# A
# Appendix

## A.1 Loop functions of lepton flavor violation and VEV alignments of flavons

We present in this appendix the loop functions relevant for the computation of the LFV observables. These are

$$F_2(x) = \frac{1-6x+3x^2+2x^3+6x^2\log(x)}{6-(1-x)^4} \tag{A.1}$$

$$G_2(x) = \frac{2-9x+18x^2-11x^3+6x^3\log(x)}{6-(1-x)^4} \tag{A.2}$$

$$D_1(x,y) = -\frac{1}{(1-x)(1-y)} - \frac{x^2\log(x)}{(1-x)^2(x-y)} - \frac{y^2\log(y)}{(1-y)^2(y-x)} \tag{A.3}$$

$$D_2(x,y) = -\frac{1}{(1-x)(1-y)} - \frac{x\log(x)}{(1-x)^2(x-y)} - \frac{y\log(y)}{(1-y)^2(y-x)} \tag{A.4}$$

### A.1.1 Potential and vev alignment in the LRSM

The Higgs potential of LRSM containing Higgs bidoublet and scalar triplets that has quadratic and quartic coupling terms is given by,

$$V_{\phi,\Delta_L,\Delta_R} = -\mu_{ij}^2 Tr[\phi_i^\dagger \phi_j] + \lambda_{ijkl} Tr[\phi_i^\dagger \phi_j] Tr[\phi_k^\dagger \phi_l] + \lambda'_{ijkl} Tr[\phi_i^\dagger \phi_j \phi_k^\dagger \phi_l] - \mu_{ij}^2 Tr[\Delta_L^\dagger \Delta_L + \Delta_R^\dagger \Delta_R]$$
$$\rho_1[(Tr[\Delta_L^\dagger \Delta_L])^2 + (Tr[\Delta_L^\dagger \Delta_L])^2] + \rho_2(Tr[\Delta_L^\dagger \Delta_L \Delta_L^\dagger \Delta_L] + Tr[\Delta_R^\dagger \Delta_R \Delta_R^\dagger \Delta_R]) + \rho_3 Tr[\Delta_L^\dagger \Delta_L \Delta_R^\dagger \Delta_R] +$$
$$\alpha_{ij} Tr[\phi_i^\dagger \phi_j](Tr[\Delta_L^\dagger \Delta_L] + Tr[\Delta_R^\dagger \Delta_R]) + \beta_{ij}(Tr[\Delta_L^\dagger \Delta_L \phi_i \phi_j^\dagger] + Tr[\Delta_R^\dagger \Delta_R \phi_i \phi_j^\dagger]) + \gamma_{ij}(Tr[\Delta_L^\dagger \phi_i \Delta_R \phi_j^\dagger] + h.c) \tag{A.5}$$

where, i,j,k,l runs from 1 to 2 with $\phi_1 = \phi$ and $\phi_2 = \tilde{\phi}$. As mentioned above after SSB, the scalar sector obtains VEV. So after the substitution of the respective VEVs and determining the traces, so after simplification the potential can be written as,

$$V = -\mu^2(v_L^2 + v_R^2) + \frac{\rho}{4}(v_L^4 + v_R^4) + \frac{\rho'}{2} + \frac{\alpha}{2}(v_L^2 + v_R^2)k^2 + \gamma v_L v_R k^2 \tag{A.6}$$

where, we have used the approximation $k' << k$, and $\rho' = 2\rho_3$. Our minimization conditions are, $\frac{\delta V}{\delta v_L} = \frac{\delta V}{\delta v_R} = \frac{\delta V}{\delta k} = \frac{\delta V}{\delta k'} = 0$

Therefore, we get,

$$\frac{\delta V}{\delta v_L} = -2\mu^2 v_L + \rho v_L^3 + \rho' v_L k^2 + \gamma v_R k^2 \tag{A.7}$$

Here, it is evident that the Majorana mass of the left-handed neutrino $M_{LL}$ is dependent on the vev $v_L$ as already defined above. Again, we have

$$\frac{\delta V}{\delta v_R} = -2\mu^2 v_R + \rho v_R^3 + \rho' v_R k^2 + \gamma v_L k^2 \tag{A.8}$$

