$keV$ scale dark matter, baryogenesis and neutrinoless double beta decay in minimal extended seesaw

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Abstract

We have studied $keV$ scale dark matter (DM), neutrinoless double beta decay (NDBD) and baryogenesis within minimal extended seesaw (MES). A generic model based on $A_4 \times Z_4$ flavor symmetry is used to explain both normal and inverted hierarchy mass pattern of neutrino and also to accommodate the $keV$ ranged sterile neutrino mass. Significant results on effective neutrino mass are observed in presence of $keV$ sterile neutrino in NDBD. In order to validate DM within this model, we have checked decay width and relic abundance of the heavy neutrino flavor and which constrained sterile neutrino DM mass. Baryogenesis is also studied simultaneously within this framework and Dirac CP phase get constrained with the results. Co-relation among the observable and model parameters are also carried out within this framework.

Keywords: Beyond Standard Model, Minimal extended seesaw, Sterile neutrino, Dark matter, NDBD, Leptogenesis

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I. INTRODUCTION

Discovery of neutrino mass, Higgs Boson has brought glory to the field of particle physics as well as to astrophysics and cosmology. Those experimental results[7–9, 14, 16, 31, 51] not only verify the theoretical predictions but also open up new portal to bring physics to the next level. Global fit results with $3\sigma$ bound and best fit values of the observed neutrino parameters are given in tabular form in table I. In spite of the glorious successes, till date there are lot more puzzles and unknowns around us like the exact nature and absolute mass scale of the neutrinos, matter-antimatter asymmetry of the Universe, presence of extra flavor of neutrinos, Dark Matter, etc.. Apart from the unknowns, several cosmological observations [13, 18, 19] as well as reactor data[6, 59, 60] reveals the fact that sterile neutrinos does exists in the Universe. Sterile neutrinos are neutral right-handed (RH) fermions and they are singlets under the SM gauge group. Unlike the active neutrinos, they are infertile, i.e., they doesn’t change flavor, however they mix only with the active neutrinos. Regardless of the fact that the exact mass scale or numbers of sterile neutrino states are still unknown, however, presence of this neutral particles may have significant contribution to new physics. As they are Majorana [77] in nature, we have choice in our hand to consider sterile neutrino mass as per our need\(^1\). Hence, existence of sterile neutrino in the picture might makes it easier to explain DM.

First proposed by F. Zwicsky in 1933, later evidences from galactic rotation curves [88], gravitational lensing and bullet clusters [43], Cosmic Microwave Background Radiation (CMBR) [26] confirms the presence of Dark Matter into the picture. Moreover past few years observation had confirmed the presence of more energetic Dark Energy along with Dark Matter (DM) and observed matter. The analysis of the tiny anisotropies in Cosmic Microwave Background Radiation(CMBR) suggested that our universe consists of 69% of dark energy, 27% of DM and the rest 4% is our observed matter [10, 26]. Dark Matter could not have electromagnetic or strong interactions, otherwise it would have produced isotopes of estimated abundance $n > 10^{-10}n_H$ [91], which contradicts the present limit of $n_H$, the hydrogen isotope density. The biggest mystery in modern physics is the origin and nature of the DM. The observed matter distribution [11, 45, 52, 89] and the known laws of physics unable to

\(^1\) Till now experimentally and observationally their mass is unconstrained [95]
explain those astrophysical discrepancies. In order to understand DM, we have to understand what it actually composed of. Dense baryonic and non-baryonic matters could be DM candidates. Under dense baryonic category Massive compact halo objects (MACHOs) were considered to be dark matter candidates [27, 70] however they are largely disfavored [43, 87, 107]. Modifications to the laws of gravitational[79] were also not so much impressive to explain DM. Thus adding new particle to the elementary particle list is the only reasonable choice we have right now in our hand.

After the failure of the baryonic particles to explain DM, we proceed towards the non-baryonic particles. The non-baryonic DM particles are divided into two broad categories depending on their mass hence the velocity. One which acquire very tiny mass hence have very large relativistic velocity are termed as Hot Dark Matter (HDM). Neutrinos falls under the HDM category. The particles with exactly opposite behavior of HDM are called cold DM (CDM), heavy and moves very slowly. Apart from these two broad categories, there is an intermediate state between these two called Warm DM (WDM). Neutrinos (HDM) are ruled out from the DM candidate list as they have very tiny mass that even with the upper mass limit[69, 74] of the neutrinos couldn’t explain the current relic density [68] of DM and high (relativistic) velocity of the neutrinos prevent the structure formation.

Hence in order to explain DM, we must require physics beyond the SM (BSM)[66, 80]. Usually, particles BSM requires to have high energy hence are massive. Several particles were proposed as DM candidate in BSM. However, there is a category of particles which could be a good DM candidate, they are relatively heavy and weakly interacting, termed as Weakly interacting massive particle (WIMP). WIMPs does not create problem in structure formation like the SM-neutrinos due to non-relativistic velocity and higher masses. Depending upon their production mechanism [94], they might be WDM(non-thermal production) or CDM(thermal production). WIMPs take different form under different scenario, like neutralions are considered as WIMP under SUSY [57, 64], Kaluza-Klein bosons as predicted by models based on extra spatial dimensions [32, 99] and minimal extension of SM scalar sector consider inert doublet scalar as WIMP DM [65, 75].

Typically, sterile neutrinos with mass $(0.4 - 50)keV$ [36] are considered as WIMP particles as they are relatively slow and much heavier as compared to the active neutrinos. The lower bound is kind of universal for sterile neutrino in order to establish itself as a DM candidate, however for successfully observe $0\nu\beta\beta$ the upper bound for sterile neutrino mass is given
by [3], which is 18.5keV. Sterile neutrino to be considered as DM candidate, they must satisfy two conditions: first, the lower bound on the DM mass [103]. Due to Pauli’s exclusion principle, fermionic DM couldn’t have arbitrary mass, since in dense regions like galaxy core, they cannot packed with a small volume. Second, the mixing angle between active and sterile neutrino must be very small such that it can decay only to a SM neutrino and a mono-energetic photon, otherwise there would be overabundance of DM. keV scale sterile neutrino does satisfy these conditions which motivate us to study keV sterile neutrino as DM with a mass scale of (1-18.5)keV.

