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Baryogenesis in minimal inverse seesaw using modular symmetry

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Abstract. In this work we have studied leptogenesis by extending the minimal inverse seesaw, ISS(2,3) with a scalar triplet $\eta = (\eta_1, \eta_2, \eta_3)$. ISS(2,3) contains two right-handed neutrinos (N_1, N_2) and three gauge singlet sterile fermions (S_1, S_2, S_3). The A_4 modular symmetry group used in the work has three Yukawa modular forms i.e. $Y = (y_1, y_2, y_3)$ of weight 2. Unlike discrete flavor symmetry, modular flavor symmetry has the potential to reduce the number of extra flavons which are required in the model. Moreover one does not have to worry about the VEV alignments of these extra flavons. We have also used Z_3 symmetry in constructing the lagrangian of the model. Furthermore the latest 3σ nu-fit values of neutrino oscillation parameters play a significant role in the calculations. We find that the model is successful in producing the value of BAU as observered by Planck collaboration.

1. Introduction

The only particle in Standard Model which motivates physicists to go beyond this standard framework is neutrino. The phenomena of neutrino oscillation confirmed that it should have mass and also its mixing among different flavors. Without a right-handed counterpart it is difficult to explain this mass of neutrino within the Standard Model. Moreover even with the right-handed neutrinos the Yukawa couplings have to be very small to generate the tiny mass. Another important phenomena observed in the universe is Baryon asymmetry. Physicists believe that there is an asymmetry between matter and anti-matter in the universe. Several cosmological observations which point to this imbalance justifies the idea of asymmetry in the universe. This inequality in their numbers is termed as Baryon Asymmety of the Universe (BAU). As the Standard Model fails to provide an explanation to this phenomena of asymmetry, people have opted for frameworks which are basically an extension of the Standard Model by adding new particles to it. For a successful explanation of baryon asymmetry the three Sakharov conditions have to be fulfilled. These conditions are: (i) B violation (ii) C and CP violation (iii) out of thermal equilibrium decay [1]. As given in literatures [2, 3, 4], one of the possible explanations is baryogenesis via leptogenesis. Accordingly the heavy fermions decay into light Standard Model fermions, thereby creating an asymmetry in the leptonic sector, which can be converted into baryon asymmetry by the sphaleron processes. Currently the value of this asymmetry as obtained from Planck data is:

$$\eta_B = (6.04 \pm 0.08) \times 10^{-10} \tag{1}$$

One of the popular Beyond the Standard Model frameworks which can provide a possible explanation to these phenomena is Inverse Seesaw. In this mechanism the Standard Model is

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extended by adding three singlet right-handed neutrinos and three gauge singlet sterile fermions. The mass of right-handed neutrinos and sterile fermions in TeV and KeV, respectively, helps to generate sub-eV mass of the active neutrinos. As discussed in [5], the mass of right-handed neutrinos affect the scale of leptogenesis. The decay of heavy neutrinos present in this framework provides a way to explain the asymmetry in the universe. As mentioned earlier, one can convert the asymmetry generated by the out-of-equilibrium decay of the heavy neutrinos into baryon asymmetry through the sphaleron processes [6, 7]. The lagrangian for this mechanism in the basis $n_L = (\nu_{L,\alpha}, N^c_{R,i}, S_j)^T$ can be written as:

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

From the above lagrangian we can write the 9×9 neutrino mass matrix ($\mathcal{M}$) for inverse seesaw as:

$$\mathcal{M} = \begin{pmatrix} 0 & M_D^T & 0 \\ M_D & 0 & M_{NS} \\ 0 & M_{NS}^T & M_S \end{pmatrix}_{9\times9}, \quad M_H = \begin{pmatrix} 0 & M_{NS} \\ M_{NS}^T & M_S \end{pmatrix} \tag{3}$$

where M_H is the mass matrix for the heavy sector. Unlike the inverse seesaw, there are two right-handed neutrinos in the framework of ISS(2,3). An important aspect of model building is the choice of symmetry. In this regard, in recent times modular symmetry has gained much importance because of certain advantages it has over discrete flavor symmetries [8]. As mentioned earlier, modular symmetry helps to reduce the number of flavons used in a model. Moreover one can get away from their VEV alignments, keeping the particle content minimal. In this symmetry the Yukawa couplings are functions of the complex variable τ, which is referred to as the complex modulus. The modular group $\Gamma(N)$ acts on the upper half of the complex plane (Imτ>0) and transforms the modulus in the following way:

$$\tau \rightarrow \frac{a\tau + b}{c\tau + d}$$

where a, b, c, d are the elements of a 2×2 matrix, such that $ad - bc = 1$. This work is based on $\Gamma(3)$ modular group. It is a level 3 modular group and is isomorphic to the discrete non-abelian symmetry group A_4. For a detailed study on modular symmetry one can refer to [9, 10, 11, 12]. In this work we have studied baryon asymmetry of the universe in minimal inverse seesaw. We find that the model is able to produce the allowed value of BAU as given by Planck data.

