Study on Leptogenesis in texture zeros of minimal inverse seesaw

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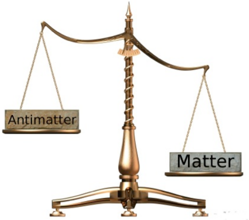
Introduction

Baryon Asymmetry of the Universe (BAU)



- Why do we exist???
- Baryon asymmetry is the excess of matter over anti-matter observed in the universe.

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.04 \pm 0.08) \times 10^{-10} \quad (1)$$

This Number demands Physics Beyond Standard Model (BSM)

Baryogenesis

Sakharov conditions for Baryogenesis

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1. Baryon number (B) violation

Baryogenesis

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2. C and CP violation

Baryogenesis

[A. D. Sakharov, JETP Lett. 5, 24 (1967).]

Sakharov conditions for Baryogenesis

1. Baryon number (B) violation
2. C and CP violation
3. Departure from thermal equilibrium

Models of Baryogenesis

- Baryogenesis at the Electroweak Phase Transition.

  (Kuzmin, Rubakov, Shaposhinikov,PLB155 (1955))
- GUT Baryogenesis through the decay of heavy particles.

  (Yashimura,PRL41 (1978))
- Baryogenesis via Leptogenesis

  (Fukugita, Yanagida,PLB 174 (1986))

Baryogenesis via Leptogenesis

- Realized in the seesaw framework where heavy RH neutrinos are present
- Lepton asymmetry is generated by the decay of RH neutrinos.

$$N_i \longrightarrow l\bar{\phi}$$
$$N_i \longrightarrow \bar{l}\phi$$
$$\epsilon = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \quad (2)$$

- Complex Yukawa Matrix is the source of natural CP violation.
- Lepton asymmetry is converted to violation Baryon asymmetry.

Inverse seesaw ISS(2,3) framework

Inverse seesaw ISS(2,3) framework

- The Standard Model is extended by the sequential addition of 2 RH neutrinos and 3 SM singlet fermions s_i

$$L = -\frac{1}{2} n_L^T C m n_L + h.c \tag{3}$$

The mass matrix in the basis $n_L = (\nu_L, N_R, s)$

$$m = \begin{pmatrix} 0 & M_d^T & 0 \\ M_d & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}$$

$$\|\mu\| \leqslant \|M_d\|, \|M\| \tag{4}$$

[Abada, A. and Lucente M., Looking for the minimal inverse seesaw realisation, Nucl. Phys. B 885 (2014) 651]

Contd..

ISS realisation is characterized by the following mass spectrum

- Three light active states with masses in sub-eV range.
- $\# N_R$ pairs of quasi-Dirac particles.
- $\#$ s$-\#\ \nu_R$ light sterile states (present only if $\#\text{s} > \# N_R$) with masses $\mathcal{O}(\mu)$
- The matrix can be block diagonalized to light and heavy sector as

$$M_\nu \approx M_d^T (M_N^T)^{-1} \mu M_N^{-1} M_d \tag{5}$$

$$M_H = \begin{pmatrix} 0 & M_N \\ M_N^T & \mu \end{pmatrix}$$

[Abada, A. et al, Dark Matter in the minimal Inverse Seesaw mechanism. JCAP, 2014(10):001, 2014]

Texture zeros in ISS(2,3)

Texture zeros in ISS(2,3)

Three matrices M_d,M_N and μ!!
The twelve $2-0$ textures of M_d in the framework of ISS $(2,3)$ are shown below:

2-0 textures of M_d		
$M_d^{(1)} = \begin{pmatrix} 0 & c & e \\ b & 0 & h \end{pmatrix}$	$M_d^{(2)} = \begin{pmatrix} a & 0 & e \\ 0 & d & h \end{pmatrix}$	$M_d^{(3)} = \begin{pmatrix} a & c & 0 \\ b & 0 & h \end{pmatrix}$
$M_d^{(4)} = \begin{pmatrix} a & 0 & e \\ b & d & 0 \end{pmatrix}$	$M_d^{(5)} = \begin{pmatrix} 0 & c & e \\ b & d & 0 \end{pmatrix}$	$M_d^{(6)} = \begin{pmatrix} a & c & 0 \\ 0 & d & h \end{pmatrix}$
$M_d^{(7)} = \begin{pmatrix} 0 & 0 & e \\ b & d & h \end{pmatrix}$	$M_d^{(8)} = \begin{pmatrix} a & c & e \\ 0 & 0 & h \end{pmatrix}$	$M_d^{(9)} = \begin{pmatrix} 0 & c & 0 \\ b & d & h \end{pmatrix}$
$M_d^{(10)} = \begin{pmatrix} a & c & e \\ 0 & d & 0 \end{pmatrix}$	$M_d^{(11)} = \begin{pmatrix} a & c & e \\ b & 0 & 0 \end{pmatrix}$	$M_d^{(12)} = \begin{pmatrix} a & 0 & 0 \\ b & d & h \end{pmatrix}$

