

Hiding neutrinoless double beta decay in the minimal seesaw mechanism

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We present a possibility that the neutrinoless double beta decay can be hidden in the minimal seesaw mechanism where the standard model is extended by two right-handed neutrinos which have a hierarchical mass structure. In this framework, the lepton number is violated due to the massive Majorana neutrinos. Especially, we investigate the case that the heavier right-handed neutrino is sufficiently heavy to decouple from the decay while the lighter one is lighter enough than the typical Fermi-momentum scale of nuclei and gives a sizable contribution to the decay. Under the specific condition on mixing elements, the lighter right-handed neutrino can give a significant destructive contribution which suppresses or even hides to the effective mass of the neutrinoless double beta decay. In this case, the flavor structure of the mixing element of the lighter right-handed neutrino with ordinary neutrinos is predicted depending on the Majorana CP violating phase of active neutrinos.

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I. INTRODUCTION

Neutrino oscillation experiments have been developed so far and have provided many properties of three active neutrinos, including mass square differences, mixing angles, and even CP violating phase which has been getting to be revealed recently. Unfortunately, all the fascinated neutrino oscillation experiments can give no hint of whether neutrinos are Dirac or Majorana fermions, which is one of the most interesting missing pieces of neutrinos. One promising possibility to attack this issue is finding the phenomenon of the neutrinoless double beta ($0\nu\beta\beta$) decay. (See as a theoretical review, for instance, Ref. [1].) It violates the lepton number by two units and shows a clear signal for physics beyond the Standard Model (SM). The decay can be mediated by massive Majorana neutrinos and the rate is characterized by the so-called effective mass m_{eff} of Majorana neutrinos, which has been constrained by various $0\nu\beta\beta$ decay experiments until today [2–27].

The seesaw mechanism [28–34] by introducing right-handed neutrinos with Majorana masses is the one of the

most attractive scenarios for explaining the origin and the observed smallness of neutrino masses. In this case, the lepton number is violated by the Majorana masses and the $0\nu\beta\beta$ decay is possible to occur. The effective mass is expressed in terms of neutrino masses, mixing angles, and CP violating phases. In the effective SM with three massive neutrinos, there is a possibility where the effective mass is highly suppressed or even vanishes by tuning the lightest active neutrino mass (see, e.g., [1]).

When right-handed neutrinos are much lighter than the unification scale $\sim 10^{16}$ GeV, or even lighter than the weak scale ~ 100 GeV, they can give a sizable contribution to m_{eff} in addition to active neutrinos' one. In such cases, the masses and mixing elements of right-handed neutrinos must be chosen appropriately without conflicting with the experimental limits on m_{eff} . When all right-handed neutrinos are lighter than a typical scale of Fermi momentum of a nucleus Λ_β ($\sim \mathcal{O}(100)$ MeV), the contributions of active neutrinos and heavier ones exactly cancel out each other due to the intrinsic property of the seesaw mechanism [35]. Further, it is shown that, when right-handed neutrinos are degenerate, m_{eff} becomes smaller than the one solely from active neutrinos [36]. Although such right-handed neutrinos are attractive to realize the baryogenesis via the oscillation mechanism [37,38], there is no concrete reason to constrain ourselves to keep the degeneracy in general.

In this paper, we present another possibility to suppress the $0\nu\beta\beta$ decay by hierarchical right-handed neutrinos. As the simplest example, we consider the extended SM with two right-handed neutrinos where one is sufficiently heavier than Λ_β to decouple from the system while the

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other is lighter than Λ_β giving a destructive contribution to the decay rate. It is shown that $m_{\text{eff}} = 0$ is possible due to the exact cancellation of the contributions between active neutrinos and the lighter right-handed neutrino if the mixing elements are chosen to be specific values. We then discuss the impacts of this cancellation conditions, especially, on the Majorana CP violating phase and the mass hierarchy of active neutrinos.

