Heavy Sterile Neutrinos and Neutrinoless Double Beta Decay

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Sterile neutrinos of mass up to a few tens of TeV can saturate the present experimental bound of neutrinoless double beta decay process. Due to the updated nuclear matrix elements, the bound on mass and mixing angle is now improved by one order of magnitude. We have performed a detailed analysis of neutrinoless double beta decay for the minimal Type I seesaw scenario. We have shown that in spite of the naive expectation that the light neutrinos give the dominant contribution, sterile neutrinos can saturate the present experimental bound of neutrinoless double beta decay process. However, in order to be consistent with radiative stability of light neutrino masses, the mass scale of sterile neutrinos should be less than 10 GeV.

1 Introduction:

Neutrinoless double beta decay ($0\nu\beta\beta$) is a very important probe of lepton number violation. The process is $(A,Z) \rightarrow (A,Z + 2) + 2e^−$, where lepton number is violated by two units. On the experimental side, there is a very lively situation as far as present and future experiments\textsuperscript{1,2} are concerned\textsuperscript{3}, and even a claim of observation of neutrinoless double beta decay\textsuperscript{4} by Klapdor and collaborators. The observation of lepton-number violating processes would be a cogent manifestation of incompleteness of the standard model, and could be even considered as a step toward the understanding of the origin of the matter. Indeed, this process can be described as creation of a pair of electrons in a nuclear transition.

The exchange of virtual, light neutrinos is a plausible mechanism\textsuperscript{5} of neutrinoless double beta decay process, provided they have Majorana mass\textsuperscript{6}. However, if the new physics scale is not too high, alternative possibilities may exist, where neutrinoless double beta decay is mostly due to mechanisms different from the light neutrino exchange. Infact this possibility has been proposed since long\textsuperscript{7} and has been widely discussed in the literatures\textsuperscript{8,9,10,11,12} (see the other references in\textsuperscript{13}). With this motivation in mind, we have considered the minimal Type I seesaw\textsuperscript{14} scenario, and we have analyzed how sterile neutrinos can give dominant contribution in neutrinoless double beta decay process. We discuss the following points in this context:

i) Large contribution from light neutrino states and constraints from cosmology.
ii) Contribution from sterile neutrino states and bound on the active-sterile mixing.
iii) Naive expectations from the sterile neutrino states in Type I seesaw.
iv) Possibility of dominant sterile neutrino contribution in Type I seesaw.
v) Upper bound on the mass scale of sterile neutrinos.

* See the exhaustive list of references in\textsuperscript{15} for the present and future experiments on $0\nu\beta\beta$. See\textsuperscript{16,17} and list of references in\textsuperscript{18} for reviews on $0\nu\beta\beta$. See\textsuperscript{19,20,21,22,23,24} for the reviews on neutrino physics.
2 Light neutrino contribution and constraints from cosmology

If the light neutrinos are Majorana particle, they can mediate the neutrinoless double beta decay process. The observable is the $ee$ element of the light neutrino mass matrix $|m_{ee}|$ (also denoted by 'effective mass'), where $|m_{ee}| = | \sum_i U_{ei}^2 m_i |$, $U$ is the PMNS mixing matrix. Certainly $m_{ee}$ is smaller than $\sum_i |U_{ei}^2| m_i$. From cosmology, we have bound on the sum of light neutrino masses i.e., $m_{\text{cosm}} = \sum_i m_i$. For the lightest neutrino mass scale $m_{\text{min}} > 0.1$ eV, relevant to the case of present experimental sensitivities, one can approximate $|m_{ee}| < m_{\text{cosm}}/3 \approx m_{\text{min}}$.

The bound coming from Heidelberg-Moscow experiment\(^1\) is $T_{1/2} > 1.9 \times 10^{25}$ yrs at 90% C.L. In terms of the effective mass of light neutrinos, the above implies\(^1\) $|m_{ee}| < 0.35$ eV. The experimental claim by Klapdor and collaborators\(^{16}\) implies $|m_{ee}| = 0.23 \pm 0.02 \pm 0.02$ eV\(^{11,26}\) at 68% C.L. This experimental hint of $0\nu2\beta$ challenges the result from cosmology\(^{27}\), as emphasized in Fig. 1. In the left panel, the effective mass $m_{ee}$ vs the lightest neutrino mass has been shown (note the region disfavored from cosmology), while the figure in the right panel (note the linear scale) shows the combination of Klapdor’s claim and the recent cosmological bound $\Sigma m_i < 0.26$ eV at 95% C.L. It is evident from the figure, that the light neutrino contribution can not reach the Klapdor’s limit\(^{16}\), if we consider the cosmological bound seriously. The above discussion suggests us to think for an alternative possibility: whether any new contribution to $0\nu2\beta$ can be large enough to saturate the experimental bound (or hint).

