Baryogenesis through leptogenesis in a $S_4$ flavon model with $\text{TM}_1$ mixing for neutrinos

based on JHEP 09, 025 (2020)

Mainak Chakraborty
Indian Association for the Cultivation of Science, Kolkata

DAE-BRNS High Energy Physics Symposium, NISER, Bhubaneswar
December, 2020
Particle content and transformation rules under different symmetry groups

<table>
<thead>
<tr>
<th></th>
<th>$L$</th>
<th>$e_R$</th>
<th>$\mu_R$</th>
<th>$\tau_R$</th>
<th>$N$</th>
<th>$\phi_C$</th>
<th>$\eta_D$</th>
<th>$\phi_D$</th>
<th>$\eta_M$</th>
<th>$\phi_M$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_4$</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$C_3$</td>
<td>1</td>
<td>1</td>
<td>$\omega$</td>
<td>$\bar{\omega}$</td>
<td>1</td>
<td>$\omega$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$C_6$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>$-\omega$</td>
<td>1</td>
<td>$-1$</td>
<td>$-1$</td>
<td>$\omega$</td>
<td>$\omega$</td>
<td>1</td>
</tr>
</tbody>
</table>

The tensor product of two triplets $(x_1, x_2, x_3)$ and $(y_1, y_2, y_3)$ leads to

$$3 \times 3 = 1 + 2 + 3' + 3$$

$$1 \equiv x_1y_1 + x_2y_2 + x_3y_3,$$

$$2 \equiv \left(2x_1y_1 - x_2y_2 - x_3y_3, \sqrt{3}(x_2y_2 - x_3y_3)\right),$$

$$3' \equiv \left(x_2y_3 + x_3y_2, x_3y_1 + x_1y_3, x_1y_2 + x_2y_1\right),$$

$$3 \equiv \left(x_2y_3 - x_3y_2, x_3y_1 - x_1y_3, x_1y_2 - x_2y_1\right).$$
The invariant lagrangian and mass matrices

\[ \mathcal{L} \supset \left( y_\tau \bar{L}\frac{\phi_C}{\Lambda} \tau_R H + y_\mu \bar{L}\frac{\phi_C^*}{\Lambda} \mu_R H + y_e \bar{L}\left(\frac{\phi_C^*\phi_C}{\Lambda^2}\right) e_R H \right) + \left( y_{D1} \bar{L}N \frac{\eta_D}{\Lambda} \tilde{H} + y_{D3} \left( \bar{L}N \right) \frac{\phi_D}{\Lambda} \tilde{H} \right) + \left( y_{M1} \bar{N}^c N \eta_M + y_{M3} \left( \bar{N}^c N \right) \frac{\phi_M}{\Lambda} \tilde{H} \right) \]

Effective seesaw mass matrix:
The Effective light neutrino mass matrix by Type-I seesaw

\[ M_{ss} = -M_D M_M^{-1} M_D^T = -\frac{M^2_w}{M_f} \left( \begin{array}{ccc} d_1 & -f_1 & f_2 \\ -f_1 & d_2 & f_1 \\ f_2 & f_1 & d_1 \end{array} \right) \]
Diagonalization

$M_{ss}$ is diagonalized as

$$U_{23}^\dagger U_{BM}^\dagger M_{ss} U_{BM}^* U_{23}^* = \text{Diag}(m_1, m_2, m_3)$$

$U_{BM} \Rightarrow (1,3)$ bi-maximal mixing matrix, $U_{23} \Rightarrow$ orthogonal rotation matrix of 23 block

$$U_{BM} = \begin{pmatrix}
    \frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\
    0 & 1 & 0 \\
    \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}}
\end{pmatrix}, ~ U_{23} = \begin{pmatrix}
    1 & 0 & 0 \\
    0 & \cos \theta_{23} & \sin \theta_{23} \\
    0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}$$

Therefore the neutrino mixing matrix is is given by

$$U_{PMNS} = V U_{BM} U_{23}.$$
Baryogenesis through Leptogenesis

RH neutrino $\rightarrow$ lepton + Higgs pair

If out of equilibrium decay of $N_i$ in conjugate process occur at different rate from actual process, net lepton number will be generated

