4 Lepton number violation and baryogenesis in type I + type II seesaw

In this chapter, we present a study of baryogenesis via leptogenesis and neutrinoless double beta decay (NDBD) in the framework of LRSM where type I and type II seesaw terms arises naturally. The type I seesaw mass term is considered to be favouring $\mu-\tau$ symmetry, taking into account the widely studied realizations of $\mu-\tau$ symmetric neutrino mass models, viz. Tribimaximal Mixing (TBM), Hexagonal Mixing (HM) and Golden Ratio Mixing (GRM) respectively. The required correction to generate a non-vanishing reactor mixing angle θ_{13} is obtained from the perturbation matrix, type II seesaw mass term in our case. We studied the new physics contributions to NDBD and baryogenesis ignoring the left-right gauge boson mixing and the heavy-light neutrino mixing, keeping mass of the gauge bosons and scalars to be around TeV and studied the effects of the new physics contributions on the effective mass, NDBD half-life and cosmological BAU and compared with the values imposed by the experiments. We tried to find the leading order contributions to NDBD and BAU, coming from type I or type II seesaw in this work.

4.1 Introduction

In recent time, understanding the origin of baryon asymmetry of the universe (BAU) has been one of the most sought after topic amongst the scientific research community. It constitutes one of the major challenges in particle physics and cosmology and our understanding of the dynamics of the universe. It appeals for a better explanation of the process beyond the most successful but inadequate Standard Model (SM) of particle physics. The left-right symmetric model (LRSM)[1, 2, 3, 4, 5, 6] is widely used BSM framework and is an appealing theory where the left and right chiralities are treated in equal footing at high energy scales. Herein, the seesaw mechanisms arise naturally. Out of different mechanisms, leptogenesis is widely considered as favorable to explain BAU in the framework of LRSM. For leptogenesis to be testable in experiments, the breaking scale of $SU(2)_R$ should be in the TeV range as well as there has to be a quasi degeneracy between at least two RH neutrinos with their mass difference comparable to their decay widths for a resonant enhancement of the CP asymmetry. The connection between leptogenesis and low energy rare processes like neutrinoless double beta decay (NDBD), lepton flavor violation (LFV) etc. cannot be overestimated. It has been extensively studied in several earlier works [7]. Generally, the seesaw (SS) mechanism connects the light neutrinos with the heavy Majorana neutrinos, the decay of whose creates the leptonic CP asymmetry which can be converted to baryon asymmetry by the electroweak sphaleron transitions. In the scheme of LRSM, due to the presence of the heavy scalar particles, NDBD receives additional contributions from RH gauge sector and the scalar triplets. Again, if the mass of the scalar triplet is heavier than the lightest RH Neutrino mass which is of TeV scale, the asymmetry produced is dominated by the decay of only the RH neutrino and the leptogenesis from the decay of fermion or scalar triplet would also be ruled out. In this case, leptogenesis can be explained from the type I SS diagrams, with the type I SS mass term, $M_\nu \approx -M_D M_{RR}^{-1} M_D^T$, with a heavy-light neutrino mixing of order $M_D M_{RR}^{-1}$, where, M_D and M_{RR} are the Dirac and Majorana masses respectively. However, it would be enthralling to study the situation where both the situations (type I and type II seesaw) are comparable in size and the corresponding outcomes.

For a generic TeV scale LRSM, for neutrino mass to be of the order of sub eV, the Dirac Yukawa coupling has to be very small which would lead to a very small efficiency factor for low scale leptogenesis to work. Several works have studied this in details and have come with some interesting outcomes that for maximal CP asymmetry (of order 1), successful BAU in LRSM requires the RH gauge boson mass to be greater than 18 TeV [8]. Again, it has been found that for some specific textures of the Dirac and Majorana neutrino mass matrices, motivated by some flavor symmetry in the leptonic sector, successful leptogenesis can also be realized for $M_{W_R} > 10$ TeV with maximal CP asymmetry [9]. The constraint on

W_R mass is very important for the survival of LR SS leptogenesis. It would be interesting to probe the lower bound on W_R mass to see if there exist any allowed parameter space in TeV scale LRSS models with successful leptogenesis for smaller values of M_{W_R}.

In chapter 3, we have studied NDBD and BAU considering different RH gauge boson mass 5, 10 and 18 TeV respectively and checked the consistency of several earlier results (second reference of [8, 9]), considering equal contributions from both the type I and type II seesaw terms. In a recent work [10], the authors have investigated if leptogenesis as a mechanism for explaining BAU can be tested at future colliders. They considered the case for two RH Neutrinos in the mass range 5-50 GeV and estimated the allowed parameter space for successful leptogenesis. However, the basic objective of this work is to find whether it is the type I or type II seesaw term which gives the leading contributions to NDBD and BAU. The RH gauge boson mass is considered to be 10 TeV, the lower bound of RH gauge boson mass as found by the authors of [9] although we have shown in the last chapter that larger values of M_{W_R} leads to better efficiencies. With reference to chapter 1, we considered the type I SS mass term to be favouring $\mu - \tau$ symmetry [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25]. The different realizations of $\mu - \tau$ symmetry which we have taken into account are Tribimaximal Mixing (TBM), Hexagonal Mixing (HM) and Golden Ratio Mixing (GRM). The perturbation to generate a non-zero reactor mixing angle is obtained from the type II seesaw term. It is quite natural to expect the model to have a lepton asymmetry, once the $\mu - \tau$ symmetry is broken, as well as also a non-vanishing θ_{13}. The observation of NDBD would be significant as it would help us in understanding the origin of BAU as it would imply that lepton number indeed is not conserved [26, 27, 28]. Furthermore, the Majorana nature [29] of neutrinos would also be established from NDBD. In LRSM, there are several contributions to NDBD that involve left and right-handed (RH) sectors individually as well as others that involve both sectors through left-right mixing accompanied by both light and heavy neutrinos. Left-right mixing is always a ratio of the Dirac and Majorana mass scales ($M_D M_{RR}^{-1}$) which appears in the type I seesaw formula. NDBD involving left-right mixing can be enhanced for specific Dirac matrices. However in our present work, we have considered only two new physics contributions to NDBD coming from the diagrams containing purely RH current mediated by the heavy gauge boson, $\mathrm{W_R}$ by the exchange of heavy RH neutrino, $\mathrm{N_R}$ and another from the charged Higgs scalar Δ_R mediated by the heavy gauge boson $\mathrm{W_R}$

[30]. We have ignored the contributions coming from the left-right gauge boson mixing and heavy-light neutrino mixing owing to the very small left-right mixing.

This chapter is organized as follows. In the next section, we summarize the implications of TeV scale LRSM in processes like BAU and other low energy observables like NDBD. In section 4.3, we present the basic steps involved in our numerical analysis and results and then give our conclusion in section 4.4

4.2 Resonant Leptogenesis (RL) and NDBD in TeV scale LRSM

Various models have been proposed and studied extensively for leptogenesis. For present-day experiments accessible at LHCs, TeV scale SS models accounts for resonant leptogenesis [31, 32, 33, 34, 35], a leptogenesis mechanism in which there is a resonant enhancement of the leptonic asymmetries when at least two heavy RH neutrinos are nearly degenerate and have a mass difference comparable to their decay widths [36]. In our analysis we considered the two nearly degenerate RH neutrinos to be of TeV range and have mass difference about 10^{-6} as per the requirement of RL. In several earlier works, it has been illustrated regarding the specific flavor structure that allows large Yukawa couplings that could serve the twin purpose of leptogenesis that could be efficient as well as testable in experiments. Notwithstanding, as far as Dirac neutrino mass matrix is concerned, we have not taken into account any specific structure of the matrix but a generalized form obtained by solving from the type I SS where the light neutrino mass matrix and the heavy RH Majorana mass matrix are considered to be known as in our previous work (second reference of [7]). However, in this work, we have taken the type I mass term to be of different types obeying $\mu - \tau$ symmetry, notably, TBM, HM and GRM respectively with reactor mixing angle, $\theta_{13} = 0$. The perturbation to generate a non-zero θ_{13} is obtained from the type II SS mass matrix, the elements of which are explicitly shown in the appendix section (appendix A.1).

The underlying idea of this work is to relate leptonic asymmetry and hence baryon asymmetry with low energy observable like NDBD as well as to find the leading order contribution on these phenomena from the SS mechanisms (whether it is type I or type II SS). In LRSM, presence of the RH Neutrinos in type I SS and the scalar triplets in type II SS propound their decays that can give rise to lepton asymmetry. However, we would consider only the decay of the RH neutrinos as in several earlier works and ignore the decay of the scalar triplets in generating leptonic asymmetry as above TeV scale, the decay of the RH neutrinos are in thermal equilibrium and would wash out any primordial preceding leptonic asymmetries.

