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Neutrinoless double beta decays tell nature of right-handed neutrinos

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Abstract: We consider the minimal seesaw model, the Standard Model extended by two right-handed neutrinos, for explaining the neutrino masses and mixing angles measured in oscillation experiments. When one of right-handed neutrinos is lighter than the electroweak scale, it can give a sizable contribution to neutrinoless double beta ($0\nu\beta\beta$) decay. We show that the detection of the $0\nu\beta\beta$ decay by future experiments gives a significant implication to the search for such a light right-handed neutrino.

Keywords: Neutrino Interactions, Neutrino Mixing, Specific BSM Phenomenology, Sterile or Heavy Neutrinos

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Contents

1 Introduction 1

2 Minimal seesaw model 2

3 Neutrinoless double beta decay and search for HNL 3

4 Conclusions 9

1 Introduction

The Standard Model (SM) of the particle physics preserves two accidental global symmetries in the (classical) Lagrangian, namely the baryon and lepton number symmetries. It is well known that these global symmetries are non-perturbatively broken at the quantum level [1, 2], especially at high temperature of the universe [3–6]. Even at the quantum level, however, a baryon minus lepton symmetry, often called $U(1)_{B-L}$,[1] has to be preserved in the SM.

The simplest way to break the global $U(1)_{B-L}$ symmetry without loss of the renormalizability is introducing right-handed neutrinos (RHνs) into the SM. Since RHνs are singlet under the SM gauge symmetries, we can write the mass term, called Majorana mass term, of it without conflicting the gauge principle. Thus, since the Majorana mass term breaks the lepton number symmetry by two units with conserving the baryon number symmetry, global $U(1)_{B-L}$ symmetry is broken. Therefore, the phenomena of the lepton number violation can be a definite signal of the existence of RHνs.

The existence of RHνs is not only for the violation of the $U(1)_{B-L}$ symmetry but also important to solve the origin of the observed tiny neutrino masses. In the renormalizable Lagrangian with RHνs, we can obtain two kinds of the neutrino masses, one is called Dirac masses and the other is called Majorana masses. When the Dirac masses are light enough compared to the Majorana masses, we can simply explain the tiny neutrino masses by the seesaw mechanism [7–13]. In addition, the violation of $U(1)_{B-L}$ can seed the origin of the baryon asymmetry of the universe.[2]

One of the most promising signals of the $U(1)_{B-L}$ violation is the neutrinoless double beta decay ($0\nu\beta\beta$ decay), which breaks the lepton number by two units while keeping the baryon number to be exact. (See, for example, articles [14–17].) The rate of the decay is characterized by a parameter called the effective mass defined by the neutrino masses

[1] Although one can consider the symmetry as gauge symmetry, we do not specifically adopt the case throughout our discussions.

[2] There are a bunch of possibilities to provide the baryon asymmetry through the lepton number violation. But the detail of the mechanism is independent of the discussions below.

and mixing angles. When we simply add Majorana masses of three (active or left-handed) neutrinos which are responsible for the neutrino oscillation into the SM, the effective mass can be predicted depending on the lightest active neutrino mass together with the unknown CP violating phases.

In view of the fundamental models for the origin of the neutrino masses, the mass of the lightest active neutrino cannot be determined uniquely, leading to different predictions on the effective mass. It should be noted that the effective mass can vanish in the normal hierarchy case of the active neutrinos in a certain parameter region of the lightest neutrino mass. In such a case, the contribution from new physics (other than active neutrinos) including RHνs would be more important for the detection. So far, no neutrinoless double beta decay is detected and the upper bounds on the effective mass have been imposed by various experiments.[3] The most stringent bound at present is 61-165 meV by the KamLAND-Zen experiment [19]. Since this limit is approaching to the predicted range in the inverted hierarchy case, the experimental results in near future can give us some implications on RHνs.

There are several interesting possibilities that the effective mass can be significantly modified due to the destructive or constructive contribution from RHνs [20–36]. This additional contribution becomes important when the masses of RHνs are smaller than or comparable to the typical scale of Fermi momentum in the decaying nucleus ($\sim \mathcal{O}(100)$ MeV).

An interesting possibility has been pointed out that RHν may hide one of the neutrinoless double beta decay processes. This is due to the destructive contribution of RHν to the effective mass [33–35]. Note that the impact of RHν does depend on the decaying nuclei. If this is the case, the mixing elements of RHν to ordinary neutrinos can be predicted in terms of its mass in a certain range which is a good target of future search experiments [31, 32].

In this paper, we project out the consequences of the opposite situation, namely the case when the neutrinoless double beta decay is observed in some nucleus, and discuss the impacts on the mixing elements of RHνs.

