Leptogenesis from decaying scalars in the extension of the Zee-Babu model

Dmitry Zhuridov (NTHU, Taiwan)
Abstract

We show that the economical extension of the Zee-Babu model can generate not only the small neutrino masses but also the baryon number asymmetry in the universe in terms of the leptogenesis.
Leptogenesis in the extension of the Zee-Babu model

Chian-Shu Chen*, Chao-Qiang Geng† and Dmitry V. Zhuridov‡

Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 300

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Abstract

We demonstrate that the extension of the Zee-Babu model can generate not only the small neutrino masses but also the baryon number asymmetry in the universe. In particular, we show that the scale of the singlet scalar responsible for the leptogenesis can be of order 1 TeV, that can be tested at the LHC and ILC. We also consider the possible minimal extension of this model to generate the dark matter.
Zee-Babu model


The Zee-Babu model is the minimal extension of the SM providing neutrino masses and mixings compatible with experiment.

It contains only 2 non-SM particles:
- h – singly charged scalar singlet;
- k – doubly charged scalar singlet.

Neutrino masses are generated radiatively in two loops.
Considered Zee-Babu model extension

TABLE I: The scalar fields, its electro-weak charges and $Z_2$ parity; $i = 1, 2$.

<table>
<thead>
<tr>
<th>Scalar</th>
<th>$SU(2)_L \times U(1)_Y$</th>
<th>$Z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>(2, 1)</td>
<td>+</td>
</tr>
<tr>
<td>$s$</td>
<td>(1, 0)</td>
<td>-</td>
</tr>
<tr>
<td>$h$</td>
<td>(1, 1)</td>
<td>+</td>
</tr>
<tr>
<td>$k_i$</td>
<td>(1, 2)</td>
<td>+</td>
</tr>
<tr>
<td>$k_3$</td>
<td>(1, 2)</td>
<td>-</td>
</tr>
</tbody>
</table>

$$V = -\mu_\phi^2 |\phi|^2 + \lambda_\phi |\phi|^4 + M_s^2 s^2 + \lambda_s s^4 + M_h^0 h^2 + \lambda_h |h|^4$$

$$+ M_{k_i}^2 |k_i|^2 + \lambda_{k_i} |k_i|^4 + \lambda_{k_{ij}} |k_i|^2 |k_j|^2$$

$$+ \lambda_{hs} |\phi|^2 s^2 + \lambda_{bh} |\phi|^2 |h|^2 + \lambda_{h_k} |\phi|^2 |k_i|^2 + \lambda_{sh2} s^2 |h|^2 + \lambda_{sk} s^2 |k_i|^2 + \lambda_{hk} |h|^2 |k_i|^2$$

$$+ \left[ \lambda_{k12} |\phi|^2 k_1^\dagger k_2 + \lambda_{h12} |h|^2 k_1^\dagger k_2 + \lambda_{s3} s (h^+)^2 k_3^- + \mu_{s3} s k_n^\dagger k_3 + \mu_{hn} (h^+)^2 k_n^- + \text{H.c.} \right]$$
Neutrino masses

The two-loop Majorana neutrino mass generation, shown in Fig. 1, takes place due to the simultaneous presence of the four couplings: the SM Yukawa $\bar{L}Y\tilde{\phi}\ell_R$, the non-SM scalar $\mu_i h^2 P_i$ ($\mu_i = \Theta \mu_{nki}$) in Eq. (1), and the two non-SM scalar–lepton

$$\mathcal{L}_Y = f_{ab} \bar{L}_a L_b h^+ + h_{iab} \ell_R^c \ell_R P_i^{++} + \text{H.c.},$$

where $P_{1,2}$ are the Majorana masses of neutrinos at the two-loop level.