Absolute neutrino mass is still a unknown to the physics community as oscillation experiments are only sensitive to the mass squared difference ($\Delta m^2_{ij}$) and on the leptonic mixing angles ($\theta_{ij}$). In spite of the fact that from oscillation experiments we get a lower bound on the heavier mass (for $\Delta m^2_{ij} > 0$, $|m_j|^2 \geq \Delta m^2_{ij}$), but there is neither upper nor a lower bound on the lightest mass ($m_j$). Rather than the mass squared differences, kinematic study of reactions involving neutrino ($\nu$) and anti-neutrino ($\bar{\nu}$) can give us information about absolute mass. Considering Majorana nature of particles, Wendell Furry [55] studied a kinetic process similar to "double beta disintegraton" without neutrino emission popularly known as neutrino-less double beta decay ($0\nu\beta\beta$) [47]. In simple word this can be expressed as

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-.$$  

The ($0\nu\beta\beta$) process explicitly violets the lepton number by creating a pair of electron. Discovery of this LNV process supported by existing theoretical picture hence ($0\nu\beta\beta$) allow leptons to take part in the process of matter-antimatter asymmetry of our universe, thus observation of such process is crucial for demonstrating baryogenesis idea [42]. Many works on ($0\nu\beta\beta$) has been done considering the SM neutrinos [29, 30]. Moreover, it is clear now that addition of a new scalar fermion and study it’s interactions within the SM particles can lead us to a broad range of new physics phenomenology. Presence of sterile neutrino is strongly motivated and highly influences current reactor neutrino anomalies. Sterile neutrino with different mass ranges play crucial role in astrophysics [90], cosmology [4, 5], collider physics [2, 20], etc.. Similar kind of studies were carried out in other context such as LRSM [23, 33], extra dimensions [93], in presence of exotic charged currents [76] or in relation with keV neutrino dark matter [104].

In connection with DM and absolute neutrino mass, the over abundance of baryonic matter
over the anti-baryonic matter is also an unsolved problem till date. The baryon asymmetry of the Universe (BAU) \( Y_B \equiv \frac{n_B - n_{\overline{B}}}{s} \sim 8.7 \times 10^{-10} \) is well explained by Baryogenesis via the mechanism of leptogenesis [54, 101]. In order to produce BAU via the process of leptogenesis [46, 48, 81], three Shakarov conditions [96] must satisfy, which states i) Baryon number must violate, ii) C and CP violation must occur and iii) the process must be an out of equilibrium process. Even though particles within SM does satisfy all these conditions, however, baryon asymmetry generated within SM is very less compared to the present observed value. As Leptogenesis occurs naturally within SM, we can extend the SM to seesaw framework in order to generate successful BAU. Moreover, all the conditions required to generate lepton asymmetry are also satisfied in the decay process of heavy RH neutrino related to seesaw framework. Within leptogenesis, CP and lepton asymmetry is produced by the loop level decay of the lightest RH neutrino into the lepton or anti-lepton doublet and Higgs doublet. The heavy Majorana mass scale let them decouple from the thermal equilibrium in the primordial expanding Universe. Due to the Majorana nature of the RH neutrinos, along with the C and CP, lepton number is also violated.

Motivated by all these literature, in this work we are considering a sterile neutrino with mass within keV range in minimally extended seesaw (MES) [93, 108], where an additional scalar singlet (sterile neutrino) is added along with three RH neutrinos. The beauty of MES framework is that it can accommodate sterile neutrino mass ranging from eV to keV. Sterile neutrino with eV as well as keV could be probed in future KATRIN experiment [78, 85]. Moreover keV sterile neutrino has a potential to effect electron energy spectrum in tritium \( \beta \) decays [100]. When \((0\nu\beta\beta)\) processes are mediated by heavy sterile neutrino, compelling results are observed as they effects the \((0\nu\beta\beta)\) amplitude. Hence the keV regime sterile neutrino in studied in this work in such a fashion that the sterile neutrino can simultaneously explain \((0\nu\beta\beta)\) within laboratory constrains along with DM signature within that range. We have also tried to verify our model to explain current BAU produced via the mechanism of thermal Leptogenesis. Non-hierarchical mass pattern for the RH neutrinos are considered satisfying current light neutrino bounds. Lightest of them is decaying to a lepton (anti-lepton) and a Higgs doublet producing lepton number violation, and then Standard

\(^2\) \(n_B\) and \(n_{\overline{B}}\) are the baryon and anti-baryon number density respectively. \(s\) in the denominator is the entropy of the current universe.
TABLE I: The latest global fit 3σ range and best fit results from recent active neutrino parameters[40].

| Parameters | NH (Best fit) | IH (Best fit) |
|------------|---------------|---------------|
| $\Delta m_{21}^2[10^{-5}eV^2]$ | 6.93-7.97(7.73) | 6.93-7.97(7.73) |
| $\Delta m_{31}^2[10^{-3}eV^2]$ | 2.37-2.63(2.50) | 2.33-2.60(2.46) |
| $\sin^2\theta_{12}/10^{-1}$ | 2.50-3.54(2.97) | 2.50-3.54(2.97) |
| $\sin^2\theta_{13}/10^{-2}$ | 1.85-2.46(2.14) | 1.86-2.48(2.18) |
| $\sin^2\theta_{23}/10^{-1}$ | 3.79-6.16(4.37) | 3.83-6.37(5.69) |
| $\delta_{13}/\pi$ | 0-2(1.35) | 0-2(1.32) |

Model sphaleron processes plays a crucial role in partially converting the lepton asymmetry into a baryon asymmetry of the Universe. Finally, we tried to correlate all these observed phenomenology under the same MES framework.

This work is organize as follows: model building with $A_4$ flavor symmetry along with $Z_4$ discrete symmetry is discussed in section II for both normal (II A) and inverted (II B) mass pattern. Numerical analysis is carried out in section III and separate sub-section for $0\nu\beta\beta$ (IIIA), dark matter (IIIB) and BAU (IIIC) are also carried out under the same numerical analysis section. Results of our study are discussed in section IV and finally we have concluded our work in V.

