Neutrino mass generation from higher dimensional operators

Toshihiko Ota

Max-Planck-Institut für Physik,
Föhringer Ring 6, 80805 München, Germany

Abstract. We discuss the scenarios in which the neutrino masses are generated through the operators with the mass dimension higher than five. Thanks for an additional suppression factor of the higher mass dimension, the tiny neutrino masses can be originated from the new physics at the TeV scale. We demonstrate the method to realize the scenario and systematically list the possible models.

Keywords: Neutrino masses, Seesaw mechanism
PACS: 12.60.Fr,14.60.Pq,14.60.St.

INTRODUCTION

If the standard model (SM) is an effective model of the fundamental theories which are realized at high energy scales, the full theory at the electroweak scale should be described with the SM Lagrangian and the series of the higher dimensional operators which are suppressed by the power of the new physics scale Λ:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda}\mathscr{O}_{d=5} + \frac{1}{\Lambda^2}\mathscr{O}_{d=6} + \frac{1}{\Lambda^3}\mathscr{O}_{d=7} + \cdots. \quad (1)$$

The higher dimensional operator of the lowest order takes the mass-dimension of five, and the only possible one with the SM particle contents is known as the Weinberg operator [1]

$$\mathscr{O}_{d=5} = (\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L), \quad (2)$$

which provides Majorana masses for neutrinos after the electroweak symmetry breaking. This is a highly favorable extension of the SM, because the resulting neutrino masses are naturally suppressed by the new physics scale, such as,

$$m_\nu \sim \frac{v^2}{\Lambda}, \quad (3)$$

where v is the electroweak scale (the vacuum expectation value of the Higgs doublet). In the seesaw mechanism [2, 3, 4, 5, 6], the dimension five operator is assumed to be induced from the tree-level diagrams which are mediated by the fields with the masses of the order of Λ. In order to realize the neutrino masses of the electron-Volt scale, Λ has to be typically $\sim \mathscr{O}(10^{13})$ GeV which is friendly with the grand unified theories but is impossible to be directly tested by collider experiments. There are some attempts to construct the models in which the neutrino masses are generated from the physics at the energy scale of TeV. A classic example is the loop-induced neutrino mass models such as Zee model [7, 8] in which the dimension five operator is induced from a one-loop diagram. The order of neutrino masses is estimated as

$$m_\nu \sim \frac{1}{16\pi^2}\frac{v^2}{\Lambda}. \quad (4)$$

Thanks for the double suppression of $1/\Lambda$ and the loop factor, tiny neutrino masses can become derived from the new physics at the TeV scale. In such a class of models, one can expect that the collider experiments will confirm the mechanism of neutrino mass generation, namely, the new particles which mediate the dimension five operator could be directly produced at the collider experiments.

In this talk, we discuss an alternative scenario with the higher dimensional operators than $d > 5$ [9, 10, 11, 12, 13, 14]. If the dimension five operator is forbidden for some reason, the next lowest higher-dimensional operator which can induces the neutrino masses is the dimension seven operator,

$$\mathscr{O}_{d=7} = (\overline{L^c}{\rm i}\tau^2 H)(H^{\sf T}{\rm i}\tau^2 L)(H^\dagger H). \quad (5)$$

The neutrino masses from this $d = 7$ operator receives an additional suppression factor $(v/\Lambda)^2$ than the ones in the $d = 5$ case:

$$m_\nu \sim \frac{v^2}{\Lambda}\left(\frac{v}{\Lambda}\right)^2. \quad (6)$$

With this extra suppression mechanism, the both tiny neutrino masses and the collider testability of the neutrino mass generation mechanism can be achieved, as in the case of the loop-induced dimension five operator.

NEUTRINO MASSES FROM $d = 7$

In order to realize the situation in which the contribution from the dimension seven operator dominates the neutrino masses, the dimension five operator must be sufficiently suppressed. For that purpose, we extend the particle contents from the SM to the two Higgs doublet model

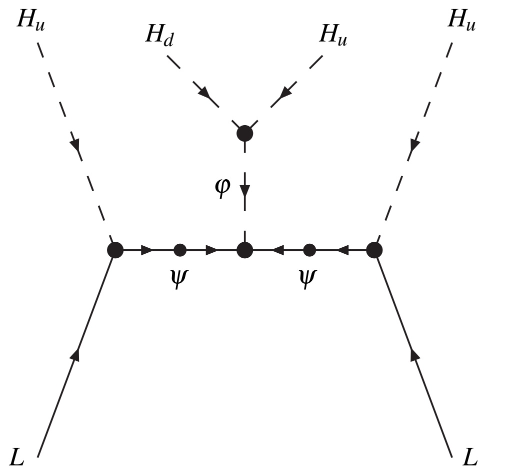

FIGURE 1. An example of tree-level decompositions of the dimension seven operator.