2 Minimal seesaw model

First of all, let us explain the framework of the present analysis, the minimal seesaw model. It is an extended Standard Model by two right-handed neutrinos ν_{RI} $(I = 1, 2)$,[4] which Lagrangian is given by

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + i\overline{\nu_{RI}}\gamma^\mu \partial_\mu \nu_{RI} \\ &\quad - \left(F_{\alpha I} \overline{L_\alpha} \Phi \nu_{RI} + \frac{M_I}{2} \overline{\nu^c_{RI}} \nu_{RI} + h.c. \right) , \end{aligned} \tag{2.1}$$

where $L_\alpha = (\nu_{L\alpha}, e_{L\alpha})^T$ $(\alpha = e, \mu, \tau)$ and Φ are the weak doublets of left-handed lepton and Higgs, respectively. The Yukawa coupling constants and the Majorana masses for neutrinos

[3]In a recent analysis [18], the differential rate of two neutrino double beta decay is discussed to constrain mixing elements of RHνs with masses at $\mathcal{O}$(0.1-10) MeV.

[4]We have to introduce two right-handed neutrinos at least to explain two different scales of neutrino mass squared differences observed by oscillation experiments.

JHEP07(2023)062

are denoted by $F_{\alpha I}$ and M_I. By assuming that the Dirac masses $F_{\alpha I}\langle\Phi\rangle$ are much smaller than the Majorana mass M_I, the seesaw mechanism works, and the mass eigenstates of neutrinos are three active neutrinos ν_i $(i = 1, 2, 3)$ with masses m_i and two heavy neutral leptons (HNLs) N_I with masses M_I.

The mass ordering of active neutrinos is not determined by the oscillation data, and two possibilities, the normal hierarchy (NH) with $m_3 > m_2 > m_1 = 0$ and the inverted hierarchy (IH) with $m_2 > m_1 > m_3 = 0$, are allowed. Note that the lightest active neutrino is massless in the considering situation. On the other hand, we can take the masses of HNLs as $M_2 \geq M_1$ without loss of generality. The left-handed (flavor eigenstate) neutrinos are then written as

$$\nu_{L\alpha} = \sum_i U_{\alpha i}\,\nu_i + \sum_I \Theta_{\alpha I}\,N_I^c\,, \tag{2.2}$$

where $U_{\alpha i}$ is the mixing matrix of active neutrinos called as the PMNS matrix while $\Theta_{\alpha I}$ is that of HNLs. As a consequence, HNLs can contribute to physics of left-handed neutrinos through the mixing $\Theta_{\alpha I}$ although it is highly suppressed.

The mixing matrix $\Theta_{\alpha I}$ can be specified as $\Theta_{\alpha I} = [M_D]_{\alpha I} M_I^{-1} = F_{\alpha I}\langle\Phi\rangle M_I^{-1}$, and the Yukawa coupling constants can be parameterized as a formula called Casas-Ibarra parameterization [37, 38] expressed as

$$F = \frac{i}{\langle\Phi\rangle} U D_\nu^{1/2} \Omega D_N^{1/2}\,, \tag{2.3}$$

where $D_\nu = \mathrm{diag}(m_1, m_2, m_3)$ and $D_N = \mathrm{diag}(M_1, M_2)$ being diagonal mass matrices of active neutrinos and HNLs, respectively. The mixing matrix of active neutrinos is expressed as

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}(1, e^{i\eta}, 1)\,, \tag{2.4}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$. δ and η are the Dirac and Majorana CP violating phases, respectively. A matrix Ω has 3×2 elements in the current setup and is given as

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix} \quad \text{for the NH case}\,, \quad \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix} \quad \text{for the IH case}\,, \tag{2.5}$$

where $\xi = \pm 1$ is a sign parameter and ω is a complex parameter. Hereafter we follow the convention of $\xi = +1$ (See ref. [32] for the detail discussions.).

3 Neutrinoless double beta decay and search for HNL

One of the most important consequences of the seesaw mechanism is that active neutrinos and HNLs are both Majorana particles. In this case the lepton number violating processes are induced by these particles, which is a clear signature of physics beyond the SM.

One promising example is the $0\nu\beta\beta$ decay, and the quest for the decay is going on by various experiments.

The rate for the $0\nu\beta\beta$ decay mediated by active neutrinos and HNLs is proportional to $|m_{\rm eff}|^2$, where $m_{\rm eff}$ is the so-called effective (neutrino) mass in the $0\nu\beta\beta$ decay. In the minimal seesaw model, it is given by

$$m_{\rm eff} = m_{\rm eff}^{\nu} + m_{\rm eff}^{N} \,. \tag{3.1}$$

Here the first term in the right-hand side of eq. (3.1) represents the contributions from active neutrinos, which is given by

$$m_{\rm eff}^{\nu} = \sum_i U_{ei}^2 \, m_i \,. \tag{3.2}$$

On the other hand, the contributions from HNLs appeared as another term in the right-hand side of eq. (3.1) are expressed as

$$m_{\rm eff}^{N} = \sum_I \Theta_{eI}^2 \, M_I \, f_\beta(M_I) \,, \tag{3.3}$$

where f_β is the suppression factor compared to $m_{\rm eff}^{\nu}$ due to the heaviness of HNLs $M_I \gg m_i$. Here we apply the result in refs. [39, 40] and assume the following form

$$f_\beta(M) = \frac{\Lambda_\beta^2}{\Lambda_\beta^2 + M^2} \,, \tag{3.4}$$

where $\Lambda_\beta = \mathcal{O}(10^2)$ MeV denotes the typical scale of the Fermi momentum in the $0\nu\beta\beta$ decay which are different depending on decaying nuclei and receives an uncertainty of the nuclear physics. Hereafter we take $\Lambda_\beta = 200\,\text{MeV}$ as a representative value.