II. THE MODEL

Symmetries has been playing an important role in model building and describing phenomenology in neutrino physics. Interestingly, discrete symmetries like $A_4$ with $Z_n$ is more popular in literature in explaining neutrino mass [15, 21, 24, 41]. $A_4$ being the discrete symmetry group of rotation with a tetrahedron invariant, consisting 12 elements and 4 irreducible representation denoted by $1, 1', 1''$ and $3$. Our present work is an extension of our previous work [44] with modified flavor symmetry. In this work, left-handed (LH) lepton doublet $l$ to transform as $A_4$ triplet whereas right-handed (RH) charged leptons ($e^c, \mu^c, \tau^c$) transform as $1, 1''$ and $1'$ respectively. Triplets $\zeta, \varphi, \varphi'$ and two singlets $\xi$ and $\xi'$ are added in order to produce broken flavor symmetry. Besides the SM Higgs $H$, we have introduced
one more Higgs doublets \((H')[62, 82]\), which remain invariant under \(A_4\). Non-desirable interactions while constructing the mass matrices were restricted using extra \(Z_4\) charges to the fields. The field content with \(A_4 \times Z_4\) charge assignment are shown in the table II.

| Field | \(l e_R \mu_R \tau_R\) | \(H H'\) | \(\zeta \phi \phi' \xi \xi'\) | \(\nu_{R1} \nu_{R2} \nu_{R3}\) | \(S \chi\) |
|-------|------------------------|----------|------------------------|-----------------|--------|
| SU(2) | 2 1 1 1 1 | 2 2 2 1 1 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'' 1' | |
| \(Z_4\) | 1 -1 -1 -1 | 1 i -1 i 1 1 -1 | 1 -i -1 -1 i | |

TABLE II: Particle content and their charge assignments under SU(2), \(A_4\) and \(Z_4 \times Z_3\) groups.

\[\langle \zeta \rangle = (v, 0, 0),\]
\[\langle \phi \rangle = (v, v, v),\]
\[\langle \phi' \rangle = (0, v, -v),\]
\[\langle \xi \rangle = \langle \xi' \rangle = v,\]
\[\langle \chi \rangle = u.\]
Following the $A_4$ product rules and using the above mentioned VEV alignment\(^3\), the charged lepton mass matrix is obtained as follows,

$$M_l = \frac{\langle H \rangle v}{\Lambda} \text{diag}(y_e, y_\mu, y_\tau).$$ \hspace{2cm} (2)

The Dirac\(^4\), Majorana neutrino mass and the sterile mass matrices are given by,

$$M'_D = \begin{pmatrix} -b & b & c \\ b & b & c \\ 0 & b & c \end{pmatrix}, \quad M_R = \begin{pmatrix} d & 0 & 0 \\ 0 & e & 0 \\ 0 & 0 & f \end{pmatrix}, \quad M_S = \begin{pmatrix} g & 0 & 0 \end{pmatrix}. \hspace{2cm} (3)$$

where, $b = \frac{\langle H \rangle v}{\Lambda} y_2$ and $c = \frac{\langle H \rangle v}{\Lambda} y_3$. Other elements are defined as $d = \lambda_1 v, e = \lambda_2 v, f = \lambda_3 v$ and $g = \rho u$. In order to achieve sterile mass in the keV range, we have assumed the VEV for the $\chi$ flavon lie around TeV scale. A rough estimate of the mass scales of parameters are given as, $\Lambda \approx 10^{14} \text{GeV}$, $v \approx 10^{13} \text{GeV}$ and $u \approx 10^{16} \text{eV}$.

Following eqn. (12), the light neutrino mass matrix takes a symmetric form as,

$$m_\nu = \begin{pmatrix} -\frac{b^2}{e} + \frac{c^2}{f} & -\frac{b^2}{e} - \frac{c^2}{f} & -\frac{b^2}{e} - \frac{c^2}{f} \\ -\frac{b^2}{e} - \frac{c^2}{f} & -\frac{b^2}{e} + \frac{c^2}{f} & -\frac{b^2}{e} - \frac{c^2}{f} \\ -\frac{b^2}{e} - \frac{c^2}{f} & -\frac{b^2}{e} - \frac{c^2}{f} & -\frac{b^2}{e} + \frac{c^2}{f} \end{pmatrix}. \hspace{2cm} (4)$$

This $m_\nu$\(^5\) is a symmetric matrix generated by $M'_D$, $M_R$ and $M_S$ matrices. Only one mixing angle and one mass square difference are achievable from it. This symmetry must be broken in order to generate two mass square differences and three mixing angles. For breaking the symmetry we introduce two new $SU(2)$ singlet flavon fields ($\eta, \eta'$) the coupling of which give rise to a matrix (6) which later on makes the active mass matrix asymmetric after adding the matrix (6) to the Dirac mass matrix, hence by breaking the earlier symmetry. This new $M_P$ matrix played a crucial role in reproducing nonzero reactor mixing angle and has significant influence in determining the octant for $\theta_{23}$ [44]. The Lagrangian that generate the matrix (6) can be written as,

$$\mathcal{L}_{M_P} = \frac{y_1}{\Lambda} (\tilde{\eta} H')_1 \nu_R^1 + \frac{y_1}{\Lambda} (\tilde{H} H')_1 \nu_R^2 + \frac{y_1}{\Lambda} (\tilde{H} H')_1 \nu_R^3. \hspace{2cm} (5)$$

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\(^3\) The triplet VEV alignment of the scalars are the solution of the respective scalars at their minimal potential.

\(^4\) $M'_D$ represents the uncorrected Dirac mass matrix which is unable to generate $\theta_{13} \neq 0$. The corrected $M_D$ is given by equation (7)

\(^5\) We have used $M'_D$ in lieu of $M_D$ in eqn. (12)
The $SU(2)$ singlet flavon fields $(\eta, \eta')$ are supposed to take $A_4 \times Z_4$ charges as same as $\varphi$ and $\varphi'$ respectively (as shown in the table II). Now, considering VEV\(^6\) for the new flavon fields as $\langle \eta \rangle = (0, v_p, 0)$ and $\langle \eta' \rangle = (0, 0, v_p)$, we get the matrix as,

$$M_P = \begin{pmatrix} 0 & 0 & p \\ 0 & p & 0 \\ p & 0 & 0 \end{pmatrix}.$$  \hspace{1cm} (6)

Hence $M_D$ from eq. (3) will take new structure as,

$$M_D = M'_D + M_P = \begin{pmatrix} -b & b & c + p \\ b & b + p & c \\ p & b & c \end{pmatrix}.$$ \hspace{1cm} (7)