The heavy RH neutrinos present in the SS term besides explaining the origin of the tiny neutrino mass can also throw light on the cosmological baryonic asymmetry of the universe (obtained from the leptonic asymmetry by the EW sphaleron transitions) as has been discussed in the earlier chapters. The lepton asymmetry is created by the decay of the heavy RH neutrinos into a lepton and a Higgs doublet $N_i \rightarrow L+\phi^c$ and its respective CP conjugate process, $N_i \rightarrow L^c + \phi$ which can occur at both tree and one loop levels. The CP violating asymmetry ϵ_i arises from the interference between the tree level graph with absorptive part of self-energy transition [37, 38, 39] describing the mixing of the decaying particles. For RL to occur, a prerequisite condition is $M_i - M_j \approx \Gamma$ which leads to an enhancement of CP asymmetry even of order 1. Under such condition, RL can occur with heavy Majorana neutrinos even as light as ≈ 1 TeV. The CP violating asymmetry ϵ_i is as defined in equation (1.97). The CP violating asymmetries ϵ_1 and ϵ_2 can give rise to a net lepton number asymmetry provided the expansion rate of the universe is larger than Γ_1 and Γ_2 at $T = M_N$. This can further be partially converted into baryon asymmetry of the universe by B+L violating sphaleron [40] interactions which are in thermal equilibrium above the critical temperature T_c.

Presently one of the most preferred explanations of BAU emanates from lepton number violation or NDBD process which could prove the Majorana nature of the neutrinos. NDBD plays a significant role to interpret the dominance of matter over anti-matter and the interrelation of NDBD and BAU has been widely studied in many previous works. In the framework of LRSM, there are various contributions to NDBD amplitude from the presence of several new heavy scalar particles apart from the standard light neutrino contribution. It has been extensively studied in many of the earlier works (see ref. [41][30]). The different new physics contributions that could arise are coming from the ones mediated by W_R, the exchange of the heavy gauge bosons (${W_L}^-$ and ${W_R}^-$), both the left and RH gauge bosons (mixed diagrams, λ and η) as well the scalar triplet (Δ_L and Δ_R) contributions.

The amplitude of these processes mostly depends upon the mixing between light and heavy neutrinos, the leptonic mixing matrix elements, the mass of the heavy neutrino (M_i), the mass of the gauge bosons, ${W_L}^-$ and ${W_R}^-$, the mass of the triplet Higgs as well as their coupling to leptons, f_L and f_R.

Howeve, in this work, we have considered only two of the aforesaid contributions to NDBD, the new physics contributions to NDBD that is the ones mediated by ${W_R}^-$ and Δ_R respectively. The diagrams arising due to the effect of $W_L - W_R$ mixing are suppressed in our case as it is found to be less than 10^{-3}. Again the diagrams arising due to light heavy neutrino mixing is proportional to $M_D {M_{RR}}^{-1}$ which is very less (around 10^{-6})and hence is negligible in our case.

4.3 Numerical Analysis and Results

Having studied several of the earlier works regarding NDBD and BAU in a TeV scale LRSM, in this work we are trying to do a comprehensive study of these phenomena within the framework of LRSM in the TeV scale, accessible in the colliders, encompassing the most studied $\mu - \tau$ symmetric neutrino mass models, viz. TBM, HM and GRM respectively. We took into consideration both the mass hierarchies, i.e., normal and inverted mass hierarchies. In one of our previous works, we studied BAU, NDBD and LFV and their correlation by considering some specific values of RH gauge boson masses, 5, 10 and 18 TeV within and above the values measured in LHCs and checked the consistency of the results with several of the earlier works.

Whereas, in this work, we considered particularly the RH gauge boson mass to be 10 TeV and tried to study the contribution of type I and type II seesaw to find the leading order and dominating contribution for BAU and NDBD. Furthermore, we have considered the different mixing patterns, namely, TBM, HM and GRM in this study. We have divided this section into two subsections consisting of firstly the analysis of resonant leptogenesis and secondly of new physics contribution to NDBD.

4.3.1 Baryogenesis via Leptogenesis

Baryogenesis via leptogenesis has been widely studied in several earlier works. Herein, we are giving detailed steps with relevant formulae involved in the framework of LRSM in our analysis. As we know that the light ν masses in the framework of LRSM can be written as a combination of type I and type II seesaw. Here, we have considered the type I mass term to be different realizations of $\mu-\tau$ symmetric neutrino mass models, namely, tribimaximal mixing (TBM), hexagonal mixing (HM) and golden ratio mixing (GRM) pattern (as in chapter 2),

$$M_{\nu}{}^{I} = U_{(\mu-\tau)} U_{Maj} M_{\nu}{}^{I(diag)} U_{Maj}{}^{T} U_{(\mu-\tau)}{}^{T}, \tag{4.1}$$

where $\mu-\tau$ represents TBM, HM and GRM and

$$U_{TBM} = \begin{bmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}, U_{HM} = \begin{bmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{\sqrt{2}}{4} & \frac{\sqrt{6}}{4} & -\frac{1}{\sqrt{2}} \\ -\frac{\sqrt{2}}{4} & \frac{\sqrt{6}}{4} & \frac{1}{\sqrt{2}} \end{bmatrix},$$
$$U_{GRM} = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{5-\sqrt{5}}} & \frac{\sqrt{2}}{\sqrt{5+\sqrt{5}}} & 0 \\ -\frac{\sqrt{2}}{\sqrt{5+\sqrt{5}}} & \frac{\sqrt{2}}{\sqrt{5-\sqrt{5}}} & -\frac{1}{\sqrt{2}} \\ -\frac{\sqrt{2}}{\sqrt{5+\sqrt{5}}} & \frac{\sqrt{2}}{\sqrt{5-\sqrt{5}}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \tag{4.2}$$

$\mathrm{M}_{\nu}{}^{\mathrm{I(diag)}} = \mathrm{XM}_{\nu}{}^{\mathrm{(diag)}}$ [42], the parameter X describes the relative strength of the type I and II seesaw terms. It can take any numerical value provided the two seesaw terms give rise to correct light neutrino mass matrix. In our case, we considered three specific values of X, X = 0.3, 0.5 and 0.7 which corresponds to more contribution from type II, equal contribution from type I and type II seesaw and more contribution from type I seesaw respectively[42]. Thus we can write M_{ν} in terms of type I and type II seesaw as,

$$U_{PMNS} M_{\nu}{}^{(\mathrm{diag})} U_{PMNS}{}^{T} = M_{\nu}{}^{II} + U_{(\mu-\tau)} U_{Maj} X M_{\nu}{}^{(\mathrm{diag})} U_{Maj}{}^{T} U_{(\mu-\tau)}{}^{T}, \tag{4.3}$$

$\mathrm{U_{PMNS}}$ being the diagonalizing matrix of the light neutrino mass matrix, M_{ν} as defined in equation (1.28). The recent neutrino oscillation data which we have adopted in our analysis is shown in the table 4.1,

PARAMETERS	3σ RANGES	BEST FIT$\pm 1\sigma$
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	7.05-8.14	7.56
$\Delta m^2_{31}[10^{-3}\text{eV}^2]$(NH)	2.41-2.60	2.50
$\Delta m^2_{31}[10^{-3}\text{eV}^2]$(IH)	2.31-2.51	2.42
$\sin^2\theta_{12}$	0.273-0.379	0.321
$\sin^2\theta_{23}$(NH)	0.445-0.599	0.547
(IH)	0.453-0.598	0.551
$\sin^2\theta_{13}$(NH)	0.0196-0.0241	0.0216
(IH)	0.0199-0.0244	0.0222
δ/π	0.87-1.94(NH)	1.21
	1.12-1.94(IH)	1.56

Table 4.1: Global fit 3σ values of ν oscillation parameters [43]

The RH Majorana neutrino mass $\mathrm{M_{RR}}$ can be written in terms of type II SS mass term as,

$$M_{RR} = \frac{1}{\gamma}\left(\frac{v_R}{M_{W_L}}\right)^2 {M_\nu}^{II}, \tag{4.4}$$

where, γ is a dimensionless parameter and has been fine tuned as $\sim 10^{-10}$. As already mentioned we have considered the $SU(2)_R$ breaking scale, v_R to be specifically 10 TeV. The left-handed (LH) gauge boson mass is $M_{W_L} = 80$ GeV. The type II SS mass term can be determined from the light neutrino mass and the type I SS mass term as,

$${M_\nu}^{II} = U_{PMNS}{M_\nu}^{(\text{diag})}{U_{PMNS}}^T - U_{(\mu-\tau)}U_{Maj}X{M_\nu}^{(\text{diag})}{U_{Maj}}^T{U_{(\mu-\tau)}}^T. \tag{4.5}$$

The elements of the type II SS mass term is shown in appendix A.1. Again,

$$M_{RR} = U_R{M_{RR}}^{(\text{diag})}{U_R}^T, {M_{RR}}^{(\text{diag})} = \text{diag}(M_1, M_2, M_3). \tag{4.6}$$

Expressing ${M_\nu}^{(diag)}$ in terms of lightest neutrino mass, $m_1(m_3)$ for NH (IH), we obtained M_{RR} varying the Majorana phases α and β from 0 to 2π and lightest neutrino mass from 10^{-3} to 10^{-1}. For leptogenesis to be testable in the colliders, i.e., for low scale leptogenesis, at least two of the lightest heavy RH neutrino has to have a very small mass difference and comparable to their decay widths. In such a case the CP asymmetry can be resonantly enhanced. By considering a very tiny mass splitting of the Majorana massesM_1 and M_2

as per requirement of resonant leptogenesis, we equated both sides of equation (4.4) and obtained M_1, M_2 and M_3, where, $M_1 \approx M_2$.