In this paper we consider the impacts of the detection of the $0\nu\beta\beta$ decay by future experiments on the properties of HNLs. The measurement of the decay rate gives the value of $|m_{\rm eff}|$. Note that $m_{\rm eff}$ is a complex number. First, we consider the case when right-handed neutrinos possess the hierarchical masses, $M_2 \gg M_1$. We then find that the mixing element of the lighter HNL Θ_{e1}^2 is given by

$$\Theta_{e1}^2 = \frac{m_{\rm eff} - m_{\rm eff}^{\nu} \left[1 - f_\beta(M_2)\right]}{M_1 \left[f_\beta(M_1) - f_\beta(M_2)\right]} \,. \tag{3.5}$$

Here we have used the intrinsic relation between mixing elements in the seesaw mechanism[5]

$$0 = \sum_i U_{ei}^2 \, m_i + \sum_I \Theta_{eI}^2 \, M_I \,. \tag{3.6}$$

It should be noted that this relation eq. (3.6) requires a fine-tuning in the second terms when M_N and $|\Theta_{eI}|$ get large enough. In addition, radiative corrections exist on the relation, especially on the Majorana masses of flavor electron neutrinos. We ignore such corrections

[5] Strictly speaking, although this relation is valid at tree level, one-loop corrections by Higgs and Z boson loops can be safely ignored under current setup [27].

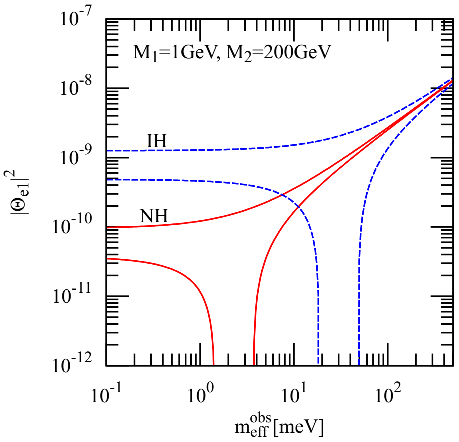

Figure 1. Upper and lower bounds on $|\Theta_{e1}|^2$ for the NH (red solid lines) and IH (blue dashed lines) cases. Here $M_1 = 1\,\mathrm{GeV}$ and $M_2 = 200\,\mathrm{GeV}$.

in our analyses, since they are expected to be subleading. Importantly, the mixing element $|\Theta_{e1}|^2$ is given by $m_{\rm eff}$ and $m_{\rm eff}^{\nu}$ together with masses M_1 and M_2. This means that, if $|m_{\rm eff}|$ is determined by the detection of the $0\nu\beta\beta$ decay, the range of $|\Theta_{e1}|^2$ can be predicted. In practice both upper and lower bounds on $|\Theta_{e1}|^2$ are obtained by varying the unknown parameters in $m_{\rm eff}^{\nu}$ (i.e., the Majorana phase η,[6] and the active neutrino masses with mass ordering) and the phase of $m_{\rm eff}$.

When $M_1 = 1\,\mathrm{GeV}$ and $M_2 = 200\,\mathrm{GeV}$,[7] these bounds are shown in figure 1 in terms of the (would-be) observed value of $|m_{\rm eff}|$ denoted by $m_{\rm eff}^{\rm obs}$. In the present analysis we take the central values of the mass squared differences, the mixing angles and the Dirac phase in the PMNS matrix given in ref. [42] for the estimation of $|m_{\rm eff}^{\nu}|$. We find that $|m_{\rm eff}^{\nu}| = 1.45$–$3.68$ meV and 18.6–48.4 meV for the NH and IH cases, respectively. It is found from eq. (3.5) that the lower bound on $|\Theta_{e1}|^2$ vanishes when $m_{\rm eff}^{\rm obs} = |m_{\rm eff}^{\nu}|(1 - f_\beta(M_2))$.

The predicted range of $|\Theta_{e1}|^2$ is shown in figure 2 where the current upper bounds and the sensitivities on $|\Theta_{e1}|^2$ by future search experiments are also shown [43–49]. We take the (would-be) observed value of the effective mass as $m_{\rm eff}^{\rm obs} = 100$ meV, 50 meV, and 10 meV.[8] Importantly, the most of the predicted range can be tested by the future experiments as depicted by black dotted liens in figure 2.

We should note that the understanding of $f_\beta(M)$ is important for the precise prediction of the mixing elements, since it contains the uncertainty of the order unity. Namely, once the uncertainty of the nuclear matrix elements gets reduced, we can predict the range of the mixing angle to be much precise.