**B. Inverted Hierarchy**

Within this MES framework, a slight modification in VEV is needed in order to give correct observed phenomenology \cite{108} in IH mode. We also have modified the Lagrangian for the $M_D$ matrix by introducing a new triplet flavon $\varphi''$ with VEV alignment as $\langle \varphi'' \rangle \sim (2v, -v, -v)$, which affects only the Dirac neutrino mass matrix and give desirable active-sterile mixing in IH. The invariant Yukawa Lagrangian for the $M_D$ matrix will be,

$$\mathcal{L}_{M_D} = \frac{y_1}{\Lambda} (\tilde{t} H \varphi')_{1\nu} \nu_{R1} + \frac{y_2}{\Lambda} (\tilde{t} H \varphi'')_{1\nu} \nu_{R2} + \frac{y_3}{\Lambda} (\tilde{t} H_3 \varphi)_{1\nu} \nu_{R3}.$$ \hspace{1cm} (8)

Hence the Dirac mass matrix takes new structure as,

$$M'_D = \begin{pmatrix} -b & -b & c \\ b & -b & c \\ 0 & 2b & c \end{pmatrix},$$ \hspace{1cm} (9)

with, $b = \frac{\langle H \rangle v}{\Lambda} y_2$ and $c = \frac{\langle H \rangle v}{\Lambda} y_3$.

This Dirac mass matrix will also give rise to a symmetric $m_{\nu}$ like the NH case. Thus, the

\(^6\) This matrix $M_P$ is considered as a perturbation into the Dirac mass matrix system hence value of the VEV are considered a order less than the VEV that are involved in $M'_D$
modified $M_D$ to break the symmetry will be given by,

$$M_D = M'_D + M_P = \begin{pmatrix} -b & -b & c + p \\ b & -b + p & c \\ p & 2b & c \end{pmatrix}.$$  \hspace{1cm} (10)

Other matrices like $M_R, M_P, M_S$ will retain their same structure throughout the inverted mass ordering.

### III. NUMERICAL ANALYSIS

We have used Minimal extended seesaw (MES) to construct the active and sterile mass matrices. In MES scenario along with the SM particle, three extra right-handed neutrinos and one additional gauge singlet chiral field $S$ is introduced. The Lagrangian of the neutrino mass terms for MES is given by:

$$-\mathcal{L}_M = \bar{\nu}_L M_D \nu_R + \frac{1}{2} \bar{\nu}_R M_R \nu_R + \bar{S} M_S \nu_R + h.c., \hspace{1cm} (11)$$

Here $M_D$ and $M_R$ are $3 \times 3$ Dirac and Majorana mass matrices respectively whereas $M_S$ is a $1 \times 3$ matrix. A detailed discussion on MES has already been carried out in our previous work [44]. Following the MES framework, we get the active neutrino mass matrix as

$$m_\nu \simeq M_D M'_R M_S^{-1} (M_S M_R^{-1} M'_S)^{-1} M_S (M_R^{-1})^T M_D^T - M_D M_R^{-1} M_D^T, \hspace{1cm} (12)$$

and the sterile neutrino mass as

$$m_s \simeq -M_S M_R^{-1} M'_S. \hspace{1cm} (13)$$

$M_S$ being a vector rather than a square matrix prevents the first term of the active neutrino mass to vanish. Exact cancellation between the two terms of the active neutrino mass term would encountered if $M_S$ were a square matrix. Using these two equations (12),(13) we find the active and sterile mass structures for both the NH as well as IH. The complete matrix picture for NH and IH are presented in table III.

In order to achieve the active neutrino masses we must diagonalize the active neutrino mass
matrix using well established unitary $U_{PMNS}$ matrix \[58\]. The diagonalize neutrino mass matrix $M_\nu$ is achieved as,

$$\text{Diag}(m_1, m_2, m_3) = U_{PMNS} M_\nu U_{PMNS}^T,$$

(14)

where $m_i$ (for $i = 1, 2, 3$) stands for three active neutrino masses.

Conventionally the leptonic mixing matrix for active neutrino is parameterized as,

$$U_{PMNS} = \begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}, P. \quad (15)$$

The abbreviations used are $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ where $\theta_{ij}$ stands for active mixing angles with $i, j = 1, 2, 3$ and $P$ would be a unit matrix $\mathbf{1}$ in the Dirac case but in Majorana case $P = \text{diag}(1, e^{i\alpha}, e^{i(\beta+\delta)})$. The Dirac and Majorana CP-violating phases are simply represented by $\delta$ and $(\alpha, \beta)$ in the $U_{PMNS}$.

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 $4 \times 4$ form as,

$$V \approx \begin{pmatrix}
(1 - \frac{1}{2}RR^\dagger)U_{PMNS} & R \\
-R^\dagger U_{PMNS} & 1 - \frac{1}{2}R^\dagger R
\end{pmatrix}, \quad (16)$$

where $R = M_D M_R^{-1} M_S^T (M_S M_R^{-1} M_S^T)^{-1}$ is a $3 \times 1$ matrix governed by the strength of the active-sterile mixing i.e., the ratio $\sigma(M_D)/\sigma(M_S)$.

The sterile neutrino of mass of order $keV$, can be added to the standard 3-neutrino mass states in NH: $m_1 < m_2 < m_3 \ll m_4$ as well as IH: $m_3 < m_1 < m_2 \ll m_4$. One Diagonalized light neutrino mass matrix for NH and IH are modified as $m^{NH}_\nu = \text{diag}(0, \sqrt{\Delta m^2_{21}}, \sqrt{\Delta m^2_{21} + \Delta m^2_{31}}, \sqrt{\Delta m^2_{41}})$ and $m^{IH}_\nu = \text{diag}(\sqrt{\Delta m^2_{31}}, \sqrt{\Delta m^2_{21} + \Delta m^2_{31}}, 0, \sqrt{\Delta m^2_{43}})$ respectively. The lightest neutrino mass is zero in both the mass ordering as demanded by the MES framework\[24\]. Here $\Delta m^2_{41} (\Delta m^2_{43})$ is the active-sterile mass square difference for NH and IH respectively.

Fixed non-degenerate values for the right-handed neutrino mass parameters as $d = 10^{12} GeV$, $e = 10^{13} GeV$ and $f = 5 \times 10^{13} GeV$ are assigned so that they can exhibit successful thermal Leptogenesis without effecting the neutrino parameters. The mass
TABLE III: The light neutrino mass matrices and the corresponding $M_D$, $M_R$ and $M_S$ matrices for NH and IH mass pattern.