Again, a net baryon asymmetry can be generated from a lepton asymmetry. We considered the lepton number violating and CP violating out of equilibrium decays of two lightest heavy RH Majorana neutrinos, N_1 and N_2 via the decay modes, $N_i \rightarrow l + \phi^c$ and its CP conjugate process, $N_i \rightarrow l^c + \phi$, with, $i = 1, 2$. Firstly, we determined the leptonic CP asymmetry, ϵ_1 and ϵ_2 using equation (1.97) where $Y_\nu = \frac{M_D}{v}$, v being the VEV of Higgs bidoublet and is 174 GeV. The decay rates in equation (1.97) can be obtained using equation (1.96).

The Dirac mass, M_D generated due to neutrino Yukawa coupling, Y_ν after electroweak symmetry breaking can be determined from the type I SS mass term provided the light neutrino mass and RH heavy neutrino mass is known. As mentioned before M_D is not of any specific texture, but we have obtained it from the type I SS equation which satisfies the current neutrino oscillation data.

We have considered M_D as,

$$\mathrm{M_D} = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_2 & a_4 & a_5 \\ a_3 & a_5 & a_6 \end{bmatrix}, \tag{4.7}$$

which is symmetric. However, we have not used any discrete symmetry for the realization of the mass structures in this work. Equating both sides of type I seesaw equation and solving for $a_1, a_2, a_3, a_4, a_5, a_6$, we obtain the matrix elements of the M_D.

Type I %	M_D (TBM)
30%	$\begin{bmatrix} 10659.6+43346.9i & -6870.95-168385i & -3291.61-289471.i \\ -6870.95-168385i & -55880.1-662058i & -13683.1-191910.i \\ -3291.61-289471.i & -13683.1-191910.i & -8403.82-76049.1i \end{bmatrix}$
50%	$\begin{bmatrix} -582583.-194667.i & -594087.+168153.i & -165725.-448698.i \\ -594087.+168153.i & -891798.-108937.i & -356298.-5249.83.i \\ -165725.-448698.i & -356298.-5249.83.i & 148675.+486078.i \end{bmatrix}$
70%	$\begin{bmatrix} 1.18038*10^6-413245i & -460528.-119600.i & -503470.-599949.i \\ -460528.-119600. & -379622.-335042.i & -353251.-15931.2i \\ -503470.-599949.i & -353251.-15931.2i & 319582.-67597.6i \end{bmatrix}$

Table 4.2: One of the M_D for the TBM mixing for different contributions of type I SS.

Type I %	M_D (HM)
30%	$\begin{bmatrix} -121178.-15371.9i & 222216.+24170.9i & -76981.5+97663.7i \\ 222216.+24170.9i & -815488.+97346.4i & 298038.-113697.i \\ -76981.5+97663.7i & 298038.-113697.i & -264278.+379952.i \end{bmatrix}$
50%	$\begin{bmatrix} -415231.+3664.61i & -220545.+97305.i & 42113.5+182121.i \\ -220545.+97305.i & -84116.4+244938.i & -164012.-10473.4i \\ 42113.5+182121.i & -164012.-10473.4i & -193244.-63998.i \end{bmatrix}$
70%	$\begin{bmatrix} 319603.-294988.i & -470313.-99820.8i & -181377.+294053.i \\ -470313.-99820.8i & 758598.-492434.i & 429434.-300049.i \\ -181377.+294053.i & 429434.-300049.i & 217576.-402082.i \end{bmatrix}$

Table 4.3: One of the M_D for the HM mixing for different contributions of type I SS.

Type I %	M_D (GRM)
30%	$\begin{bmatrix} 110551.+646944.i & -369919.+90392.4i & -83843.7-438691.i \\ -369919.+90392.4i & -1.54621*10^6-487430.i & 94740.-622680. \\ -83843.7-438691.i & 94740.-622680.i & 511074.-382628.i \end{bmatrix}$
50%	$\begin{bmatrix} 439547.+117224.i & 510615.-463048.i & 208226.+255947.i \\ 510615.-463048.i & 1.03558*10^6-89213.3i & 620647.-48081.9i \\ 208226.+255947.i & 620647.-48081.9i & -233246.-487847.i \end{bmatrix}$
70%	$\begin{bmatrix} 463242.-1.45202*10^6 i & -686213.-17676.5i & -389607.+126272.i \\ -686213.-17676.5i & 716739.-745091.i & 317860.+424951.i \\ -389607.+126272.i & 317860.+424951.i & 308970.+537833.i \end{bmatrix}$

Table 4.4: One of the M_D for the GRM mixing for different contributions of type I SS.

We have shown just one of the M_D for different contributions of type I SS for the different mixing patterns. We have used these M_Ds for our further analysis.

The CP violating asymmetries ϵ_1 and ϵ_2 can give rise to a net lepton number asymmetry provided the expansion rate of the universe is larger than Γ_1 and Γ_2. The net baryon asymmetry is then calculated using [44],

$$\eta_B \approx -0.96 \times 10^{-2} \sum_i (k_i \epsilon_i), \tag{4.8}$$

k_1 and k_2 being the efficiency factors measuring the washout effects linked with the out of equilibrium decay of N_1 and N_2. We can define the parameters, $K_i \equiv \frac{\Gamma_i}{H}$ at temperature, $T = M_i$, $H \equiv \frac{1.66\sqrt{g_*}T^2}{M_{Planck}}$ is the Hubble's constant with $g_* \simeq 107$ and $M_{Planck} \equiv 1.2 \times 10^{19} GeV$ is the Planck mass. The decay width can be estimated using equation (1.96). For simplicity, the efficiency factors, k_i can be calculated using the formula (from[45]),

$$k_1 \equiv k_2 \equiv \frac{1}{2}\left(\sum_i K_i\right)^{-1.2}, \tag{4.9}$$

which holds validity for two nearly degenerate heavy Majorana masses and $5 \leq K_i \leq 100$. We have used the formula (1.99) in calculating the baryon asymmetry. The observed BAU from cosmological studies constrained by Big bang Nucleosynthesis (BBN) and determined with good precision by WMAP experiment as [46],

$$\eta_B = \frac{n_B}{n_\gamma} = \left(6.5^{+0.4}_{-0.3}\right) \times 10^{-10}. \tag{4.10}$$

We compare our results with this cosmological observed value of BAU. The result is shown as a function of lightest neutrino mass and Majorana phase α in fig 4.1,4.2 for different values of X, i.e., different contributions of seesaw. It is evident from the figure that the cosmological observed BAU from RL can be obtained for different contributions of type I seesaw, 30%, 50% and 70%. As seen in figure 4.1 IH seems to be a better prediction for BAU irrespective of the mixing patterns (except for the GRM with 50% and 70% type I SS contribution) and the results are more scattered for lightest neutrino mass varying from 0.001 to 0.01 than for higher values of lightest neutrino mass. It is seen that for $m_{lightest}$ of around (0.05-0.1)eV are closer to the experimental observation of BAU. Minute observation of figure 4.1 also shows that irrespective of the mass hierarchy, all the mixing patterns considered are giving closer results of BAU when compared to the experimental bound. However, for some values of α, results seem to be closer to the observed BAU and it shows a slight variation for different contributions of SS. Figures 4.3, 4.4, 4.5 are contour plots showing the variation of BAU with both the Majorana phases α and β. All the mixing patterns show almost similar results, but on minute observation of the figures, we can see that there is a correlation between the Majorana phases which is again different for both the mass hierarchies. For the phase α, in case of IH, greater parameter space is obtained satisfying the experimental bound for a greater contribution of type I SS in TBM, GRM and HM mixing scenarios.

4.3.2 NDBD from heavy RH neutrino and scalar triplet contribution

There are several new physics contributions to NDBD amplitudes due to the presence of the heavy scalar particles in LRSM. In the present work, we have considered the contributions coming from the heavy RH neutrino contribution coming from the exchange of W_R bosons and the scalar Higgs triplet. The effective neutrino mass corresponding to these contributions is given by,

$$\mathrm{m_{N+\Delta_R}}^{\mathrm{eff}} = \mathrm{p}^2 \frac{\mathrm{M_{W_L}}^4}{\mathrm{M_{W_R}}^4} \frac{\mathrm{U_{Rei}}^{*2}}{\mathrm{M_i}} + \mathrm{p}^2 \frac{\mathrm{M_{W_L}}^4}{\mathrm{M_{W_R}}^4} \frac{\mathrm{U_{Rei}}^2 \mathrm{M_i}}{\mathrm{M_{\Delta_R}}^2}. \tag{4.11}$$

Here, $< \mathrm{p}^2 >= \mathrm{m_e m_p} \frac{\mathrm{M_N}}{\mathrm{M_\nu}}$ is the typical momentum exchange of the process, where $\mathrm{m_p}$ and $\mathrm{m_e}$ are the mass of the proton and electron respectively and $\mathrm{M_N}$ is the nuclear matrix element (NME) corresponding to the RH neutrino exchange. We know that TeV scale LRSM plays an important role in $0\nu\beta\beta$ decay. We have considered the values $\mathrm{M_{W_R}} = 10$ TeV, $\mathrm{M_{W_L}} = 80$ GeV, $\mathrm{M_{\Delta_R}} \approx$3TeV, the heavy RH neutrino $\approx$ TeV which are within the recent collider limits. The allowed value of p, the virtuality of the exchanged neutrino is in the range $\sim$ (100-200) MeV [30] and we have considered p$\simeq$ 180 MeV in our analysis as in earlier works.

