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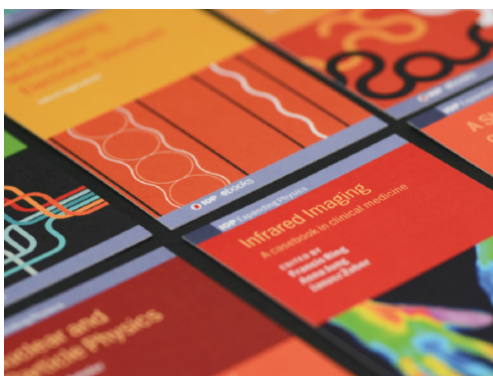
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Radiative neutrino mass model with a TeV scale gauge symmetry

Daijiro Suematsu

Institute for Theoretical Physics, Kanazawa University, Kanazawa 920-1192, Japan

E-mail: suematsu@hep.s.kanazawa-u.ac.jp

Abstract. The radiative neutrino mass model can relate neutrino masses to dark matter at TeV regions. In order for thermal leptogenesis to work well in this model, both finely degenerate mass of the right-handed neutrinos and a tiny neutrino Yukawa coupling are necessary for resonant out-of-equilibrium decay. We show these features could be realized through an extension of the model with a $U(1)$ gauge symmetry. This extension can also bring about a small quartic scalar coupling between the Higgs doublet scalar and an inert doublet scalar, and the origin of the Z_2 symmetry which guarantees the stability of dark matter.

1. Introduction

After the discovery of the Higgs particle, a next theoretical target is to find a certain extension of the standard model (SM) so as to include some mechanism for neutrino mass generation and dark matter (DM), which are now confirmed through various experiments and observations. Among such trials at a TeV scale, the scotogenic model [1] (a one-loop radiative neutrino mass model) is a simple and phenomenologically interesting one, in which the SM is extended with right-handed neutrinos N_i and an extra doublet scalar η . Since a Z_2 symmetry is imposed on the model and odd parity is assigned only these new fields among ingredients, the lightest neutral one of them is stable to be DM. Such a candidate could be the lightest N_i or the lightest neutral component of η . However, if we identify the lightest N_i with DM, the DM relic abundance requires that the neutrino Yukawa couplings are of $O(1)$. They cause too large lepton flavor violation ($\mu \rightarrow e\gamma$ etc.) and also the vacuum instability due to the quantum effect on scalar quartic couplings [2, 3].

If DM is assumed to be the lightest neutral component of η , these problems could be overcome and the model is a good candidate of the extension of the SM at a TeV scale. In this framework, the baryon number asymmetry in the Universe, which is another big issue beyond the SM, has also been studied on the basis of thermal leptogenesis due to the decay of a right-handed neutrino [4, 5]. Since masses of the right-handed neutrinos are supposed to be TeV scales, resonant effect in the decay is necessary for the sufficient amount of generation of lepton number. It requires the fine degeneracy among the masses of the right-handed neutrinos. Simultaneously, the neutrino Yukawa coupling relevant to this decay has to be extremely small for the realization of out-of-equilibrium N_i decay. This situation makes the thermal leptogenesis in this model unnatural and artificial. In this presentation, we consider to remedy this problem by extending the model with a $U(1)$ gauge symmetry which is broken at a scale of $O(1)$ TeV.



2. An extended model with a $U(1)$ gauge symmetry

We consider an extension of the scotogenic model [1] by adding a $U(1)_X$ gauge symmetry, a singlet scalar S and right-handed singlet fermions \tilde{N}_i [6]. The $U(1)_X$ charge is assigned only for new ingredients such as $Q_X(S) = 2$, $Q_X(\eta) = -1$, $Q_X(N_i) = 1$, and $Q_X(\tilde{N}_i) = -1$. Lagrangian contains the following new terms other than the ones included in the scotogenic model:

$$-\mathcal{L}_N = f_{\alpha i} \frac{S^\dagger}{M_*} \tilde{N}_i \eta^\dagger \ell_\alpha + M_i N_i \tilde{N}_i + \frac{y_i}{2} S^\dagger N_i N_i + \frac{\tilde{y}_i}{2} S \tilde{N}_i \tilde{N}_i + \text{h.c.} \\ + \frac{\lambda'_5}{2} \left[\frac{S}{M_*} (\phi^\dagger \eta)^2 + \text{h.c.} \right] + \lambda_6 (S^\dagger S) (\phi^\dagger \phi) + \lambda_7 (S^\dagger S) (\eta^\dagger \eta) + \kappa (S^\dagger S)^2 + m_S^2 S^\dagger S, \quad (1)$$

where ℓ_α is a left-handed doublet lepton and ϕ is the doublet Higgs scalar. Both $f_{\alpha i}$ and λ'_5 are $O(1)$ coupling constants and M_* is a cut-off scale of the model. If the singlet S has a vacuum expectation value, the coupling λ_5 in the original model and neutrino Yukawa couplings $\tilde{h}_{\alpha i}$ for \tilde{N}_i are determined as $\lambda_5 = \lambda'_5 \frac{\langle S \rangle}{M_*}$ and $\tilde{h}_{\alpha i} = f_{\alpha i} \frac{\langle S^\dagger \rangle}{M_*}$. Both magnitude of λ_5 and $\tilde{h}_{\alpha i}$ is crucial for the neutrino mass determination. If $|\langle S \rangle| \ll M_*$ is satisfied, they could take suitable values.