Matrix arises from eq. (14) give rise to complex quantities due to the presence of Dirac and the Majorana phases. Since the leptonic CP phases are still unknown, we vary them within their allowed $3\sigma$ ranges $(0, 2\pi)$. The Global fit $3\sigma$ values for other parameters like mixing angles, mass square differences are taken from [40]. The active neutrino mass matrix emerges from our model matrices is left with three parameters for each case. Comparing the model mass matrix with the one produced by light neutrino parameters given by eq. (14), we numerically evaluate the model parameters satisfying the current $3\sigma$ bound for the neutrino parameters.

As $m_s$ depends only on $M_R$ and $M_S$, so due to the non-degenerate value of $M_R$, the $m_s$ structure let us study the active-sterile mixing strength $R$. The active-sterile mixing matrix also have a specific form due to the particular $M_S$ structure. In case of inverted mass ordering (i.e., $m_2 > m_1 > m_3$) of the neutrinos. Referring to [108], we
Table IV: Sterile neutrino mass and active-sterile mixing matrix. They are similar in both the mass pattern.

In this work we have mainly focused in validating MES to study observables like neutrinoless double beta decay, dark matter and baryogenesis in presence of sterile neutrino and finally try to find correlation among those observables.

A. Neutrino-less Double Beta Decay ($0\nu\beta\beta$):

We have assumed that the heavy sterile neutrino mediate the observed $0\nu\beta\beta$ process. Under the SM framework considering sterile neutrinos mediate the $0\nu\beta\beta$ decay at tree-level, the decay amplitude is proportional to [3]:

$$\Sigma \, G_F^2 \, U_{ei}^2 \, \gamma_\mu P_R \frac{p^+ + m_i}{p^2 - m_i^2} \gamma_\nu P_L \simeq \Sigma \, G_F^2 \, U_{ei}^2 \, m_i \, \frac{1}{p^2} \gamma_\mu P_R \gamma_\nu,$$

where $G_F$ is the Fermi constant, $m_i$ the physical neutrino mass and $p$ is the neutrino virtual momentum such that $p^2 = (125\,MeV)^2$. The effective electron neutrino Majorana mass for the active neutrinos in the $0\nu\beta\beta$ process is read as,

$$m^3_{\nu_{eff}} = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 + m_3 |U_{e3}|^2,$$

The phase "effective electron neutrino" is used as only electrons were involved in the double decay process.

If the SM is extended by $N_S$ extra sterile fermions, presence of those extra states will modify the decay amplitude which corrects the effective mass as [25]

$$m_{eff} = \sum_{i=1}^{3+N_S} U_{ei}^2 \frac{m_i}{p^2 - m_i^2}.$$


where $U_{ei}$ is the $(3 + N_S \times 3 + N_S)$ matrix with extra active-sterile mixing elements. As we have considered only one sterile state, hence the effective electron neutrinos mass is modified as [24],

$$m_{3e}^{3+1} = m_{\nu e}^3 + m_4 |U_{e4}|^2,$$

(20)

where $|U_{e4}|$ is obtained from the first element of the $R$ matrix and $m_4$ is constrained within [1-18.5]keV [3] satisfying both $0\nu\beta\beta$ and DM phenomenology under MES framework simultaneously in this model.

A large number of experimental and theoretical progresses were made so far and still counting in order to validate the decay process. Interestingly, no solid evidences from experiments confirmed till date to proof $0\nu\beta\beta$ process. However, next-generation experiments are currently running in pursue of more accurate limit [17, 22, 61, 63, 84] on the effective mass which might solve the absolute mass problem. Recent results from various experiments give strong bounds on the effective mass $m_{eff}$. Kam-LAND ZEN Collaborating [56] and GERDA [12] which uses Xenon-136 and Germanium-76 nuclei respectively gives the most constrained upper bound upto 90% CL with

$$m_{eff} < 0.06 - 0.165 \text{ eV}.$$ 

Various ongoing and future experiments with their bounds on effective mass were shown in table V. In this work, we consider the future sensitivity of $m_{eff}$ upto 0.01eV.

**B. Dark Matter**

Motivated from literature we are in a stage where we can consider sterile neutrino withing $keV$ regime to explain DM. Sterile neutrinos to be sololy contribute to the 100% of current DM density it’s mass should lie above 0.4keV [50]. However, some authors have claimed that WIMP sterile neutrinos can contribute upto 48% of DM [1]. Since they cannot thermalize easily, the simplest production mechanism is via mixing with the active neutrinos in the primordial plasma [49]. Important things to note here, is that sterile neutrino DM is practically always produced out of thermal equilibrium, and therefore its primordial momentum distribution is in general not given by a Fermi-Dirac distribution. Indeed, sterile neutrinos in equilibrium have the same number density as ordinary neutrinos, i.e., $112 cm^3 \cdot$ With the sterile neutrino mass above 0.4 $keV$, this would lead to the energy density to-
| Experiments (Isotope) | $|m_{eff}|eV$ | Half-life$^a$ | Ref. |
|-----------------------|--------------|--------------|------|
| KamLAND-Zen(800 Kg)(Xe-136) | 0.025 – 0.08 | $1.9 \times 10^{25}$ (90%CL) | [56] |
| KamLAND2-Zen(1000Kg)(Xe-136) | $< 0.02$ | $1.07 \times 10^{26}$ (90%CL) | [56] |
| GERDA Phase II (Ge-76) | 0.09 – 0.29 | $4.0 \times 10^{25}$ (90%CL) | [12] |
| CUORE (Te-130) | 0.051 – 0.133 | $1.5 \times 10^{25}$ (90%CL) | [17] |
| SNO+ (Te-130) | 0.07 – 0.14 | $\sim 10^{26–27}$ | [63] |
| SuperNEMO (Se-84) | 0.05 – 0.15 | $5.85 \times 10^{24}$ (90%CL) | [22] |
| AMoRE-II (M0-100) | 0.017 – 0.03 | $3 \times 10^{26}$ (90%CL) | [28] |
| EXO-200(4 Year)(Xe-136) | 0.075 – 0.2 | $1.8 \times 10^{25}$ (90%CL) | [102] |
| nEXO(5yr+5yr w/Ba Tagging)(Xe-136) | 0.005 – 0.011 | $\sim 10^{28}$ | [72] |

$^a$ in years.

TABLE V: Sensitivity of few past and future experiments with half-life in years.

day $\rho_{\text{sterile},eq} \simeq 45 \text{keV/cm}^3$, which significantly exceeds the critical density of the Universe $\rho_{\text{crit}} = 10.5h^2 \text{keV/cm}^3$. Therefore, sterile neutrino DM cannot be a thermal relic (unless entropy dilution is exploited), and its primordial properties are in general different from such a particle.