II. SEESAW MODEL WITH TWO RIGHT-HANDED NEUTRINOS

We consider here the simplest extension of the SM to explain the observed neutrino masses by adding two right-handed neutrinos¹ ν_{RI} ($I = 1, 2$),

$$\mathcal{L}_\nu = i\overline{\nu_{RI}}\gamma^\mu\partial_\mu\nu_{RI} - \left(F_{\alpha I}\overline{\ell}_\alpha\Phi\nu_{RI} + \frac{M_I}{2}\overline{\nu_{RI}}\nu_{RI} + \text{H.c.} \right) \quad (1)$$

where Φ and ℓ_α ($\alpha = e, \mu, \tau$) are the Higgs and lepton doublets of the weak $SU(2)$. Neutrino Yukawa coupling constants and Majorana masses of right-handed neutrinos are denoted by $F_{\alpha I}$ and M_I , respectively. Here and hereafter, we work in the basis where the Yukawa coupling matrix of charged leptons and the Majorana mass matrix of right-handed neutrinos are diagonal.

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \text{diag}(1, e^{i\eta}, 1), \quad (4)$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$. δ and η are the Dirac and Majorana CP violating phases, respectively. The 3×2 matrix Ω can be expressed as

$$\Omega = \begin{cases} \begin{pmatrix} 0 & 0 \\ c_\omega & -s_\omega \\ \xi s_\omega & \xi c_\omega \end{pmatrix} & \text{for the NH case} \\ \begin{pmatrix} c_\omega & -s_\omega \\ \xi s_\omega & \xi c_\omega \\ 0 & 0 \end{pmatrix} & \text{for the IH case} \end{cases}, \quad (5)$$

where $s_\omega = \sin\omega$ and $c_\omega = \cos\omega$, respectively. $\xi = \pm 1$ is sign parameter and ω is a complex parameter, i.e.,

¹The extension to the case with three right-handed neutrinos is straightforwardly possible. However, since the number of parameters is increased, the impacts discussed below would be blurred. This issue is beyond our scope.

The electroweak symmetry breaking gives the neutrino masses of Dirac type $[M_D]_{\alpha I} = F_{\alpha I}\langle\Phi\rangle$ in addition to the Majorana type M_I . When $|[M_D]_{\alpha I}| \ll M_I$, the seesaw mechanism for neutrino masses is realized. In addition to massive active neutrinos ν_i ($i = 1, 2, 3$), there are heavy neutrinos N_I with masses M_I which almost correspond to right-handed neutrino states (we simply call them as right-handed neutrinos from now on). These states take part in weak gauge interactions through the mixing as

$$\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I}N_I^c, \quad (2)$$

where $U_{\alpha i}$ is the mixing matrix of active neutrinos [39,40] while the mixing elements of N_I are given by $\Theta_{\alpha I} = [M_D]_{\alpha I}M_I^{-1}$.

Based on the parametrization proposed by Casas and Ibarra [41,42], the Yukawa couplings are written as

$$F = \frac{i}{\langle\Phi\rangle}UD_\nu^{1/2}\Omega D_N^{1/2}. \quad (3)$$

Here $D_\nu = \text{diag}(m_1, m_2, m_3)$ is the diagonal mass matrix of active neutrinos. In the considering case, the lightest active neutrino is massless, and then $m_3 > m_2 > m_1 = 0$ for the normal hierarchy (NH) case and $m_2 > m_1 > m_3 = 0$ for the inverted hierarchy (IH) case. $D_N = \text{diag}(M_1, M_2)$ is the mass matrix of right-handed neutrinos. The mixing matrix of active neutrinos is expressed as

$\omega = \omega_r + i\omega_i$. Further, we introduce

$$X_\omega = \exp[\omega_i], \quad (6)$$

since it represents the overall strength of the Yukawa couplings (see, e.g., the discussion in Ref. [36]). In practice, the Yukawa couplings scale as $F \propto X_\omega$ or X_ω^{-1} for $X_\omega \gg 1$ or $\ll 1$.

Throughout this analysis, we choose the convention in which ξ is selected to be positive, and fix θ_{ij} and δ in the mixing matrix U to be the central values of the latest global fit of neutrino oscillation data [43,44].

