Chapter 18
keV Sterile Neutrino Mass Model and Related Phenomenology

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Abstract We study a model of *keV* scale sterile neutrino within the framework of a minimal extended seesaw and check its effect on neutrinoless double beta decay ($\nu\beta\beta$) study. This framework is based on A_4 flavour symmetry and the discrete $Z_4 \times Z_3$ symmetry to stabilize the model and construct desired mass matrices for neutrino mass. We use a non-trivial Dirac mass matrix with broken $\mu - \tau$ symmetry to generate the leptonic mixing. A non-degenerate mass structure for right-handed neutrinos is considered to verify the observed baryon asymmetry of the universe via the mechanism of thermal leptogenesis.

18.1 Introduction

In this work, we have considered a sterile neutrino flavour with mass in the *keV* range under minimal extended seesaw (MES) [1], where an additional fermion singlet (sterile neutrino) is added along with three RH neutrinos. A sterile neutrino can affect the electron energy spectrum in tritium β-decays, and we have studied the influence of a *keV* scale sterile neutrino in the effective mass spectrum. Typically, sterile neutrinos with mass (0.4–50) *keV* are considered WIMP particles since they are relatively slow and much heavier than active neutrinos. In fact, to successfully observe $0\nu\beta\beta$, the upper bound for sterile neutrino mass should be 18.5 *keV*. Hence, we have chosen a mass range for the *keV* regime sterile neutrino within (1–18.5) *keV*. The study of *keV* sterile neutrino as a dark matter candidate has skipped in this study and can be found in [2]. It is well know that our universe is matter-dominated, and there is an asymmetry in the baryon number that is observed. Baryogenesis is a process that explains the scenario of baryon asymmetry of the universe (BAU). Numerical definition for baryon asymmetry at current date reads as, $Y_{\Delta B}\left(\equiv \frac{n_B - n_{\overline{B}}}{s}\right) = (8.75 \pm 0.23) \times 10^{-11}$[3]. The SM does not have enough ingredients (Shakarov conditions) to explain this

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Table 18.1 Particle content and their charge assignments under SU(2), A_4 and $Z_4 \times Z_3$ groups for NH mode

Particles	l	e_R	μ_R	τ_R	H_1	H_2	ζ	φ	ξ	ξ'	ν_{R1}	ν_{R2}	ν_{R3}	S	χ
SU(2)	2	1	1	1	2	2	1	1	1	1	1	1	1	1	1
A_4	3	1	$1''$	$1'$	1	1	3	3	1	$1'$	1	$1'$	1	$1''$	$1'$
Z_4	1	1	1	1	1	i	1	i	1	−1	1	−i	−1	i	−i
Z_3	1	1	1	1	1	1	1	1	1	1	1	1	1	ω^2	ω

asymmetry. Hence, we have to go beyond the SM framework to explain baryogenesis. Several popular mechanisms explain baryogenesis, and thermal leptogenesis is one of the most convenient and economical ways. In thermal leptogenesis, the decay of the lightest right-handed (RH) neutrino to a lepton doublet and a Higgs doublet produces sufficient lepton asymmetry, which is then converted into baryon asymmetry. Here, we have attempted to verify baryogenesis produced via the mechanism of thermal leptogenesis within our model, and finally correlate baryogenesis and $0\nu\beta\beta$ under the same framework.

18.2 Model Framework

Apart from the type-I seesaw particle content, few extra flavons are added to construct the model. Two triplets $\zeta and \varphi$ and two singlets ξ and ξ' are added to produce broken flavour symmetry. Besides the SM Higgs H_1, we have also introduced additional Higgs doublets (H_2) to make the model work. Non-desirable interactions were restricted using extra Z_4 and Z_3 charges to the fields. To accommodate sterile neutrino into the framework, we add a chiral gauge singlet S, which interacts with the RH neutrino ν_{R1} via A_4 singlet ($1'$) flavon χ to give rise to sterile mixing matrix. We used dimension-5 operators for Dirac neutrino mass generation. The particle content with $A_4 \times Z_4 \times Z_3$ charge assignment under NH are shown in the Table 18.1. In lepton sector, the leading order invariant Yukawa Lagrangian is given by,

