Neutrinoless double beta decays tell nature of right-handed neutrinos

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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 (0νββ) decay. We show that the detection of the 0νββ decay by future experiments gives a significant implication to the search for such light right-handed neutrino.

The Standard Model (SM) of the particle physics preserve 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 [11, 2], especially at high temperature of the universe [3–5]. Even at the quantum level, however, a baryon minus lepton symmetry, often called $U_{B-L}^1$, has to be preserved in the SM.

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

The existence of RHs is not only for the violation of the $U_{B-L}^1$ symmetry but also important to solve the origin of the observed tiny neutrino masses. In the renormalizable Lagrangian with RHs, we can obtain two kind of the neutrino masses, one is called Dirac masses and another is called Majorana masses. When enough hierarchy between these masses is realized, we can simply explain the tiny neutrino masses by the seesaw mechanism [7–13]. In addition, the violation of $U_{B-L}^1$ can seeds the origin of the baryon asymmetry of the universe #2.

One of the most promising signals of the $U_{B-L}^1$ violation is the neutrinoless beta decay, which breaks the lepton number by two units while keeping the baryon number. (See, for example, articles [14][17].) The rate of the decay is characterized by the effective mass defined by the neutrino masses 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 (NH) case of the active neutrinos in a certain parameter region. In such a case, the contribution from new physics (other than active neutrinos) including RHs 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 (IH) case, the experimental results in near future can give us some implication on RHs.

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

Recently, we have pointed out one interesting possibility that RHs may hide one of the neutrinoless double beta decay processes [20][21] (see also Refs. [22][23]). This is due to the destructive contribution of RH to the effective mass. Note that the impact of RHs does depend on the decaying nuclei. If this is the case, the mixing elements of RH can be predicted in terms of its mass in a certain range which is a good target of future search experiments.

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

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#1 We do not specifically consider the symmetry as the gauge symmetry.

#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.

#3 In a recent analysis [13], the differential rate of two neutrinoless double beta decay is discussed to constrain mixing elements of RHs with masses at $O(0.1-10)$ MeV.
discuss the impacts on the mixing elements of RHνs.

First of all, let us explain the framework of the present analysis, the minimal seesaw model. It is the Standard Model extended by two right-handed neutrinos νRI (I = 1, 2), which Lagrangian is given by

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + i \bar{\nu}_{RI} \gamma^\mu \partial_\mu \nu_{RI} - \left( F_{\alpha I} \bar{L}_\alpha \Phi \nu_{RI} + \frac{M_I}{2} \bar{\nu}_{RI} \nu_{RI} + h.c. \right),
\]

where \( L_\alpha = (\nu_{L\alpha}, e_{L\alpha})^T (\alpha = e, \mu, \tau) \) and \( \Phi \) are the weak doublets of left-handed lepton and Higgs, respectively. The Yukawa coupling constants and the Majorana masses for neutrinos are denoted by \( F_{\alpha I} \) and \( M_I \). By assuming that the Dirac masses \( F_{\alpha I} (\Phi) \) are much smaller than the Majorana mass \( M_I \), the seesaw mechanism works, and the mass eigenstates of neutrinos are three active neutrinos \( \nu_i \) \((i = 1, 2, 3)\) 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 \( m_3 > m_1 > m_2 = 0 \), 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) neutrinos are then written as

\[
\nu_{L\alpha} = \sum_i U_{\alpha i} \nu_i + \sum_I \Theta_{\alpha I} N_I^c,
\]

where \( U_{\alpha i} \) is the mixing matrix of active neutrinos called as the PMNS matrix while \( \Theta_{\alpha I} \) is that of HNLs.

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 \( 0\nuββ \) decay, and the quest for the decay is going on by various experiments.

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

\[
m_{\text{eff}} = m_{\nu}^\nu + m_{\nu}^N.
\]

Here the first term in the right-hand side represents the contributions from the active neutrinos, which is given by

\[
m_{\nu}^\nu = \sum_i U_{ei}^2 m_i.
\]

On the other hand, the contributions from HNLs are expressed as

\[
m_{\nu}^N = \sum_I \Theta_{eI}^2 M_I f_{\beta}(M_I),
\]

where \( f_{\beta} \) is the suppression factor compared to \( m_{\nu}^\nu \) due to the heaviness of HNLs \( M_I \gg m_i \). Here we apply the result in Ref. [24, 25] and assume the following form

\[
f_{\beta}(M) = \frac{\Lambda_{\beta}^2}{\Lambda_{\beta}^2 + M^2},
\]

where \( \Lambda_{\beta} = O(10^2) \) MeV denotes the typical scale of the Fermi momentum in the \( 0\nuββ \) decay. Hereafter we take \( \Lambda_{\beta} = 200 \) MeV as a representative value.

In this letter we consider the impacts of the detection of the \( 0\nuββ \) decay by future experiments on the properties of HNLs. The measurement of the decay rate gives the value of \( |m_{\text{eff}}| \). Note that \( m_{\text{eff}} \) 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 \( |\Theta_{e1}|^2 \) of the lighter HNL is given by

\[
|\Theta_{e1}|^2 = \frac{m_{\text{eff}} - m_{\nu}^\nu [1 - f_{\beta}(M_2)]}{M_1 [f_{\beta}(M_1) - f_{\beta}(M_2)]}
\]

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

\[
0 = \sum_i U_{ei}^2 m_i + \sum_I \Theta_{eI}^2 M_I.
\]

Importantly, the mixing element \( |\Theta_{e1}|^2 \) is given by \( m_{\text{eff}} \) and \( m_{\nu}^\nu \) together with masses \( M_1 \) and \( M_2 \). This means that, if \( |m_{\text{eff}}| \) is found by the detection of the \( 0\nuββ \) 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 \( m_{\text{eff}}^\text{obs} \) (i.e., the Majorana phase \( \eta \) and the mass ordering) and the phase of \( m_{\text{eff}} \).