CP asymmetry parameter (flavoured):

$$
\varepsilon_i^\alpha = \frac{\Gamma(N_i \rightarrow l_\alpha^- H^+, \nu_\alpha H^0) - \Gamma(N_i \rightarrow l_\alpha^+ H^-, \nu_\alpha^c H^{0*})}{\sum_{\alpha} \left[ \Gamma(N_i \rightarrow l_\alpha^- H^+, \nu_\alpha H^0) + \Gamma(N_i \rightarrow l_\alpha^+ H^-, \nu_\alpha^c H^{0*}) \right]},
$$

Unflavoured asymmetry parameter $\Rightarrow$ $\varepsilon_i = \sum_{\alpha} \varepsilon_i^\alpha$

$$
\varepsilon_i = f(M_D'^\dagger M_D') \times \text{loop function}
\varepsilon_i^\alpha = f((M_D'^\dagger)_{i\alpha} (M_D')_{\alpha j}) \times \text{loop function}
$$
Computation of final asymmetry

Formal solution (upon neglecting the scattering terms and $\Delta L = 2$ terms)

$$\eta_{B-L}^f = \eta_{B-L}^{in} e^{-\sum_i \int_{z_{in}}^{\infty} W_i^i(z') dz' - \sum_i \varepsilon_i \kappa_i^f},$$

Analytic expression of final efficiency factor ($z \to \infty$) corresponding to $N_1$

$$\kappa_1^f(K_1) \simeq \kappa(K_1) = \frac{2}{K_1 z_B(K_1)} \left(1 - e^{-\frac{K_1 z_B(K_1)}{2}}\right),$$

the efficiency factor corresponding to $N_2$

$$\kappa_2^f = \kappa(K_2) e^{-\int_0^\infty W_{ID}^1(z) dz} = \kappa(K_2) e^{-\frac{3\pi K_1}{8}}.$$

Goodness of analytical approximation $\to K_1$ and $\delta_{12} = (M_2 - M_1)/M_1$

Boltzmann solution and analytic approximation match with each other in the strong washout regime for hierarchical RH neutrinos
Different regimes of leptogenesis

**Flavoured leptogenesis → importance of $N_2$ leptogenesis**

- $M_1 > 10^{12}$ GeV: three lepton flavours ($e, \mu, \tau$) are indistinguishable
- $10^9 < M_1(\text{GeV}) < 10^{12}$: $\tau$ flavour has separate identity, whereas $e$ and $\mu$ flavours act indistinguishably as a single entity
- $M_1 < 10^9$ GeV: all the three lepton flavours ($e, \mu, \tau$) are distinguishable
**Final $B - L$ asymmetry (2 flavour regime)**

Asymmetry generated by $N_1$ and $N_2$ along $\tau$ direction

$$N_{\Delta_\tau} = -\varepsilon_{1\tau} \kappa^f_{1\tau} - \varepsilon_{2\tau} \kappa^f_{2\tau} e^{-\frac{3\pi K_{1\tau}}{8}}$$

Along $\tau_\perp$ direction

$$N_{\Delta_{\tau_\perp}} = -\varepsilon_{1\tau_\perp} \kappa^f_{1\tau_\perp} - p_{12} \varepsilon_{2\tau_\perp} \kappa^f_{2\tau_\perp} e^{-\frac{3\pi K_{1\tau_\perp}}{8}}$$

along $|l^\tau_{1\perp}\rangle$

$$N_{\Delta_{\tau_\perp}} = -(1 - p_{12}) \varepsilon_{2\tau_\perp} \kappa^f_{2\tau_\perp} \leftarrow \text{pure } N_2 \text{ contribution}$$

Total final asymmetry

$$N^f_{B-L} = N_{\Delta_\tau} + N_{\Delta_{\tau_\perp}} + N_{\Delta_{\tau_\perp}}$$
Numerical results

parameters to be constrained \( \rightarrow k, Re(z), Im(z), M_w^2/M_f \)

Figure: left panel: constrained by oscillation data, right panel: oscillation data + positive \( Y_B \)
Significance of $N_2$ contribution and Goodness of analytical fit

Table: $(Y_B)_1$ and $(Y_B)_2$ denote the results produced by the solution of Boltzmann equations with and without pure $N_2$ contribution respectively. Similarly $(Y_B)_{\kappa_1}$ and $(Y_B)_{\kappa_2}$ are the values of final baryon asymmetry evaluated using the analytical formula. $E$ is the percentage errors given by

$$E\% = \left| \frac{(Y_B)_{\kappa_1} - (Y_B)_1}{(Y_B)_1} \right| \times 100 \quad (\text{Expt. } Y_B = (8.55 - 9.37) \times 10^{-11}).$$