Thus,

$$\mathrm{p}^2 \frac{\mathrm{M_{W_L}}^4}{\mathrm{M_{W_R}}^4} \simeq 10^{10}\mathrm{eV}^2. \tag{4.12}$$

However, equation (**??**) is valid only in the limit $\mathrm{M_i}^2 \gg |< \mathrm{p}^2 >|$ and $\mathrm{M_\Delta}^2 \gg |< \mathrm{p}^2 >|$.

To evaluate $\mathrm{m_{N+\Delta_R}}^{\mathrm{eff}}$, we need the diagonalizing matrix of the heavy RH Majorana mass matrix $\mathrm{M_{RR}}$, U_{Rei} and its mass eigenvalues, $\mathrm{M_i}$. $\mathrm{M_{RR}}$ can be written in the form (from reference [42]),

$$\mathrm{M_{RR}} = \frac{1}{\gamma}\left(\frac{\mathrm{v_R}}{\mathrm{M_{W_L}}}\right)^2 \mathrm{M_\nu}^{\mathrm{II}}, \tag{4.13}$$

For the new physics contribution in which the type II term acts as the perturbation, we have also evaluated the half-life of the $0\nu\beta\beta$ decay process using equation (1.91) where the effective mass is given by,

$$|\mathrm{m}_{\beta\beta}|^2 = \left|\mathrm{m_\nu}^{\mathrm{eff}}\right|^2 = \left|\mathrm{m_N}^{\mathrm{eff}} + \mathrm{m_{\Delta_R}}^{\mathrm{eff}}\right|^2 \tag{4.14}$$

is the effective neutrino mass governing NDBD, ${G_0}^\nu$ contains the phase space factors and $M^{0\nu}$ is the nuclear matrix element (NME). Considering the values of the phase factors(${G_0}^\nu$) [47, 48] [49], NME [50, 51] and mass of electron, we have obtained the half-life as a function of the lightest mass in the different mixing patterns for both NH and IH, as shown in figure 4.6. Fig. 4.6 shows that the half-life governing NDBD (from the new physics contribution) shows different results for the different mixing patterns as well as for the different mass ordering. It is evident from the figures that IH in all the cases have better predictions for NDBD as far as the experimental bound propounded by KamLAND-Zen is concerned. But out of the different mixing patterns, GRM for IH suggests better predictions. Whereas for NH the results are more scattered than IH and some of the values even lie out of the experimental range in comparison to IH. In figure 4.3.2 we have shown the half-life variations with Majorana phase α which again shown different results for the different mixing patterns. From the plots, it is evident that both NH and IH satisfies the experimental bound for a large parameter space. However, the results for NH are more scattered in comparison to

IH. In figures 4.8, 4.9 and 4.10, we have shown contours with α, β in the two axes and half-life governing NDBD as the contour. It is seen that the parameter space for α is more constrained for the IH in all the mixing patterns. In figure 4.11, we have shown a correlation of BAU with NDBD half-life to see if they have a common parameter space in which both BAU and NDBD satisfies the experimental results. Observing the plots minutely, we can't say much about the leading contribution, but very less parameter space is satisfying both NDBD and BAU simultaneously irrespective of the mass hierarchies. We have summarized the plots of BAU and NDBD for three different values of X, i.e., for different contributions of seesaw as follows,

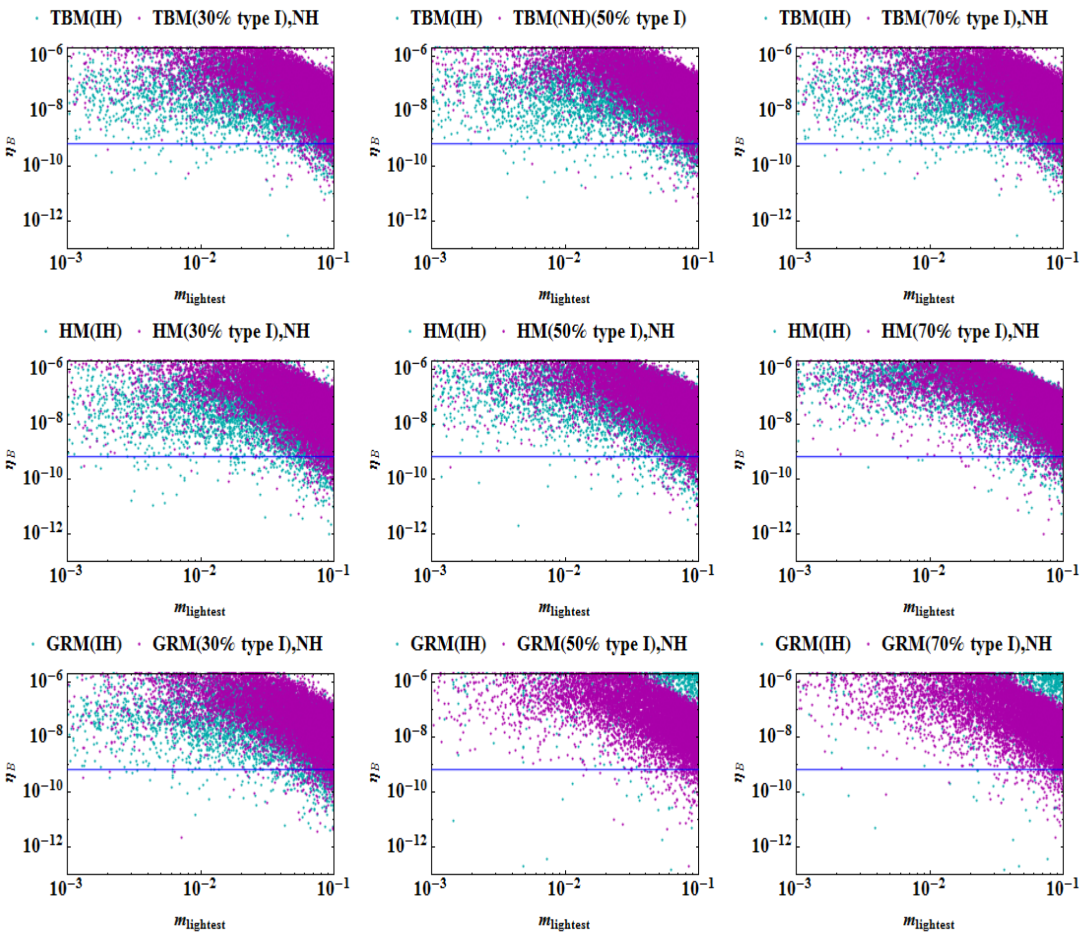

Figure 4.1: BAU as a function of lightest neutrino mass, m_1 / m_3 for NH/IH for different values of X, i.e., different contributions of type I SS. The blue horizontal line indicates the bound on cosmological BAU from PLANCK '15.

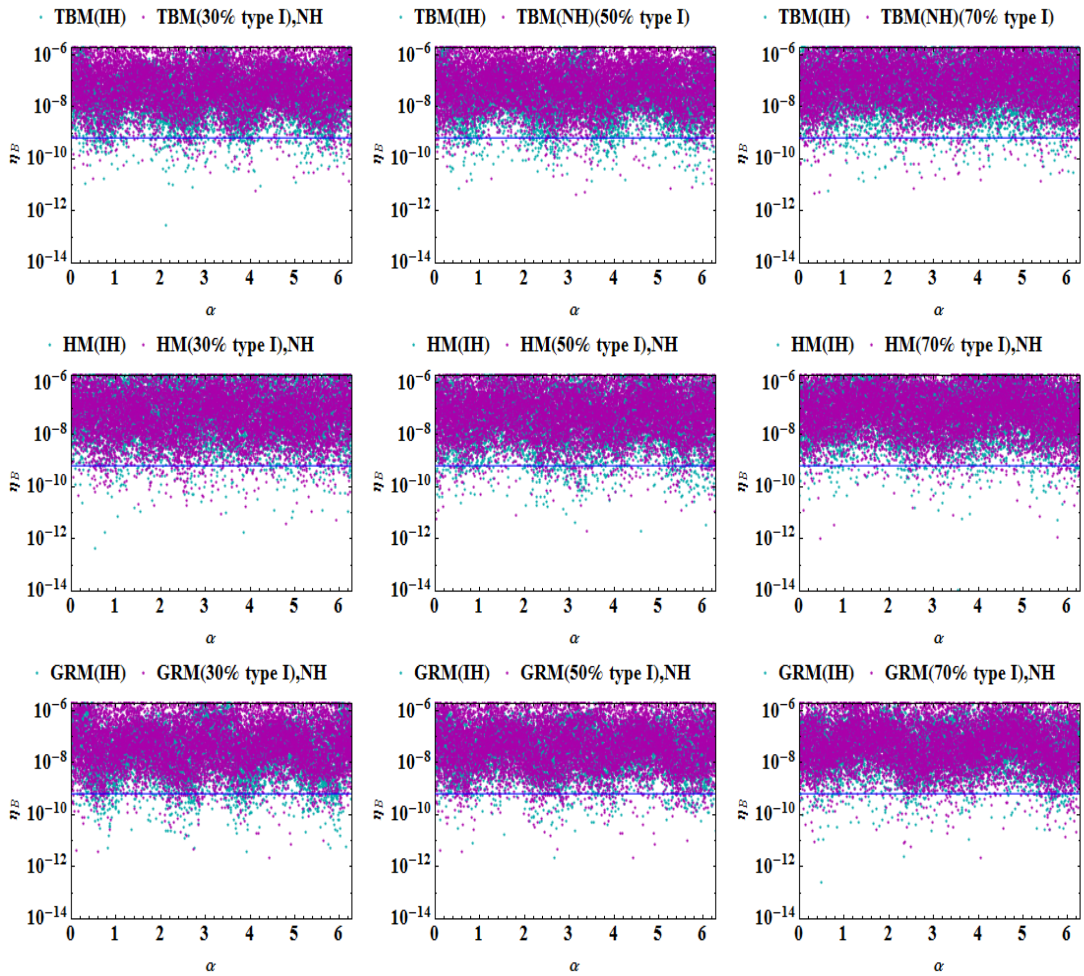

Figure 4.2: BAU as a function of Majorana phase α for NH/IH for different contributions of type I SS. The blue horizontal line indicates the bound on cosmological BAU from PLANCK '15.