The mass matrix of the right-handed neutrinos is expressed as

$$\frac{1}{2} (N_i, \tilde{N}_i) \begin{pmatrix} |y_i| e^{i\gamma_i} \langle S^\dagger \rangle & M_i \\ M_i & |\tilde{y}_i| e^{i\tilde{\gamma}_i} \langle S \rangle \end{pmatrix} \begin{pmatrix} N_i \\ \tilde{N}_i \end{pmatrix} + \text{h.c.} \quad (2)$$

The mass eigenstates $\mathcal{N}_{\pm i}$ are written as

$$\mathcal{N}_{+i} = e^{-i\frac{\xi_i}{2}} \left(N_i \cos \theta_i + \tilde{N}_i e^{-i\xi_i} \sin \theta_i \right), \quad \mathcal{N}_{-i} = i e^{-i\frac{\xi_i}{2}} \left(-N_i \sin \theta_i + \tilde{N}_i e^{-i\xi_i} \cos \theta_i \right), \quad (3)$$

and the difference of mass eigenvalues $M_{\pm i}$ is found to be

$$\Delta_i \equiv \frac{M_{+i} - M_{-i}}{M_{-i}} \simeq \frac{\langle S \rangle}{M_i} \frac{|y_i| \cos(\gamma_i - \xi_i) + |\tilde{y}_i| \cos(\tilde{\gamma}_i + \xi_i)}{\sin 2\theta_i}, \quad (4)$$

where θ_i and ξ_i are determined by the parameters contained in the mass matrix (2). If $\tilde{h}_{\alpha i}$ is assumed to take the same value as the Yukawa coupling $h_{\alpha i}$ of N_i , the flavor structure of the model becomes very simple. In that case, the Yukawa couplings of $\mathcal{N}_{\pm i}$ can be rewritten as

$$g_{\alpha i}^{(+)} = h_{\alpha i} \left(1 + \cos \xi_i \sin 2\theta_i \right)^{\frac{1}{2}} e^{i(\delta_{+i} - \frac{\xi_i}{2})}, \quad g_{\alpha i}^{(-)} = h_{\alpha i} \left(1 - \cos \xi_i \sin 2\theta_i \right)^{\frac{1}{2}} e^{i(\delta_{-i} - \frac{\xi_i}{2})}. \quad (5)$$

The neutrino mass induced through one-loop diagrams with \mathcal{N}_{+i} or \mathcal{N}_{-i} in an internal fermion line is given by

$$\mathcal{M}_{\alpha\beta} = \sum_i \sum_{s=\pm} \left| g_{\alpha i}^{(s)} g_{\beta i}^{(s)} \lambda_5 \right| e^{i(2\delta_{si} - \xi_i)} \Lambda(M_{si}), \quad (6)$$

where $\Lambda(M_{\pm i}) = \frac{\langle \phi \rangle^2}{8\pi^2} \frac{M_{\pm i}}{M_\eta^2 - M_{\pm i}^2} \left(1 + \frac{M_{\pm i}^2}{M_\eta^2 - M_{\pm i}^2} \ln \frac{M_{\pm i}^2}{M_\eta^2} \right)$. If the model has two sets of (N_i, \tilde{N}_i) , neutrino mass eigenvalues required for the explanation of the neutrino oscillation data could be derived.

3. Degenerate masses and a tiny neutrino Yukawa coupling

Since the scale $\Lambda(M_{\pm i})$ is estimated as $\Lambda(M_{\pm i}) = O(10^9)$ eV for M_η and $M_{\pm i}$ in the TeV range, eq.(6) suggests that the atmospheric neutrino data require the relevant neutrino Yukawa couplings to satisfy $\sum_i \left| g_{\alpha i}^{(\pm)} g_{\beta i}^{(\pm)} \lambda_5 \right| = O(10^{-11})$. On the other hand, if \mathcal{N}_{-1} is identified with the lightest right-handed neutrino, its decay should occur in out-of-thermal equilibrium for

