Theoretical and phenomenological consequences of neutrino mass, leptogenesis and dark matter within Beyond Standard Model (BSM)

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Conclusion and future outlook

This chapter includes an accumulated conclusion drawn from all the works carried out in this thesis. The crucial findings that we have obtained by the consideration of two different models and their phenomenological consequences are represented in details in this section of the thesis. In chapters 2&3, we study the impact of various phenomena in a scotogenic model. However in the latter chapter, we introduce flavor symmetries, thereby constraining the model unlike in chapter 2. Also, the analysis of dark matter in both the models differ depending on their production mechanism. Again in chapters 4&5, we introduce another model viz. the neutrino two Higgs doublet model(ν2HDM). But the additional particle content varies in both the chapters. Overall, the phenomenology studied in these models include: light neutrino mass, baryon asymmetry of the Universe, neutrinoless double beta decay, dark matter and lepton violating processes. We check the feasibility of our models by incorporating constraints from various experiments corresponding to the phenomenology it predicts. Further in the last part of this chapter, we provide a brief outlook on the future of neutrino physics and related cosmology. Now, we divide the conclusions arising from each of the works in the following sections.

6.1 Conclusion

6.1.1 Chapter 2

In this chapter, we carry out a detailed analysis on an extension of the SM popularly known as the *scotogenic model*. The scotogenic model consists of a Higgs doublet (η) and three singlet neutral fermions (N_k) in addition to the SM particle content. All the SM particles are even and the additional fields are odd under an additional Z_2 symmetry. The possibility of a DM candidate comes from the Z_2 odd lightest particle. We carry out this work with the dark matter mass strictly focusing in the intermediate dark matter mass range, also known as the inert Higgs doublet model (IHDM) desert, which lies between $M_W < M_{DM} \leq 550$ GeV. The phenomenology carried out in this work along with DM are baryogenesis via the mechanism of thermal leptogenesis and neutrinoless double beta decay. We also consider constraint from lepton flavor violating processes. In our work, the out-of-equilibrium decay of $N_2 \to l\eta, \bar{l}\eta^*$, where η is the inert Higgs doublet constituting the dark matter candidate η_R^0 , generates the observed baryon asymmetry of the Universe. Furthermore, we study the relic abundance of the dark matter candidate (lightest of η) for two different choice of mass splitting between the DM (LSP) and the next heavier scalar (nLSP). The mixture of thermal and non-thermal production of DM abundance for various masses within the IHDM desert is also analysed simultaneously. Since, the non-thermal production of DM within the IHDM desert is a consequence of late decays of N_1, thus, the lifetime of N_1 will be more than sphaleron time resulting in the discripency to generate the baryon asymmetry. Again the mass splitting between the inert scalars of the inert scalar doublet have a prime role in thermal production of DM unlike that for non-thermal prodcution of DM. Although the inequality in the values of scalar mass splittings do create a difference in generating the observed relic abundance via non-thermal production.

We show correlation plots of dark matter mass (M_{DM}), RHN mass (M_2), lightest neutrino mass eigenvalue (m_l) and quartic coupling parameter (λ_5) with the latest observed value of BAU. A particular range of quartic coupling is considered, i.e. $10^{-2}-5$, which is accountable for reproducing the observed baryon asymmetry of the Universe for $M_2 = 10^7 - 5\times 10^8$ GeV. We also calculate the effective mass of light neutrinos including the experimental bounds obtained from KamLAND-Zen. We thereby show a correlation plot between BAU result and $0\nu\beta\beta$, which has a constrained parameter space for both the mass ordering. From the correlation plots between the various parameters and observed Planck limit of BAU, we can conclude that the NH is more preferable over the IH.