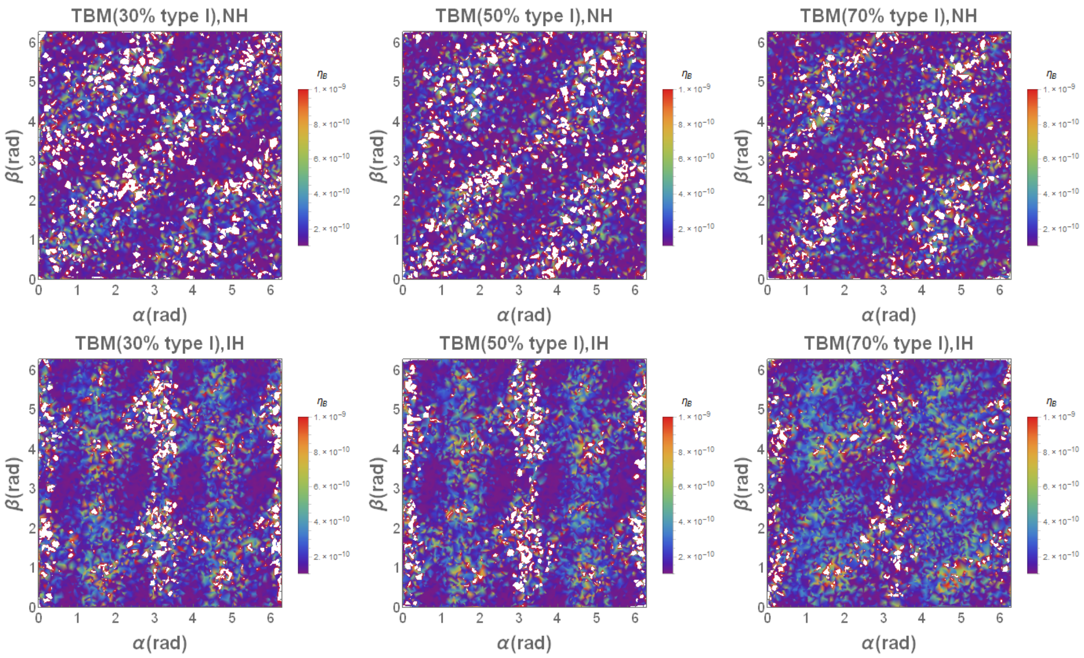

Figure 4.3: Contour plot showing the Majorana phases α and β in the two axes with BAU parameter η_B as the contour for TBM mixing pattern for both NH/IH.

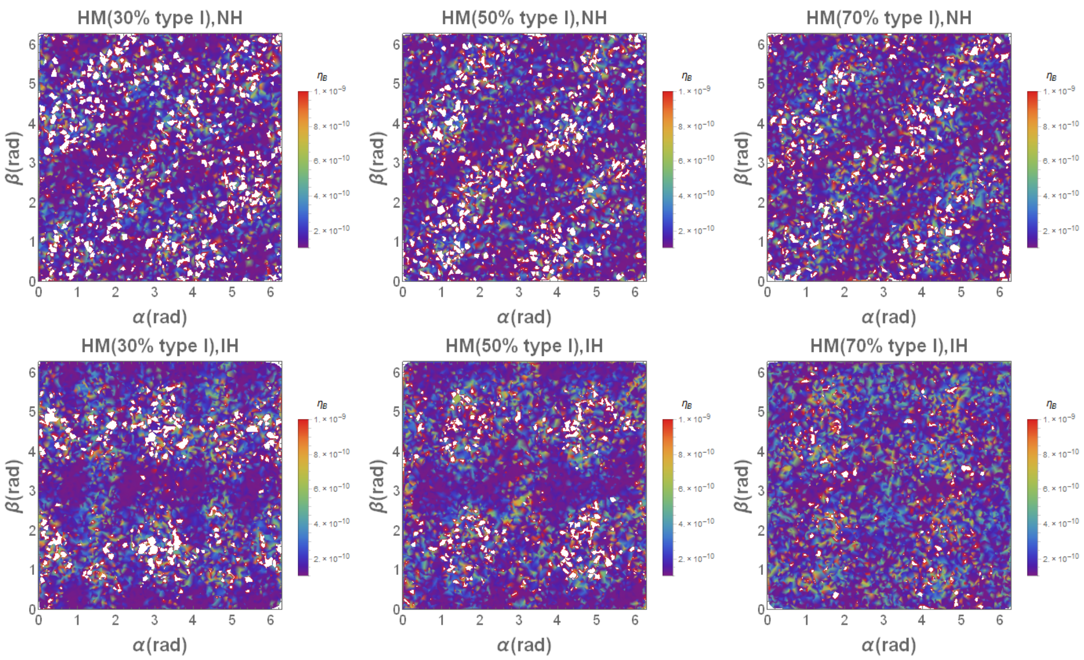

Figure 4.4: Contour plot showing the Majorana phases α and β in the two axes with BAU parameter η_B as the contour for HM mixing pattern for both NH/IH.

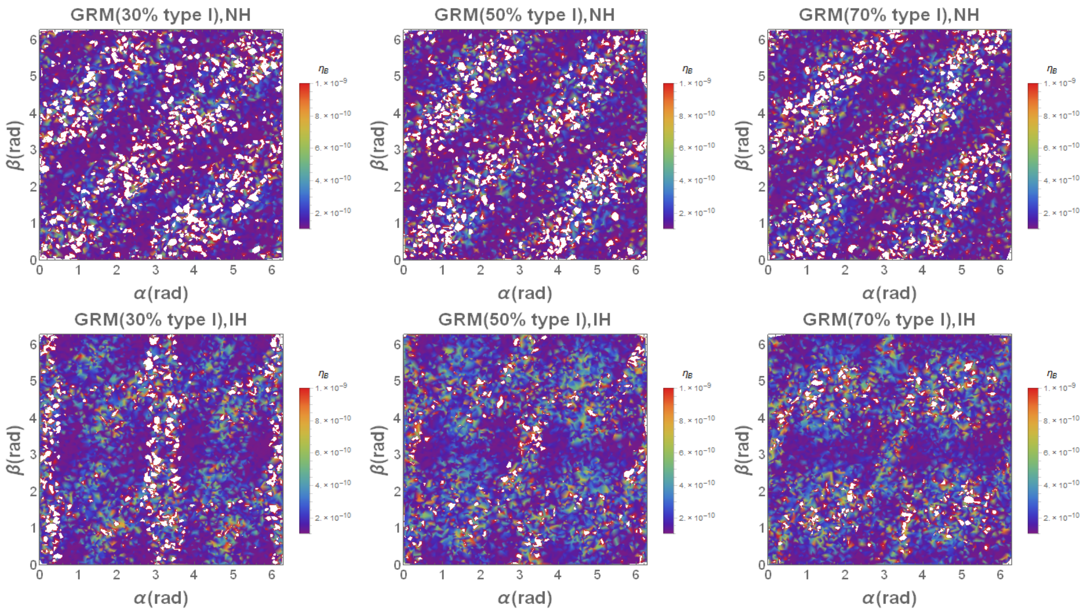

Figure 4.5: Contour plot showing the Majorana phases α and β in the two axes with BAU parameter η_B as the contour for GRM mixing pattern for both NH/IH.

