Lepton Flavor Violation in A_4 and Z_4 Flavor Symmetric Scotogenic Model

Bichitra Bijay Boruah[a] *, Lavina Sarma[a] and Mrinal Kumar Das[a]
[a]Department of Physics, Tezpur University
Tezpur 784028, India

***Abstract*: In this work, we have considered the scotogenic model which is a simple extension of the Standard Model and realized the model by using discrete symmetries A4 and Z4. In this flavor symmetric scotogenic model the non-zero reactor mixing angle is produced by assuming a non-degeneracy in the loop factor. We have analysed different lepton flavor violating (LFV) processes and studied their impact on neutrino phenomenology.**

***Keywords*— Standard Model ,Scotogenic model, Discrete symmetries**

INTRODUCTION :

Scotogenic model is an extension of the Inert Higgs Doublet Model(IHDM)[1-3] and the IHDM is nothing but a minimal extension of the Standard Model(SM) by a Higgs field which is a doublet under SU(2)L gauge symmetry with hypercharge Y=1 and a built-in discrete Z_2 symmetry[4]. The necessity of this modification took place as the inert Higgs doublet model(IHDM) could only accommodate dark matter, whereas it failed in explaining the origin of neutrino masses at a renormalizable level . In this model, three neutral singlet fermions N_i with i=1,2,3 are added in order to generate neutrino masses and assign them with a discrete Z_2 symmetry. Here, Ni is odd under Z_2 symmetry, whereas the SM fields remain Z_2 even. We have realised scotogenic model using A4 and Z_4 flavor symmetry. Scotogenic model already has an inbuilt Z_2 symmetry which provides the explanation of dark sector within this framework. The particle content and respective charge corresponding to the discrete symmetries are given in Table1. The discrete symmetries, i.e A_4 and Z_4 will impose constraints on the Yukawa coupling matrix, thereby, constraining the model. Neutrino mass in scotogenic model is given as:

$$M_{ij}^{\nu} = \sum_k \frac{Y_{ij}Y_{jk}}{16\pi^2} M_{N_K} \left[\frac{m^2_{\eta_R^0}}{m^2_{\eta_R^0} - M^2_{N_K}} ln \frac{m^2_{\eta_R^0}}{M^2_{N_K}} - \frac{m^2_{\eta_I^0}}{m^2_{\eta_I^0} - M^2_{N_K}} ln \frac{m^2_{\eta_I^0}}{M^2_{N_K}} \right]$$

where M_k represents the mass eigenvalue of the mass eigenstate N_k of the neutral singlet fermion N_k in the internal line with indices j=1,2,3 running over the three neutrino generation with three copies of N_k and Y is the Yukawa coupling matrix. The potential of scotogenic model contains different quartic couplings along with interaction term. Motivation of this work is to constrain the Y matrix and study neutrino phenomenology such as lepton flavor violation.

FLAVOR SYMMETRIC SCOTOGENIC MODEL:

In this section we have realized scotogenic model using discrete symmetry A_4 and Z_4 , the particle content and the charge assignments under above mentioned symmetries are given in Table1.

Table 1. Charge assignment of the particles under A_4.and Z_4

Field	l_L	l_{R1}	l_{R2}	l_{R3}	N_i	φ	η	χ_S	χ_T	χ
A_4	3	1	1''	1'	3	1	1	3	3	1
Z_4	i	i	i	i	-1	1	1	-1	i	i

We have considered the flavon alignment $<\chi_T>= v(1,0,0)$, $<\chi_S>= v(1,1,1)$, $<\chi>= u$[5], with this alignment the charge lepton mass matrix is given by-

$$M_l = \frac{\varphi < v_T >}{\Delta} \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

Now, the Yukawa coupling matrix can be written as-

$$Y = \begin{pmatrix} 2a+b & -a & -a \\ -a & 2a & b-a \\ -a & b-a & 2a \end{pmatrix}$$

