Leptogenesis in the Exceptional Supersymmetric Standard Model

Steve King\textsuperscript{1}, Rui Luo\textsuperscript{2}, David Miller\textsuperscript{2} and Roman Nevzorov\textsuperscript{2}

\textsuperscript{1}University of Southampton, \textsuperscript{2}University of Glasgow

SUSY08, Seoul, June 2008
Outline

1. The BAU problem and the Framework of leptogenesis
2. The ESSM
3. Leptogenesis in the ESSM
4. Result of lepton asymmetry
5. Summary
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

\[ \mathcal{L} = \mathcal{L}_{SM} + h_{ik} \bar{N}_{Ri} \ell_{Lk} H - \frac{1}{2} M_{Ni,j} N_{Ri} N_{Rj} + h.c. \]

• Seesaw Mechanism

\[ m_\nu = hh^T \frac{v^2}{M_R} \]

\( M_R \sim 10^{14} \text{ GeV} \) to explain \( m_\nu \sim 10^{-1} \text{ eV} \) [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]

\[ \epsilon_{i,\ell_k} \equiv \frac{\Gamma_{N_i \rightarrow \ell_k + H} - \Gamma_{N_i \rightarrow \ell_k^* + H^*}}{\Gamma_{\text{total}}} \]

- We are interested in the asymmetry induced by the lightest RH neutrino \( \epsilon_1 \). In non-susy models,

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

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

\[ \epsilon_{1,\ell_k} = -\frac{1}{4\pi} \sum_{j=2,3} \text{Im} \left[ \frac{(h^\dagger h)_{1j} h_{1k}^\dagger h_{kj}}{(h^\dagger h)_{11}} \right] \frac{M_1}{M_j} \]
Exceptional Supersymmetric Standard Model (E6SSM) [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
\[
E_6 \rightarrow SO(10) \times U(1)_X, \quad U(1)_N = \frac{1}{4} U(1)_X + \frac{\sqrt{15}}{4} U(1)_\psi \\
SO(10) \rightarrow SU(5) \times U(1)_\psi
\]

**Particle content of E6SSM**

- 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

\[
L_4, \bar{L}_4
\]
\textbf{E}_6\text{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 \(S \equiv S_3\)

\[
W_{E_6\text{SSM}} \simeq \lambda_i S(H_{1i}H_{2i}) + \kappa_i S(D_i \overline{D}_i) + f_{\alpha\beta}(H_d H_{2\alpha}) S_\beta + \tilde{f}_{\alpha\beta}(H_{1\alpha} H_u) S_\beta \\
+ h^U_{ij}(H_u Q_i)u^c_j + h^D_{ij}(H_d Q_i)d^c_j + h^E_{ij}(H_d L_i)e^c_j + h^N_{ij}(H_u L_i)N^c_j \\
+ \frac{1}{2} M_{ij} N^c_i N^c_j + \mu' (L_4 \overline{L}_4) + h^E_{4j}(H_d L_4)e^c_j + h^N_{4j}(H_u L_4)N^c_j
\]

\(L_4\) has one lepton number.

- The breaking of \(Z_2^H\) gives extra terms in the superpotential:
  \[
  W_N = \xi_{\alpha ij}(H_{2\alpha} L_i) N^c_j + \xi_{\alpha 4j}(H_{2\alpha} L_4) N^c_j
  \]

- Model I, \(D\) - diquark
  \[
  W_1 = g^Q_{ijk} D_i (Q_j Q_k) + g^q_{ijk} \overline{D}_i d^c_j u^c_k
  \]

- Model II, \(D\) - leptoquark
  \[
  W_2 = g^N_{ijk} N^c_i D_j d^c_k + g^E_{ijk} e^c_i D_j u^c_k + g^D_{ijk} (Q_i L_j) \overline{D}_k
  \]

- The superpotential of interactions of RH neutrinos can be rewritten with compact notations:
  \[
  W_N = h^N_{kij} (H^u_k L_x) N^c_j + g^N_{kij} D_k d^c_i N^c_j
  \]

where \(x = 1, 2, 3, 4, \ k, i, j = 1, 2, 3\)
CP Asymmetry in $E_6$ SSM, $Z^H_2$ conserved case

- New contributions to $N_1$ decay in the case of conserved $Z^H_2$:
  \[ N_1 \to L_x + H^u_k, \quad N_1 \to \tilde{L}_x + \tilde{H}^u_k, \quad \tilde{N}_1 \to \tilde{L}_x + \tilde{H}^u_k, \quad \tilde{N}_1 \to \tilde{L}_x + H^u_k \]

Here $x, y = 1, 2, 3, 4$ and $i, k = 3$, representing the Higgs in the SM.