$$\begin{aligned}\mathcal{L} \supset\ & \tfrac{y_2}{\Lambda}(\bar{l}\tilde{H}_1\zeta)_1\nu_{R1} + \tfrac{y_2}{\Lambda}(\bar{l}\tilde{H}_1\varphi)_{1''}\nu_{R2} + \tfrac{y_3}{\Lambda}(\bar{l}\tilde{H}_2\varphi)_1\nu_{R3} \\ & \tfrac{y_1}{\Lambda}(\bar{l}\tilde{H}_1\zeta')_1\nu_{R1} + \tfrac{y_1}{\Lambda}(\bar{l}\tilde{H}_1\varphi')_{1''}\nu_{R2} + \tfrac{y_1}{\Lambda}(\bar{l}\tilde{H}_2\varphi')_1\nu_{R3} \\ & +\tfrac{1}{2}\lambda_1\xi\overline{\nu^c_{R1}}\nu_{R1} + \tfrac{1}{2}\lambda_2\xi'\overline{\nu^c_{R2}}\nu_{R2} + \tfrac{1}{2}\lambda_3\xi\overline{\nu^c_{R3}}\nu_{R3} + \tfrac{1}{2}\rho\chi\overline{S^c}\nu_{R1}.\end{aligned} \tag{18.1}$$

In this Lagrangian, various Yukawa couplings are represented by y_i, λ_i (for $i = 1, 2, 3$) and ρ for respective interactions. Λ is the cut-off scale of the theory, which is around the GUT scale. The scalar flavons involved in the Lagrangian acquire VEV along $\langle\zeta\rangle = (v, 0, 0)$, $\langle\varphi\rangle = (v, v, v)$, $\langle\xi\rangle = \langle\xi'\rangle = v$ and $\langle\chi\rangle = v_\chi$ by breaking the flavour symmetry, while $\langle H_i\rangle (i = 1, 2)$ get VEV (v_i) by breaking EWSB at electroweak scale. We have added a perturbation to the Dirac mass matrix to break the trivial

$\mu - \tau$ symmetry in the light neutrino mass matrix so that we can get non-zero reactor mixing angle.[1] The Lagrangian for the perturbative matrix is given by the second line of Eq. (18.1). New $SU(2)$ singlet flavon fields (ζ' and φ') are considered and supposed to take $A_4 \times Z_4 \times Z_3$ charges as same as ζ and φ respectively. After breaking flavour symmetry, they acquire VEV along $\langle\zeta'\rangle = (v_p, 0, 0)$ and $\langle\varphi'\rangle = (0, v_p, 0)$ directions, giving rise to the M_P matrix.

18.2.1 Neutrino Mass and Mixing Angles

Minimal extended seesaw(MES) is realized in this work to construct active and sterile masses. Under MES framework, the active and sterile masses are realized as follows:

$$m_\nu \simeq M_D M_R^{-1} M_S^T (M_S M_R^{-1} M_S^T)^{-1} M_S (M_R^{-1})^T M_D^T - M_D M_R^{-1} M_D^T, \tag{18.2}$$

$$m_s \simeq -M_S M_R^{-1} M_S^T. \tag{18.3}$$

The mass scale of M_S being slightly higher than the M_D scale, which is near to the EW scale, while M_R is around 10^{13} GeV.

A fixed non-degenerate values for the right-handed neutrino mass parameters as $R_1 = 5 \times 10^{12}$ GeV, $R_2 = 10^{13}$ GeV and $R_3 = 5 \times 10^{13}$ GeV are assigned in such a fashion that they can demonstrate favourable thermal leptogenesis without effecting the neutrino parameters. The mass matrix generated from Eq. (18.2) gives rise to complex parameters due to the presence of Dirac and the Majorana phases. As the leptonic CP phases are still unknown, we vary them within their allowed 3σ ranges $(0, 2\pi)$. Since we have included one extra generation of neutrino along with the active neutrinos in our model, thus the final neutrino mixing matrix for the active-sterile mixing takes 4×4 form as