When \( M_1 = 1 \) GeV and \( M_2 = 200 \) GeV, these bounds are shown in Fig. 1 in terms of the \( (m_{\nu}^\nu) \) observed value of \( |m_{\text{eff}}| \) denoted by \( m_{\text{eff}}^\text{obs} \). 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. [26] for the estimation of \( |m_{\text{eff}}| \). We
find that $|m_{\text{eff}}| = 1.45 - 3.68$ meV and $18.6 - 48.4$ meV for the NH and IH cases, respectively. It is found from Eq. (7) that the lower bound on $|\Theta_1^e|^2$ vanishes when $m_{\text{eff}}^\text{obs} = m_\nu(1 - \beta(M_2))$.

The predicted range of $|\Theta_1^e|^2$ is shown in Fig. 2 where the current upper bounds and the sensitivities on $|\Theta_1^e|^2$ by future search experiments are also shown [27,33]. We take the (would-be) observed value of the effective mass as $|m_{\text{eff}}| = 100$ meV, 50 meV, and 10 meV. Importantly, the most of the predicted range can be tested by the future experiments.

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. For this purpose the better understanding of the nuclear matrix elements of the $0\nu\beta\beta$ decay mediated by HNL is crucial.

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

$$M_1 = M_2 = M_N.$$  (9)

In this case, the total effective mass is given by

$$m_{\text{eff}} = m_{\text{eff}}^\nu [1 - \beta(M_N)],$$  (10)

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

$$M_N = \Lambda_\beta \left[ \frac{m_{\text{eff}}^\text{obs}}{|m_{\nu}| - m_{\text{eff}}^\text{obs}} \right].$$  (11)

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

$$|\Theta_1^e + \Theta_2^e| = \frac{|m_{\text{eff}}^\nu|}{\Lambda_\beta} \sqrt{\frac{m_{\text{eff}}^\nu - m_{\text{eff}}^\text{obs}}{m_{\text{eff}}^\text{obs}}}. \quad (12)$$

These results are shown in Fig. 3. Here we take the Majorana phase as $\eta = 0$, and $|m_{\text{eff}}| = 3.54$ meV and 48.4 meV for the NH and IH cases, respectively. It is seen that the observed effective mass $m_{\text{eff}}^\text{obs}$ of a few 10 meV corresponds to the Majorana mass $M_N \approx O(0.1 - 1)$ GeV and the mass ordering is the IH since HNL contributions are always destructive to the active neutrino ones. The relation between $M_N$ and $|\Theta_1^e + \Theta_2^e|$ is shown in Fig. 4. We find that in order to test the degenerate case the improvement of the sensitivity by future experiments is required especially for the NH case.

Before concluding the paper, we stress the impact of the difference among the $0\nu\beta\beta$ decay nuclei [21]. Throughout this paper, we have assumed the approximated form of the suppression function $f_\beta$ to be Eq. (6) 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 $\nu/\beta\beta$ experiments. This effect may be quantified by the choice the typical Fermi momentum in this analysis.

In Fig. 5 we plot the upper and lower values of the predicted effective mass with different Fermi momentum from 200 MeV while assuming the $\nu/\beta\beta$ 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. Interestingly, the predicted effective mass can be significantly enhanced when $\Lambda_\beta$ becomes larger enough than 200 MeV and $M_1$ gets heavier. By inserting Eq. (7) into the expression of the effective mass, we can obtain

$$\tilde{m}_{\text{eff}} = \left[1 - \tilde{f}_\beta(M_2)\right] m'_{\text{eff}}$$

$$+ \left|m_{\text{eff}} - m'_{\text{eff}} \right| \left[1 - \tilde{f}_\beta(M_2)\right] \tilde{f}'_\beta(M_1) - \tilde{f}'_\beta(M_2) / \tilde{f}_\beta(M_1) - \tilde{f}_\beta(M_2), \quad (13)$$

where $\Lambda_\beta = 200$ MeV in $\tilde{f}_\beta$ but $\Lambda_\beta \neq 200$ MeV in $\tilde{f}'_\beta$ which is denoted as $\tilde{\Lambda}$. Since the last fraction in the RHS of Eq. (13) can be simplified as

$$\tilde{f}_\beta(M_1) - \tilde{f}_\beta(M_2) = \tilde{\Lambda}_\beta^2 \left( \tilde{\Lambda}_\beta^2 + M_1^2 \right) \left( \tilde{\Lambda}_\beta^2 + M_2^2 \right)$$

which is larger than $M_1$ in $\tilde{\Lambda}_\beta$.

Namely, the effective mass is enhanced as $M_1$ gets greater/suppressed than the typical Fermi momentum in $\tilde{f}_\beta$ by the factor $\tilde{\Lambda}_\beta^2 / \tilde{\Lambda}_\beta^2$. As clearly seen, since significant enhancement/suppression could happen depending on the values of $\Lambda_\beta$ due to the contributions from HNLs. Thus, we can claim that the multiple detection by the $\nu/\beta\beta$ experiments using different nuclei is crucial to reveal the properties of HNLs.

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 $\nu/\beta\beta$ 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 experiment. Therefore, comprehensive studies on the neutrinoless double beta decays in the seesaw mechanism is necessary to extract the concrete information of the heavy neutral leptons.

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