Where,

$$b = Y'' \, u/_{\Delta}$$

$$a = Y' \, {}^{v_s}/_{\Delta}$$

Right handed neutrino mass matrix is:

$$M_N = \begin{pmatrix} M & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

To obtain a diagonal right handed neutrino mass matrix which is not diagonal in this basis we rotate the basis using a unitary matrix given by

$$U = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

Because of this rotation the Yukawa matrix will be –

$$Y = \begin{pmatrix} -a & -a & 2a+b \\ b-a & 2a & -a \\ 2a & b-a & -a \end{pmatrix}$$

In this basis charge lepton mass matrix remains diagonal .
As already mentioned, the realisation of scotogenic model is done through $A_4 \times Z_4$ flavor symmetry in this study. Within this model, a loop contribution factor r_i is adressed via the relation $r_i \propto {}^{1}/_{M}$. So, the contribution of right handed neutrino can be given by diag(r_1,r_2,r_3)[6]. However, due to the degeneracy in the RHN masses, the loop factor also becomes degenerate. Due to this reason we get a mu- tau symmetric neutrino mass matrix which is ruled out by neutrino oscillation experiments. symmetry we have to consider the non-degenerate right handed neutrino mass spectrum. Firstly we will take the condition r_1 not equal to $r_2 = r_3 = r$ and further split the degeneracy of N_2 and N_3 by a small amount d, i.e $r_3 = r_2 + d$. Now the structure of the light neutrino mass matrix will deviate from mu-tau symmetry. We can produce observed baryogenesis via the mechanism of leptogenesis in our model. However, the leptogenesis process must occur by the out of equilibrium decay of the RHN, in our case N_1. As discussed in many literatures, we now know that there exists a lower bound of about 10TeV for the lightest of the RHNs(M_{N1}) in the Scotogenic model considering the vanilla leptogenesis scenario. For a heirarchical mass of RHN, i.e $M_{N1} << M_{N2}$, M_{N3} , the leptogenesis produced by the decay of N_2 and N_3 are supressed due to the strong washout effects produced by N_1 or N_2 and N_3 mediated interactions. Thereby, the lepton asymmetry is produced only by the virtue of N_1 decay and this is further converted into the baryon asymmetry of the Universe(BAU) by the electroweak sphaleron phase transitions. In this model we have studied BAU. Although in this work ,we have analysed different lepton flavor violating (LFV) processes such as $l_\alpha \to l_\beta \gamma$ and $l_\alpha \to 3l_\beta$, and studied their impact on neutrino phenomenology.

LEPTON FLAVOR VIOLATING PROCESSES:

No experiment so far has observed a flavor violating process involving charged leptons. However, many experiments are currently going on to set strong limits on the most relevant LFV observables, in order to constraint parameter space involved in many new physics models. In this section we will discuss various lepton flavor violating processes (LFV) such as $l_\alpha \to l_\beta \gamma$ and $l_\alpha \to 3l_\beta$. Currently muon decay experiments are most prominent in nature which provides stringent limits for most models. The MEG collaboration[7] has been able to set the impressive bound on muon decay BR($l_\alpha \to l_\beta \gamma$)<4.2 * 10^{-13}. This is expected to improve as the experiment is upgraded to MEG II[8]. In case of $l_\alpha \to 3l_\beta$ decay, contraints comes from SINDRUM experiment to be BR($l_\alpha \to 3l_\beta$)<10^{-12} which is set long ago. The future Mu3e experiment announces a sensitivity of 10^{-16}, which would imply a 4 orders of magnitude improvement on the current bound. The detailed analytical derivations of different branching ratios of lepton flavor violating processes are addressed in various litraratures such as [9]. We have analysed braching ratio of of these processes using current 3 sigma range of neutrino oscillation parameter to validated our models predictions.