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{figure1.pdf}
\caption{In the left panel, the red and green regions represent the effective light neutrino mass for normal and inverted hierarchy. In the right panel, the same but using a linear scale to emphasize the region presently under study. Moreover, we show in light colors the regions resulting from the combination of the recent cosmological bound and Klapdor’s claim at 95% C.L.}
\end{figure}

3 Heavy Sterile Neutrino contribution

Consider $n_h$ generation of heavy sterile neutrinos with mass $M_i$ and mixing $V_{ei}$. Let us define $\eta_\nu = U_{ei}^2 m_i/m_\nu$ and $\eta_N = V_{ei}^2 m_p/M_i$. The traditional expression of the half-life is:

$$\frac{1}{T_{1/2}} = G_{0\nu} |M_\nu \eta_\nu + M_N \eta_N|^2,$$

where $M_\nu$ and $M_N$ are the nuclear matrix elements for light and heavy exchange respectively, $G_{0\nu}$ is the phase-space factor\(^{20}\). One can recast this into a useful form\(^{28}\):

$$\frac{1}{T_{1/2}} = K_{0\nu} \left| \frac{\Theta_{ei}^2}{\langle p^2 \rangle - \mu_i^2} \right|^2,$$

where $K_{0\nu} = G_{0\nu} (M_N m_p)^2$ and $\langle p^2 \rangle = -m_e m_p M_N M_\nu$. This agrees with the Eq. 1 if one identifies, $(\mu_i, \Theta_{ei}) = (m_i, U_{ei})$ for $\mu_i \to 0$ and $(M_i, V_{ei})$ for $\mu_i \to \infty$. The scale of comparison is
\( \langle p^2 \rangle \sim (200)^2 \text{ MeV}^2 \), the typical size of Fermi momentum inside the nucleus. Using Eq. 2, we obtain the bound on the mass and mixing parameters, shown in Fig. 2. In addition, we also show the bounds coming from different meson decay experiments as well as heavy neutrino decay experiments\(^{31}\) for comparison\(^1\). The upper yellow region in Fig. 2 is disfavored by neutrinoless double beta decay experiment. The thick black line in the middle gray band represents the present bound on the mass and mixing angle, where the updated nuclear matrix elements\(^{26}\) \( M_\nu = 5.24 \) and \( M_N = 363 \) have been used. In terms of numerical values, the bound corresponds to \( \frac{G_F^2}{\pi} \leq 7.6 \times 10^{-9} \text{ GeV}^{-1} \). The upper thin black line corresponds to the previous bound\(^{31,32}\) while the lower line represents rather a conservative limit. Evidently, the most stringent bound on active-sterile neutrino mixing comes from neutrinoless double beta decay experiment.

Figure 2: Bounds on the mixing between the electron neutrino and a (single) sterile neutrino as obtained from Eq. 2. For comparison, we also show other experimental constraints as compiled in Atre et al. See text for details.

4 Type I seesaw and naive expectation

In this section, we consider the minimal seesaw scenario Type I seesaw\(^{25}\). We discuss what is the \textit{naive expectations} from the sterile neutrino states in a) neutrinoless double beta decay process b) heavy neutrino searches at colliders c) lepton flavor violating processes. In order to discuss the above mentioned points, we denote the mass scale of \( M_D \) and \( M_R \) by two parameters \( m \) and \( M \) respectively. The \textit{naive expectations} from the sterile neutrino states are shown in Fig. 3. The details of the figure are as follows,

- The three gray bands are excluded from the following considerations: (a) \( M > 200 \text{ MeV} \), i.e., heavy sterile neutrinos are assumed to act as point-like interactions in the nucleus. (b) \( m < 174 \text{ GeV} \), in order to ensure perturbativity of the Yukawa couplings; (c) \( M > m \), namely, seesaw in a conventional sense.

