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Study of two-loop neutrino mass generation models

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ABSTRACT

We study the models with the Majorana neutrino masses generated radiatively by two-loop diagrams due to the Yukawa $\rho\bar{\ell}_R^c\ell_R$ and effective $\rho^{\pm\pm}W^{\mp}W^{\mp}$ couplings along with a scalar triplet Δ, where ρ is a doubly charged singlet scalar, ℓ_R the charged lepton and W the charged gauge boson. A generic feature in these types of models is that the neutrino mass spectrum has to be a normal hierarchy. Furthermore, by using the neutrino oscillation data and comparing with the global fitting result in the literature, we find a unique neutrino mass matrix and predict the Dirac and two Majorana CP phases to be 1.41π, 1.11π and 1.48π, respectively. We also discuss the model parameters constrained by the lepton flavor violating processes and electroweak oblique parameters. In addition, we show that the rate of the neutrinoless double beta decay ($0\nu\beta\beta$) can be as large as the current experimental bound as it is dominated by the short-range contribution at tree level, whereas the traditional long-range one is negligible.

1. Introduction

Although the data from neutrino experiments have implied that at least two neutrinos carry nonzero masses [1–5], the origin of these masses is still a mystery. Apart from the mass generation of

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Dirac neutrinos given by the Yukawa couplings with the existence of right-handed neutrinos (ν_R), seesaw mechanisms with type-I [6–10], type-II [11–17] and type-III [18] can generate masses for Majorana neutrinos by realizing the Weinberg operator $(\bar{L}_L^c \Phi)(\Phi^T L_L)$ at tree-level, where Φ and L_L are the doublets of Higgs and left-handed lepton fields, respectively. In these scenarios, either heavy degrees of freedom or tiny coupling constants are required in order to conceive the small neutrino masses. On the other hand, models with the Majorana neutrino masses generated at one-loop [19,20], two-loop [21–24] and higher loop [25–28] diagrams have also been proposed without introducing ν_R. Due to the loop suppression factors, the strong bounds on the coupling constants and heavy states are relaxed, resulting in a somewhat natural explanation for the smallness of neutrino masses.

Among the loop-level mass generation mechanisms, there is a special type of the neutrino models [23,24] in which a doubly charged singlet scalar $\rho : (1, 4)$ and a triplet $\Delta : (3, 2)$[1] under $SU(2)_L \times U(1)_Y$ are introduced to yield the new Yukawa coupling $\rho \bar{\ell}_R^c \ell_R$ with the charged lepton ℓ_R as well as the effective gauge coupling $\rho^{\pm\pm} W^{\mp} W^{\mp}$ due to the mixing between $\rho^{\pm\pm}$ and $\Delta^{\pm\pm}$, leading to the neutrino masses through two-loop diagrams [23]. As this model is the simplest way to realize the ρWW coupling, we name it as the minimal two-loop-neutrino model (MTM) [23]. It is interesting to note that $\rho^{\pm\pm} W^{\mp} W^{\mp}$ can also be induced from non-renormalizable high-order operators [29–31]. Although MTM can depict neutrino masses at two-loop level, the assumption on the absence of the $\bar{L}^c L \Delta$ term makes this model unnatural. To solve this problem, one can simply extend MTM by adding an extra doublet scalar, which together with Δ carries an odd charge under an Z_2 symmetry [32]. We call this model as the doublet two-loop-neutrino model (DTM). On the other hand, $\rho^{\pm\pm} W^{\mp} W^{\mp}$ could be granted by inner-loop diagrams, such as those [27,28] with three-loop contributions to neutrino masses, in which the neutral particle in the inner-loops could be a candidate for the stable dark matter.

In this study, we will demonstrate that the neutrino mass matrix can be determined in these models by the experimental data. In particular, the neutrino mass spectrum is found to be a normal hierarchy. In addition, the neutrinoless double beta decay ($0\nu\beta\beta$) is dominated by the short-range contribution at tree level due to the effective coupling of $\rho^{\pm\pm} W^{\mp} W^{\mp}$ [23,24,28–30,33,34], instead of the traditional long-range one. However, the neutrino masses in this type of the models are usually oversuppressed as there is not only a two-loop suppression factor, but also a small ratio m_l/v with the charged lepton mass m_l and vacuum expectation value (VEV) $v = 246$ GeV of the Higgs field. Furthermore, the lepton flavor violation (LFV) processes could also limit the new Yukawa couplings. To have a large enough neutrino mass, the mixing angle or mass splitting between the two doubly-charged states should be large, which inevitably leads to a significant contribution to the electroweak oblique parameters, especially the T parameter. We will calculate the neutrino masses in detail and check whether there is a tension between these masses and the constraint from the oblique parameter T.

This paper is organized as follows. In Section 2, we study the neutrino masses in the two-loop neutrino models. In Section 3, the constraints on the model parameters from lepton flavor violating processes and electroweak oblique parameters are studied. We present the conclusions in Section 4.

2. Two-loop neutrino masses

In MTM, we introduce the scalars $\rho : (1, 4)$ and $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^0) : (3, 2)$ under $SU(2)_L \times U(1)_Y$. The relevant terms in the Lagrangian are given by

$$-\mathcal{L} = -\mu_\Phi^2(\Phi^\dagger\Phi) + M_\Delta^2(\Delta^\dagger\Delta) + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \bar{\lambda}_3(\Delta^\dagger\Delta)_1(\Phi^\dagger\Phi)_1 + \bar{\lambda}_4(\Delta^\dagger\Delta)_3(\Phi^\dagger\Phi)_3$$
$$+ \left[Y_{ab}(\bar{L}_L^c)_a \Delta (L_L)_b + \frac{C_{ab}}{2}\rho(\bar{\ell}_R^c)_a(\ell_R)_b - \mu\Delta(\Phi^\dagger)^2 + \frac{\kappa}{2}\rho^*\Delta^2 + \bar{\lambda}\rho^*\Delta\Phi^2 + \text{H.c.}\right], \quad (1)$$

where $\Phi = (\Phi^+, \Phi^0)^T$ with $\Phi^0 = (\Phi_R + i\Phi_I)/\sqrt{2}$ is the SM doublet scalar, the indices of a and b represent e, μ and τ, and the subscripts of 1 and 3 in the quartic terms stand for the SU(2) singlet and triplet scalars inside the parentheses, respectively. After the spontaneous symmetry breaking, Φ

[1] The convention for the electroweak quantum numbers (I, Y) with $Q = I + Y/2$ is used throughout this paper.