Table: Possible two zero textures of M_d in ISS(2,3)

[Gautam, N. and Das, M.K., Impact of texture zeros on dark matter and neutrinoless double beta decay in inverse seesaw, NPB 971(2021)115519]

Texture zeros in ISS(2,3)

The two zero textures of the Dirac mass matrix M_D can be further classified to

$$A1 = \begin{pmatrix} 0 & c & e \\ b & 0 & h \end{pmatrix}; A2 = \begin{pmatrix} a & 0 & e \\ b & d & 0 \end{pmatrix}; A3 = \begin{pmatrix} a & c & 0 \\ 0 & d & h \end{pmatrix} \quad (6)$$

$$B1 = \begin{pmatrix} a & c & e \\ 0 & 0 & h \end{pmatrix}; B2 = \begin{pmatrix} a & c & e \\ 0 & d & 0 \end{pmatrix}; B3 = \begin{pmatrix} a & c & e \\ b & 0 & 0 \end{pmatrix} \quad (7)$$

The textures A1, A2, and A3 lead to one zero texture of the neutrino mass matrix. The structures of M_N and μ are

$$M_N = \begin{pmatrix} f & 0 & 0 \\ 0 & g & 0 \end{pmatrix}, \ \mu = \begin{pmatrix} p & 0 & 0 \\ 0 & p & 0 \\ 0 & 0 & p \end{pmatrix} \quad (8)$$

Leptogenesis in ISS (2,3) framework

Governing equations for BAU calculation

- The BAU can be expressed as,

$$Y_B = c \sum_i \kappa_i \epsilon_i \tag{9}$$

where the value of c is 10^{-2}

The CP asymmetry generated by the decay of N_i into any lepton flavor can be obtained as,

$$\epsilon_i = \frac{1}{8\pi} \sum_{j \neq i} \frac{Im[(hh^\dagger)_{ij}]}{\sum_\beta |h_{i\beta}|^2} f^\nu_{ij} \tag{10}$$

where, $h_{i\alpha}$ represents effective Yukawa coupling in the diagonal mass basis. f^ν is given as,

$$f^\nu_{ij} = \frac{(M_j^2 - M_i^2) M_i \Gamma_j}{(M_j^2 - M_i^2)^2 + M_j^2 \Gamma_j^2} \tag{11}$$

- Γ_i represents decay width of the heavy-neutrino N_i.

$$\Gamma_i = \frac{M_i}{8\pi} (hh^\dagger)_{ii} \tag{12}$$

Contd...

The expressions for κ depending on the scale of the wash out factor K.

$$-\kappa \approx \sqrt{0.1K}\,\text{exp}[-4/(3(0.1K)^{0.25})], \quad \text{for} \quad K \geq 10^6 \tag{13}$$

$$\approx \frac{0.3}{K(\ln K)^{0.6}}, \quad \text{for} \quad 10 \leq K \leq 10^6 \tag{14}$$

$$\approx \frac{1}{2\sqrt{K^2+9}}, \quad \text{for} \quad 0 \leq K \leq 10. \tag{15}$$

where, the wash out factor K is,

$$K_i = \frac{\Gamma_i}{H(z=1)} = \frac{M_i}{8\pi}(hh^\dagger)_{ii} \times \frac{M_{Pl}}{1.66\sqrt{g*}M_i^2}$$

$H = 1.66\sqrt{g_*}\frac{M_i^2}{M_{pl}}$ with g_* approximately 110.

[Steve Blanchet, P. S. Bhupal Dev and R. N. Mohapatra,Leptogenesis with TeV Scale Inverse Seesaw in SO(10), Phys. Rev. D82, 115025 (2010).]