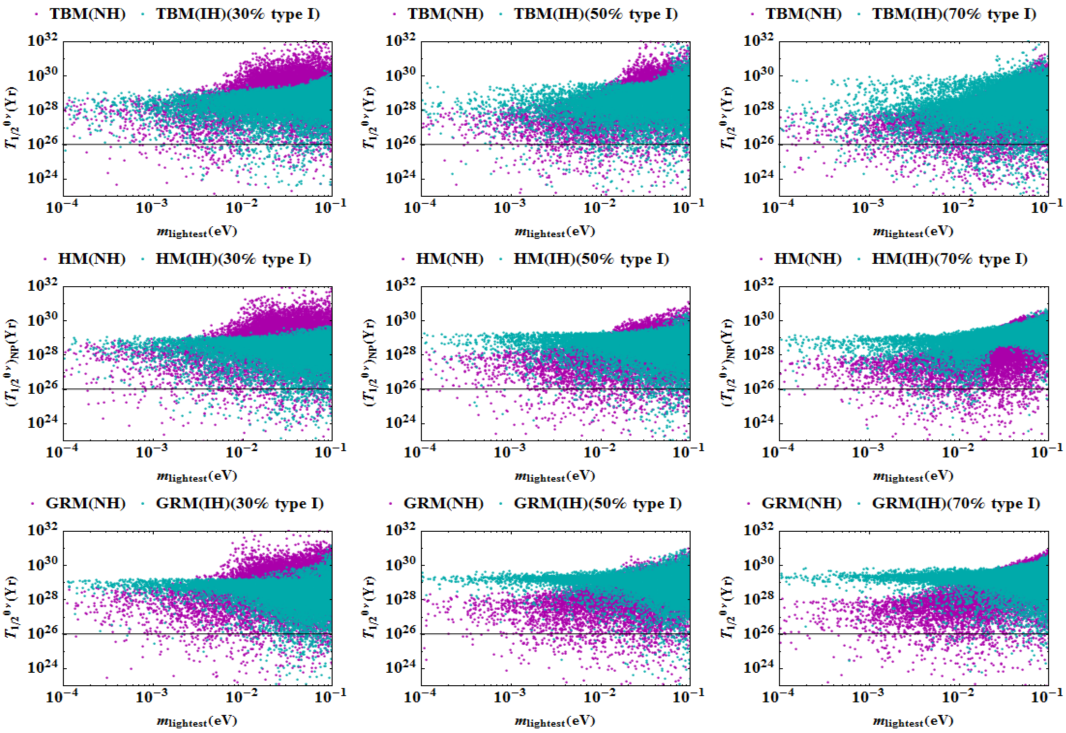

Figure 4.6: The half-life governing NDBD as a function of lightest neutrino mass m_1 / m_3 for NH/IH for different values of X, i.e., different contributions of type I SS. The black horizontal line indicates the KamLAND-Zen bound on half-life.

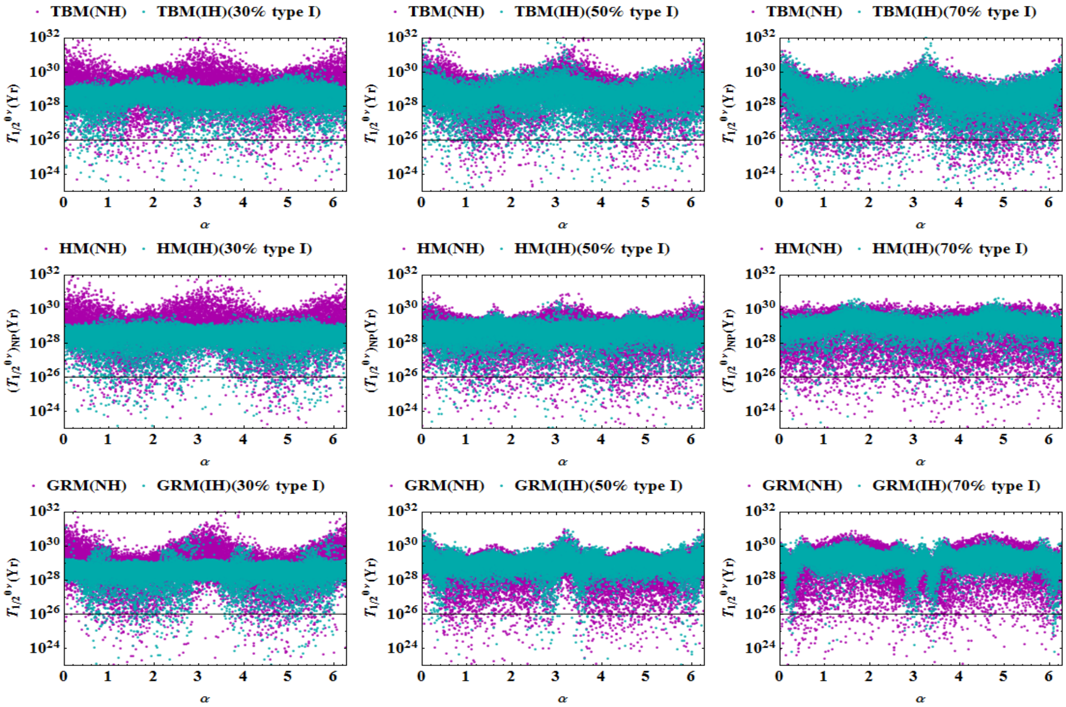

Figure 4.7: The half-life governing NDBD as a function of Majorana phases α for NH/IH for different values of X, i.e., different contributions of type I SS. The black horizontal line indicates the KamLAND-Zen bound on half-life.

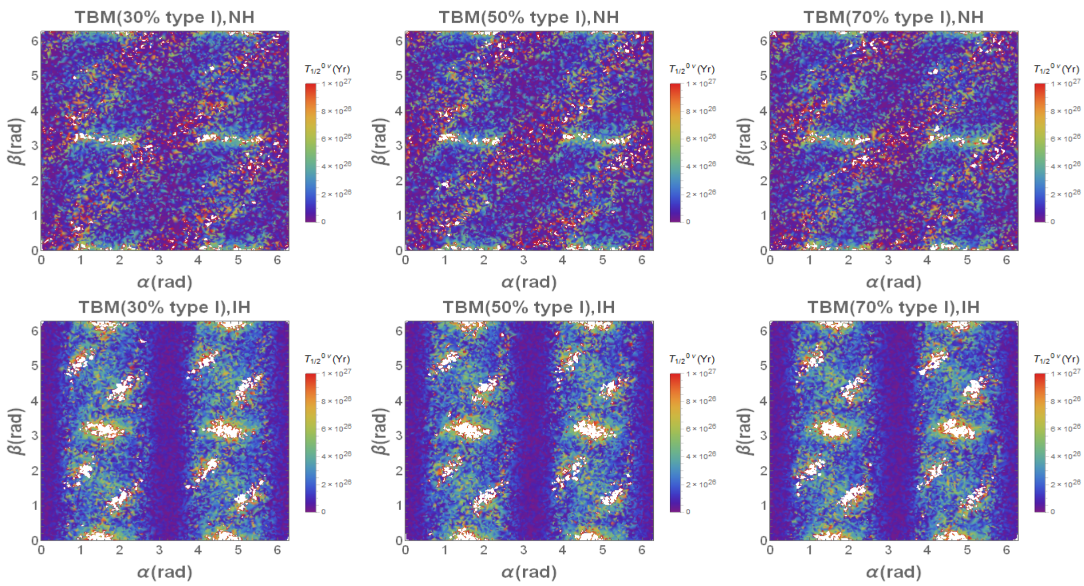

Figure 4.8: Contour plot showing the Majorana phadsses α and β in the two axes with half-life governing NDBD as the contour for TBM mixing pattern for both NH/IH.

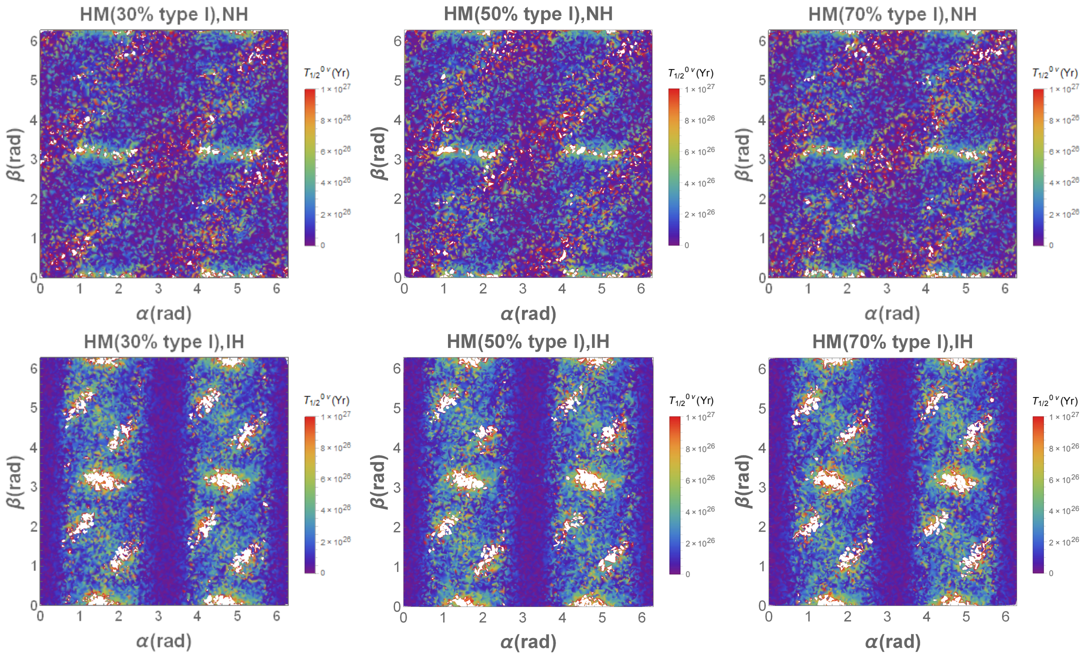

Figure 4.9: Contour plot showing the Majorana phases α and β in the two axes with half-life governing NDBD as the contour for HM mixing pattern for both NH/IH.