$$V \simeq \begin{pmatrix} (1 - \frac{1}{2} W W^\dagger) U_{PMNS} & W \\ -W^\dagger U_{PMNS} & 1 - \frac{1}{2} W^\dagger W \end{pmatrix}, \tag{18.4}$$

here, U is the unitary PMNS matrix and $W = M_D M_R^{-1} M_S^T (M_S M_R^{-1} M_S^T)^{-1}$ is a 3×1 matrix governed by the strength of the active-sterile mixing, i.e., the ratio $\frac{\mathcal{O}(M_D)}{\mathcal{O}(M_S)}$. Using MES, the mass matrices obtained for active neutrinos and active-sterile mixing elements are shown in Table 18.2. Respective interaction terms from the Lagrangian 18.1 are parametrized as D_1, D_2, R_1, R_2, R_3, P and G to minimize the complexity. We have solved the model parameters of the active mass matrix using current global fit 3σ values for the light neutrino parameters and carried out our analysis accordingly.

[1] When the $m_{\mu\mu}$ and $m_{\tau\tau}$ positions in the light neutrino mass matrix are same, one cannot achieve non-zero reactor mixing angle (θ_{13}). Recently, it was found that the reactor mixing angle have non-zero value, $\theta_{13} = 8.5° \pm 0.2°$.

Table 18.2 The active and sterile neutrino mass matrices and corresponding Dirac (M_D), Majorana(M_R) and sterile(M_S) mass matrices for NH and IH mode. The active-sterile mixing matrices (W) and sterile mass for NH and IH mass pattern are also shown in respective columns

Matrices	Mass structures
Normal Heirarchy $M_R = \begin{pmatrix} R_1 & 0 & 0 \\ 0 & R_2 & 0 \\ 0 & 0 & R_3 \end{pmatrix}$ $M_D = \begin{pmatrix} D_1 & D_1 & D_2+P \\ 0 & D_1+P & D_2 \\ P & D_1 & D_2 \end{pmatrix}$ $M_S = \begin{pmatrix} G & 0 & 0 \end{pmatrix}$	$-m_\nu = \begin{pmatrix} \frac{D_1^2}{R_2}+\frac{(D_2+P)^2}{R_3} & \frac{D_1(D_1+P)}{R_2}+\frac{D_2(D_2+P)}{R_3} & \frac{D_1^2}{R_2}+\frac{D_2(D_2+P)}{R_3} \\ \frac{D_1(D_1+P)}{R_2}+\frac{D_2(D_2+P)}{R_3} & \frac{(D_1+P)^2}{R_2}+\frac{D_2^2}{R_3} & \frac{D_1(D_1+P)}{R_2}+\frac{D_2^2}{R_3} \\ \frac{D_1^2}{R_2}+\frac{D_2(D_2+P)}{R_3} & \frac{D_1(D_1+P)}{R_2}+\frac{D_2^2}{R_3} & \frac{D_1^2}{R_2}+\frac{D_2^2}{R_3} \end{pmatrix}$ $m_S \simeq \frac{G^2}{\lambda_1 v}$ $W = \begin{pmatrix} \frac{D_1}{G} \\ 0 \\ \frac{P}{G} \end{pmatrix}$
Inverted Hierarchy $M_R = \begin{pmatrix} R_1 & 0 & 0 \\ 0 & R_2 & 0 \\ 0 & 0 & R_3 \end{pmatrix}$ $M_D = \begin{pmatrix} D_1 & -D_1 & D_2+P \\ 0 & -D_1+P & D_2 \\ P & 2D_1 & D_2 \end{pmatrix}$ $M_S = \begin{pmatrix} G & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} \frac{D_1^2}{R_2}+\frac{(D_2+P)^2}{R_3} & \frac{D_1(D_1-P)}{R_2}+\frac{D_2(D_2+P)}{R_3} & \frac{-2D_1^2}{R_2}+\frac{D_2(D_2+P)}{R_3} \\ \frac{D_1(D_1-P)}{R_2}+\frac{D_2(D_2+P)}{R_3} & \frac{(D_1-P)^2}{R_2}+\frac{D_2^2}{R_3} & \frac{-2D_1(D_1-P)}{R_2}+\frac{D_2^2}{R_3} \\ -\frac{2D_1^2}{R_2}+\frac{D_2(D_2+P)}{R_3} & -\frac{2D_1(D_1-P)}{R_2}+\frac{D_2^2}{R_3} & \frac{4D_1^2}{R_2}+\frac{D_2^2}{R_3} \end{pmatrix}$ $m_S \simeq \frac{G^2}{\lambda_1 v}$ $W = \begin{pmatrix} \frac{D_1}{G} \\ 0 \\ \frac{P}{G} \end{pmatrix}$