![Diagram of neutrino and lepton interactions]

FIG. 1: Majorana masses of neutrinos at the two-loop level.
Leptogenesis

To study the leptogenesis, the relevant terms in the Lagrangian are given by

\[ \bar{L}_a Y_{aa} \tilde{\phi} \ell_{aR} - \mu_{sn} S P_{n}^{++} P_{3}^{--} - \mu_n (h^+)^2 P_{n}^{--} - h_{nab} \tilde{\ell}_{aR}^c \ell_{bR} P_{n}^{++} + \text{H.c.,} \]

with \( n = 1, 2 \).

![Diagram](image)

**FIG. 2:** \( S \rightarrow P_{3}^{++} \ell_{aR}^\pm \ell_{bR}^\pm \) at tree level (upper) and self-energy corrections to the wave functions of \( P_i \) (lower) and \( i, j = 1, 2 \).
The $S$ decay width at the leading order in $M_S^2/M_i^2$ is written as

$$\Gamma_S = \frac{1}{(2\pi)^3} \frac{1}{96} \frac{1}{4} \sum_{ijab} \rho_{ab} \mu_{s_i} \mu_{s_j}^* h_{iab}^* h_{jab} \frac{(M_S^2 - M^2_3)^2 (M_S^2 + 5M_3^2)}{M_i^2 M_j^2 M_S^3},$$

where $\rho_{ab} = 2 - \delta_{ab}$. The reduced lepton asymmetry

$$\epsilon \equiv n_L/n_S = 2[B(S \rightarrow \ell\ell P_3^{++}) - B(S \rightarrow \ell^c\ell^c P_3^{--})],$$

where $n_L = n_\ell - n_{\bar{\ell}}$ with $n_\ell$, $n_{\bar{\ell}}$ and $n_S$ being the number densities of leptons, antileptons and $S$, can be rewritten as

$$\epsilon \simeq 2A \sum_{ab} \rho_{ab} \left\{ \text{Im}[\mu_{s_1} \mu_{s_2}^* h_{1ab}^* h_{2ab}] \left(\frac{|\mu_1|^2}{M_1^2} - \frac{|\mu_2|^2}{M_2^2}\right) + \text{Im}[\mu_1 \mu_2^* \mu_{s_1}^* \mu_{s_2}] \left(\frac{|h_{1ab}|^2}{M_1^2} - \frac{|h_{2ab}|^2}{M_2^2}\right) \right\} + \text{Im}[h_{1ab} h_{2ab}^* \mu_1^* \mu_2] \left(\frac{|\mu_{s_1}|^2}{M_1^2} - \frac{|\mu_{s_2}|^2}{M_2^2}\right),$$

where

$$A = \frac{1}{2\pi M_1^2 M_2^2} \left(\sum_{ijab} \frac{\rho_{ab} \mu_{s_i} \mu_{s_j}^* h_{iab}^* h_{jab}}{M_i^2 M_j^2 M_S^2}\right)^{-1}.$$
For the successful leptogenesis at $T < M_S$ we require $M_3 < M_S < \min(M_h, M_i)$. The time evolution of the $n_L$ can be described by the Boltzmann equation

\[
\frac{dn_L}{dt} + 3Hn_L = \frac{\epsilon}{2}\langle \Gamma_S \rangle (n_S - n_S^{eq}) - \langle \Gamma_S \rangle \left( \frac{n_S^{eq}}{n_{\gamma}} \right) n_L - 2\langle \sigma |v| \rangle n_\gamma n_L,
\]

where $n_S^{eq}$ is the equilibrium number density of $S$, $n_\gamma$ is the photon density, $\langle \rangle$ represents thermal averaging, $\sigma = \sigma^{++} + \sigma^{--}$ with $\sigma^{++} = \sigma (\ell^+ \ell^+ P_3^{\pm\pm} \rightarrow \ell^\pm \ell^\pm P_3^{\pm\pm})$. The density of $S$ satisfies

\[
\frac{dn_S}{dt} + 3Hn_S = -\langle \Gamma_S \rangle (n_S - n_S^{eq}) - \langle \sigma_s |v| \rangle (n_S^2 - n_S^{eq2}),
\]