The significant conclusion we observe from our analysis is that the mass splitting, $\Delta M_{\eta^\pm} = \Delta M_{\eta_I^0}$ plays a vital role in the production of relic abundance via thermal production only. As, for thermal production of DM, we could generate relic for $\Delta M_{\eta^\pm} = \Delta M_{\eta_I^0} = 1$ GeV but failed in the case of $\Delta M_{\eta^\pm} = \Delta M_{\eta_I^0} = 10$ GeV for the same value of $\lambda_L = 0.0001$, which therefore satisfies the LEP constraints[237] as it rules out values of mass splitting greater than 8 GeV. This draws attention to how effective the mass splitting could be in the IHDM. It also motivates us to study the non-thermal production of dark matter. For non-thermal production of dark matter, we observe current relic abundance for the appropriate choice of decay width and coupling parameters with $\Delta M = 1$ GeV and $\Delta M = 10$ GeV. However, for $\Delta M_{\eta^\pm} = 10$ GeV and $\Delta M_{\eta_I^0} = 0.01$ GeV, we observe certain variations in the relic abundance curve. Thus, realising that the choice of mass splitting doesnot affect the relic abundance generated via non-thermal production unless they are equal.

6.1.2 Chapter 3

In this chapter, we have realized the scotogenic model with the help of discrete flavor symmetries $A_4 \otimes Z_4$. This work primarily aims at the criterias required to produce texture one zero in the Yukawa coupling matrix. It is already known that flavor symmetries play a significant role in constraining the Yukawa coupling matrix in a model. Thus, we can achieve the desired texture one zero Yukawa coupling matrix by the assumption of certain vev alignments of the flavons introduced in this work. The flavons in our model are namely $\chi, \chi^{'}$ and $\chi^{''}$ and by proper consideration of their vev alignments we are able to construct three different structures of Yukawa coupling matrix with a zero element in it. Furthermore, one of the vital requirements to generate the light neutrino mass matrix is to have a broken $\mu-\tau$ symmetry. From our model, two structures of Yukawa coupling matrix (i.e. Case I and Case II) turns out to be $\mu-\tau$ symmetric, thus we discard these two structures. Only Case III is allowed for further analysis as it fulfills the condition of $\mu-\tau$ asymmetry. The neutrino oscillation parameters θ_{12} and θ_{13} are also in the 3σ global fit credible region (CR) for the allowed structure of Yukawa coupling matrix. Additionally, we take some particular range of free parameters such as $M_1 = 10^4 - 10^5$ GeV, $M_2 = 10^6 - 10^7$ GeV, $M_3 = 5 \times 10^7 - 10^8$ GeV, $m_{\eta_R^0} = 450 - 750$ GeV, $m_l = 10^{-13} - 10^{-11}$ eV and $\lambda_5 = 10^{-3} - 1$, and proceed with the calculation of various phenomena for the allowed Yukawa coupling matrix. In order to make the model feasible, we have studied the neutrino phenomenology like $0\nu\beta\beta$, lepton flavor violation and also have added a tinch of cosmology via BAU. The one zero texture matrix in eq.(3.6) is evaluated in our work. We see that the allowed Case III satisfies the KamLAND-Zen limit and Planck limit for $m_{\beta\beta}$ and BAU respectively from fig.(3.5) and fig.(3.6). Thus, from the extensive analysis we have carried out, we can consider Case III to abide by the experimental constraints along with a naturally broken $\mu-\tau$ symmetry. Furthermore, for the validity of the model w.r.t dark matter phenomenology, we have assumed the dark matter(lightest of the inert doublet scalar) mass M_{DM} in the range $450 - 750$ GeV.

As we have considered two distinct values of the mass splittings between the inert scalars, we can draw conclusion that for the lower value of mass splitting, i.e. $\Delta M_{\eta^\pm} = \Delta M_{\eta_I^0} = 0.9$ GeV, a wider range of allowed DM mass is obatined. The consistency of this result is shown for a benchmark value of DM-Higgs coupling $\lambda_L = 0.00005$ as well as for quite a broad space of λ_L as can be seen in fig.(3.3) and fig.(3.4). Thus, as a whole we can contemplate this discrete flavor realization of the scotogenic model to be sound in explaining various beyond standard model phenomenologies. It also plays a crucial role in distinguishing between the most desirable structure of the Yukawa coupling matrices which is the centre of interest in this work.