So, the right handed Majorana mass $M_{RR}$ is dependent on the vev $v_R$. Similarly, the calculations for the same can be carried out and it can be found out the Dirac mass term $M_D$ can be expressed in terms of the vev for the Higgs bidoublet as also defined previously.
Now, we are to determine a relation between the VEVs for the scalars and so after using the minimization conditions and simplifying the equations, we come to a relation given by,

$$v_L v_R = \frac{\gamma}{\xi} k \tag{A.9}$$

where, $\xi = \rho - \rho'$.
The neutrino mass for LRSM is given as a summation of the type-I and type-II term as already mentioned above. So, in the approximation that $k' << k$, and if we consider that our Yukawa coupling $Y^l$ corresponding to the neutrino masses is $y_D$ and the coupling $\widetilde{Y^l}$ for the charged fermion masses is denoted by $y_L$, so considering $y_D k >> y_l k'$ we can write,

$$M_\nu = \frac{k^2}{v_R} y_D f_R^{-1} y_D^T + f_L v_L \tag{A.10}$$

Since, for due to left-right symmetry, we can consider $f_L = f_R = f$, so the above equation can be written as,

$$M_\nu = \frac{k^2}{v_R} y_D f^{-1} y_D^T + f v_L \tag{A.11}$$

So, from this equation we can come to a relation given by,

$$M_\nu = (f\frac{\gamma}{\xi} + y_D f^{-1} y_D^T)\frac{k^2}{v_R} \tag{A.12}$$

Here, we can consider two situations, namely

- If $f(\frac{\gamma}{\xi}) << y_D f^{-1} y_D^T$, the light neutrino mass is given by the type-I term $M_D M_{RR}^{-1} M_D^T$. That is, here type-I is dominant and the light neutrino mass is from the suppression of heavy $\nu_R$.

- If $f(\frac{\gamma}{\xi}) >> y_D f^{-1} y_D^T$, the light neutrino mass is given by the type-II term $f v_L$. That is, in this case type-II mass term is dominant and the light neutrino mass is because of the tiny value of $v_L$.

In our work, we have three flavons with $A_4$ flavor symmetry. After this we follow the same procedure given below for the scotogenic model to get the vev alignment.

### A.1.2 VEV alignments of flavons in the scotogenic model

In this section we will evaluate the vev alignment of the flavons considered in the model by minimizing the potential and solving it simultaneously. The relevent potential can be written in terms of the field $\chi_T$, $\chi_S$ and their interaction terms. The interaction terms are forbidden in the model due the additional $Z_4$ symmetry. The potential is given by-

$$V = V(\chi_T) + V(\chi_S) + V_{int} \tag{A.13}$$

with,

$$V(\chi_T) = -m_{\chi_T}^2(\chi_T^\dagger \chi_T) + \lambda_1(\chi_T^\dagger \chi_T)^2 \tag{A.14}$$

and

$$V(\chi_S) = -m_{\chi_S}^2(\chi_S^\dagger \chi_S) + \lambda_1(\chi_S^\dagger \chi_S)^2 \tag{A.15}$$

The triplet flavons can be written in the form-

$$< \chi_T >= (\chi_{T_1}, \chi_{T_2}, \chi_{T_3}), \; < \chi_S >= (\chi_{S_1}, \chi_{S_2}, \chi_{S_3}) \tag{A.16}$$

Considering $A_4$ product rule the potential terms for $\chi_T$ will be of the form -

$$\begin{aligned} V(\chi_T) = &-\mu^2(\chi^\dagger_{T_1}\chi_{T_1}+\chi^\dagger_{T_2}\chi_{T_3}+\chi^\dagger_{T_3}\chi_{T_2}) \\ &+\lambda_2[(\chi^\dagger_{T_1}\chi_{T_1}+\chi^\dagger_{T_2}\chi_{T_3}+\chi^\dagger_{T_3}\chi_{T_2})^2+(\chi^\dagger_{T_3}\chi_{T_3}+\chi^\dagger_{T_2}\chi_{T_1}+\chi^\dagger_{T_1}\chi_{T_2}) \\ &\times(\chi^\dagger_{T_2}\chi_{T_2}+\chi^\dagger_{T_1}\chi_{T_3}+\chi^\dagger_{T_3}\chi_{T_1})+(2\chi^\dagger_{T_1}\chi_{T_1}-\chi^\dagger_{T_2}\chi_{T_3}-\chi^\dagger_{T_3}\chi_{T_2})^2 \\ &+2(2\chi^\dagger_{T_3}\chi_{T_3}-\chi^\dagger_{T_1}\chi_{T_2}-\chi^\dagger_{T_2}\chi_{T_1})\times(2\chi^\dagger_{T_2}\chi_{T_2}-\chi^\dagger_{T_3}\chi_{T_1}-\chi^\dagger_{T_1}\chi_{T_3})] \end{aligned} \tag{A.17}$$