III. NEUTRINOLESS DOUBLE BETA DECAY

In the considering model, the effective mass in the $0\nu\beta\beta$ decay is given by

$$m_{\text{eff}} = m_{\text{eff}}^\nu + m_{\text{eff}}^N, \quad (7)$$

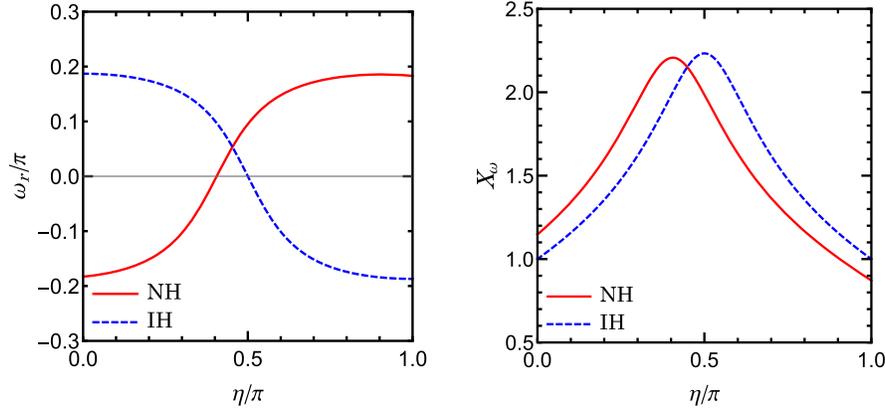


FIG. 1. Required values of ω_r (left) and X_ω (right) for the vanishing effective mass in the NH or IH case (red solid or blue dashed line).

where the contribution from active neutrinos is

$$m_{\text{eff}} = \sum_i U_{ei}^2 m_i. \quad (8)$$

Note that since only two right-handed neutrinos are introduced, it is impossible to cancel the effective mass from active neutrinos by tuning the lightest neutrino mass. The contribution from right-handed neutrinos is

$$m_{\text{eff}}^N = \sum_I f_\beta(M_I) \Theta_{eI}^2 M_I. \quad (9)$$

The function f_β represents the suppression by the propagator effect of right-handed neutrinos, and we use the approximate formula

$$f_\beta(M_I) = \frac{\Lambda_\beta^2}{\Lambda_\beta^2 + M_I^2}, \quad (10)$$

where Λ_β is a typical scale of Fermi momentum of a nucleus which is evaluated as a few hundred MeV varied depending on nucleus and modelings [45–48].

We consider the case where $M_1 < \Lambda_\beta \ll M_2$ and take $f_\beta(M_1) = 1$ and $f_\beta(M_2) = 0$ approximately. Thus, the effective mass becomes independent of Λ_β . In this case, the effective neutrino mass is expressed as

$$m_{\text{eff}} = \begin{cases} (s_\omega U_{e2} m_2^{1/2} - c_\omega U_{e3} m_3^{1/2})^2 & \text{for the NH case} \\ (s_\omega U_{e1} m_1^{1/2} - c_\omega U_{e2} m_2^{1/2})^2 & \text{for the IH case} \end{cases}. \quad (11)$$

Importantly, we find out that the effective mass vanishes if the complex parameter ω satisfies

$$\tan \omega = \begin{cases} \frac{U_{e3} m_3^{1/2}}{U_{e2} m_2^{1/2}} & \text{for the NH case} \\ \frac{U_{e2} m_2^{1/2}}{U_{e1} m_1^{1/2}} & \text{for the IH case} \end{cases}. \quad (12)$$

In Fig. 1, we show the real and imaginary parts of ω satisfying the cancellation condition (12). It is found from Eq. (12) that the maximal value of X_ω is achieved by the CP violating phases $\delta + \eta = -\pi/2$ for the NH case while $\eta = \pi/2$ in the IH case. Notice that X_ω becomes unity (i.e., no imaginary part of ω) when $\eta = -\delta$ in the NH case and $\eta = 0(\pi)$ in the IH case, respectively.

IV. DISCUSSIONS AND CONCLUSIONS

It is, therefore, found that the contribution to m_{eff} from active neutrinos can be obscured by the light right-handed neutrino when Eq. (12) is fulfilled. In this case, we can determine the mixing elements of N_1 for a given mass depending on the Majorana phase. This point is illustrated in Fig. 2.