6.1.3 Chapter 4

In this chapter, we carry out our investigation on a flavor symmetric ν2HDM by extending it with a dark sector. This work is mainly a detailed exploration including a comparative study of different phenomenological consequences corresponding to variation in the arbitrary angles of the rotational matrix. The realization of ν2HDM is accomplished with the help of flavor symmetries $A_4 \otimes Z_4$. An interesting feature of this model is that it can accomodate both neutrino as well as DM phenomenology and build up a connection between them. Unlike the scotogenic model, here we can generate the light neutrino mass at tree level by consideration of an extra scalar doublet which is assigned $L = -1$[71]. Further, we numerically calculate the Yukawa coupling matrix, which is the source for various phenomenologies such as BAU, neutrinoless double beta decay and DM studied in this work. Most importantly, we have chosen the rotational matrix R and the values of the arbitrary angles such that we can obtain critical results and study its impact on the cosmological phenomena we have discussed. Based on different literatures[68, 264], we have chosen the value of lightest RHN mass as $10^4 - 10^6$GeV, lightest active neutrino mass in the range $10^{-13} - 10^{-11}$eV, vev of the scalar doublet (ϕ) $v = 0.1 - 30$GeV so as to achieve TeV scale leptogenesis.

We have also correlated the BAU with values of tanβ and analyzed its variation for the different values of ω_{12}. From fig.(4.2),(4.3) and (4.4), we can draw a conclusion that the choice of $\omega_{12} = 10^{-1} + 10^{-1}i$ is more preferable in satisfying the observable value of BAU given by Planck limit. Also, we have obtained a constraint range of the free parameters and the Yukawa couplings corresponding to the two choices of the arbitrary angles. In plot (4.4) we obtain points which abide by the constraint from both BAU and relic abundance simultaneously which is a vital part of the analysis. We have also generated some important results in context with the decay parameter. Depending on ω_{12} values, we can generalise the transition in association between K_{N_1} and m_l for both NH and IH. Considering the DM scenario, it is viable to have a warm DM candidate as it obeys the constraint coming from small structure formation and relic abundance corresponding to the allowed space for decay parameter in comparison to hot DM. Simultaneously, it is also possible to obtain a warm DM source when the decay parameter donot fall in the very weak washout regime. Therefore, it is seen from fig.(4.5) that for $\omega_{12} = 10^{-1} + 10^{-1}i$ we obtain the preferable range of K_{N_1} which further explains the warm DM. For warm DM, $m_\xi \sim 10$ keV gives significant observed relic abundance, however, small DM mass correspond to hot DM which again is constrained by small structure formation. Also, a variation in the branching ratio range is obtained depending on the two different values of ω_{12}. Thus, it can be said that $\text{Br}_\xi \simeq 10^{-5} - 10^{-3}$ is the favorable range for $\omega_{12} = 10^{-1} + 10^{-1}i$ in satisfying the Planck limit for relic abundance, whereas for $\omega_{12} = 10^{-12} + 10^{-12}i$, the range of branching ratio that produces the observed relic abundance is $\text{Br}_\xi \simeq 10^{-6} - 10^{-3}$. Summarizing the above results, we can finally admit that for the choice of $\omega_{12} = 10^{-1} + 10^{-1}i$, the value of K_{N_1} falls in the weak washout region which further is successful in generating the desired BAU, relic abundance and also the small structure formation for both NH and IH. Also, the Yukawa couplings obtained from the model are successful in producing the branching ratioBr$(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ corresponding to the lepton flavor violating process as shown in fig.(4.1). Thus, we can come to the conclusion that our model can explain the light neutrino mass, leptogenesis and dark matter for the choice of free parameters considered and the values of Dirac masses obtained in our work.