Taking derivative with respect to $\chi_{T_1}$, $\chi_{T_2}$ and $\chi_{T_3}$ and equating it to zero will give the minimization condition. After solving we will get three set of solutions which are basically the possible alignments given by-

$$\begin{aligned} &(1)\ \chi_{T_1}\to\frac{\mu_2}{\sqrt{10\lambda_2}},\chi_{T_2}\to 0,\chi_{T_3}\to 0 \implies <\chi_T>=\frac{\mu_2}{\sqrt{10\lambda_2}}(1,0,0) \\ &(2)\ \chi_{T_1}\to\frac{\mu_2}{2\sqrt{3\lambda_2}},\chi_{T_2}\to\frac{\mu_2}{2\sqrt{3\lambda_2}},\chi_{T_3}\to\frac{\mu_2}{2\sqrt{3\lambda_2}} \implies <\chi_T>=\frac{\mu_2}{2\sqrt{3\lambda_2}}(1,1,1) \\ &(3)\ \chi_{T_1}\to\frac{2\mu_2}{\sqrt{51\lambda_2}},\chi_{T_2}\to-\frac{\mu_2}{\sqrt{51\lambda_2}},\chi_{T_3}\to-\frac{\mu_2}{\sqrt{51\lambda_2}} \implies <\chi_T>=\frac{\mu_2}{\sqrt{51\lambda_2}}(2,-1,-1) \end{aligned} \tag{A.18}$$

Similarly we get the solutions for $\chi_S$. We have used the first set of solution to generate the charge lepton mass matrix and second set of solution to get the Dirac neutrino mass.

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**PAPER PRESENTED IN WORKSHOP/CONFERENCE**

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1. **B.B Boruah** and M. K. Das; **National Conference on Trends in Modern Physics, Assam Don Bosco University, Assam. Feb 24-25,2020.**

2. **B.B Boruah**, L. Sarma and M. K. Das; **International Conference on Trends in Modern Physics, Assam Don Bosco University, Assam. February 26-27,2021.**

3. **B.B Boruah** and M. K. Das; **"DAE-BRNS Symposium on High Energy Physics"**, National Institute of Science Education and Research,Odisha, India, December 14-18, 2020.

4. **B.B Boruah** and M. K. Das; **"National Conference on Emerging Trends in Physics -2021"**,Tezpur University,India,16 June,2021.

5. **B.B Boruah**, L. Sarma and M. K. Das; **"XII Biennial National Conference of PANE -2021"**, Tripura University,India, December 15-17,2021.

# LIST OF PUBLICATIONS

## Research Publications in International Refereed Journals:

1. **Boruah, B. B.**, & Das., M. K.; *Neutrinoless double-beta decay and lepton flavor violation in discrete flavor symmetric left right symmetric model,* ***Int.J.Mod.Phys.A 37 (2022) 06, 2250026****, arXiv:2111.10341.*

2. **Boruah, B. B.**, Sarma, L., & Das., M. K.; *Lepton flavor violation and leptogenesis in discrete flavor symmetric scotogenic model",* ***Nucl.Phys.B 969 (2021) 115472****, arXiv:2103.05295.*

3. Sarma, L., **Boruah, B. B.** & Das., M. K.; *Dark matter and low scale leptogenesis in a flavor symmetric neutrino two Higgs doublet model(ν2HDM)* ***Eur.Phys.J.C 82 (2022) 5, 488.****,arXiv:2106.04124 .*

4. **Boruah, B. B.**, Gautam, N., & Das., M. K.; *Neutrinoless double beta decay and Sterile dark matter in extended left right symmetric model", arXiv:2206.00696:* ***Under review.***.

## Conference Proceedings:

- **Boruah, B. B.**, & Das., M. K.; Realization of Left-Right Symmetric Model by Discrete Flavor Symmetries, **Springer Proceedings,Progresses in Modern Physics, 2021, ISBN: 978-981-16-5140-3.** , International Conference on Trends in Modern Physics -2021.

- **Boruah, B. B.**, Sarma, L & Das., M. K.; LFV in a $A_4$ and $Z_4$ flavor symmetric scotogenic model, **IJERT, ISSN: 2278-0181.** , PANE-2021 Conference Proceedings

- Sarma, L, **Boruah, B. B.** & Das., M. K.; Neutrinoless double beta decay in a flavor symmetric scotogenic model, **Springer Proceedings,Progresses in Modern Physics, 2021, ISBN: 978-981-16-5140-3.** , International Conference on Trends in Modern Physics -2021.

# Book Chapter:

- **Boruah, B. B.**, & Das., M. K.; Leptogenesis in $A_4 \otimes Z_4$ flavor symmetric scotogenic model, **Frontiers in Basic Physics and Applications, ISBN:978-93-1953-5-3.**

- Sarma, L, **Boruah, B. B.** & Das., M. K.;Scotogenic Model and its Implication in Neutrino Physics and Related Cosmology: A Brief Review, **published in Frontiers in Basic Physics and Applications, Knowledge Publications, ISBN 978-81-933014-8-7.**