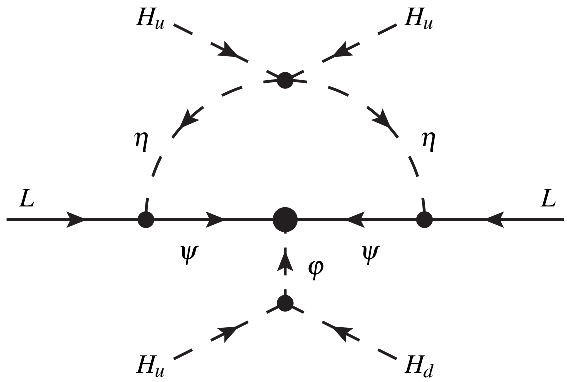

FIGURE 2. An example of decompositions of the dimension seven operator at the one-loop level.

and introduce the discrete symmetry Z_5. With an appropriate charge assignment of Z_5 such as

$$q(L) = 1, \quad q(H_d) = 3, \quad q(H_u) = 0, \quad q(e^c) = 1, \tag{7}$$

the dimension five operators are forbidden, and the dimension seven operator

$$\mathscr{O}_{d=7} = (\overline{L^c}\mathrm{i}\tau^2 H_u)(H_u^{\mathsf{T}}\mathrm{i}\tau^2 L)(H_d^{\mathsf{T}}\mathrm{i}\tau^2 H_u) \tag{8}$$

and the Yukawa interaction for the charged leptons are allowed.

Next, let us discuss the fundamental theories at the high energy scales, which derive the effective interaction Eq. (8) at the electroweak scale. They can be obtained by decomposing the effective interaction into the diagrams which consists of the renormalizable interactions. We listed the all possible decompositions at the tree-level in Ref. [11]. One example is shown in Fig. 1, in which the SM singlet fermion (4-spinor) ψ and scaler φ are introduced as the mediation fields. Unlike the type I seesaw, the SM singlet fermion cannot take the Majorana mass term, because of the Z_5 charge. It forms the Dirac mass term instead. The lepton number is violated explicitly on the vertex of $\overline{\psi^c}\psi\varphi$. This model is also understood in the manner of the inverse seesaw [15, 16]. There are three neutral fermions (left-handed 2-spinors) which are ν_L, ψ_R^c and ψ_L in this model, and two Dirac mass terms — m_D for ψ_R^c-ν_L and M for ψ_R^c-ψ_L — are allowed under Z_5. The Majorana masses for ψ_L are forbidden by Z_5, but they are allowed as the higher order operator mediated by φ, which is suppressed by $1/\Lambda$. The mass matrix for the neutral fermions $(\nu_L\ \psi_R^c\ \psi_L)$ is summarized as

$$\begin{pmatrix} 0 & m_D^{\mathsf{T}} & 0 \\ m_D & 0 & M \\ 0 & M^{\mathsf{T}} & H_d^0 H_u^0/\Lambda \end{pmatrix}. \tag{9}$$

In other words, this model provides a reason why the Majorana mass of ψ_L must be suppressed in the inverse seesaw scenario.

LOOP-INDUCED $d = 7$ OPERATORS

It is an interesting extension to derive the dimension seven operator from loop diagrams. In such a class of models, the order of neutrino masses are approximately expressed as

$$m_\nu \sim \frac{1}{16\pi^2}\frac{v^2}{\Lambda}\left(\frac{v}{\Lambda}\right)^2, \tag{10}$$

and the new physics scale Λ is further lowered by the both higher dimension effect and the loop suppression factor. To realize this situation, not only the dimension five operators but also the tree-level dimension seven operators should be restrained. Following the method of the dark doublet model [17, 18], we invoke an additional matter parity Z_2 and introduce an $SU(2)_L$ doublet η (dark doublet) with the odd charge under the parity. Assigning