[6]Since one of two Majorana CP-violating phases can be absorbed by redefinition of the lightest active neutrino field in the current minimal setup, we discuss and analyse with the unique Majorana CP-violating phase here and hereafter. (This phase is conventionally written as α_{21}.) The fact is clearly discussed in many literature, e.g. [41].

[7]These values, especially M_2, are just reference values. Our requirement on M_2 is just to take heavier enough than M_1.

[8]The limits and sensitivities on the mixing elements from the current and future $0\nu\beta\beta$ decay experiments have been discussed in [27].

JHEP07(2023)062

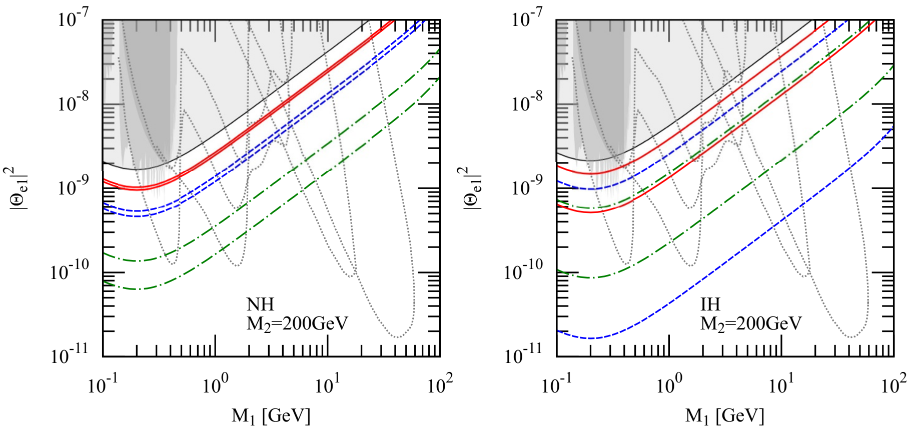

Figure 2. Upper and lower bounds on $|\Theta_{e1}|^2$ for the NH (left) and IH (right) cases. We take $m_{\rm eff}^{\rm obs}$ =100 meV (red sold lines), 50 meV (blue dashed lines), and 10 meV (green dot-dashed lines). Here $M_2 = 200\,\text{GeV}$. The current (conservative) upper bound on $|\Theta_{e1}|^2$ from $|m_{\rm eff}| < 165$ meV is shown by black solid line (and the light-gray region is already excluded). The dark-gray regions are excluded by the direct search experiments [43–45]. The dotted lines shows the sensitivities by the future experiments [46–49]. See the detail in the main text.

Next, let us consider the case when the masses of HNLs are degenerate

$$M_1 = M_2 = M_N \,. \tag{3.7}$$

In this case, the total effective mass is given by

$$m_{\rm eff} = m_{\rm eff}^{\nu} \left[1 - f_\beta(M_N)\right] \,, \tag{3.8}$$

and hence the total value is always smaller than the that from active neutrinos $|m_{\rm eff}| < |m_{\rm eff}^{\nu}|$ as long as HNLs participate the $0\nu\beta\beta$ decay. Note that the arguments of $m_{\rm eff}$ and $m_{\rm eff}^{\nu}$ are the same. In this case, we find the interesting consequences if $|m_{\rm eff}|$ is measured: First, the mass of degenerate HNLs is determined depending on the measured value of $|m_{\rm eff}|$ as

$$M_N = \Lambda_\beta \sqrt{\frac{m_{\rm eff}^{\rm obs}}{|m_{\rm eff}^{\nu}| - m_{\rm eff}^{\rm obs}}} \,. \tag{3.9}$$

This shows that, once $m_{\rm eff}^{\rm obs}$ is fixed, the unknown Majorana phase in $m_{\rm eff}^{\nu}$ determines M_N. Second, the sum of the mixing elements is found to be

$$\left|\Theta_{e1}^2 + \Theta_{e2}^2\right| = \frac{|m_{\rm eff}^{\nu}|}{\Lambda_\beta} \sqrt{\frac{|m_{\rm eff}^{\nu}| - m_{\rm eff}^{\rm obs}}{m_{\rm eff}^{\rm obs}}} \,. \tag{3.10}$$

These results are shown in figure 3. Here we take the Majorana phase as $\eta = 0$, and $|m_{\rm eff}^{\nu}| = 3.54$ meV and 48.4 meV for the NH and IH cases, respectively. It is seen that the observed effective mass $m_{\rm eff}^{\rm obs}$ of a few tens meV corresponds to the Majorana mass $M_N \simeq \mathcal{O}(0.1-1)\,\text{GeV}$ and the mass ordering is the IH since HNL contributions are always