2. The Model

This work is based on minimal inverse seesaw mechanism which has two right-handed neutrinos (N_1, N_2) and three Standard Model gauge singlet sterile fermions (S_1, S_2, S_3). We have extended the particle content by adding an extra scalar triplet, $\eta = (\eta_1, \eta_2, \eta_3)$. The lagrangian of the model has been constructed using A_4 modular group. The three Yukawa modular forms of weight 2, $Y = (y_1, y_2, y_3)$ present in the group play a significant role in this process. Accordingly under group A_4, the right-handed neutrinos N_1 and N_2 transform as $1'$ and $1''$; sterile fermions (S_i), lepton doublets (L) and η transform as triplets. The flavon ϕ is used to get a diagonal mass matrix for the charged leptons without affecting the neutrino sector. These charge assignments have been highlighted in table 1.

In the table below, K_I denotes the modular weights of the particles. Moreover Z_3 symmetry group in the model restricts certain interactions among the particles. After symmetry breaking

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Table 1. Charge assignments of particles under the groups considered in the model.

Fields	L	N_1	N_2	S_i	H	ϕ	η	Y
A_4	3	$1'$	$1''$	3	1	1	3	3
Z_3	ω^2	ω	ω	1	ω	ω	ω	ω^2
K_I	0	-2	-2	0	0	2	0	2

one of the η's acquire VEV (vacuum expectation value) as $\eta = v_\eta(1,0,0)$. Taking into account the different charge assignments of particles, the Yukawa lagrangian of the model is found to be:

$$\begin{aligned}\mathcal{L} &= \alpha_1 E_1^c H_d (L\phi)_1 + \alpha_2 E_2^c H_d (L\phi)_{1'} + \alpha_3 E_3^c H_d (L\phi)_{1''} \\ &+ N_1(LY)_3\eta + N_2(LY)_3\eta + \beta_1 N_1 (SY)_{1''} + \beta_2 N_2 (SY)_{1'} + \mu_0 (SS)_1\end{aligned} \tag{4}$$

The first line in eq. (4) represents the charged leptons mass terms. The first two terms in the second line are for Dirac mass of the neutrinos (M_D) and the next two terms denote the mixing between right-handed neutrinos and sterile fermions (M_{NS}). The final term in the equation repesents the mass of sterile neutrinos (M_S). β_1 and β_2 are the weightons and are associated with the right-handed neutrino masses. They play a role similar to that of flavons. A brief discussion about them can be found in [13, 14] The order of Dirac mass matrix M_D is 3×2, M_{NS} is 2×3 and for the sterile neutrino (M_S) it is 3×3. With these matrices one can express the mass matrix of the active neutrinos. For ISS(2,3) this matrix takes the form as given below [15, 16]:

$$m_\nu = M_D.d.M_D^T \tag{5}$$

d in eq. (5) is a 2×2 matrix which is obtained from the inverse of heavy mass matrix M_H,

$$M_H^{-1} = \begin{pmatrix} 0 & M_{NS} \\ M_{NS}^T & M_S \end{pmatrix}^{-1} = \begin{pmatrix} d_{2\times 2} & ..... \\ ...... & ..... \end{pmatrix} \tag{6}$$

The matrix in eq. (5) can be diagonalised with a unitary matrix to find the values of model parameters. With the help of these parameter values we can study the related neutrino phenomenologies.