6.1.4 Chapter 5

This chapter includes the same model as discussed in chapter 4, i.e. the ν2HDM, however the extended particle content differs in both the cases. Also, here the discrete symmetry used in order to realize this model is $A_4 \otimes Z_8$. We have basically done a phenomenological analysis of neutrino and related cosmology in this work. This model is an extension to the SM constituents by three right handed neutrino fields (N_1, N_2, N_3), one Higgs doublet (η) in addition to a new gauge singlet (S) and four sets of flavon ($\varphi, \xi, \chi, \zeta$) fields. The Dirac mass matrix (M_D'), Majorana mass matrix (M_R), sterile mass matrix (M_S) are constructed as required using the A_4 product rules and by proper choice of the vev alignment of flavons. As the light neutrino mass matrix donot have a naturally broken $\mu - \tau$ symmetry, therfore, we add a perturbation (M_P) in M_D' in order to break the $\mu - \tau$ symmetry. This results in generating a non zero reactor mixing angle and thereby, obtaining a 4×4 active-sterile mass matrix similar to the MES framework. We analyse the phenomenologies for both the normal and inverted heirarchies extensively in this work. We solve the model parameters by comparing the active-sterile neutrino matrix diagonalised by the active-sterile mixing matrix in eq.(5.39). After evaluation of the model parameters, the sterile neutrino mass (which is the probable dark matter candidate) and DM-active mixing angle is numerically obtained. In this work, we have considered non resonant production of sterile neutrino and thus the constraints from Lyman-α and X-ray are implemented accordingly. The variation of active-DM mixing angle with DM mass is studied and it is observed that the data points satisfy the Lyman-α and X-ray constraints in the IH case but are disfavored for NH. The decay rate of the DM for the process $S \longrightarrow \nu + \gamma$ is also calculated. We obtain a low decay rate which establishes the stability of the dark matter candidate in the cosmological scales. The relic abundance of the dark matter candidate is also checked and studied w.r.t the variation in DM mass. Also in this case, we see that the number of data points that satisfy the Lyman-α and X-ray constraints in IH are more than that compared to NH. Overall, the dark matter phenomenology is more compatible for IH. Baryogenesis via the process of leptogenesis is also studied in our work as it has a significant role to play in phenomenological analysis. In this work, baryon asymmetry of the Universe is generated through the out of equilibrium decay of $N_1 \to l\eta, \bar{l}\eta^*$, where N_1 is lightest right handed neutrino. We study BAU as a function of lightest right handed neutrino mass (N_1), DM mass, lightest active neutrino mass and perturbation (p) considering constraints from Planck limit. We also calculate the effective neutrino mass and then study its variation with lightest active neutrino mass and validate the results obtained by incorporating the KamLAND-Zen limit. Also the allowed parameter space of model parameters is generated w.r.t the effective mass of active neutrinos. In conclusion we can say that IH has shown a wider range of parameter space in case of dark matter compared to NH. An identical allowed parameter space in both the heirarchies is seen in neutrino phenomenology and BAU. Thus, we can consider our model to be consistent in addressing dark matter, neutrino phenomenology and baryon asymmetry of the universe simultaneously.

6.2 Future outlook

Based on the drawbacks of Standard Model, we have planned this thesis which incorporates two popular models wherein various beyond SM phenomenologies are addressed. It is well known that both scotogenic model and ν2HDM are successful in connecting neutrino and dark matter phenomenology. In addition to it even low scale leptogenesis can aslo be achieved simultaneously.

However, there are many other possibilities that can be explored in this sector. We can realise these models with the help of modular symmetry and thereby, reduce the flavon fields involved in the mass generation. A more constrained model may increase its viability in future collider experiments like LHC and LEP. In case of scotogenic model, we can further study the IHDM desert and look upon the probability of increasing its flexibility to inspect the scalar dark matter sector. We can also propose new dark matter candidates in ν2HDM and check its feasibility w.r.t the bounds from various direct, indirect detection experiments.