JHEP07(2023)062

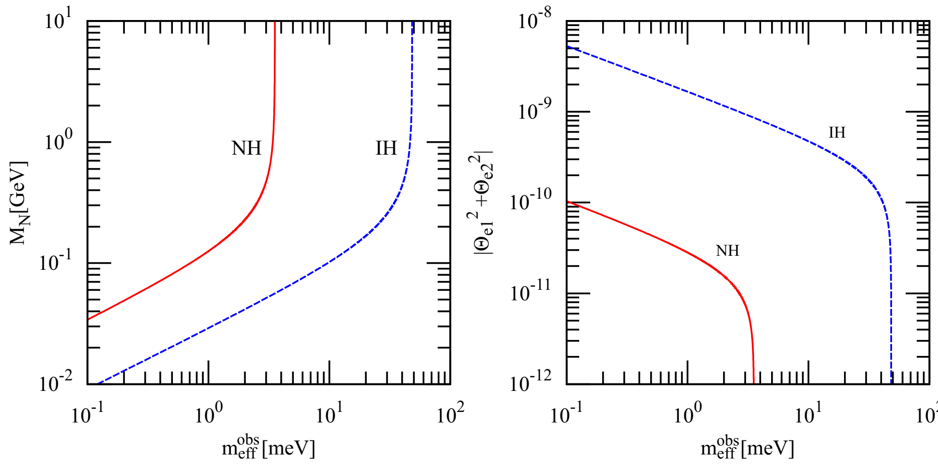

Figure 3. The degenerate mass M_N and mixing element $|\Theta_{e1}^2 + \Theta_{e2}^2|$ in terms of the observed value $m_{\rm eff}^{\rm obs}$ in the NH (red solid line) or IH (blue dashed line). We take the Majorana phase $\eta = 0$.

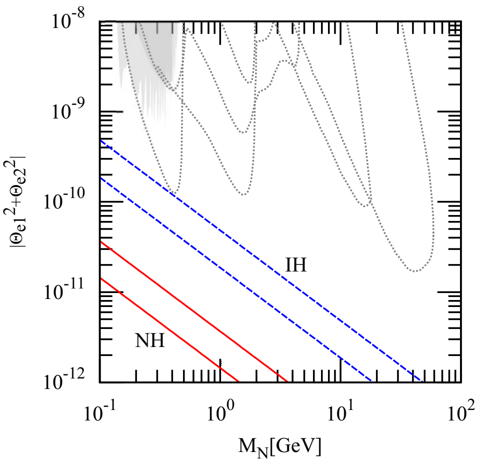

Figure 4. Range of the mixing element $|\Theta_{e1}^2 + \Theta_{e2}^2|$ in terms of the degenerate mass M_N by taking the Majorana phase $\eta = 0$–π in the NH (red solid line) or IH (blue dashed line). The gray-shaded regions are excluded by the direct search experiments [45]. The dotted lines shows the sensitivities by the future experiments [46–49].

destructive to the active neutrino ones. The relation between M_N and $|\Theta_{e1}^2 + \Theta_{e2}^2|$ is shown in figure 4. We find that in order to directly test the degenerate case the improvement of the sensitivity by future experiments is required especially for the NH case. However, the measurement of the $0\nu\beta\beta$ decay can give some hints of RHνs as discussed above.

Before concluding the paper, we stress the impact of the difference among the $0\nu\beta\beta$ decay nuclei [33]. Throughout this paper, we have assumed the approximated form of the suppression function f_β to be eq. (3.4) and fixed the typical Fermi momentum as $\Lambda_\beta = 200$ MeV. The important point is that the nuclear matrix elements including the suppression factor due to HNLs are different depending on the decaying nuclei used in the $0\nu\beta\beta$ experiments. This effect may be quantified by the choice the typical Fermi momentum in this analysis.

JHEP07(2023)062

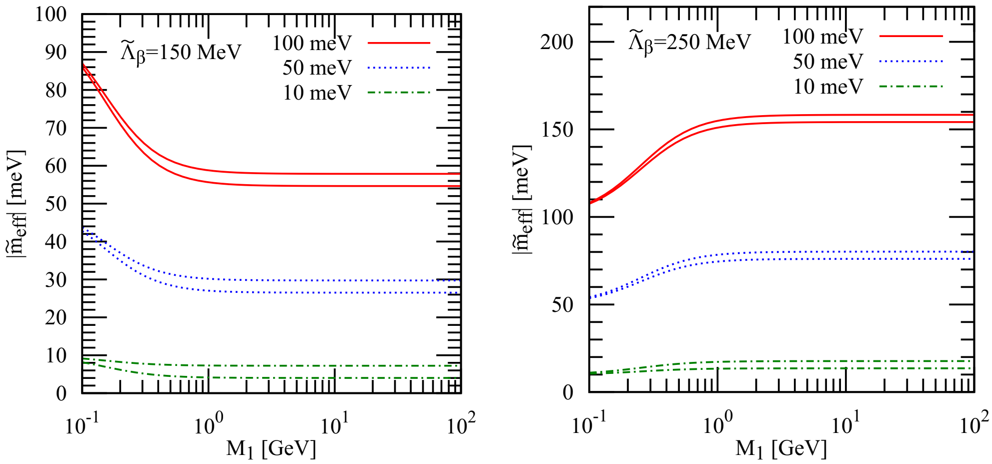

Figure 5. Upper and lower bounds of predicted effective mass with $\tilde{\Lambda}_\beta = 150$ MeV (left) and $\tilde{\Lambda}_\beta = 250$ MeV (right) in the NH case. We assume that the effective mass observed in the nucleus with $\Lambda_\beta = 200$ MeV to be 100 meV (red, solid), 50 meV (blue, bashed), and 10 meV (green, dot-dashed). Here, we fix $M_2 = 200$ GeV.

