Leptogenesis in the Exceptional Supersymmetric Standard Model

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Outline

The Baryon Asymmetry of Universe

- Matter is dominant over anti-matter in the present Universe ★ WMAP's result:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}$$

  need to be explained.....

- Ingredients in Leptogenesis
  - Majorana RH neutrino mass (violating L)
    + Sphaleron process (violating $B + L$, conserving $B - L$)
  - Complexity of Yukawa couplings
- The Lagrangian of SM + RH neutrinos

$$\mathcal{L} = \mathcal{L}_{SM} + h_{ik} \bar{N}_{Ri} \ell_{Lk} H - \frac{1}{2} M_{Nij} N_{Ri} N_{Rj} + h.c.$$

- Seesaw Mechanism

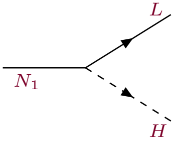
$$m_\nu = h h^T \frac{v^2}{M_R}$$

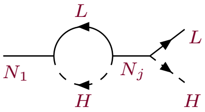
$M_R \sim 10^{14}\, GeV$ to explain $m_\nu \sim 10^{-1}\, eV$ [Mohapatra. 1980]

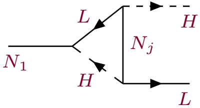
CP Asymmetry in Leptogenesis

- The Majorana nature of RH neutrino allows it to decay into both lepton and anti-lepton. The ratio is the same at tree level, but small differences arise at loop level [Yanagida. 86]

$$\epsilon_{i,\ell_k} \equiv \frac{\Gamma_{N_i \to \ell_k + H} - \Gamma_{N_i \to \bar{\ell}_k + H^*}}{\Gamma_{total}}$$







- We are interested in the asymmetry induced by the lightest RH neutrino ϵ_1. In non-susy models,

$$\epsilon_{1,\ell_k} = -\frac{1}{8\pi} \sum_{j=2,3} \frac{\mathrm{Im}\left[(h^\dagger h)_{1j} h^\dagger_{1k} h_{kj}\right]}{(h^\dagger h)_{11}} \left[f_V\left(\frac{M_j^2}{M_1^2}\right) + f_S\left(\frac{M_j^2}{M_1^2}\right)\right],$$

where $f_V(x) = \sqrt{x}\left[-1 + (x+1)\ln\left(1+\frac{1}{x}\right)\right]$, $f_S(x) = \frac{\sqrt{x}}{x-1}$.

- In the case of $M_1 \ll M_{2,3}$, it can be written as

$$\epsilon_{1,\ell_k} = -\frac{1}{4\pi} \sum_{j=2,3} \frac{\mathrm{Im}\left[(h^\dagger h)_{1j} h^\dagger_{1k} h_{kj}\right]}{(h^\dagger h)_{11}} \frac{M_1}{M_j}.$$

$\mathrm{E_6SSM}$

Exceptional Supersymmetric Standard Model ($\mathrm{E_6SSM}$) [King. 06] is based on

$$SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N \,,$$

a subgroup of E_6, where

$$E_6 \to SO(10) \times U(1)_\chi \,, \qquad SO(10) \to SU(5) \times U(1)_\psi \,,$$

$$U(1)_N = \frac{1}{4} U(1)_\chi + \frac{\sqrt{15}}{4} U(1)_\psi \,.$$

Particle content of $\mathrm{E_6SSM}$

- 3 generations of the 27 fundamental representation of E_6. $\Rightarrow$ anomalies cancelation.

  $$Q_{Li} \quad L_{Li} \quad u_{Ri} \quad d_{Ri} \quad e_{Ri} \quad N_i \quad H_{1i} \quad H_{2i} \quad S_i \quad D_i \quad \bar{D}_i$$

  with i the family index.
- Besides 27, extra fields with one generation $\Rightarrow$ gauge unification

  $$L', \bar{L}'$$

$\mathrm{E}_6\mathrm{SSM}$

- Z_2^H symmetry $\Rightarrow$ suppress the proton decay and *FCNC*
  - Odd for all fields, except $H_d \equiv H_{1,3}$, $H_u \equiv H_{2,3}$ and $S \equiv S_3$

$$
\begin{aligned}
W_{\mathrm{E_6SSM}} \quad \simeq \quad & \lambda_i S(H_{1i}H_{2i}) + \kappa_i S(D_i\overline{D}_i) + f_{\alpha\beta}(H_d H_{2\alpha})S_\beta + \tilde{f}_{\alpha\beta}(H_{1\alpha}H_u)S_\beta \\
& + h_{ij}^U (H_u Q_i) u_j^c + h_{ij}^D (H_d Q_i) d_j^c + h_{ij}^E (H_d L_i) e_j^c + h_{ij}^N (H_u L_i) N_j^c \\
& + \frac{1}{2} M_{ij} N_i^c N_j^c + \mu'(L'\overline{L}') + h_{4j}^E (H_d L') e_j^c + h_{4j}^N (H_u L') N_j^c \, .
\end{aligned}
$$

L' has one lepton number.