	$ g_{\alpha 1}^{(-)} $	$ g_{\alpha 1}^{(+)} $	Δ_1	ε	$(M_{\tilde{\sigma}}, m_X)$	A	B	C	D
A	3.12×10^{-9}	5.66×10^{-4}	1.00×10^{-5}	-1.73×10^{-3}	(200, 300)	5.2×10^{-10}	2.3×10^{-9}	4.2×10^{-10}	5.6×10^{-10}
B	6.71×10^{-9}	7.07×10^{-4}	1.00×10^{-5}	-2.71×10^{-3}	(60, 100)	3.9×10^{-10}	1.7×10^{-9}	1.5×10^{-10}	1.9×10^{-10}
C	1.17×10^{-8}	5.66×10^{-4}	2.00×10^{-5}	-5.04×10^{-4}	(200, 10^{-3})	4.0×10^{-10}	1.8×10^{-9}	1.6×10^{-10}	2.2×10^{-10}
D	1.46×10^{-8}	7.07×10^{-4}	2.00×10^{-5}	-7.88×10^{-4}	(600, 600)	7.0×10^{-10}	3.1×10^{-9}	1.1×10^{-9}	1.4×10^{-9}

Table 1 Relevant quantities to the leptogenesis.**Table 2** Baryon number asymmetry Y_B .

leptogenesis to work well. As long as $\left(\sum_{\alpha} |g_{\alpha 1}^{(-)}|^2\right)^{\frac{1}{2}} \leq 10^{-8}$ is satisfied, the decay is found not to reach the equilibrium at $T \gtrsim 100$ GeV. This condition for $g_{\alpha 1}^{(-)}$ shows that \mathcal{N}_{-1} cannot contribute to the neutrino mass generation. Since \mathcal{N}_{+1} is supposed to cause a main contribution to the neutrino mass generation, its coupling should satisfy $|g_{\alpha 1}^{(+)}|^2 = O\left(\frac{10^{-11}}{|\lambda_5|}\right)$. As found in eq. (5), the simultaneous realization of the above conditions is possible even for $|h_{\alpha i}| \sim 10^{-3}$ as long as $\cos \xi_1 \sin 2\theta_1 \simeq 1$ is satisfied. Other nonzero neutrino mass eigenvalues could be determined through the second pair (N_2, \tilde{N}_2) .

Resonant leptogenesis can be considered in this framework. The dominant contribution to the CP asymmetry ε in the \mathcal{N}_{-1} decay comes from the resonance appearing in the one-loop self-energy diagram. In that case, ε is known to be expressed as

$$\varepsilon = \frac{\cos 2\theta_1 \sin 2\xi_1}{1 - \sin^2 2\theta_1 \cos^2 \xi_1} \frac{2\Delta_1 \tilde{\Gamma}_{\mathcal{N}_{+1}}}{4\Delta_1^2 + \tilde{\Gamma}_{\mathcal{N}_{+1}}^2}, \quad (7)$$

where we use the expression of the neutrino Yukawa couplings $|g_{\alpha 1}^{(\pm)}|$ given in eq. (5). The mass degeneracy Δ_1 is defined in eq. (4) and $\tilde{\Gamma}_{\mathcal{N}_{+1}}$ stands for the decay width of \mathcal{N}_{+1} divided by M_{+1} .

In the numerical analysis, we assume $\langle S \rangle = M_1 = 2$ TeV and $M_{\eta} = 1$ TeV. Other parameters ($|y_i|, |h_{\alpha 1}|$) in (N_1, \tilde{N}_1) sector are fixed at A($10^{-5}, 4 \times 10^{-4}$), B($10^{-5}, 5 \times 10^{-4}$), C($2 \times 10^{-5}, 4 \times 10^{-4}$), and D($2 \times 10^{-5}, 5 \times 10^{-4}$). The relevant quantities to leptogenesis are given in Table 1 for each case, where $\gamma_1 \sim 9 \times 10^{-5}$ and 4×10^{-5} are assumed in the cases A, B and C, D, respectively. In Table 2, we show the baryon number asymmetry predicted for each case by assuming the singlet scalar mass $M_{\tilde{\sigma}}$ and the $U(1)_X$ gauge boson mass m_X . These results show that the model could generate the sufficient baryon number asymmetry required from the observation if the relevant parameters take suitable values.

The neutrino oscillation data requires $|\lambda_5| = O(10^{-4})$ for the above numerical results. It is consistent with the constraint derived from the dark matter direct search. The values of λ_5 and $\tilde{h}_{\alpha 1}$ used in the above study could be realized for the cut-off scale such as $M_* = O(10^4)$ TeV here. Even if we change the assumed values of M_1 and $\langle S \rangle$, a similar result is expected to be obtained for an appropriate choice of M_* , $|y_i|$ and $|\tilde{y}_i|$. The model gives a promising simple extension for the scotogenic model, which can unify the neutrino mass, the dark matter, and the baryon number asymmetry in the Universe in a consistent way.

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