3. Baryogenesis

Baryon asymmetry is one of the unsolved mysteries of the universe. One of the ways to explain this asymmetry is baryogenesis via leptogenesis. Among its different types, our work is based on resonant leptogenesis which can be found in numerous literature. In minimal inverse seesaw generation of this asymmetry is attributed to the decay of heavy right-handed neutrinos. ISS(2,3) has five heavy neutrinos: two right-handed neutrinos and three sterile neutrinos. Among these heavy particles, four of them form two pairs, say (N_i, S_i). The masses of these two particles are almost degenerate. This slight mass difference is controlled by the Majorana term M_S. Due to this reason, they are called quasi-Dirac pair. After formation of these pairs, the lightest pair decays into Standard Model leptons and an asymmetry is generated in the leptonic sector. This asymmetry created in the leptonic sector is then converted into baryon asymmetry via the sphaleron process. Moreover the asymmetry produced because of the decay of the heavy pair is washed out. In order to calculate the CP-asymmetry in the leptonic sector we need a basis where the matrix M_H is diagonal. The lagrangian in this basis changes into:

$$\mathcal{L_S} = h_{i\alpha} N_i \eta L_\alpha + M_i N_i^T C^{-1} N_i + h.c. \tag{7}$$

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In the above equation $h_{i\alpha}$'s are the couplings in the diagonal basis. The relation between these couplings in mass eigenstates to the flavor states are given in [17, 18]. The CP-asymmetry for the decay of a heavy fermion i.e. $\psi_i \to l_\alpha \eta$ $(\bar{l_\alpha}\eta)$ into leptons is given by the following expression [19]:

$$\epsilon_i = \frac{\sum_\alpha[\Gamma(\tilde{\psi} \to l_\alpha \eta) - \Gamma(\tilde{\psi} \to \bar{l_\alpha}\eta^\dagger)]}{\sum_\alpha[\Gamma(\tilde{\psi} \to l_\alpha \eta) + \Gamma(\tilde{\psi} \to \bar{l_\alpha}\eta^\dagger)]} = \frac{1}{8\pi}\sum_{i\neq j}\frac{Im[(hh^\dagger)^2_{ij}]}{(hh^\dagger)_{ii}} f_{ij} \tag{8}$$

f_{ij} is the self energy correction for Majorana particles. Moreover the dominant contribution to CP-asymmetry comes from the self-energy diagram. Γ in the above expression represents the decay width corresponding to the lightest quasi-Dirac pair. Thus the final expression for BAU takes the form:

$$Y_B = 10^{-2}\sum \kappa_i \epsilon_i \tag{9}$$

In eq. (9) k_i denotes the dilution factor and 10^{-2} is the relativistic number density of the fermions which is normalised to entropy density, s. The values of k_i is dependent on the washout factor associated with the decay of the heavy pair. Also it is worth mentioning that washout comes from scattering also. This can be attributed to inverse decay and L number violating scatterings of the lightest ψ. Due to mass degeneracy of the decaying particles, it has contribution from both these channels. But these contributions cancel each other and has no relevance for the final asymmetry.

4. Results and discussions

In order to determine the values of model parameters we have diagonalised the mass matrix for light neutrinos using the unitary PMNS mixing matrix, U_{PMNS}. For this we have used the latest 3σ values of the oscillation parameters [20].

$$m_\nu = U^T_{PMNS}\text{diag}(m_1, m_2, m_3)U_{PMNS} \tag{10}$$

By equating the corresponding elements in eq. (10) we can determine the values of the parameters. m_1, m_2, m_3 are the mass eigenvalues of the three active neutrinos. These eigenvalues can be expressed in terms of atmospheric and solar mass squared differences for both the hierarchies. As a result for normal hierarchy diag(m_1, m_2, m_3)=diag$(0, \sqrt{m_1^2 + \Delta m^2_{solar}}, \sqrt{m_1^2 + \Delta m^2_{atm}})$ whereas for inverted hierarchy it becomes diag(m_1, m_2, m_3)=diag$(\sqrt{m_3^2 + \Delta m^2_{atm}}), \sqrt{\Delta m^2_{atm} + \Delta m^2_{solar}}, 0)$. For further calculations we have used the following values: v_η is taken in the range (30-50) GeV, β_1 and β_2 are considered in the range $[10^2, 10^3]$ GeV and $[10^6, 10^7]$ GeV. The coupling for sterile neutrinos (μ) is taken to be (30-40) KeV. The real part of τ lies in the range: Re$(\tau)\to$[-0.9, 0.9] and its imaginary part is :Im$(\tau)\to$[0.2, 4]. In table (2) we show the values of the Yukawa modular forms for both inverted and normal hierarchies.

Table 2. Values of the Yukawa modular forms.