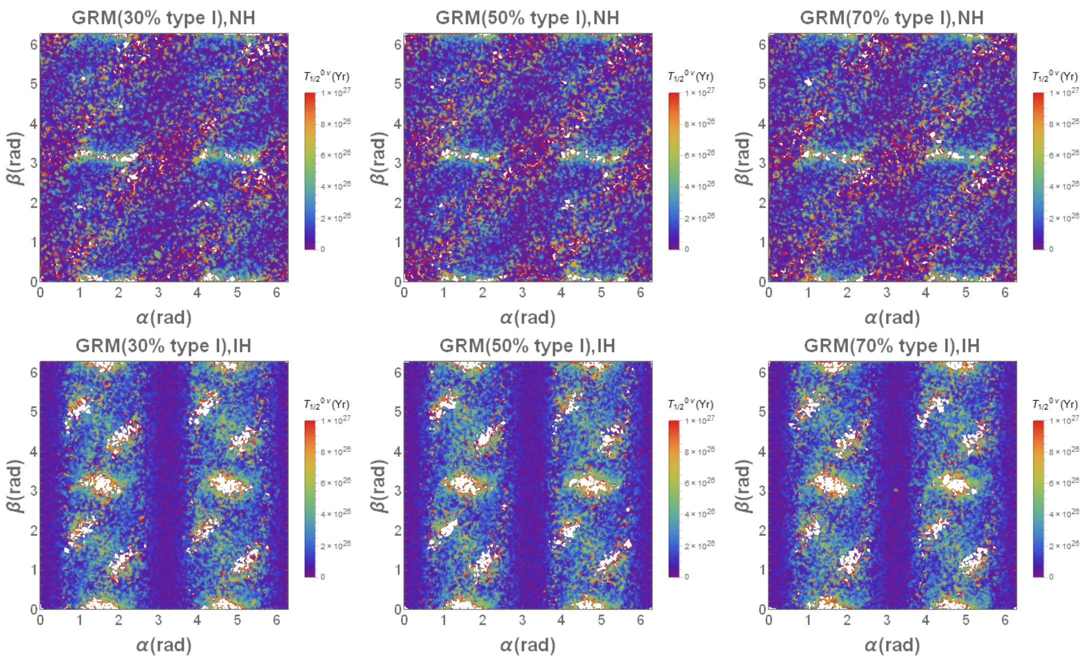

Figure 4.10: Contour plot showing the Majorana phases α and β in the two axes with half-life governing NDBD as the contour for GRM mixing pattern for both NH/IH.

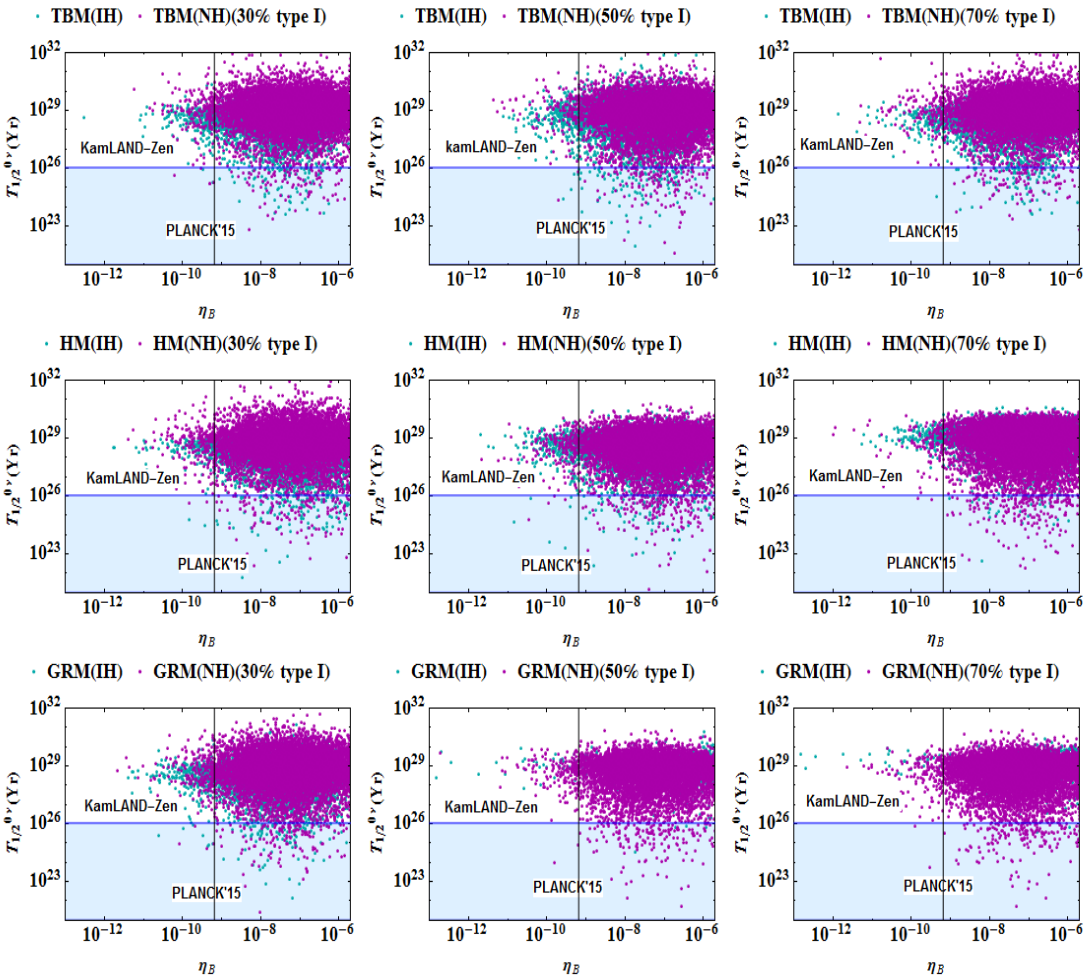

Figure 4.11: Half-life governing NDBD Vs BAU for different mixing patterns for NH/IH for different values of X.

4.4 Discussion and Conclusion

In this work, we have done a phenomenological study of BAU and NDBD in the framework of TeV scale LRSM with the primary focus to see the contributions of type I and type II SS terms to the aforementioned phenomenon considering both normal and inverted mass hierarchy of neutrino mass spectrum. In particular, we have considered the type I SS mass term to be $\mu - \tau$ symmetric, namely, TBM, HM and GRM respectively whereas the perturbations to generate non-zero θ_{13} has been obtained from the type II SS term. It would be enthralling to explore the situations where both the contributions from type I and type II SS are comparable in size or to speculate the dominance of either of the SS terms to study BSM phenomenon like BAU and NDBD. Based on our study, we could arrive at the following conclusions,

- Successful leptogenesis can be accounted for considering M_{W_R} as 10 TeV for a model independent analysis irrespective of different mixing patterns.

- The baryon asymmetry, η_B is found in the observable range in all the cases irrespective of the mass hierarchies and the type I/II seesaw contribution. Most of the observed values are found in the lightest mass range varying from 0.05 to 0.1 eV.

- η_B Vs α plot shows us that IH tends to be a little closer to the observed value of η_B although both the hierarchies are consistent with the experimentally observed value. Further, there is a dependence on α which varies for the different contributions of the seesaw. We cannot conclude much about the mixing pattern from this result.

- The variation of BAU with both the Majorana phases α and β shows almost similar results for all the mixing patterns, but we can see that there is a correlation between the Majorana phases which is different for NH and IH. In the case of IH, greater parameter space is obtained for α satisfying the experimental bound of BAU for leading type I contribution.

- In new Physics contributions to NDBD in TeV scale LRSM, TBM, HM, GRM shows results within experimental bound for a wide range of lightest neutrino mass varying from 10^{-3} to 10^{-1}, however for X= 0.7 (i.e. leading type I contribution), the results are widely scattered for lightest neutrino mass varying from 10^{-2} to 10^{-1} in comparison to X=0.3 (i.e. leading type II contribution) in case of NH. Again, most of the results are concentrated for higher values of lightest neutrino mass ranging from around 0.02 to 0.1 eV. However, the results are not much dependent on the mixing patterns through a careful observation of all the plots, we can say that IH is more consistent with the experimental results.

  Similar results are seen for the variations of half-life governing NDBD with Majorana phase α. Results for leading type II contribution are more scattered for NH in all the mixing scenarios. However, there is a dependence on the Majorana phase as can be seen from the figures.

- Variation of NDBD with both the Majorana phases α and β shows that there is a dependence on the phases irrespective of the mixing patterns and for IH, the parameter space seems to be constrained for α satisfying the experimental bounds.
- While correlating both BAU and NDBD, we have seen almost similar results for all the mixing patterns and the parameter space for both BAU and NDBD satisfying the observed experimental bounds is very less irrespective of the mass hierarchies.

In brief, we can state that regarding the leading order contribution, not much can be concluded in the case of baryogenesis from our analysis. Whereas NDBD is more consistent with type I leading contribution. And regarding the mass hierarchy, after a careful observation of all the results, we may conclude that IH gives better predictions in explaining both BAU and NDBD. Further detailed analysis is to be persued considering some discrete groups in analyzing the structures of the mass matrices we have considered in our analysis and also the variation with the other neutrino parameters to give a rather strong conclusion which we leave for our future study.