- The breaking of Z_2^H gives extra terms in the superpotential:

$$
W_N = \xi_{\alpha ij}(H_{2\alpha}L_i)N_j^c + \xi_{\alpha 4j}(H_{2\alpha}L')N_j^c \, .
$$

  - Model I, D - diquark

$$
W_1 = g_{ijk}^Q D_i \, (Q_j Q_k) + g_{ijk}^q \overline{D}_i d_j^c u_k^c \, ,
$$

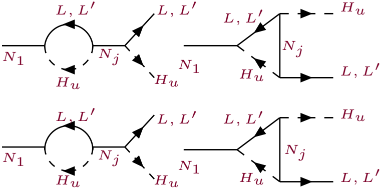
  - Model II, D - leptoquark

$$
W_2 = g_{ijk}^N N_i^c D_j d_k^c + g_{ijk}^E e_i^c D_j u_k^c + g_{ijk}^D \, (Q_i L_j) \, \overline{D}_k \, .
$$

CP Asymmetry in $\mathrm{E_6SSM}$, $\mathrm{Z_2^H}$ conserved case

- New contributions to N_1 decay in the case of conserved Z_2^H :

$$N_1 \to L' + H_u\,, \qquad N_1 \to \widetilde{L}' + \widetilde{H}_u\,,$$
$$\widetilde{N}_1 \to \overline{L}' + \overline{\widetilde{H}}_u\,, \qquad \widetilde{N}_1 \to \widetilde{L}' + H_u$$



- Z_2^H conserved case, distributed in L, L' and ordinary leptons respectively

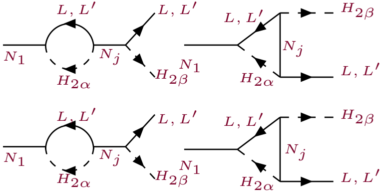
$$\epsilon_{1,\,\ell_k} = \epsilon_{1,\,\widetilde{\ell}_k} = \epsilon_{\widetilde{1},\,\ell_k} = \epsilon_{\widetilde{1},\,\widetilde{\ell}_k} \simeq -\frac{3}{8\pi}\sum_{j=2,3} \frac{\mathrm{Im}\left[\left((h^\dagger h)_{1j} + h_{41}^{N*} h_{4j}^{N}\right) h_{1k}^\dagger h_{kj}\right]}{(h^\dagger h)_{11} + |h_{41}^N|^2}\,\frac{M_1}{M_j}\,,$$

$$\epsilon_{1,\,L'} = \epsilon_{1,\,\widetilde{L}'} = \epsilon_{\widetilde{1},\,L'} = \epsilon_{\widetilde{1},\,\widetilde{L}'} \simeq -\frac{3}{8\pi}\sum_{j=2,3} \frac{\mathrm{Im}\left[(h_{41}^{N*} h_{4j}^{N})^2 + (h_{41}^{N*} h_{4j}^{N})(h^\dagger h)_{1j}\right]}{(h^\dagger h)_{11} + |h_{41}^N|^2}\,\frac{M_1}{M_j}\,.$$

CP Asymmetry in E_6SSM, Z_2^H violating case (model I)

- In Z_2^H symmetry violating case (Model I), new channels:

$$
\begin{aligned}
&N_1 \to L_k + H_{2\beta}, \quad &&N_1 \to \widetilde{L}_k + \widetilde{H}_{2\beta},\\
&\widetilde{N}_1 \to \overline{L}_k + \overline{\widetilde{H}}_{2\beta}, \quad &&\widetilde{N}_1 \to \widetilde{L}_k + H_{2\beta},\\
&N_1 \to L' + H_{2\beta}, \quad &&N_1 \to \widetilde{L}' + \widetilde{H}_{2\beta},\\
&\widetilde{N}_1 \to \overline{L}' + \overline{\widetilde{H}}_{2\beta}, \quad &&\widetilde{N}_1 \to \widetilde{L}' + H_{2\beta}.
\end{aligned}
$$