Yukawa couplings	Normal Hierarchy	Inverted Hierarchy
$\lvert y_1 \rvert$	0.91 - 2.5	0.93 - 1.8
$\lvert y_2 \rvert$	0.5 - 1.4	0.01 - 0.7
$\lvert y_3 \rvert$	0.2 - 0.8	0.03 - 0.6

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Next we find the CP-asymmetry for calculating Baryon asymmetry of the universe. For this we use eq. (8). And finally the value of BAU is evaluated from eq. (9). It is found that there are sufficient values of BAU that is found to lie in the allowed Planck limit. Fig. (1) and (2) show the relations between BAU and lightest right-handed neutrino M_1. It is clear from the figures that for normal hierarchy the values of BAU lies from 10^4 GeV to 10^7 GeV of M_1 whereas for inverted hierarchy this region is found to lie in between 10^5 to 10^7 GeV.

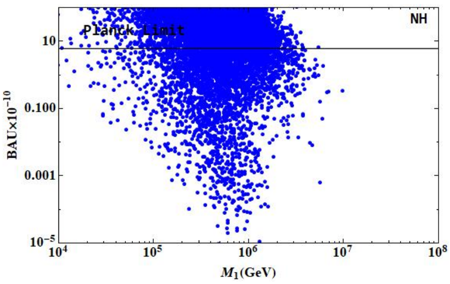

Figure 1. Corelation between M_1 and BAU for normal hierarchy.

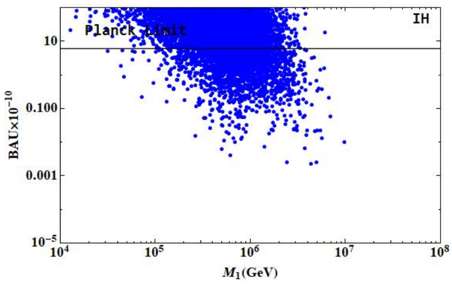

Figure 2. Corelation between M_1 and BAU for inverted hierarchy.

5. Conclusion

We have carried out this work in the minimal inverse seesaw mechanism where we have used the A_4 modular group to construct the desired lagrangian. Due to the use of modular symmetry, number of flavons used in the work have been reduced. As such we have used only a single flavon ϕ to get a diagonal charged lepton mass matrix. The neutrino sector remains unaffected by this flavon. Moreover Z_3 symmetry group also plays a significant role in constructing the lagrangian of the model. We find that the values of complex modulus τ lies within the fundamental domain, Re(τ)→[-0.9, 0.9] and Im(τ)→[0.2, 4]. For leptogenesis we calculate the CP-asymmetry associated with the decay of the lightest quasi-Dirac pair. Finally we calculate the value of BAU from our model. It is found that there are sufficient values which lie in the allowed Planck value of BAU, thereby justifying its validity.

References

[1] Sakharov A D 1967 *Pisma Zh. Eksp. Teor. Fiz.* **5** 32–35
[2] Kolb E W and Wolfram S 1980 *Phys. Lett. B* **91** 217–221
[3] Barbieri R, Creminelli P, Strumia A and Tetradis N 2000 *Nucl. Phys. B* **575** 61–77
[4] Pilaftsis A and Underwood T E J 2005 *Phys. Rev. D* **72** 113001
[5] Alanne T, Hugle T, Platscher M and Schmitz K 2019 *JCAP* **03** 037
[6] Trodden M 2004 *eConf* **C040802** L018
[7] Kolb E W and Turner M S 1990 vol 69 ISBN 978-0-201-62674-2
[8] Feruglio F 2019 pp 227–266 (*Preprint* 1706.08749)
[9] Nomura T, Okada H and Patra S 2021 *Nucl. Phys. B* **967** 115395
[10] Nomura T and Okada H 2020 (*Preprint* 2007.15459)
[11] Novichkov P P, Penedo J T, Petcov S T and Titov A V 2019 *JHEP* **07** 165
[12] Gogoi J, Gautam N and Das M K 2023 *Int. J. Mod. Phys. A* **38** 2350022
[13] Behera M K and Mohanta R 2022 *Front. in Phys.* **10** 854595
[14] Behera M K and Mohanta R 2022 *J. Phys. G* **49** 045001
[15] Abada A, Arcadi G, Domcke V and Lucente M 2017 *JCAP* **12** 024
[16] Abada A, Arcadi G and Lucente M 2014 *JCAP* **10** 001
[17] Chakraborty I, Roy H and Srivastava T 2022 *Nucl. Phys. B* **979** 115780
[18] Covi L, Roulet E and Vissani F 1996 *Phys. Lett. B* **384** 169–174
[19] Agashe K, Du P, Ekhterachian M, Fong C S, Hong S and Vecchi L 2019 *JHEP* **04** 029
[20] Esteban I, Gonzalez-Garcia M C, Maltoni M, Schwetz T and Zhou A 2020 *JHEP* **09** 178