BAU in Invese Seesaw Model

In the (N_i, s_i) flavor basis, we have the 2×2 matrices a

$$\tilde{M}_i = \begin{pmatrix} 0 & M_{N_i} \\ M_{N_i} & \mu_{ii} \end{pmatrix} = \begin{pmatrix} 0 & M_{N_i} \\ M_{N_i} & \varepsilon_i M_{N_i} e^{i\theta_i} \end{pmatrix} \quad (16)$$

The M_i is diagonalized with real and positive eigenvalues by a unitary transformation $U_i^T M_i U_i$ where

$$U_i = \begin{pmatrix} -icos\alpha_i e^{i\theta_i/2} & sin\alpha_i e^{i\theta_i/2} \\ isin\alpha_i e^{-i\theta_i/2} & cos\alpha_i e^{-i\theta_i/2} \end{pmatrix}$$

and the mixing angles are given by

$$cos\alpha_i \simeq \frac{1}{\sqrt{2}}(1 + \frac{\varepsilon_i}{4}), sin\alpha_i \simeq \frac{1}{\sqrt{2}}(1 - \frac{\varepsilon_i}{4}) \quad (17)$$

The corresponding mass eigenvalues are given by

$$M_i \simeq M_{N_i}(1 \pm \frac{\varepsilon_i}{2}), (i = 1, 2; j = 1, 2, 3, 4) \quad (18)$$

BAU in Inverse Seesaw Model

The expressions for CP asymmetry for the decay of one of the quasi-Dirac particles (say i=1) in terms of the Yukawa couplings in flavor basis,

$$\epsilon_1 = \frac{1}{8\pi}\sum_{j\neq 1}\frac{Im[(hh^\dagger)_{1j}]}{\sum_\beta |h_{1\beta}|^2} f^\nu_{1j} = \frac{\varepsilon_2}{16\pi\sum_\beta |y_{1\beta}|^2} Im[e^{i(\theta_1-\theta_2)}\sum_\alpha y^*_{1\alpha}y_{2\alpha}]f^\nu_{13} \quad (19)$$

$$\epsilon_2 = \frac{1}{8\pi}\sum_{j\neq 2}\frac{Im[(hh\dagger)^2_{2j}]}{\sum_\beta |h_{1\beta}|^2} f_{2j^v} \simeq \frac{\varepsilon_2}{16\pi\sum |y_{1\beta}|^2} Im[ie^{i(\theta_1-\theta_2)}(\sum y^*_{1\alpha}y_{2\alpha})^2]f^v_{23} \quad (20)$$

Here, $\varepsilon_i = \frac{\mu_{ii}}{M_{Ni}} << 1$.

[Blanchet S. et al, Leptogenesis with TeV Scale Inverse Seesaw in SO(10), Phys. Rev.D82, 115025 (2010).]

Contd...

In our model $M_{N_1} = f$, $M_{N_2} = g$,$\mu_{11} = \mu_{22} = p$ and thus it leads to the diagonalising matrix of M in our model as

$$U_1 = \begin{pmatrix} -\frac{1}{2f}(p + \sqrt{4f^2 + p^2}) & 1 \\ -\frac{1}{2f}(p - \sqrt{4f^2 + p^2}) & 1 \end{pmatrix} \tag{21}$$

$$U_2 = \begin{pmatrix} -\frac{1}{2g}(p + \sqrt{4g^2 + p^2}) & 1 \\ -\frac{1}{2g}(p - \sqrt{4g^2 + p^2}) & 1 \end{pmatrix} \tag{22}$$

Contd..

The expressions for α_1 and α_2 are obtained as,

$$cos\alpha_1 \simeq \frac{1}{\sqrt{2}}(1+\frac{p}{4f}), sin\alpha_1 \simeq \frac{1}{\sqrt{2}}(1-\frac{p}{4f}) \tag{23}$$

$$cos\alpha_2 \simeq \frac{1}{\sqrt{2}}(1+\frac{p}{4g}), sin\alpha_2 \simeq \frac{1}{\sqrt{2}}(1-\frac{p}{4g}) \tag{24}$$

Comparing these matrices arising from our model with the previous equation and with further simplifications, we obtain the expressions for $e^{i(\theta_1-\theta_2)}$ as,

$$e^{i(\theta_1-\theta_2)} = \frac{32fg}{(4g+p)(4f-p)} \tag{25}$$

[Gautam N.,Das M.K., Neutrino mass, leptogenesis and sterile neutrino dark matter in inverse seesaw framework, International Journal of Modern Physics A 36(2021) 2150146.]