- The remaining \( (m - M) \)-plane is divided in various regions by the three oblique lines, defined as follows: (1) The leftmost oblique line (between white and blue region) corresponds to neutrino mass \( M_\nu \sim m^2/M = 0.1 \text{ eV} \). The region below this line is excluded from light neutrino mass constraint. (2) The line between pink and blue region represents the contribution from heavy sterile neutrinos, which saturate the Heidelberg-Moscow bound\(^1\). The region below this line is excluded, since contribution larger than the experimental bound is achieved in this region. (3) The oblique line that separates the pink and yellow region corresponds to large mixing between active and sterile neutrinos, i.e., \( V_{\mu i} \sim m/M \sim 10^{-2} \). In the region below this line, the production of the heavy Majorana neutrinos in colliders is not suppressed by a small coupling\(^{34,35}\). (4) Finally, we also show the constraints coming from \( \mu \to e\gamma \) process\(^{36,37}\).

\(^1\) For more detail on the bounds from meson decay and heavy neutrino decay, see\(^{31}\). Also, to compare the bounds coming from lepton number violating \( B^- \) meson decays, see Aaij \textit{et al.}\(^{33}\).
The above discussion clearly suggests, that the *naive expectations* on Type I seesaw rules out large contribution to $0\nu2\beta$ from heavy sterile neutrinos, or the prospect of heavy neutrino searches at collider or even a rapid $\mu \rightarrow e\gamma$ transition.

5 Dominant sterile contribution in multiflavor scenario

In this section we show how to achieve a dominant sterile neutrino contribution in neutrinoless double beta decay process. For this purpose, we go beyond naive dimensional analysis, discussed in the previous section. However, to achieve dominant contribution to $0\nu2\beta$ from sterile neutrinos, the light neutrino masses have to be smaller than the *naive seesaw expectation*. Below, we discuss this possibility in detail.

5.1 Vanishing seesaw condition and the perturbation

We are interested to the case when the *naive expectation* for the light neutrino mass, $M_T^D M_R^{-1} M_D \sim m^2/M$, typical of Type I seesaw, does not hold. For this purpose, let us start with the vanishing seesaw condition $M_T^D M_R^{-1} M_D = 0$. This is compatible with an invertible right handed mass matrix $M_R$ and a non-trivial Dirac mass matrix $M_D$, if in the Dirac-diagonal basis the two matrices have the following form\[^3\]:

\[
M_D = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m \end{pmatrix}; \quad M_R = \begin{pmatrix} 0 & 0 & M_1 \\ 0 & M_2 & M_3 \\ M_1 & M_3 & M_4 \end{pmatrix}
\]

The light neutrino masses will be generated as a perturbation of this vanishing seesaw condition. For definiteness, we consider the following perturbation of the Dirac and Majorana mass matrix:

\[
M_D = m \text{ diag}(0, \epsilon, 1) \quad M_R^{-1} = M^{-1} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & \epsilon \end{pmatrix} \Rightarrow M_\nu = \frac{m^2}{M} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon^2 & \epsilon \\ 0 & \epsilon & \epsilon \end{pmatrix}
\]

where $\epsilon$ is the perturbing element and $\epsilon < 1$. In Eq. 4 we have written down elements which are of $O(1)$. For notational clarity we skip writing the coefficients of $O(1)$ terms explicitly. It is evident from Eq. 4 that the light neutrino mass matrix depends crucially on the perturbing element $\epsilon$, and as $\epsilon \to 0$, the light neutrino mass matrix becomes zero.

5.2 Sterile contribution in neutrinoless double beta decay

For $M_i^2 \gg |p^2| \sim (200)^2$ MeV$^2$ and for real $M_R$, the amplitude for the light and heavy neutrinos are represented by $\frac{m_{\text{max}}}{p}$ and $(M_T^D M_R^{-3} M_D)_{ee}$ respectively. Going from Dirac-diagonal to the flavor basis, the sterile contribution will be $\kappa \frac{m^2}{M^2}$ where the factor $\kappa$ contains the information of

