out of equilibrium) satisfied.

SM prediction is too small \(\sim 10^{-20}\).

Require new sources of \(CP\) and \(B - L\) violation.

From lepton sector??
Leptogenesis

- Lepton asymmetry converted to baryon asymmetry by sphaleron processes. [Fukugita, Yanagida '86]
- Introduce heavy SM singlet sterile neutrinos ($N$):
  \[ \mathcal{L}_N = (Y_D \bar{L} \Phi N + \text{h.c.}) + M_N NN \]
- $\mathcal{L}$ comes from the Majorana mass term ($M_N$) of these heavy neutrinos.
- Yukawa couplings ($Y_D$) provide new source of $CP$ violation.
- Asymmetry generated in the out-of-equilibrium decay of the heavy sterile neutrino for $\Gamma_N < H (T = M_N)$.
- Also explains the observed small LH neutrino masses via seesaw mechanism.
$\epsilon_{i\alpha} = \frac{\Gamma(N_i \rightarrow L_\alpha \Phi) - \Gamma(N_i \rightarrow \bar{L}_\alpha \Phi^\dagger)}{\Gamma(N_i \rightarrow L_\alpha \Phi) + \Gamma(N_i \rightarrow \bar{L}_\alpha \Phi^\dagger)} = \frac{1}{8\pi} \sum_{j \neq i} \frac{\text{Im}[(YY^\dagger)_{ij}^2]}{\sum_\beta |Y_{i\beta}|^2} f \left( \frac{M_j^2}{M_i^2} \right)$

where $f(x) = \sqrt{x} \left[ 1 - (1 + x) \log \left( \frac{1+x}{x} \right) \right]$ is the $L$-violating self-energy and vertex loop factor.
Scale of RH neutrino mass

- **Vanilla Leptogenesis** [Davidson, Ibarra ’02]
  
  Hierarchical RH neutrino masses ($M_1 \ll M_2$):

  \[ f \left( \frac{M_2^2}{M_1^2} \right) \approx -\frac{M_1}{2M_2} \]

- Requires $M_1 \gtrsim 10^9 \text{ GeV}$ for sufficiently large $CP$-asymmetry.
- Gravitino problem – requires $T_{RH} \lesssim 10^9 \text{ GeV}$. (see talk by O. Seto)
Vanilla Leptogenesis [Davidson, Ibarra ’02]
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Resonant leptogenesis [Pilaftsis, Underwood ’04]
Quasi-degenerate RH neutrino masses ($M_1 \simeq M_2$):

$$f \left( \frac{M_2^2}{M_1^2} \right) \simeq \frac{(M_2^2 - M_1^2)M_1^2}{(M_2^2 - M_1^2)^2 + (M_2\Gamma_2 - M_1\Gamma_1)^2}$$

- Possible to have $M_1$ as low as $\sim$ TeV!
- “Collider-friendly” provided Yukawa couplings are large enough.
- Interesting effects in flavor sector. (see talk by F. Deppisch)
Departure from thermal equilibrium

- Effective $B - L$ asymmetry generated by decay of the lightest heavy RH neutrino.
- Solve Boltzmann equations in expanding universe to get the deviation from its equilibrium distribution.

$$\frac{dN_{N_1}}{dz} = -(D + S)(N_{N_1} - N_{N_1}^{eq}),$$

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{eq}) - WN_{B-L}$$

- $D = \Gamma_D/(Hz)$ accounts for decays and inverse decays.
- $S = \Gamma_S/(Hz)$ represents the $\Delta L = 1$ scatterings.
- $W = \Gamma_W/(Hz)$ is the washout term (contributed by inverse decay and $\Delta L = 1, 2$ processes) competing with the decay source term.
Some Definitions

- **Washout parameter**

\[ K = \frac{\Gamma_D(z = \infty)}{H(z = 1)} = \frac{\tilde{m}_1}{m_*} \]

where \( \tilde{m}_1 = \left(\frac{M_D^\dagger M_D}{M_1}\right)_{11} \) (effective neutrino mass) and \( m_* \approx 1.08 \times 10^{-3} \) eV (equilibrium neutrino mass).

- **Efficiency factor**

\[ \kappa(z) = \int_z^\infty dz' \frac{dN_{N_1}}{dz'} \frac{D}{D + S} e^{-\int_{z}^{z''} dz'' W(z'')} \]

\( \kappa_f = \kappa(\infty) \to 1 \) for \( N_{N_1}^1 = N_{N_1}^{eq} \) and \( W = 0 \).

- **Baryon asymmetry**

\[ \eta_B = \frac{a_{\text{sph}}}{f} \epsilon_1 \kappa_f \simeq 10^{-2} \epsilon_1 \kappa_1(\infty) \]
Leptogenesis with Type-I Seesaw

- SM singlet RH Majorana neutrinos ($N$).
  
  [Minkowski ’77; Yanagida ’79; Glashow ’79; Gell-Mann, Ramond, Slansky ’80; Mohapatra, Senjanović ’80]

  $$\mathcal{L}_{\text{mass}} = (\overline{LM_D N} + \text{h.c.}) + NM_N N$$

  $$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}; \quad m_{\nu}^{\text{light}} = -M_D M_N^{-1} M_D^T$$

- TeV-scale $M_N$ possible only for tiny Yukawas: $M_D \lesssim m_e$.