Bibliography

[1] Pati, J. C. and Salam, A. Lepton Number as the Fourth Color. *Phys. Rev. D*, 10:275, 1974.

[2] Mohapatra, R. N. and Pati, J. C. Left-Right Gauge Symmetry and an Isoconjugate Model of CP Violation. *Phys. Rev. D*, 11:566, 1975.

[3] Senjanovic, G. and Mohapatra R. N. Exact Left-Right Symmetry and Spontaneous Violation of Parity. *Phys. Rev. D*, 12:1502, 1975.

[4] Mohapatra, R. N. and Marshak, R. E. Local B-L Symmetry of Electroweak Interactions, Majorana Neutrinos, and Neutron Oscillations. *Phys. Rev. Lett.*, 44:1644, 1980.

[5] Senjanovic, G. Spontaneous breakdown of parity in a class of gauge theories. *Nucl. Phys. B*, 153:334-364, 1979.

[6] Mohapatra, R. N and Marshak, R. E. Local B-L Symmetry of Electroweak Interactions, Majorana Neutrinos and Neutron Oscillations. *Phys. Rev. Lett.*, 44:1316, 1980.

[7] Ahn, Y. H., Kang, S. K., Kim, C. S. and Nguyen, T. P. *Phys. Rev. D*, 82:093005 (1981)

[8] Frere, J. M., Hambye, T. and Vertongen, G. Is leptogenesis falsifiable at LHC? *JHEP*, 0901: 051, 2009.

[9] Dev, P. S. B., Lee, C. H., and Mohapatra, R. N. TeV Scale Lepton Number Violation and Baryogenesis. *J. Phys. Conf. Ser.*, 631: 012007, 2015.

[10] Antusch, S., et al. Probing Leptogenesis at Future Colliders. *JHEP*, 09: 124, 2018.

[11] Schechter, J., Valle, J. W. F. Neutrino decay and spontaneous violation of lepton number. *Phys. Rev. D*, 25: 774 (1982);

[12] Vissani, F. A study of the scenario with nearly degenerate Majorana neutrinos. *arXiv 9708483*, 1997.

[13] Harrison, P. F., Perkins, D. H., and Scott, W. G. Tri-bimaximal mixing and the neutrino oscillation data. *Phys. Lett. B*, 530:167, 2002.

[14] Harrison, P. F. and W. G. Scott Symmetries and Generalisations of Tri-Bimaximal Neutrino Mixing. *Phys. Lett. B*, 535:163, 2002.

[15] Xing, Z. Z. Nearly tri bimaximal neutrino mixing and CP violation. *Phys. Lett. B*, 533:85 2002.

[16] Altarelli, G., Feruglio, F. Tri-bimaximal neutrino mixing from discrete symmetry in extra dimensions. *Nucl. Phys. B*, 720:64, 2005.

[17] Altarelli, G. and Feruglio, F. Tri-bimaximal neutrino mixing, A(4) and the modular symmetry. *Nucl. Phys. B*, 741:215, 2006.

[18] King, S. F. and Luhn, C. Neutrino Mass and Mixing with Discrete Symmetry. *Rept. Prog. Phys.*, 76:056201, 2013.

[19] Everett, L. L. and Stuart, A. J. Icosahedral (A(5)) Family Symmetry and the Golden Ratio Prediction for Solar Neutrino Mixing. *Phys. Rev. D*, 79:085005, 2009.

[20] Ma, E. and Wegman, D. Nonzero theta(13) for neutrino mixing in the context of A(4) symmetry. *Phys. Rev. Lett.*, 107:061803, 2011.

[21] Altarelli, G., Feruglio, F., Merlo, L. and Stamou, E. Discrete Flavour Groups, θ_{13} and Lepton Flavour Violation. *JHEP*, 08:021, 2012.

[22] Borah, M., Borah, D., Das, M. K. and Patra, S. Perturbations to $\mu-\tau$ Symmetry, Leptogenesis and Lepton Flavour Violation with Type II Seesaw. *Phys. Rev. D*, 90:095020, 2014.

[23] Rivera-Agudelo, D. C., Perez-Lorenzana, A . Generating θ_{13} from sterile neutrinos in $\mu-\tau$ symmetric models. *Phys. Rev. D*, 92:073009, 2015.

[24] Rivera-Agudelo, D. C., Perez-Lorenzana, A. Leptonic CP phases near the $\mu-\tau$ symmetric limit. *Phys. Lett. B*, 760:153, 2016.

[25] Fukuyama, T. Twenty years after the discovery of $\mu - \tau$ symmetry. *PTEP*, B11:033, 2017.

[26] Fukugita, M. and Yanagida, T. Baryogenesis Without Grand Unification. *Phys Lett. B*, 174:45, 1986.

[27] Davidson, S., Nardi, E. and Nir, Y. Leptogenesis. *Phys. Rept.*, 466:105, 2008.

[28] Blanchet, S. and Bari, P. D. The minimal scenario of leptogenesis. *New J. Phys.*, 14:125012, 2012.

[29] Schechter, J. and Valle, J. W. F. Neutrinoless Double beta Decay in SU(2) x U(1) Theories. *Phys. Rev. D*,25:2951, 1982.

[30] Chakrabortty, J. and Devi, H. Z. and Goswami, S. and Patra, S. Neutrinoless double-β decay in TeV scale Left-Right symmetric models. *JHEP*, 08:008, 2012.

[31] Pilaftsis, A. and Underwood, T. E. J. Resonant Leptogenesis. *Nucl. Phys. B*, 692:303, 2004.

[32] Flanz, M., Paschos, E. A., Sarkar, U. and Weiss, J. Baryogenesis through mixing of heavy Majorana neutrinos. *Phys. Lett. B*, 389:693, 1996.

[33] Hambye, T., Russell, J. M. and West, S. M. TeV scale resonant leptogenesis from supersymmetry breaking. *JHEP*, 0407:070, 2004.

[34] Dev, P. S. B. TeV Scale Leptogenesis. *arXiv:1506.00837*, 2015.

[35] Blanchet, S., Chacko, Z., Granor, S. S. and Mohapatra, R. N. Leptogenesis with TeV Scale Inverse Seesaw in SO(10). *Phys. Rev. D*, 82:076008, 2010.

[36] Pilaftsis, A. CP violation and baryogenesis due to heavy Majorana neutrinos. *Phys. Rev. D*, 56:5431, 1997.

[37] Flanz, M., Paschos, E. A. and Sarkar, U. Baryogenesis from a lepton asymmetric universe, *Phys. Lett. B*, 345:248, 1995.

[38] Covi, L., Roulet, E. and Vissani, F. CP violating decays in leptogenesis scenarios. *Phys Lett.B*, 384:169, 1996.

[39] Covi, L., Roulet, E. and Vissani, F. CP violating decays in leptogenesis scenarios. *Phys Lett. B*, 345:248, 1995.

[40] Kuzmin, V. A., Rubakov, V. A. and Shaposhnikov, M. E. On anomalous electroweak baryon-number non-conservation in the early universe. *Phys. Lett. B*, 155:36, 1985.

[41] Hirsch, M., Klapdor-Kleingrothaus, H. V., Panella, O. Double beta decay in left-right symmetric models. *Phys. Lett. B*, 374:7-12, 1996.

[42] Borah, D. and Dasgupta, A. Neutrinoless Double Beta Decay in Type I+II Seesaw Models. *JHEP*, 11:208, 2015.

[43] Salas, P. F. D., et al. Status of neutrino oscillations 2018: first hint for normal mass ordering and improved CP sensitivity. *Phys.lett.B*, 06:019, 2018.

[44] Xing, Z. Z., Zhou, S. Tri-bimaximal neutrino mixing and flavor-dependent resonant leptogenesis. *Phys.Lett.B*, 653:278-287, 2007.

[45] Blanchet, S. and Bari, P. D. Leptogenesis beyond the limit of hierarchial heavy neutrino masses. *JCAP*, 06:023, 2006.

[46] Ade, P.A.R., et al.[Planck Collaboration], Planck 2015 results. XIII. Cosmological parameters. *Astron. Astrophys. A13*, 594:41-45, 2016.

[47] Kotila, J. and Iachello, F. Phase-space factors for double-β decay. *Phys. Rev. C*, 85:034316, 2012.

[48] Stefanik, D., Dvornicky, R., Simkovic, F. and Vogel, P. Reexamining the light neutrino exchange mechanism of $0\nu\beta\beta$ with left and right-handed leptonic and hadronic current. *Phys. Rev. C*, 92(5):055502, (2015).

[49] Dev, P. S. B., Goswami, S. and Mitra, M. TeV Scale Left-Right Symmetry and Large Mixing Effects in Neutrinoless Double Beta Decay. *Phys. Rev. D*, 91:113004 2015.

[50] Pantis, G., Simkovik, F., Vergados, J. D. and Faessler, A. Neutrinoless Double Beta Decay within QRPA with Proton-Neutron Pairing. *Phys. Rev. C*, 53:695, 1996.

[51] Hyvarinen, J., Suhonen, J. Nuclear matrix elements for $0\nu\beta\beta$ decays with light or heavy Majorana-neutrino exchange. *Phys. Rev. C*, 91:024613 , 2015.