TABLE 1. Particle contents and charge assignments for the dimension seven neutrino mass generation. In the case of the tree-level realization (Fig. 1), only Z_5 is taken, and ψ and φ are introduced as the mediators. To derive the operator from the one-loop diagram shown in Fig. 2, the both Z_5 and Z_2 are adopted, and the dark doublet η is also necessary. The symbol $\mathbf{X}_Y^{\mathscr{L}}$ indicates the representations of the fields; $\mathbf{X}$ for $SU(2)_L$, Y for $U(1)_Y$, and $\mathscr{L}$ for Lorenz group; i.e., Dirac spinor (D) and scalar (s).

	L	e^c	H_u	H_d	$\psi(\mathbf{1}_0^D)$	$\varphi(\mathbf{1}_0^s)$	$\eta(\mathbf{2}_{1/2}^s)$
Z_5	1	1	0	3	1	3	0
Z_2	+	+	+	+	−	+	−

the odd charge also to the SM singlet fermion ψ, we have to substitute η for H_u in the Yukawa interactions $\bar{\psi} H_u \mathrm{i}\tau^2 L$ in Fig. 1. These two η-legs are closed with a quartic interaction

$$\frac{\lambda}{2}(\eta^\dagger H_u)(\eta^\dagger H_u) + \text{H.c.} \tag{11}$$

to construct the one-loop diagram shown in Fig. 2. The charge assignments are summarized in Tab. 1. Although the neutrino masses in this model cannot be analyzed in the simple inverse seesaw way any more, the order of them can still be estimated in Eq. (10). Thanks for the double suppression from loop and higher mass dimension, the new physics scale can stay around TeV, even if we assume that the order $\mathscr{O}(0.1)$ coupling for each fundamental interaction.

DISCUSSIONS AND SUMMARY

In order to realize the higher dimensional neutrino mass generation mechanism, we introduced the Z_5 matter parity and assigned the charge to the Higgs fields. However, the scalar potential with this Z_5 symmetry actually respects the $U(1)$ symmetry which includes the Z_5 at the renormalizable level. Therefore, the vacuum expectation values of the Higgs doublets break not only the electroweak symmetry but also the new $U(1)$ symmetry (which can be described as the combination of the Peccei-Quinn symmetry and the $U(1)$ of hypercharge), and it results that a dangerous Nambu-Goldstone boson. To circumvent this difficulty, we assume that the $U(1)$ (and also Z_5) is explicitly but softly broken by the Higgs cross mass term

$$\mathscr{V} = m_3^2 H_d^\mathsf{T} \mathrm{i}\tau^2 H_u + \text{H.c.} \tag{12}$$

The dimension five operator recurs through this mass term. However, it is suppressed as

$$\mathscr{L}_{d=5} = \frac{1}{16\pi^2}\frac{m_3^2}{\Lambda^3}(\overline{L^c}\mathrm{i}\tau^2 H_u)(H_u^\mathsf{T}\mathrm{i}\tau^2 L), \tag{13}$$

which gives only a sub-dominant effect to the neutrino masses. Another possible solution with the extended scalar sector is discussed in Ref. [11].

The models shown in the last sections include the mixing between the neutrinos and the extra neutral fermions, which is estimated from the seesaw relation as the order of v/Λ. This large mixing could affect the neutrino oscillation phenomena as the non-unitary elements of the lepton mixing matrix (see e.g., Ref. [19]). That is one of the particular low-energy signatures of this class of models. The non-unitarity also leads to the charged lepton flavour violating process $\ell_\beta \to \ell_\alpha \gamma$ at the one-loop level. Since the masses of the mediation fields are expected to lie at the TeV scale, it is possible to discover them directly at collider experiments. It can be expected that the synergy of all these experimental information will reveal this class of neutrino mass generation mechanism. It may be also worth to mention that the new particles with the odd parity of Z_2 can be a good candidate of the dark matter in the models of the radiative neutrino masses, because the exact Z_2 parity makes the lightest parity-odd particle stable, which is the same as the R-parity in SUSY models.

ACKNOWLEDGMENTS

This talk is based on the collaboration works [11, 14] with Florian Bonnet, Daniel Hernandez, Shinya Kanemura, and Walter Winter. We would like to thank Belen Gavela for useful discussion.

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