- Both dilution and washout effects very large: $\frac{D}{D+S} \ll 1$ and $W \gg 1$ – highly suppressed efficiency!

- Not “LHC-friendly” for heavy gauge bosons: $M_{Z'} > 2.5 \text{ TeV}$ for $B-L$ models [Blanchet, Chacko, Granor, Mohapatra ’09] and $M_{WR} > 18 \text{ TeV}$ for LR models [Frere, Hambye, Vertongen ’08].
Inverse Seesaw

- Mostly Dirac $N$. Add another gauge singlet Majorana fermion $S$. [Mohapatra '86; Mohapatra, Valle '86]

\[
\mathcal{L}_{\text{mass}} = (\bar{L}M_D N + \bar{N}M_N S + \text{h.c.}) + S\mu S
\]

\[
\mathcal{M}_\nu = \begin{pmatrix}
0 & M_D & 0 \\
M_D^T & 0 & M_N \\
0 & M_N^T & \mu
\end{pmatrix};
\]

\[
m_{\nu}^{\text{light}} \simeq (M_D M_N^{-1}) \mu (M_D M_N^{-1})^T \quad \text{for} \ \mu \ll M_N
\]

- TeV scale $M_N$ even with large $M_D \sim m_t$ for $\mu \sim \text{keV}$.

- Smallness of $\mu$ is natural in ’t Hooft sense.

- Distinct collider phenomenology. [del Aguilla, de Blas '09]

- Also observable effects in the leptonic sector. [BD, Mohapatra ’09]
Leptogenesis in Inverse Seesaw

- Large Yukawa ($\sim 10^{-1} - 10^{-2}$) $\implies$ Large $D$.
- The *naive* washout parameter is also very large (due to inverse decay).

For TeV RH neutrino mass,

$$K_1 = \frac{(M_D^\dagger M_D)_{11}}{M_1 m_*} \sim 10^{12}$$
Leptogenesis in Inverse Seesaw

- Large Yukawa ($\sim 10^{-1} - 10^{-2}$) $\implies$ Large $D$.
- The *naive* washout parameter is also very large (due to inverse decay). For TeV RH neutrino mass,
  \[
  K_1 = \frac{(M_D^\dagger M_D)_{11}}{M_1 m_*} \sim 10^{12}
  \]
- However, *destructive interference* within each quasi-Dirac RH neutrino pair in inverse seesaw:
  \[
  \mathcal{M}_{RH} = \begin{pmatrix}
  0 & M_N \\
  M_N^T & \mu
  \end{pmatrix}
  \]
  Mass splitting within $(i, j)$ pair: $M_i - M_j \propto \mu_{ii}$.
- Define *effective washout parameter* $K_{i}^{\text{eff}} = \delta_1^2 K_1$ where
  \[
  \delta_1 = \frac{|M_1 - M_2|}{\Gamma_1} \sim \frac{\mu_{11}}{\Gamma_1} \sim 10^{-6}
  \]
  for $\Delta L = 2$ washout process $\ell \Phi \to \bar{\ell} \Phi^\dagger$. Makes $K_{i}^{\text{eff}} \sim \mathcal{O}(1)$. 
Gauge Scattering Effects

- Similar destructive interference effects for gauge scatterings (small $S$).
- Processes involving two external heavy-states (e.g. $NN \xrightarrow{Z'} e_R \bar{e}_R$, $q_R \bar{q}_R$ and $NN \xrightarrow{W} e_R \bar{e}_R$) are doubly Boltzmann suppressed.
- Also lepton flavor equilibration ($\ell_\alpha \Phi \leftrightarrow \ell_\beta \Phi$) means flavor effects not important in this case.

(for flavor effects in gauge scatterings, see talk by P. Schwallier)
Decay and Scattering Rates

![Graph showing decay and scattering rates](image_url)
The Efficiency Factor

\[ \kappa_i(z) \simeq \int_{z_0}^{z} dz' \frac{dN_{eq}^i(z')}{dz'} \frac{D(K_i, z')}{D(K_i, z') + D_{WR}(z') + 4S_z N_{eq}^i(z') + S_{WR}(z')} \]

\[ \times \exp \left[ - \int_{z'}^{z} dz'' \left\{ \sum_i W_{ID}(K_i, z'') + W_{WR}(z'') \right\} \delta_i^2 \right] \]

- \( D \gg S \implies \text{Small dilution effect: } \frac{D}{D+S} \sim \mathcal{O}(1) \).
- \( \delta_i^2 \ll 1 \implies \text{Small washout effect: } W\delta^2 \equiv K_{\text{eff}} \sim \mathcal{O}(1) \).
- Combination of \( \mu^2 \) suppression and Yukawa enhancement make the efficiency factor essentially independent of \( W_R \) mass.
- Lower bounds on \( W_R \) and \( Z' \) much weakened (below 1 TeV).
Efficiency and CP Asymmetry
Baryon Asymmetry

\[ \eta_B \]

\[ M_{N_3} (\text{GeV}) \]
Summary

- TeV Scale LR symmetry compatible with leptogenesis for inverse seesaw.
- Magnitude of $\mathcal{L}$ Majorana mass is directly proportional to the neutrino mass, instead of inversely as in usual Type-I case.
- Allows Yukawa couplings to be large (of order 0.1).
- Keeps both washout and dilution in control.
- Lowers the allowed range of $W_R$ and $Z'$ mass to “collider accessible” region.
- Makes leptogenesis accessible at LHC.