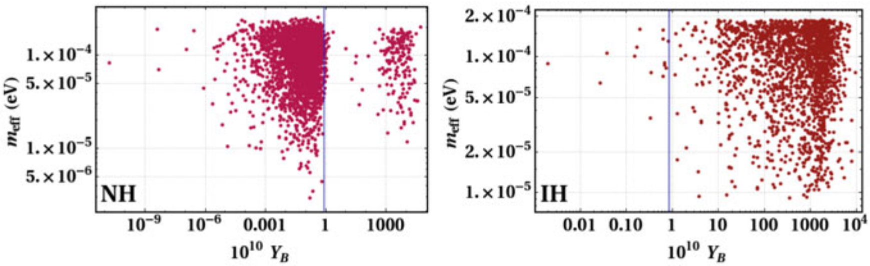

Fig. 18.1 Correlation between baryogenesis and $0\nu\beta\beta$ for both normal and inverted hierarchy mass pattern in presence of a single generation of keV sterile neutrino. The vertical blue line represents the current BAU value, $Y_B = (8.7 \pm 0.06) \times 10^{-11}$

18.2.2 Baryogenesis and $0\nu\beta\beta$

We have considered a hierarchical mass pattern for RH neutrinos, among which the lightest will decay to Higgs and lepton. This decay would produce sufficient lepton asymmetry to give rise to the observed baryon asymmetry of the universe. We have used the parametrization from [3], where the working formula of baryon asymmetry produced is given by

$$Y_B = ck\frac{\epsilon_{11}}{g_*}. \tag{18.5}$$

The quantities involved in this Eq. 18.5 can be found in [3, 4].

The baryon asymmetry of the universe can be calculated from Eq. (18.5) followed by the evaluation of lepton asymmetry. The Yukawa matrix is constructed from the solved model parameters D_1, D_2 and P, which is analogous to the 3×3 Dirac mass matrix.

As we have considered only one sterile state, hence the effective electron neutrinos mass is modified as [1]

$$m_{eff}^{3+1} = m_{eff}^{3_\nu} + m_4|\theta_S|^2, \tag{18.6}$$

where, $|\theta_S|$ is obtained from the first element of the W matrix and m_4 is constrained within [1–18.5] keV satisfying both $0\nu\beta\beta$ and DM phenomenology under MES framework simultaneously.

In Fig. 18.1, we have plotted baryogenesis values obtained from our model along X-axis and effective mass from $0\nu\beta\beta$ along Y-axis for both normal and inverted hierarchy mass pattern. These results correlated both these observables, and NH mass pattern shows more promising results compared to the IH pattern.

18.3 Conclusion

In this study, we have checked the viability of keV sterile neutrino giving an observable effect in $0\nu\beta\beta$ and baryogenesis via the mechanism of thermal leptogenesis. We have used A_4 based flavour model with discrete $Z_4 \times Z_3$ to construct desired Yukawa coupling matrices. A singlet gauge fermion S is considered, which couples with the right-handed neutrino. The Dirac neutrino mass matrix, M_D, is modified using a matrix, M_P, which is generated via the same fashion as M_D to make the active mass matrix $\mu - \tau$ asymmetric.

In conclusion, we have found that sterile neutrino has an observable effect in $0\nu\beta\beta$ study. Under MES, it is possible to correlated baryogenesis and $0\nu\beta\beta$ for both the mass ordering. However, NH mass pattern becomes more favourable than IH pattern in the correlation study.

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