Numerical Analysis

- The light neutrino mass matrix can be written as,

$$M_\nu = U_{\text{PMNS}} M_\nu^{\text{diag}} U_{\text{PMNS}}^T \tag{26}$$

where $U_{PMNS} = U.P$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

where $c_{ij} = cos\theta_{ij}$ and $s_{ij} = sin\theta_{ij}$. $P = diag(1, e^{\frac{i\alpha_{21}}{2}}, e^{\frac{i\alpha_{31}}{2}})$

- The diagonal mass matrix of the light neutrinos can be written as, $m_\nu^{\text{diag}} = \text{diag}(0, \sqrt{m_1^2 + \Delta m_{solar}^2}, \sqrt{m_1^2 + \Delta m_{atm}^2})$ for normal hierarchy and $m_\nu^{\text{diag}} = \text{diag}(\sqrt{m_3^2 + \Delta m_{atm}^2}, \sqrt{\Delta m_{solar}^2 + \Delta m_{atm}^2}, m_3)$ for inverted hierarchy.

Contd...

Oscillation parameters	3σ(NO)	3σ(IO)
$\frac{\Delta m^2_{21}}{10^{-5}eV^2}$	6.81 - 8.03	6.81 - 8.03
$\frac{\Delta m^2_{31}}{10^{-3}eV^2}$	2.43 - 2.60	2.40-2.58
$sin^2\theta_{12}$	0.275- 0.344	0.275- 0.344
$sin^2\theta_{23}$	0.407 - 0.620	0.407 - 0.623
$sin^2\theta_{13}$	0.0203 - 0.0239	0.0204 - 0.0239
$\frac{\delta}{\pi}$	0.87 - 1.94	1.12- 1.94

Table I:Latest Global Fit Neutrino Oscillation Data.[NuFIT 5.3 (2024)]

Results and Discussion

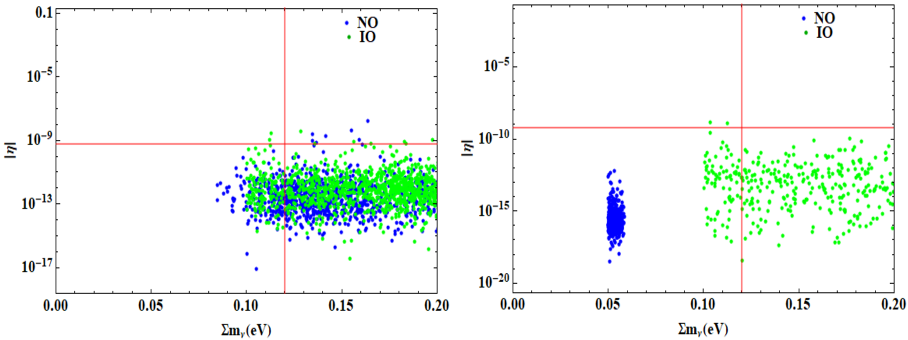


Figure: BAU as a function of sum of neutrino masses in NO and IO for textures A1 and A2. The horizontal red line represents the Planck limits on BAU.

[Gautam, N., Das., M. K.; Phys.Lett.B 833 (2022) 1373021]

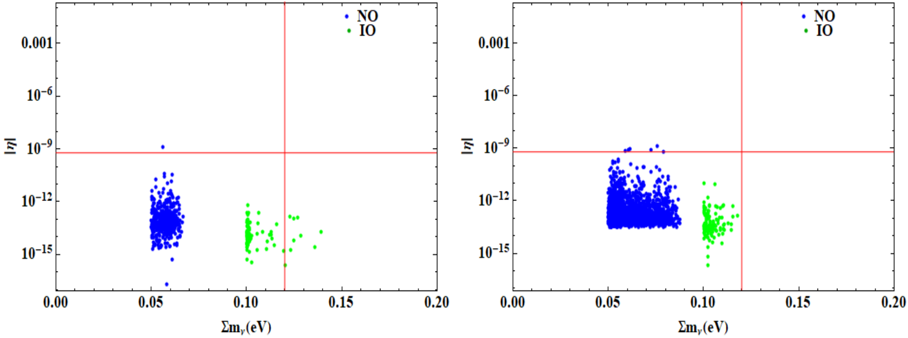
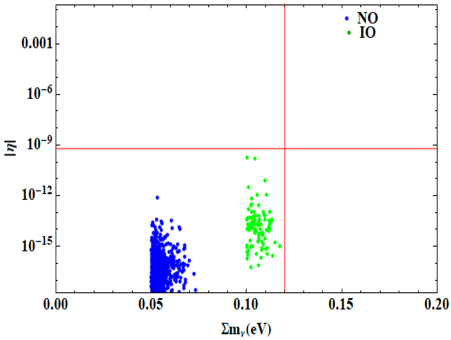