In figure 5, we plot the upper and lower values of the predicted effective mass with different Fermi momentum from 200 MeV while assuming the $0\nu\beta\beta$ decay is observed at the experiment with $\Lambda_\beta = 200$ MeV in the NH case. We can obtain similar behavior straightforwardly in the IH case as well. We take the observed value of the effective mass to be 100 meV, 50 meV, or 10 meV. The uncertainly comes from both of the Majorana phase and the phase in the observed Majorana mass, $m_{\rm eff}^{\rm obs}$. Interestingly, the predicted effective mass can be significantly enhanced when Λ_β becomes larger enough than 200 MeV and M_1 gets heavier. By inserting eq. (3.5) into the expression of the effective mass, we can obtain

$$\begin{aligned}\tilde{m}_{\rm eff} &= \left[1 - \tilde{f}_\beta(M_2)\right] m_{\rm eff}^\nu \\ &\quad + \left[m_{\rm eff} - m_{\rm eff}^\nu \left[1 - f_\beta(M_2)\right]\right] \frac{\tilde{f}_\beta(M_1) - \tilde{f}_\beta(M_2)}{f_\beta(M_1) - f_\beta(M_2)}\,,\end{aligned} \tag{3.11}$$

where $\Lambda_\beta = 200\,\text{MeV}$ in f_β but $\Lambda_\beta \neq 200\,\text{MeV}$ in $\tilde{f}_\beta$ which is denoted as $\tilde{\Lambda}_\beta$. Since the last fraction in the right-hand side of eq. (3.11) can be rewritten as

$$\frac{\tilde{f}_\beta(M_1) - \tilde{f}_\beta(M_2)}{f_\beta(M_1) - f_\beta(M_2)} = \frac{\tilde{\Lambda}_\beta^2}{\Lambda_\beta^2} \frac{\left(\Lambda_\beta^2 + M_1^2\right)\left(\Lambda_\beta^2 + M_2^2\right)}{\left(\tilde{\Lambda}_\beta^2 + M_1^2\right)\left(\tilde{\Lambda}_\beta^2 + M_2^2\right)} \simeq \frac{\tilde{\Lambda}_\beta^2}{\Lambda_\beta^2} \frac{\left(\Lambda_\beta^2 + M_1^2\right)}{\left(\tilde{\Lambda}_\beta^2 + M_1^2\right)}\,, \tag{3.12}$$

where we have assumed N_2 is decoupled from the system, we can understand the feature of the predicted effective mass as follows. The predicted effective masses in a different decaying nucleus, $\tilde{m}_{\rm eff}$, are comparable to the observed effective mass, $m_{\rm eff}$, for $M_1 \ll \Lambda_\beta$, no matter what kind of nuclei is used. On the other hand, for $M_1 \gg \Lambda_\beta$, $\tilde{m}_{\rm eff}$ can receive the factor of $\tilde{\Lambda}_\beta^2/\Lambda_\beta^2$. As clearly seen, since a significant enhancement/suppression could happen depending on the type of nucleus due to the contributions from HNLs. Thus, we can claim that the multiple detection by the $0\nu\beta\beta$ experiments using different nuclei is crucial to reveal the properties of HNLs.

JHEP07(2023)062

4 Conclusions

In conclusions, we have considered the minimal seesaw model with two right-handed neutrinos. It has been shown that, if the effective mass in the $0\nu\beta\beta$ decay will be measured by future experiments, the possible range of the mixing elements for the lighter heavy neutral lepton (right-handed neutrino) is determined. Especially, when two heavy neutral leptons are hierarchical and the lighter mass is below the electroweak scale, N_1 is a good target of the direct search experiments.

It has also been shown that the predicted effective mass can depend on nucleus of the neutrinoless double beta decay experiment. Therefore, comprehensive studies on the neutrinoless double beta decays in the seesaw mechanism are necessary to extract the concrete information of the heavy neutral leptons.

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References

[1] G. 't Hooft, *Symmetry Breaking Through Bell-Jackiw Anomalies*, *Phys. Rev. Lett.* **37** (1976) 8 [INSPIRE].

[2] G. 't Hooft, *Computation of the Quantum Effects Due to a Four-Dimensional Pseudoparticle*, *Phys. Rev. D* **14** (1976) 3432 [*Erratum ibid.* **18** (1978) 2199] [INSPIRE].

[3] S. Dimopoulos and L. Susskind, *On the Baryon Number of the Universe*, *Phys. Rev. D* **18** (1978) 4500 [INSPIRE].

[4] N.S. Manton, *Topology in the Weinberg-Salam Theory*, *Phys. Rev. D* **28** (1983) 2019 [INSPIRE].