- CP asymmetry in the Z_2^H breaking case

$$
\begin{aligned}
\epsilon_{1,\,\ell_k} &= -\frac{1}{8\pi A_1}\sum_{j=2,3} \mathrm{Im}\Big\{2A_j h^{N\dagger}_{1k} h^N_{kj} + \Big(h^{N\dagger}_{1k} h^N_{kj} \times \Big[h^{N*}_{41} h^N_{4j} + (h^{N\dagger} h^N)_{1j}\Big]\\
&\quad + \sum_{\alpha} \xi^\dagger_{\alpha 41} h^N_{4j} \xi_{\alpha kj} h^{N\dagger}_{1k} + \sum_{\alpha,\,i} \xi^*_{\alpha i1} h^N_{ij} \xi_{\alpha kj} h^{N\dagger}_{1k}\Big)\Big\} \frac{M_1}{M_j}\,,\\
\epsilon_{1,\,L'} &= -\frac{1}{8\pi A_1}\sum_{j=2,3} \mathrm{Im}\Big\{2A_j h^{N*}_{41} h^N_{4j} + \Big((h^{N*}_{41} h^N_{4j})^2 + \Big[(h^{N\dagger} h^N)_{1j}\\
&\quad + \sum_{\alpha} \xi^*_{\alpha 41} \xi_{\alpha 4j}\Big] h^{N*}_{41} h^N_{4j} + \sum_{\alpha,\,i} \xi^*_{\alpha 1i} h^N_{ij} \xi_{\alpha j} h^{N*}_{41}\Big)\Big\} \frac{M_1}{M_j}\,,
\end{aligned}
$$

where

$$
A_j = (h^{N\dagger} h^N)_{1j} + h^{N*}_{41} h^N_{4j} + \sum_{\alpha,i=1-4} \xi^*_{\alpha i1} \xi_{\alpha ij}\,.
$$

CP Asymmetry in $\mathrm{E_6SSM}$, $\mathrm{Z_2^H}$ violating case (model II)

- In Z_2^H symmetry violating case (Model II), new decay channels:

$$N_1 \to D_k + \widetilde{q}_j\,, \quad N_1 \to \widetilde{D}_k + q_j\,, \quad \widetilde{N}_1 \to D_k + q_j\,, \quad \widetilde{N}_1 \to \widetilde{D}_k + \widetilde{q}_j\,,$$

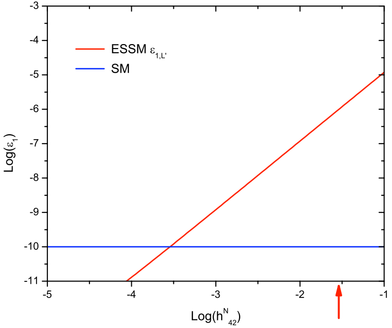
  - The lepton number conserved in leptoquark D can be released via consequent decays

$$D_k \to L_i + \widetilde{q}_j^\dagger$$

  - Baryon number from decays is canceled and only lepton asymmetry is generated

CP Asymmetry in E_6SSM: Result

- The upper bound on *CP* asymmetry can be enhanced



ϵ_1 versus Yukawa coupling h^N_{42}, assuming $M_1 \simeq 10^6\, GeV$, $M_2 \simeq 10^8\, GeV$, $h \simeq 10^{-5}$, $h^N_{41} \simeq 10^{-5}$ and maximal δ_{CP}.

- To generate baryon asymmetry effectively, the washout factor $K \equiv \Gamma_{N_1}/H(M_1) \sim 1$ is required [Antusch. hep-ph/0609038], $h \sim h^N_{41} \sim 10^{-5}$ could lead to maximal efficiency factor $\eta_e \sim 0.1$.
- The total baryon asymmetry $Y_B = \eta_e\, \epsilon_{1,L'}\, Y^{eq}_{N_1}(z \ll 1) \sim 10^{-9}$, where $Y^{eq}_{N_1}(z \ll 1) \sim 10^{-2} - 10^{-3}$.

Summary

- Leptogenesis provides an elegant explanation to BAU.
- $\mathrm{E_6SSM}$
- New contribution of *CP* asymmetry from E_6SSM .
- Enough baryon asymmetry can be generated.
- Both E_6SSM and Majorana property of neutrino need to be tested (LHC/ILC and $0\nu\beta\beta$) .