The most important criteria for a DM candidate is its stability at least on cosmological scale. The lightest sterile neutrino is not totally stable and may decay into SM particles. In the presence of sterile neutrinos, the leptonic weak neutral current is non-diagonal in mass eigenstates [71], so the $N_S$ can decay at tree-level via $Z$-exchange, as $N_S \rightarrow \nu_i \bar{\nu}_j \nu_j$, where $\nu_i, \nu_j$ are mass eigenstates. The $keV$ sterile neutrino decaying to the SM neutrinos (flavor eigenstates) via $N_S \rightarrow \nu_\alpha \nu_\beta \bar{\nu}_\beta$ gives the decay width as [71, 86],

$$\Gamma_{N_S \rightarrow 3\nu} = \frac{G_F^2 m_{N_S}^5}{96\pi^3} \sin^2 \theta_{NS} = \frac{1}{4.7 \times 10^{10} \text{sec}} \left(\frac{m_{NS}}{50 \text{ keV}}\right)^5 \sin^2 \theta_{NS},$$

(21)

where $\theta_{NS}$ and $m_{NS}$ represents the active-sterile mixing angle and sterile mass respectively. This decay width must give a lifetime of the particle much longer than the age of the Universe. This put a bound on the mixing angle such that

$$\theta_{NS} < 1.1 \times 10^{-7} \left(\frac{50 \text{ keV}}{m_{N_S}}\right)^5.$$  

(22)
The mass squared difference emerging out of this bound is already much smaller than current solar mass squared difference. To overcome this short come, either we another sterile neutrino into the picture or consider a one loop mediated radiative decay process of \( N_S \rightarrow \nu + \gamma \). This put a stronger bound than the earlier \( N_S \rightarrow 3\nu \) decay process leading to a monochromatic X-ray line signal. However, as discussed in many literature [50], the decay rate is negligible with respect to the cosmological scale because of the small mixing angle. The decay rate for the \( N_S \rightarrow \nu + \gamma \) process is given as [1, 83]

\[
\Gamma_{S \rightarrow \nu\gamma} \approx 1.32 \times 10^{-32} \left( \frac{\sin^2 2\theta_{SN}}{10^{-10}} \right) \left( \frac{m_{DM}}{100 \text{KeV}} \right)^5
\]  

(23)

Relic abundance of the Universe can be worked out starting from the Boltzmann equation. Many author have solved evaluated the relic abundance formula considering sterile neutrino into the frame, which is proportional to the mass of the sterile neutrino and sum of the active sterile mixing angles. We used results from [1, 50, 83] to check whether our model able to produce observed relic abundance if we consider the sterile neutrino in \( keV \) range. The working formula is given by:

\[
\Omega_S h^2 \approx 0.3 \left( \frac{\sin^2 2\theta_{S\nu}}{10^{-10}} \right) \left( \frac{m_S}{100 \text{KeV}} \right)^2
\]  

(24)

where \( \theta_{S\nu} \) is the sum of all the active-sterile mixing angles and \( m_S \) represents the \( keV \) ranged Dark matter mass.

As seen from the above equations, the decay rate and as well as the relic abundance depend on mixing and mass of the DM candidate. Hence, the same set of model parameters which are supposed to produce correct neutrino phenomenology can also be used to evaluate the relic abundance and the decay rate of the sterile neutrino.
C. Baryogenesis via Leptogenesis:

The model considered in this work has been successfully established neutrino phenomenology. Moreover, Leptogenesis is an integral part of seesaw mechanism as seesaw demands lepton number violation, eventually a new CP violating phases in the neutrino Yukawa interactions is generated, and it is assumed that heavy singlet neutrinos decay out of equilibrium. Thus, all three Sakharov conditions are satisfied naturally in this scenario. One have to check whether this amount of leptogenesis would successfully give the appropriate amount of observed baryon asymmetry of the Universe within our model. There are a lots of options to produce a baryon asymmetry within seesaw itself (one can go through the review work from [46] for details). However, In this work, we have considered "thermal leptogenesis", where the heavy RH neutrinos are hierarchal ($M_{\nu_R1} \ll M_{\nu_R2,3}$) and the decay process lightest among them giving rise to CP asymmetry. A numerous discussion has been carried in details out for thermal leptogenesis [37, 53] and as per our preferred mass for lightest RH neutrino, we have restrict our lepton asymmetry to produced in a single flavor. In the early Universe, at temperatures above the electroweak phase transition (EWPT) [73], there is a rapid violation of $B+L$, which convert the resulting lepton asymmetry to baryon asymmetry.

In the SM renormalizable Lagrangian both baryon number ($B$) and lepton number ($L$) are conserved independently, however, due to chiral anomaly, there are non perturbative gauge field configurations [39], which fuel up the anomalous $B+L$ violation\(^7\). These whole process of conversion of lepton asymmetry to baryon asymmetry via $B+L$ violation is popularly termed as "sphalerons" [67].

The working formula of baryon asymmetry produced is given by -

$$Y_B = ck \frac{\epsilon_{11}}{g_*}, \quad (25)$$

where,

- $c$ is the conversion factor that measures the fraction of lepton asymmetry being converted to baryon asymmetry. This value is approximately 12/37.

\(^7\) $B - L$ is already conserved.
• $k$ is the dilution factor due to wash out processes, which can be parametrized as,

$$k \simeq \sqrt{0.1K}\exp\left[\frac{-4}{3(0.1K)^{0.25}}\right], \quad \text{for} \quad K \geq 10^6,$$

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

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

(26)

Here, $K$ is defined as,

$$K = \frac{\Gamma_1}{H(T = M_{\nu_{R1}})} = \frac{(\lambda^\dagger \lambda)_{11} M_{\nu_{R1}}}{8\pi M_{\text{Planck}}} \frac{M_{\text{Planck}}}{1.66\sqrt{g_*} M^2_{\nu_{R1}}},$$

(27)

where, $\Gamma_1$ is the decay width of $\nu_{R1}$, defined as, $\Gamma_1 = \frac{(\lambda^\dagger \lambda)_{11} M_{\nu_{R1}}}{8\pi}$ and the Hubble constant at $T = M_{\nu_{R1}}$ is defined as $H(T = M_{\nu_{R1}}) = \frac{M_{\text{Planck}}}{1.66\sqrt{g_*} M^2_{\nu_{R1}}}$.