RESULT AND ANALYSIS:

In our work, we do a random scan for the free parameters of our model given by:

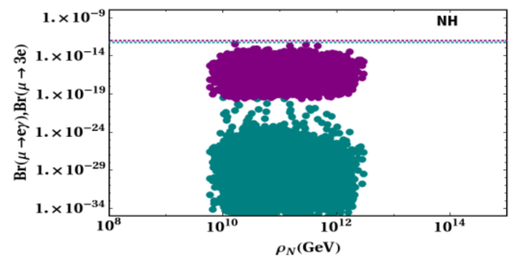
Table 2. Free parameters of the model and their ranges

Parameter	Parameter spaces
M_{N1}	10^4 GeV - 10^5 GeV
M_{N2}	10^8 GeV – 10^9 GeV
$^{\eta}r^{0}$	400 GeV-800GeV
λ_5	$10^{-8} – 10^{-4}$

We choose the parameter space in such a way so as to fulfill the constraints coming from various phenomenologies. Considering the lightest RHN in TeV scale is a significant characteristic for vanilla leptogenesis in Scotogenic model\ci. A lower bound of about 10 TeV is set for N_1, which has been verified in many literatures. Again, an inert Higgs doublet cannot possibly produce the observed relic density in the mass regime $M_w < M_{DM} < 550$ GeV, also called the IHDM desert. Thus, we have considered the lightest of the inert scalar doublet in the range given in Table 2 in order to abide by the bounds from Planck limit to be a probable dark matter candidate and also to check its viability in the range 400-800 GeV. Again the charged scalar of the inert doublet is taken to be ($^{\eta}r^{0}$+5) GeV, following the constraints from LEP II[10]. The choice of quartic coupling between the SM Higgs and inert doublet λ_5 not equal 0 is to cause violation of the lepton number.

We have computed all the branching ratio of LFV decays taking consideration of contraints coming from the model. Variation of decay BR($l_\alpha \to l_\beta \gamma$) and BR($l_\alpha \to 3l_\beta$) as a function of ρ_N (where $\rho_N =(M_N/m_{\eta^+})^2$) is depicted in Fig1. In this case for both the mass orderings, we get BR($l_\alpha \to l_\beta \gamma$) in the range 10^{-18} to 10^{-13} and BR($l_\alpha \to 3l_\beta$) spanning from 10^{-33} to 10^{-23}, which are consistant with current and near future experimental limits.

In Fig. we have ploted the variation of $R_{\mu e}$ which is the ratio of two LFV decays $l_\alpha \to l_\beta \gamma$ and $l_\alpha \to 3l_\beta$ against the lightest neutrino mass eigenvalue for both the mass orderings. From this we can infer that in case of both NH/IH $l_\alpha \to l_\beta \gamma$ decay supress the $l_\alpha \to 3l_\beta$ decay in our prameter spaces. Also, we can see that the parameter space of lightest active neutrino mass for which we get this kind of suppression is in the range (10^{-3}-1)eV. Further, we have also generated a plot Fig. depicting the co relation between $R_{\mu e}$ and ρ_N and it is observed that the viable range for ρ_N is (10^{10} -10^{12})GeV.



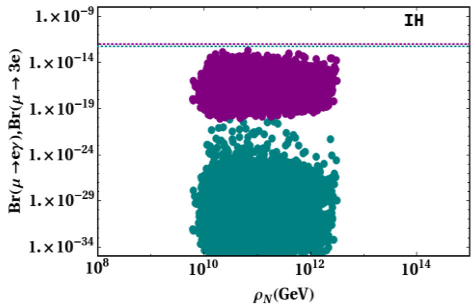


Figure1: BR($l_\alpha \to l_\beta\gamma$) and BR($l_\alpha \to 3l_\beta$) as function of ρ_N for NH and IH. The dashed horizontal lines are the recent upper bounds.

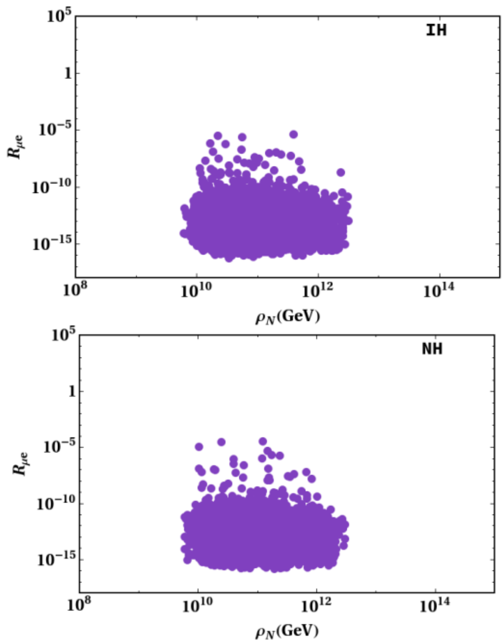


Figure2. Variation of Rμe and ρ_N for NH and IH.