[5] F.R. Klinkhamer and N.S. Manton, *A Saddle Point Solution in the Weinberg-Salam Theory*, *Phys. Rev. D* **30** (1984) 2212 [INSPIRE].

[6] V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, *On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe*, *Phys. Lett. B* **155** (1985) 36 [INSPIRE].

[7] P. Minkowski, *$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?*, *Phys. Lett. B* **67** (1977) 421 [INSPIRE].

[8] T. Yanagida, *Horizontal gauge symmetry and masses of neutrinos*, *Conf. Proc. C* **7902131** (1979) 95 [INSPIRE].

[9] T. Yanagida, *Horizontal Symmetry and Masses of Neutrinos*, *Prog. Theor. Phys.* **64** (1980) 1103 [INSPIRE].

[10] P. Ramond, *The Family Group in Grand Unified Theories*, in the proceedings of the *International Symposium on Fundamentals of Quantum Theory and Quantum Field Theory*, Palm Coast, FL, U.S.A., 25 February – 2 March 1979, [hep-ph/9809459] [INSPIRE].

[11] M. Gell-Mann, P. Ramond and R. Slansky, *Complex Spinors and Unified Theories*, *Conf. Proc. C* **790927** (1979) 315 [arXiv:1306.4669] [INSPIRE].

[12] S.L. Glashow, *The future of elementary particle physics*, in *Proc. of the Cargése Summer Institute on Quarks and Leptons*, Cargése, July 9–29, 1979, eds. M. Lévy et al., Plenum, 1980, New York, U.S.A., p. 707.

[13] R.N. Mohapatra and G. Senjanovic, *Neutrino Mass and Spontaneous Parity Nonconservation*, *Phys. Rev. Lett.* **44** (1980) 912 [INSPIRE].

[14] M. Doi, T. Kotani and E. Takasugi, *Double beta Decay and Majorana Neutrino*, *Prog. Theor. Phys. Suppl.* **83** (1985) 1 [INSPIRE].

[15] H. Päs and W. Rodejohann, *Neutrinoless Double Beta Decay*, *New J. Phys.* **17** (2015) 115010 [arXiv:1507.00170] [INSPIRE].

[16] S. Dell'Oro, S. Marcocci, M. Viel and F. Vissani, *Neutrinoless double beta decay: 2015 review*, *Adv. High Energy Phys.* **2016** (2016) 2162659 [arXiv:1601.07512] [INSPIRE].

[17] M.J. Dolinski, A.W.P. Poon and W. Rodejohann, *Neutrinoless Double-Beta Decay: Status and Prospects*, *Ann. Rev. Nucl. Part. Sci.* **69** (2019) 219 [arXiv:1902.04097] [INSPIRE].

[18] P.D. Bolton, F.F. Deppisch, L. Gráf and F. Šimkovic, *Two-Neutrino Double Beta Decay with Sterile Neutrinos*, *Phys. Rev. D* **103** (2021) 055019 [arXiv:2011.13387] [INSPIRE].

[19] KamLAND-Zen collaboration, *Search for Majorana Neutrinos near the Inverted Mass Hierarchy Region with KamLAND-Zen*, *Phys. Rev. Lett.* **117** (2016) 082503 [*Addendum ibid.* **117** (2016) 109903] [arXiv:1605.02889] [INSPIRE].

[20] J. Lopez-Pavon, S. Pascoli and C.-F. Wong, *Can heavy neutrinos dominate neutrinoless double beta decay?*, *Phys. Rev. D* **87** (2013) 093007 [arXiv:1209.5342] [INSPIRE].

[21] D. Gorbunov and I. Timiryasov, *Testing νMSM with indirect searches*, *Phys. Lett. B* **745** (2015) 29 [arXiv:1412.7751] [INSPIRE].

[22] J. Lopez-Pavon, E. Molinaro and S.T. Petcov, *Radiative Corrections to Light Neutrino Masses in Low Scale Type I Seesaw Scenarios and Neutrinoless Double Beta Decay*, *JHEP* **11** (2015) 030 [arXiv:1506.05296] [INSPIRE].

[23] M. Drewes and B. Garbrecht, *Combining experimental and cosmological constraints on heavy neutrinos*, *Nucl. Phys. B* **921** (2017) 250 [arXiv:1502.00477] [INSPIRE].

[24] M. Drewes and S. Eijima, *Neutrinoless double β decay and low scale leptogenesis*, *Phys. Lett. B* **763** (2016) 72 [arXiv:1606.06221] [INSPIRE].

[25] T. Asaka, S. Eijima and H. Ishida, *On neutrinoless double beta decay in the νMSM*, *Phys. Lett. B* **762** (2016) 371 [arXiv:1606.06686] [INSPIRE].

[26] M. Chrzaszcz et al., *A frequentist analysis of three right-handed neutrinos with GAMBIT*, *Eur. Phys. J. C* **80** (2020) 569 [arXiv:1908.02302] [INSPIRE].

[27] P.D. Bolton, F.F. Deppisch and P.S. Bhupal Dev, *Neutrinoless double beta decay versus other probes of heavy sterile neutrinos*, *JHEP* **03** (2020) 170 [arXiv:1912.03058] [INSPIRE].