• $g_*$ is the massless relativistic degree of freedom in the thermal bath and within SM, it is approximately 110.

• $\epsilon_{11}$ is the lepton asymmetry produced by the decay of the lightest RH neutrino $\nu_{R1}$. This is formulated as below,

In order to produce non vanishing lepton asymmetry the decay of $\nu_{R1}$ must have lepton number violating process with different decay rate to final state with particle and anti-particle. Asymmetry in lepton flavor $\alpha$ produced in the decay of $\nu_{R1}$ is defined as,

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(\nu_{R1} \rightarrow l_\alpha H) - \Gamma(\nu_{R1} \rightarrow \bar{l}_\alpha H)}{\Gamma(\nu_{R1} \rightarrow lH) + \Gamma(\nu_{R1} \rightarrow \bar{l}H)},$$

(28)

where $\bar{l}_\alpha$ is the antiparticle of $l_\alpha$ and $H$ is the Higgs doublet present in our model.

Following the calculation for non-degenerate RH mass, from the work of [46], we obtain the asymmetry term as,

$$\epsilon_{\alpha\alpha} = \frac{1}{8\pi} \frac{1}{|\lambda^\dagger \lambda|_{11}} \sum_j^{2,3} \text{Im}(\lambda^*_{\alpha 1})(\lambda^\dagger \lambda)_{1j} \lambda_{\alpha j} g(x_j)$$

$$+ \frac{1}{8\pi} \frac{1}{|\lambda^\dagger \lambda|_{11}} \sum_j^{2,3} \text{Im}(\lambda^*_{\alpha 1})(\lambda^\dagger \lambda)_{1j} \lambda_{\alpha j} \frac{1}{1 - x_j},$$

(29)

\[\text{For degenerate mass with mass spiting equal to decay width, one have to consider resonant leptogenesis.}\]
where \( x_j \equiv \frac{M^2_j}{M^2_{11}} \) and within the SM \( g(x_j) \) is defined as,

\[
g(x_j) = \sqrt{x_j} \left( \frac{2 - x_j - (1 - x_j^2) \ln(1 + x_j/x_j)}{1 - x_j} \right)
\]

(30)

The second line from equation (29) violates the single lepton flavors however it conserves the total lepton number, thus it vanishes when we take sum over \( \alpha \) :

\[
\epsilon_{11} \equiv \sum_\alpha \epsilon_{\alpha\alpha} = \frac{1}{8\pi} \frac{1}{|\lambda|_1} \sum_j^{2,3} \text{Im}[\lambda_\dagger \lambda]_{1j}^2 g(x_j)
\]

(31)

The \( \lambda \) used here is the Yukawa matrix generated from the Dirac mass matrix and the corresponding index in the suffix says the position of the matrix element.

Now we are in a situation to calculate the baryon asymmetry of the Universe from equation (25) followed by the evaluation of lepton asymmetry using equation (31). The Yukawa matrix is constructed from the solved model parameters \( b, c \) and \( p \), which is analogous to the \( 3 \times 3 \) Dirac mass matrix. Within our study the \( K \) value lies within the range \( 10 \leq K \leq 10^6 \), hence we have used the middle parametrization of the dilution factor from equation (26).

IV. RESULTS

Under the hypothesis that, in future experiments will verify the existence of at least one heavy sterile neutrino in \( keV \) range, we work out the possibility of its effect on \( 0\nu\beta\beta \) and verifying the fact that this sterile neutrino could behave as DM within the mass range of \((1-18.5)keV\). We have plotted electron effective neutrino mass \((m_{\text{effective}})\) against the lightest neutrino mass \((m_{\text{lightest}})\) in fig. 2. Horizontal gray line gives the future sensitivity of upper bound on effective mass upto \( 10^{-2}eV \) and the vertical blue line gives the upper bound on sum of the active neutrino masses\((0.17eV)\). In the upper part of figure 2, the NH(black) and IH(orange) contributions are coming only from the active neutrinos whereas in the lower two figures, NH and IH contributions are shown separately in presence of the \( keV \) sterile neutrino. Here, one can see that presence of the sterile neutrino gives a wider and improved data range in both the mass ordering. These extra contribution and improvements in effective mass are solely depends upon the mass of the sterile neutrino and the mixing angle with the sterile neutrino. In fig. 3, we have done the same analysis of \( m_{\text{effective}} \) vs. \( m_{\text{lightest}} \) for different active sterile mixing angle. Very interesting results are observed
from both the NH as well as IH that for $m_4|U_{e4}|^2 > 10^{-4}$ i.e. $(|U_{e4}|^2 > 10^{-7})$, NDBD fails the future experimental bound. From these results we get the upper bound on the active-sterile mixing angles and it is also obvious from the fact that the active-sterile mixing angle must be very small otherwise there would be overproduction of Dark matter in our universe. In figure 4, we have plotted effective electron neutrino mass in presence of the $keV$ sterile neutrino with the model parameter $p$ from the $M_P$ matrix. The significance of this parameter is that, it produces the non-zero reactor mixing angle within our model. Hence, simultaneously satisfying the effective electron neutrino mass limit with constrained region in both the mass ordering gives us the privilege to fix the parameter range in the model. We have also shown projection of effective electron neutrino mass in presence of $keV$ sterile neutrino with two model parameters by the two axes in figure 5. All the model parameters have successfully projected the effective mass below its upper limit. In the plot legends, one can find that below the orange shade, there is the current upper bound of the effective mass and there are little amount of shading regions with red and orange in both the mass ordering. However, in our case NH mode is more favored and more constrained with the experimental results.