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Figure 3: Naive expectations on Type I seesaw model are displayed on the $(m - M)$-plane. The constraints from $0\nu2\beta$ transition heavy Majorana neutrino searches in colliders and lepton flavor violating decays are shown. See the text for detailed explanation.
the change of basis. For the particular example which we have discussed in the previous section, this turns out to be:

\[
(M_D^T M_R^{-3} M_D)^{(FL)} = \xi \frac{m^2}{M^3} \times \begin{cases} 
\frac{(U_{e2}^* \sqrt{m_2} + U_{e3}^* \sqrt{m_3})^2}{m_2 + m_3} & \text{with normal hierarchy} \\
\frac{(U_{e2}^* \sqrt{m_2} + U_{e1}^* \sqrt{m_1})^2}{m_1 + m_2} & \text{with inverted hierarchy}
\end{cases}
\]

where \( \xi \) is an \( \mathcal{O}(1) \) factor that depends on the elements of \( M_R \). The light neutrino contributions are \( |m_{ee}| = |m_3 U_{e3}^2 - m_2 U_{e2}^2| \) (resp., \( |m_{ee}| = |m_2 U_{e2}^2 - m_1 U_{e1}| \)) for normal (resp., inverted) mass hierarchy. Note that, both the numerator and denominator in Eq. 5 depends on the light neutrino masses \( m_{1,2} \) or \( m_{1,3} \) in the same way. Hence, the sterile neutrino contributions are not suppressed from the smallness of light neutrino mass. Depending on the factor \( \frac{m^2}{M^3} \), the sterile neutrinos can give dominant contribution in neutrinoless double beta decay\(^\text{3}\). To give an estimate, for \( \frac{m^2}{M^3} \sim 7.6 \times 10^{-9} \text{ GeV}^{-1} \), the sterile neutrinos can saturate the present bound\(^\text{11}\) on 0ν2β half-life. See the texts in\(^\text{3}\) for the other cases leading to similar conclusions.

6 Upper bound on the sterile neutrino mass scale

In this section, we discuss what could be the upper bound on the sterile neutrinos mass scale \( M \), that is consistent with radiative stability. Note that, the dominant contribution in 0ν2β will imply that the Dirac mass scale \( m \) and Majorana mass scale of sterile neutrinos \( M \) should be related as follows:

\[
M = 16 \text{ TeV} \times \left( \frac{T_{1/2}}{1.9 \times 10^{25} \text{ yrs}} \right)^{1/6} \left( \frac{\mathcal{M}_N \times \kappa}{363 \times 1} \right)^{1/3} \left( \frac{m}{174 \text{ GeV}} \right)^{2/3}
\]

Hence, if \( m \) reaches to its upper bound 174 GeV, \( T_{1/2} = 1.9 \times 10^{25} \) yrs, and the nuclear matrix element is \( \mathcal{M}_N = 363 \), sterile neutrinos of mass up to \( M \sim 16 \text{ TeV} \) can saturate the experimental bound. However, the question is whether the loop correction of the light neutrino masses can put further constraints on this mass scale. Note that in this case, when \( M \sim 16 \text{ TeV} \) and \( m \sim 174 \text{ GeV} \), one will need excessive fine-tuning \( \epsilon \sim 10^{-9} \) to satisfy the neutrino mass constraint \( \epsilon \frac{m^2}{M^3} < 0.1 \text{ eV} \). Decreasing \( M \) as well as \( m \) from their maximum values will however reduce the fine-tuning\(^\text{3}\).

The one loop correction to the light neutrino mass is\(^\text{23}\) \( \delta M_\nu \sim \frac{\epsilon^2}{(4\pi)^2} \frac{m^2}{M} \log(M_1/M_2) \), if \( M \) is larger than electroweak scale. On the other hand, for \( M \) smaller than electroweak scale, the loop correction has a polynomial nature, i.e., \( \delta M_\nu \sim \frac{\epsilon^2}{(4\pi)^2} \frac{m^2}{M} \frac{M^2}{M_{3\nu}} \). If combined with the following two considerations: a) smallness of light neutrino mass \( \epsilon \frac{m^2}{M} < 0.1 \text{ eV} \) and b) sterile neutrinos saturating the present bound on 0ν2β half-life, the sterile neutrino mass scale turns out to be smaller than 10 GeV. See\(^\text{3}\) for a detailed discussion.

7 Conclusion

Neutrinoless double beta decay is a major experiment to probe lepton number violation. On the experimental side, there is scope of order of magnitude improvement of the half-life of this process. We have considered the most basic Type I seesaw scenario and studied the sterile neutrino contribution in detail. We find that due to improvement of nuclear matrix elements, the bound on active-sterile mixing angle is now improved by one order of magnitude. Despite of the naive expectations that the light neutrinos give dominant contribution, heavy sterile neutrinos can saturate the present experimental bound.

\(^{1} \text{See}^{\text{3}} \text{ for discussion on another interesting seesaw scenario that leads to similar conclusion.}\)
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