Figure: BAU as a function of the sum of neutrino masses in class in A3 and B1. The horizontal red line represents the Planck limits on BAU.

[Gautam, N., Das., M. K.; Phys.Lett.B 833 (2022) 1373021]



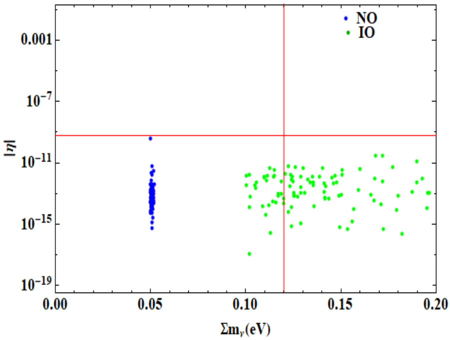


Figure: BAU as a function of the sum of neutrino masses in class the classes B2 and B3. The horizontal red line represents the Planck limits on BAU.

[Gautam, N., Das., M. K.; Phys.Lett.B 833 (2022) 1373021]

Discussion

- A1 leads to the BAU that is consistent with the latest cosmology data. A small space is available that agrees with both the experimental data on mass-squared differences and the current cosmological bound.
- A2 does not yield the observed BAU in the case of NO. However, the texture A2 in ISS(2,3) can lead to the observed BAU in IO.
- In A3, a small parameter space is available that agrees with both the limits in NO. This texture can yield BAU in IO as well.

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- In A3, a small parameter space is available that agrees with both the limits in NO. This texture can yield BAU in IO as well.

Discussion

- Texture B1 can lead to the correct BAU in NO and does not yield the observed BAU in the case of IO.
- The amount of BAU obtained in B2 is quite less than the observed values in both cases.
- The texture B3 in NO is good in the prediction of the observed BAU. However, a small parameter space of B3 is in good agreement with the upper limits on the sum of the light neutrino masses.

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- We have studied the effect of two zero textures of Dirac mass matrix M_d on leptogenesis in the framework of inverse seesaw ISS(2,3).
- The textures A1, A3, B1, and B3 in NO give rise to the observed baryon asymmetry. The other three textures in NO are not in agreement with the current cosmological limit on BAU.

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- One can obtain the required BAU in A1, A2 in IO

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- One can obtain the required BAU in A1, A2 in IO
- B2 fails to explain the required BAU in both NO and IO
- All the textures are in good agreement with the current cosmological limit on the sum of the light neutrino masses.

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Thank you!!!

Extra slides

The Yukawa couplings in this diagonal mass basis are related to the couplings in the flavor basis as follows:

$$\begin{aligned} h_{1\alpha} &\simeq \frac{ie^{-i\theta_1}}{\sqrt{2}}(1+\frac{\epsilon_1}{4})y_{1\alpha} \\ h_{2\alpha} &\simeq \frac{e^{-i\theta_1}}{\sqrt{2}}(1-\frac{\epsilon_1}{4})y_{1\alpha} \\ h_{3\alpha} &\simeq \frac{ie^{-i\theta_2}}{\sqrt{2}}(1+\frac{\epsilon_2}{4})y_{2\alpha} \\ h_{4\alpha} &\simeq \frac{e^{-i\theta_2}}{\sqrt{2}}(1-\frac{\epsilon_2}{4})y_{2\alpha} \end{aligned} \tag{27}$$

[Blanchet S. et al, Leptogenesis with TeV Scale Inverse Seesaw in SO(10), Phys. Rev.D82, 115025 (2010).]