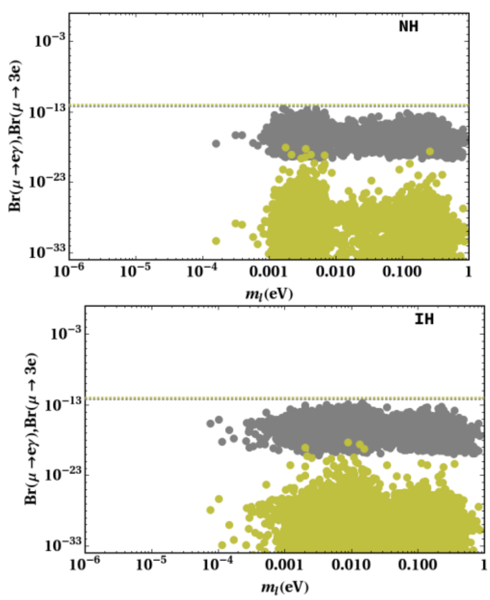


Figure3: BR($l_\alpha \to l_\beta\gamma$) and BR($l_\alpha \to 3l_\beta$) as function of lightest neutrino mass for NH and IH. The dashed horizontal lines are the recent upper bounds.

CONCLUSIONS:

In this work we basically realized the scotogenic model of neutrino mass generation with the help of discrete flavor symmetry A_4 and Z_4. We have computed the branching ratios of different lepton flavor violating processes considering proper choice of free parameter and constraining them with with relevant experimental bounds. We have checked the validity of the model by incorporating these braching ratios which are contrained by the model and verified these with bounds provided by the experiments.

REFERENCES:

[1] L. Lopez Honorez and C. E. Yaguna, "The inert doublet model of dark matter revisited," JHEP 09 (2010) 046, arXiv:1003.3125 [hep-ph]
[2] L. Lopez Honorez, E. Nezri, J. F. Oliver, and M. H. Tytgat, "The Inert Doublet Model: An Archetype for Dark Matter," JCAP 02 (2007) 028, arXiv:hep-ph/0612275.
[3] A. Arhrib, R. Benbrik, and N. Gaur, "H → γγ in Inert Higgs Doublet Model," Phys. Rev. D85 (2012) 095021, arXiv:1201.2644 [hep-ph].
[4] E. Ma, "Verifiable radiative seesaw mechanism of neutrino mass and dark matter," Phys. Rev. D 73 (2006) 077301, arXiv:hep-ph/0601225.
[5] A. Adulpravitchai, M. Lindner, and A. Merle, "Confronting Flavour Symmetries and extended Scalar Sectors with Lepton Flavour Violation Bounds," Phys. Rev. D 80 (2009) 055031, arXiv:0907.2147 [hep-ph].
[6] S. Pramanick, "Radiative generation of realistic neutrino mixing with A4," arXiv:1903.04208 [hep-ph].
[7] MEG Collaboration, A. Baldini et al., "Search for the lepton flavour violating decay μ + → e +γ with the full dataset of the MEG experiment," Eur. Phys. J. C 76 no. 8, (2016) 434, arXiv:1605.05081 [hep-ex].
[8] Mu3e Collaboration, A.-K. Perrevoort, "Searching for Lepton Flavour Violation with the Mu3e Experiment," PoS NuFact2017 (2017) 105, arXiv:1802.09851 [physics.ins-det].
[9] T. Toma and A. Vicente, "Lepton Flavor Violation in the Scotogenic Model," JHEP 01 (2014) 160, arXiv:1312.2840 [hep-ph].
[10] E. Lundstrom, M. Gustafsson, and J. Edsjo, "The Inert Doublet Model and LEP II Limits," Phys. Rev. D 79 (2009) 035013, arXiv:0810.3924 [hep-ph].