<table>
<thead>
<tr>
<th>$M_w$</th>
<th>$M_1 \times 10^{-12}$</th>
<th>$M_2/M_1$</th>
<th>$(Y_B)_1 \times 10^{11}$</th>
<th>$(Y_B)_2 \times 10^{11}$</th>
<th>$(Y_B)_{\kappa_1} \times 10^{11}$</th>
<th>$(Y_B)_{\kappa_2} \times 10^{11}$</th>
<th>$E%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.49</td>
<td>1.90</td>
<td>8.09</td>
<td>2.76</td>
<td>8.87</td>
<td>3.07</td>
<td>9.6</td>
</tr>
<tr>
<td>2.04</td>
<td>1.55</td>
<td>1.90</td>
<td>8.42</td>
<td>2.87</td>
<td>9.23</td>
<td>3.19</td>
<td>9.61</td>
</tr>
<tr>
<td>2.08</td>
<td>1.62</td>
<td>1.90</td>
<td>8.75</td>
<td>2.99</td>
<td>9.6</td>
<td>3.32</td>
<td>9.71</td>
</tr>
<tr>
<td>2.12</td>
<td>1.68</td>
<td>1.90</td>
<td>9.09</td>
<td>3.10</td>
<td>9.97</td>
<td>3.45</td>
<td>9.68</td>
</tr>
<tr>
<td>2.16</td>
<td>1.74</td>
<td>1.90</td>
<td>9.44</td>
<td>3.22</td>
<td>10.35</td>
<td>3.58</td>
<td>9.63</td>
</tr>
<tr>
<td>2.20</td>
<td>1.81</td>
<td>1.90</td>
<td>9.79</td>
<td>3.34</td>
<td>10.73</td>
<td>3.71</td>
<td>9.60</td>
</tr>
</tbody>
</table>
We have investigated a flavon model based on Standard Model with $S_4$ discrete symmetry group adhering to Type-I seesaw → leads to $\text{TM}_1$ mixing

Neutrino oscillation phenomenology is described using four parameters ← constrained using $3\sigma$ limit of oscillation data

Baryon asymmetry through flavoured and unflavoured leptogenesis

Estimation of final baryon asymmetry ⇒ solution of coupled Boltzmann equation/appropriate analytical fit → Equivalence between these two methods has been shown clearly with corresponding numerical results

Substantial contribution from $N_2$ leptogenesis in the context of flavoured leptogenesis
Summary

- We have investigated a flavon model based on Standard Model with $S_4$ discrete symmetry group adhering to Type-I seesaw $\rightarrow$ leads to $TM_1$ mixing
- Neutrino oscillation phenomenology is described using four parameters $\leftarrow$ constrained using $3\sigma$ limit of oscillation data
- Baryon asymmetry through flavoured and unflavoured leptogenesis
- Estimation of final baryon asymmetry $\Rightarrow$ solution of coupled Boltzmann equation/appropriate analytical fit $\Rightarrow$ Equivalence between these two methods has been shown clearly with corresponding numerical results
- Substantial contribution from $N_2$ leptogenesis in the context of flavoured leptogenesis

Thank You!
<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 2.7$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bfp $\pm 1\sigma$</td>
<td>3$\sigma$ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304 \pm 0.012$</td>
<td>0.269 → 0.343</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.44 \pm 0.78$</td>
<td>31.27 → 35.86</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.570 \pm 0.024$</td>
<td>0.407 → 0.618</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$49.0^{+1.1}_{-1.4}$</td>
<td>39.6 → 51.8</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02221 \pm 0.00068$</td>
<td>0.02034 → 0.02430</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.57 \pm 0.13$</td>
<td>8.20 → 8.97</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$195^{+51}_{-25}$</td>
<td>107 → 403</td>
</tr>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.42^{+0.21}_{-0.20}$</td>
<td>6.82 → 8.04</td>
</tr>
<tr>
<td>$\Delta m_{32}^2$</td>
<td>$+2.514^{+0.028}_{-0.027}$</td>
<td>+2.431 → +2.598</td>
</tr>
</tbody>
</table>

**with SK atmospheric data**