- $Z^H_2$ conserved case, distributed in $L_x$ and ordinary leptons respectively

\[
\varepsilon_1, \varepsilon_x \simeq -\frac{3}{8\pi} \sum_{j=2,3} \text{Im} \left[ (h^{N\dagger}h^N)_{1j} h^{N\dagger}_x h^N_{xj} \right] \frac{M_1}{M_j}
\]
CP Asymmetry in $E_6$ SSM, $Z_2^H$ violating case (model I)

- In $Z_2^H$ symmetry violating case (Model I), the 1st and 2nd generations of Higgs are considered ($k = 1, 2, 3$).

  \[ N_1 \to L_x + H_k^u, \quad \tilde{N}_1 \to \tilde{L}_x + \tilde{H}_k^u, \quad \tilde{N}_1 \to \tilde{L}_x + \tilde{H}_k^u \]

- Similarly, one-loop calculation gives CP asymmetries of different final states:

  \[ \varepsilon_{1, \ell_x}^k = \varepsilon_{\tilde{1}, \ell_x}^k = \varepsilon_{\tilde{1}, \ell_x}^k = \frac{1}{8\pi A_1} \sum_{j=2,3} \text{Im} \left\{ 2 A_j h_{kx1}^N h_{kxj}^N \frac{M_1}{M_j} \right\} \]

  \[ + \sum_{m, y} h_{my1}^N h_{mxyj}^N h_{kyj}^N h_{kx1}^{N*} \frac{M_1}{M_j} \]

  where $A_j = \sum_{m, y} h_{my1}^N h_{myj}^N$ and $x, y = 1, 2, 3, 4, \quad i, k = 1, 2, 3$. 

CP Asymmetry in E6SSM, $Z^H_2$ violating case (model II)

- In $Z^H_2$ symmetry violating case (Model II), new decay channels:

  \[
  N_1 \rightarrow D_k + \tilde{d}^c_i, \quad N_1 \rightarrow \tilde{D}_k + d^c_i \\
  \tilde{N}_1 \rightarrow \overline{D}_k + d_i, \quad \tilde{N}_1 \rightarrow \overline{D}_k + \tilde{d}^c_i
  \]

  where $i, k = 1, 2, 3$

- The lepton number conserved in leptoquark $D$ can be released via consequent decays $D \rightarrow L + \tilde{q}^\dagger$
  - Baryon number from decays is canceled and only lepton asymmetry is generated

- The CP asymmetry is defined as

  \[
  \varepsilon_{1, q_k}^i = \frac{\Gamma_{N_1 q_k}^i - \Gamma_{N_1 \tilde{q}_k}^i}{\sum_{j, m} \left( \Gamma_{N_1 q_m}^j + \Gamma_{N_1 \tilde{q}_m}^j \right)}
  \]

- The CP asymmetries are expressed as

  \[
  \varepsilon_{1, D_k}^i = \frac{1}{8\pi A_0} \sum_{j=2,3} \text{Im} \left\{ 2\tilde{A}_j g^N_{kij} g^{N*}_{ki1} \frac{M_1}{M_j} + \sum_{m, n} g^{N*}_{mn1} g^N_{mij} g^N_{knj} g^{N*}_{ki1} \frac{M_1}{M_j} \right\}
  \]

  where $\tilde{A}_j = A_j + \frac{3}{2} \sum_{m, n} g^{N*}_{mn1} g^N_{mnj}$ and $A_0 = \sum_k, i g^N_{ki1} g^{N*}_{ki1}$
Lepton Asymmetry in Constrained Sequential Dominance of See-saw model

- In the basis where RH neutrino mass matrix is diagonal and LH neutrinos in ew eigenstates.

\[
M_N = \begin{pmatrix} M_A & 0 & 0 \\ 0 & M_B & 0 \\ 0 & 0 & M_C \end{pmatrix}
\]

\[
h^N = \begin{pmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix}
\]

- It is natural to assume \( |A_iA_j| \gg |B_iB_j| \gg |C_iC_j| \), in the case of strong-hierarchy of RH neutrino masses. And \( |A_1| \ll |A_{2,3}| \)

- The LH neutrino masses from see-saw model:

\[
m_3 \simeq \frac{(|A_2|^2 + |A_3|^2)v^2}{M_A}, \quad m_2 \simeq \frac{|B_1|^2v^2}{s_{12}^2M_B}, \quad m_1 \simeq O\left(\frac{|C|^2v^2}{M_C}\right)
\]

where \( v \) is the vev of Higgs potential, and \( s_{12} \equiv \sin \theta_{12} \sim \sqrt{1/3} \)

- For \( m_1 \ll m_2 \ll m_3 \), LH neutrino masses can be determined: \( m_1 \sim 0 \), \( m_2 \sim 8.7 \times 10^{-3} \text{ eV} \), \( m_3 \sim 4.9 \times 10^{-2} \text{ eV} \). Then Yukawa couplings depend on RH neutrino mass \( M_{A,B} \).
Lepton Asymmetry with $L_4$

- Lepton asymmetries versus leptoquark couplings in $E_6SSM$ $Z_2$ conserved case

- We take $M_1 = 10^6$ GeV, and $M_2 = 10M_1$.
- Lepton asymmetries are expected to be $\sim 10^{-4} - 10^{-6}$, to generate right amount of baryon asymmetry.
Lepton Asymmetry in model I

We take \( M_1 = 10^6 \) GeV, and \( M_2 = 10M_1 \)
We take $M_2 = 10 M_1$. Notice that the asymmetries are not sensitive to the scale of $M_1$. 
Summary

- Leptogenesis provides an elegant explanation to BAU.
- $E_6$SSM
- New contribution of $CP$ asymmetry from $E_6$SSM
- Result in the Sequential Dominance scenario
- Lepton Asymmetries can be enhanced drastically.
- Boltzmann equations is going to be solved for Baryon asymmetry.

for more details, see arXiv:0806.0330