where $\sigma_s$ is the cross section of the scattering processes $SS \rightarrow \phi \rightarrow$ all, shown below

\[
\begin{align*}
S & \quad \rightarrow \quad g, b, W^-, Z \ldots \\
S & \quad \rightarrow \quad \phi \\
\phi & \quad \rightarrow \quad g, \bar{b}, W^+, Z \ldots
\end{align*}
\]
The reaction density for the scattering $SS \rightarrow \phi \rightarrow \text{all}$ can be written as

$$\gamma_s = \frac{T}{64\pi^2} \int_{4M_S^2}^{\infty} ds \hat{\sigma}_s(s) \sqrt{s} K_1(\sqrt{s}/T),$$

where $K_1$ is the modified Bessel function and $\hat{\sigma}_s$ is the reduced cross section given by $2(s - 4M_S^2)\sigma_S(s)$ with

$$\sigma_s = \frac{1}{\pi \sqrt{s}} \frac{1}{\sqrt{s - 4M_S^2}} \left( \frac{\lambda_{\phi_S} v}{M_Z} \right)^2$$

with the SM Higgs vev $v = 246$ GeV. The scattering term is negligible for small (large) values of $\lambda_{\phi_S}$ ($M_S$), in particular, we have bounds

$$\lambda_{\phi_S} < 10^{-5} \quad \text{for} \quad M_S \sim 1 \text{ TeV},$$

$$\lambda_{\phi_S} < 10^{-4} \quad \text{for} \quad M_S \sim 10^2 \text{ TeV}.$$
Consistency with BAU and small neutrino masses

The out-of-equilibrium condition $\Gamma_S < H(T = M_S)$ is satisfied for

$$\vert \mu_{si} h_{jab} \vert < 640 M_i M_j / \sqrt{\rho_{ab} M_S M_{Planck}}.$$  

In the EWPT, the lepton asymmetry $L = \epsilon/(2g_*)$ is converted to the net baryon asymmetry per entropy density

$$B \equiv \frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s}$$

due to the relation

$$B_f = \frac{28}{79} (B - L),$$

where $f$ represents the present value and there is no initial $B$. We obtain

$$n_B/n_\gamma = 10^{-2}\epsilon.$$
The allowed ranges for $M_\alpha (\alpha = h^\pm, P_i^{\pm \mp})$, $h_{iab} \equiv h_0$ and $\mu_i \equiv \mu$ are given by

$$
\frac{0.42}{\sqrt{\kappa}} \text{ TeV} \leq M_\alpha < 10^3 \kappa^4 \text{ TeV}, \quad \frac{0.1}{\kappa} \text{ TeV} < \mu < 10^3 \kappa^5 \text{ TeV}, \quad \frac{0.01}{\kappa^2} \leq h_0 \leq \kappa;
$$

$$
\frac{0.78}{\sqrt{\kappa}} \text{ TeV} \leq M_\alpha < 274 \kappa^4 \text{ TeV}, \quad \frac{0.36}{\kappa} \text{ TeV} < \mu < 274 \kappa^5 \text{ TeV}, \quad \frac{0.036}{\kappa^2} \leq h_0 \leq \kappa;
$$

for the normal and inverted hierarchies of the neutrino masses, respectively, where the parameter $\kappa (\geq \mu/M_h)$ is taking to be $\sim 1$. Taking the central values $h_0 \sim 0.1$ and $\mu \sim 1 \text{ TeV}$ and the neutral singlet mass $M_S \sim 100 \text{ TeV}$, we get

$$\epsilon \sim 1 \text{ TeV}^2 M_1^{-2}, \quad \mu_s \equiv \mu_{si} \lesssim 10^{-5} \text{ TeV}^{-1} M_1^2 \quad (M_1 < M_2)$$

with $\mu_s$ and $M_1$ in TeV. It is easy to satisfy this condition and describe observed baryon number asymmetry $n_B/n_\gamma = 6 \times 10^{-10}$, e.g., we have $\mu_s < 100 \text{ TeV}$ and $\epsilon \sim 10^{-7}$ for $M_1^2 \sim 10^7 \text{ TeV}^2$. Finally, the requirement for the t-channel scattering processes $SS \to P_i P_i$ to be negligible gives bound $\mu_s < 10 \text{ TeV}$.
Searches for CHAMPs & CHAMP-ions

Charged massive particle (CHAMP) with charge N bound electromagnetically to a nucleus results in an atom with the same chemistry as the element with atomic number Z-N.