Apart from the NDBD, we have also studied Dark Matter signature of the $keV$ sterile neutrino in fig. 6. Decay width ($\Gamma$) and relic abundance of the DM ($\Omega_{DM} h^2$) are plotted against the DM mass ($m_{DM}$) for both the mass ordering. Sterile neutrino to behave as a DM, it’s life-time must be greater than the age of the Universe so that it’s remnant still remains in the Universe, hence the decay width of the WIMP particle must be very less. Within our study we have consider the upper limit of decay width to be less than $10^{-28}$ ($sec^{-1}$). Sterile neutrino mass hence the DM mass is constrained in a very narrow region i.e., $(1−18.5)keV$ to be a relic particle. The relic abundance results of the WIMP in both the mass ordering, satisfy the proper bound with different sterile mass ranges. The DM mass range is very narrow $(1−3)keV$ in case of NH mode, while a broad mass spectrum satisfies the upper relic abundance bound in IH mode $(1−10)keV$. The detection of an unidentified line was reported recently in the stacked spectrum of galaxy clusters [38], in the individual spectra of nearby galaxy clusters [35, 38], in the Andromeda galaxy [35], and in the Galactic Center region [34, 92]. The position of the line is $E = 3.55keV$ with an uncertainty in position $\simeq 0.05keV$. If the line is interpreted as originating from a two-body decay of a DM particle, then the latter has its mass at about $m_S \simeq 7.1keV$ and the lifetime $\tau_{DM} \simeq 10^{27.8\pm0.3}$ sec [35].
Within our study both the decay width and the relic abundance of the Universe are satisfied in both the mass ordering. However, NH results are more consistent while satisfying both the DM criterion with mass (1-3)keV. In IH mode relic abundance limit is shown within DM mass range from 1keV to around 10keV while decay width is satisfied with a small mass upto 3keV.

Along with the $\nu\beta\beta$ and DM results, we have also carried the results for baryogenesis and showed correlation among the observables. In figure 7, we have varied the Dirac delta phase $\delta$ with the baryon asymmetry of the Universe calculated in our model in both the mass orderings. Both these results shows that BAU is possible within our model. In order to observe successful baryogenesis, we get constrained on the Dirac phase, whose value lies nearly around $(2-4)$ in both the mass ordering, while results in IH are relatively poor. Similar results can be seen from fig. 10, where we have projected BAU in between Dirac and Majorana phases. Correlation among the effective neutrino mass in presence of $keV$ sterile neutrino with the BAU is also shown in figure 8. From both results of NH and IH, it is obvious that NH mode is more preferable to study baryogenesis within the framework.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Electron neutrino effective mass vs. the lightest neutrino mass.}
\end{figure}
FIG. 3: Variation of effective mass for different range of active-sterile mixing angle.

FIG. 4: Variation of $p$ with effective mass in presence of sterile neutrino.

of MES. Moreover, we have shown contour plots in figure 9, where a measured BAU is projected in the frame between sterile neutrino mass and effective electron neutrino mass and we have seen that IH mode is almost neglected by the model while we get some region satisfying current BAU bound in NH mode.
FIG. 5: Projection of effective electron neutrino mass in presence of keV sterile neutrino with two model parameters by the axes. First column shows the results of normal hierarchy while the second column shows results for inverted hierarchy mode.
FIG. 6: Variation of decay width and the relic abundance of the universe vs. the Dark matter mass. The blue lines give the upper limit of the decay width and relic abundance in respective figures.

FIG. 7: Variation of Dirac delta phase with BAU in both the mass ordering.
FIG. 8: Correlation between effective neutrino mass with BAU in NH and IH respectively.

FIG. 9: Projection of BAU with sterile mass and effective electron neutrino mass in the axes for both the mass ordering.
FIG. 10: Projection of BAU between Dirac and Majorana phases
V. Conclusion

In this work, MES framework is extensively studied to check the viability of $keV$ sterile neutrino to behave as a warm dark matter simultaneously giving an observable effect in $0\nu\beta\beta$ and BAU. $A_4$ based flavor model with a discrete Abelian symmetry $Z_4$ is used to construct the desired Yukawa coupling matrices. Here, the Dirac mass $M_D$ is a $3 \times 3$ complex matrix, the Majorana mass matrix $M_R$, which arises due to the coupling of right-handed neutrinos is also a $3 \times 3$ complex symmetric diagonal matrix with non-degenerate eigenvalues. A singlet gauge fermion $S$ is considered which couples with the right-handed neutrino and produces a singled row $1 \times 3$ $M_S$ matrix with one non-zero entry. The Dirac mass matrix 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. Few interesting points based on the results are discussed as follows,

- Presence of an extra heavy sterile flavor has significant effect in effective neutrino mass. One can find a broader effective mass range in active-sterile case than the only active neutrino case. Normal hierarchy (NH) is more favourable than the inverted hierarchy mode for $0\nu\beta\beta$ in this MES framework.

- Consequential bounds on active-sterile mixing angle is obtained for future sensitivity in effective mass from fig. 3, which restricts the upper bound on the mixing element up to $10^{-7}$ for $U_{e4}$.

- In fig. 4 and 5, strong constrained regions for the model parameters are obtained through the $0\nu\beta\beta$ calculation, which by the by gives strict bounds on the Yukawa couplings related to the model parameters.

- From DM analysis, results from decay width and relic abundance restricts DM mass (sterile neutrino mass) within few $keV$. In spite of the fact that several authors put different bounds for thermal relic mass for the sterile neutrino and very few results are consistent with X-ray observations. Lyman-$\alpha$ forest of high resolution quasar spectra with hydrodynamical N-body simulations gives bounds ranging from $M_S \geq 1.8keV$ to $M_S \geq 3.3keV$ [98, 105, 106]. Anyway, these bounds may vary depending upon various uncertainties effecting the constrains [97]. Within MES framework, NH predicts sterile
mass range from \((1 – 3\text{keV})\) and IH results for relic abundance gives DM mass up to \(10\text{keV}\).

- BAU is satisfied in this framework and NH is more efficient in producing the observed matter-antimatter density. This model has successfully correlate \(0\nu\beta\beta\) with BAU, which can be found in fig. 8.

- Projection of BAU with sterile mass and effective mass in presence of sterile neutrino in fig. 9 give an unsatisfactory remark while observing IH. Nonetheless, BAU value is very small, NH manage to project the value. However, IH fails to correlate them in a single frame.

- In NH mode within this model, a constrained bound on Dirac CP-phase is obtained from BAU study, which can be seen in the density plot of fig. 10 with Majorana phases in the x-axis. Majorana phases covers the whole \(0 – 2\pi\) range, whereas CP phase is constrained between the value \((2 – 4)\) satisfying observed BAU.

In conclusion, the MES mechanism is analyzed in this work. Apart from active and sterile mass generation, this model can also be used to study the connection between effective mass in neutrinoless double beta decay in a wider range of sterile neutrino mass simultaneously explaining \(keV\) scale sterile neutrino as WIMP DM particle and baryogenesis via the mechanism of thermal leptogenesis and connecting all these observables in a single framework.

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34