[28] A.S. Riis and S. Hannestad, *Detecting sterile neutrinos with KATRIN like experiments*, *JCAP* **02** (2011) 011 [arXiv:1008.1495] [INSPIRE].

[29] S. Mertens et al., *Sensitivity of Next-Generation Tritium Beta-Decay Experiments for keV-Scale Sterile Neutrinos*, *JCAP* **02** (2015) 020 [arXiv:1409.0920] [INSPIRE].

[30] A. Abada, Á. Hernández-Cabezudo and X. Marcano, *Beta and Neutrinoless Double Beta Decays with KeV Sterile Fermions*, *JHEP* **01** (2019) 041 [arXiv:1807.01331] [INSPIRE].

JHEP07(2023)062

[31] T. Asaka, H. Ishida and K. Tanaka, *Hiding neutrinoless double beta decay in the minimal seesaw mechanism*, *Phys. Rev. D* **103** (2021) 015014 [arXiv:2012.12564] [INSPIRE].

[32] T. Asaka, H. Ishida and K. Tanaka, *What if a specific neutrinoless double beta decay is absent?*, *PTEP* **2021** (2021) 063B01 [arXiv:2012.13186] [INSPIRE].

[33] A. Halprin, S.T. Petcov and S.P. Rosen, *Effects of Light and Heavy Majorana Neutrinos in Neutrinoless Double Beta Decay*, *Phys. Lett. B* **125** (1983) 335 [INSPIRE].

[34] C.N. Leung and S.T. Petcov, *On the Possibility of Destructive Interference Between Light and Heavy Majorana Neutrinos in Neutrinoless Double beta Decay*, *Phys. Lett. B* **145** (1984) 416 [INSPIRE].

[35] M. Blennow, E. Fernandez-Martinez, J. Lopez-Pavon and J. Menendez, *Neutrinoless double beta decay in seesaw models*, *JHEP* **07** (2010) 096 [arXiv:1005.3240] [INSPIRE].

[36] W. Dekens et al., *Sterile neutrinos and neutrinoless double beta decay in effective field theory*, *JHEP* **06** (2020) 097 [arXiv:2002.07182] [INSPIRE].

[37] J.A. Casas and A. Ibarra, *Oscillating neutrinos and $\mu \to e, \gamma$*, *Nucl. Phys. B* **618** (2001) 171 [hep-ph/0103065] [INSPIRE].

[38] A. Abada et al., *Flavour Matters in Leptogenesis*, *JHEP* **09** (2006) 010 [hep-ph/0605281] [INSPIRE].

[39] A. Faessler, M. González, S. Kovalenko and F. Šimkovic, *Arbitrary mass Majorana neutrinos in neutrinoless double beta decay*, *Phys. Rev. D* **90** (2014) 096010 [arXiv:1408.6077] [INSPIRE].

[40] J. Barea, J. Kotila and F. Iachello, *Limits on sterile neutrino contributions to neutrinoless double beta decay*, *Phys. Rev. D* **92** (2015) 093001 [arXiv:1509.01925] [INSPIRE].

[41] A. Ibarra and G.G. Ross, *Neutrino phenomenology: The case of two right-handed neutrinos*, *Phys. Lett. B* **591** (2004) 285 [hep-ph/0312138] [INSPIRE].

[42] I. Esteban et al., *The fate of hints: updated global analysis of three-flavor neutrino oscillations*, *JHEP* **09** (2020) 178 [arXiv:2007.14792] [INSPIRE].

[43] PIENU collaboration, *Search for Massive Neutrinos in the Decay $\pi \to e\nu$*, *Phys. Rev. D* **84** (2011) 052002 [arXiv:1106.4055] [INSPIRE].

[44] PIENU collaboration, *Improved search for heavy neutrinos in the decay $\pi \to e\nu$*, *Phys. Rev. D* **97** (2018) 072012 [arXiv:1712.03275] [INSPIRE].

[45] NA62 collaboration, *Search for heavy neutral lepton production in K^+ decays to positrons*, *Phys. Lett. B* **807** (2020) 135599 [arXiv:2005.09575] [INSPIRE].

[46] FCC-ee study Team collaboration, *Search for Heavy Right Handed Neutrinos at the FCC-ee*, *Nucl. Part. Phys. Proc.* **273-275** (2016) 1883 [arXiv:1411.5230] [INSPIRE].

[47] SHiP collaboration, *Sensitivity of the SHiP experiment to Heavy Neutral Leptons*, *JHEP* **04** (2019) 077 [arXiv:1811.00930] [INSPIRE].

[48] I. Krasnov, *DUNE prospects in the search for sterile neutrinos*, *Phys. Rev. D* **100** (2019) 075023 [arXiv:1902.06099] [INSPIRE].

[49] MATHUSLA collaboration, *An Update to the Letter of Intent for MATHUSLA: Search for Long-Lived Particles at the HL-LHC*, arXiv:2009.01693 [INSPIRE].