Interestingly, the flavor structure of the mixing elements highly depends on the values of Majorana phase η . This pattern of the mixing elements may be tested by future direct search experiments of right-handed neutrinos. In the NH case $|\Theta_{\mu 1}|^2 \gg |\Theta_{e 1}|^2$ and then the experiments like the peak search in $K \rightarrow \mu + N_1$, for instance, would help the observation. On the other hand, in the IH case $|\Theta_{e 1}|^2$ or $|\Theta_{\mu 1}|^2$ becomes dominant depending on η , and $K \rightarrow e + N_1$ or $K \rightarrow \mu + N_1$ would be the golden channel for the discovery. Since the relative sizes of the mixing elements are not so much identical, we can extract important information of the mass hierarchy and the Majorana phase η from the combination of $|\Theta_{e 1}|^2$ and $|\Theta_{\mu 1}|^2$ under the situation of no $0\nu\beta\beta$ decay is observed.

When the effective mass vanishes, the lifetime of N_1 can be predicted by M_1 and η . In the mass region of interest, the possible decay channels are $N_1 \rightarrow \nu\nu\nu$ and $N_1 \rightarrow \nu e^+ e^-$ (when $M_1 > 2m_e$) and we find the range of the lifetime is

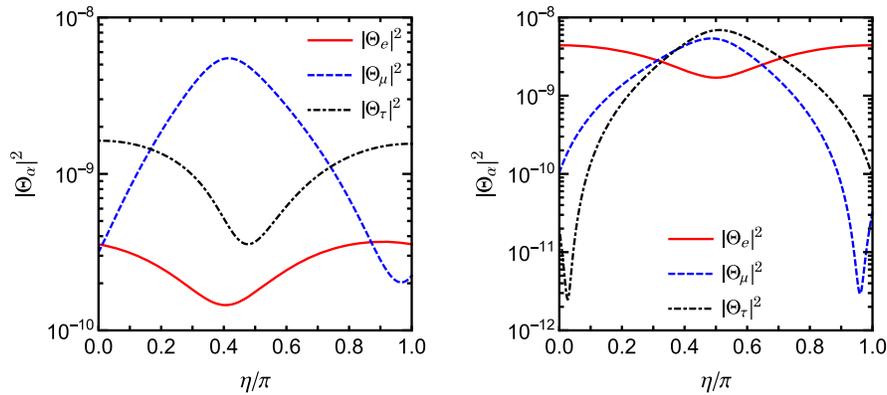


FIG. 2. Mixing elements $|\Theta_{\alpha 1}|^2$ for the vanishing effective neutrino mass in the NH (left) and IH (right) cases. Here, $M_1 = 10$ MeV for both cases. The solid (red), dashed (blue), and dot-dashed (black) lines represent $\alpha = e, \mu$, and τ , respectively.

$$\tau \simeq \begin{cases} (5-6) \times 10^7 \text{ sec} \left(\frac{10 \text{ MeV}}{M_1}\right)^4 & \text{for the NH case} \\ (0.9-2) \times 10^7 \text{ sec} \left(\frac{10 \text{ MeV}}{M_1}\right)^4 & \text{for the IH case} \end{cases}. \quad (13)$$

The suggested values of the lifetime are so long that N_1 decays after the onset of the big bang nucleosynthesis (BBN) and would destroy the success of the BBN and/or conflict with the observational data of the cosmic microwave background radiation. One possibility to avoid this difficulty is the dilution of the N_1 abundance by the late time entropy production. Such an additional production may be realized by the decay of the heavier right-handed neutrino N_2 [49].

To summarize, we have examined the neutrinoless double beta decay in the seesaw mechanism by two right-handed neutrinos. The Majorana nature of active neutrinos and right-handed neutrinos breaks the lepton number of the theory, which may lead to the neutrinoless double beta decay. When the masses of right-handed neutrinos, however, are lighter than or comparable to the

scale Λ_β , they can give a significant effect, and the effective mass can vanish in some cases.

In this paper, we have found a possibility when $M_1 \lesssim \Lambda_\beta \ll M_2$. It has been shown that N_1 contribution can obliterate the neutrinoless double beta decay even if active neutrinos do contribute it. If this is the case, the unknown parameters related to right-handed neutrinos appeared in Ω are highly restricted and the mixing elements of N_1 can be determined by the Majorana phase and the mass hierarchy of active neutrinos. Inversely speaking, we may obtain important information of the missing piece of neutrino properties, namely, the Majorana phase and the mass hierarchy, from the relative sizes among the mixing elements of right-handed neutrinos measured at the future terrestrial experiments together with no neutrinoless double beta decay.

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