Exclusion plot for CAMPs considered as DM:

Figure 2. Exclusion plot for CHAMPs (solid lines) and neutral CHAMPs (dotted lines). See text for more details.
Yield of $X^\pm$ scalar singlets with $10 \text{ TeV} < M_X < 100 \text{ TeV}$

$Y_{ab}^{\pm} \sim 2 \times 10^{-11}$ (it can be reduced by the Sommerfeld boost factor $\sim 10^3 - 10^5$)

$Y_{min} \sim 10^{-17}$ (for the unitarity cross section)

Bounds for $R^\pm$ relics from hydrogen experiments

$Y_{R^+} \leq 0.9 \times 10^{-38} \left( \frac{\Omega_R h^2}{0.0223} \right)$ for $M_R < 1.6 \text{ TeV}$ \quad ($M_X \approx M_R$)

$Y_{R^+} \leq 6 \times 10^{-25} \left( \frac{\Omega_R h^2}{0.0223} \right)$ for $10 \text{ TeV} < M_R < 6 \times 10^4 \text{ TeV}$

Hence yield of $X^\pm$ is practically forbidden.
Yield of $X^{\pm \pm}$ scalar singlets with $10 \, \text{TeV} < M_X < 100 \, \text{TeV}$

$$\frac{Y^{\pm \pm}}{Y^{\pm 1}} \sim \frac{\sigma^{\pm 1}_{ann}}{\sigma^{\pm 2}_{ann}} = \frac{1}{16} \quad \implies \quad Y^{\pm \pm} \sim 10^{-16} \quad \text{with BF} \sim 10^4$$

**Bound from WMAP 5-year results** \quad ($\Omega_X h^2 \lesssim 0.13$)

$$M_X Y_X (T_{now}) \leq 4.6 \times 10^{-13} \, \text{TeV}$$

Hence $X^{\pm \pm}$ with $10 \, \text{TeV} < M_X < 100 \, \text{TeV}$ make up $\leq 10^{-3}$ of the DM.
This fraction can be reduced by using larger BF.

**Bound from mass spectroscopy of helium**

$$Y_{X^{++}} \leq 3 \times 10^{-19} \, \text{TeV} \quad \text{for} \quad 20 \, \text{GeV} < M_X < 10 \, \text{TeV}$$
How $X^-$ avoids hydrogen limits?

The abundances of hydrogen complexes ($X3p$, $X\alpha p$, $XLi$, etc.) are lower compared to the abundances of neutral ones ($X2p$, $X\alpha$, etc.), e.g., $Li/H \sim 10^{-9}$.

(In the case of $X^-$ the hydrogen complexes are more trivial: $X2p$, $X\alpha$, etc.)

How to avoid astrophysical limits?

- $X$ is assumed to be non-dominant component of DM;
- $X$ is blown out of the galaxy by shock acceleration in supernovae.
How to rule out stable $X^{\pm\pm}$?

*Indirect way:* Improvement of hydrogen bound for $M_{R^+} > 10$ TeV.

*Direct way:* Mass spectroscopy of natural helium for $M_{R^{++}} > 10$ TeV.

Note that the considered model can be easily extended to include the stable DM.
Conclusion

• We have investigated a new mechanism for the leptogenesis in the extension of the ZB model.
• We have shown that the observed BAU can be produced through the decay of neutral scalar for both normal and inverted hierarchies of the neutrino masses.

• One of the advantages of the mechanism is that neither the degeneracy of masses nor the unnatural hierarchy of the couplings is required.