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Pinning Down Two Right-Handed Neutrinos with Neutrinoless Double Beta Decay

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The addition of two gauge singlet right-handed neutrinos to the Standard Model conveniently explains neutrino oscillations, while also potentially explaining the matter-antimatter asymmetry. The possible Majorana nature of neutrinos resulting from this modification can lead to observable signals in the form of neutrinoless double beta decay. Recent calculations show that the neutrinoless double beta decay rates may be underestimated in the standard parametrisation, calling for a better computation from an EFT perspective. The computations reveal significant differences in the amplitude, especially for light neutrinos where the ultrasoft mode becomes relevant. We show that, in the inverted mass ordering of neutrinos, with future limits on neutrinoless double beta decay, it is possible to precisely pin down the regions in the mass-coupling parameter space where a model with two right-handed neutrinos could exist, and that these regions are subject to cosmological constraints while also being a target for future collider and beam dump searches.

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1. Introduction

Several open questions unanswered by the Standard Model potentially have their solutions lying somewhere within the realm of sterile neutrinos. The presence of right-handed neutrinos (RHNs), which give rise to heavy neutrino mass eigenstates, aka heavy neutral leptons (HNLs) or sterile neutrinos, can give the active neutrinos small masses and explain neutrino oscillations [1], while also providing additional CP-violation to produce the observed baryon asymmetry of the universe (BAU).

Given that RHNs would be SM gauge singlets, nothing forbids them from having a Majorana mass term, which in turn results in Majorana nature of neutrinos. This points towards lepton-number-violating (LNV) processes, such as neutrinoless double beta decay ($0\nu\beta\beta$), that can give unmistakeable signals of physics beyond the Standard Model. We discuss how $0\nu\beta\beta$ and the correct amount of BAU, along with other experiments, can make a minimal seesaw model completely testable in the near future.

2. Neutrinoless double beta decay rates with massive neutrinos

The $0\nu\beta\beta$ half-life is, in terms of the isotope-dependent phase space factor G_{01} and the nucleon axial coupling $g_A \simeq 1.27$,

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{01}\, g_A^4 \left| \sum_i V_{ud}^2 \frac{m_i}{m_e} \mathcal{U}_{ei}^2\, \mathcal{A}(m_i) \right|^2 , \tag{1}$$

where $V_{ud} \simeq 0.97$ is the up-down CKM matrix element, m_e is the electron mass, and m_i are the neutrino mass eigenvalues. $\mathcal{U}_{ei}$ are the elements of the first row of the neutrino mixing matrix, and $\mathcal{A}(m_i)$ is the mass-dependent amplitude of the decay.

The amplitude saturates to a constant value for small neutrino masses, and thus for active neutrinos one can factor out $\mathcal{A}(0)$ from the rate. The computation gets more involved once heavier neutrinos are added into the mix. The mass-dependent amplitude is then usually approximated with the simple functional form [2, 3]

$$\mathcal{A}(m_i) = \mathcal{A}(0) \frac{\langle p^2 \rangle}{\langle p^2 \rangle + m_i^2} , \tag{2}$$

where the fit parameter $\langle p^2 \rangle \sim m_\pi^2$ and $\mathcal{A}(0)$ depend on nuclear many-body computations. This, however, only captures the contributions from the potential momentum region of the exchanged neutrino, and in general one needs to consider all the available regions [4–8]:

- Hard region, with $k_0 \sim |\vec{k}| \sim \Lambda_\chi$,
- Soft region, with $k_0 \sim |\vec{k}| \sim m_\pi$,
- Potential region, with $k_0 \sim \frac{|\vec{k}|^2}{m_N} \sim \frac{m_\pi^2}{m_N}$,
- Ultrasoft region, with $k_0 \sim |\vec{k}| \sim \frac{m_\pi^2}{m_N}$,

where $\Lambda_\chi \sim$ GeV is the chiral scale, and m_π and m_N are the pion and nucleon masses. Although small on its own, the ultrasoft contribution can become the dominant contribution in the presence of light sterile neutrinos if there are no other sources of neutrino mass; if $\sum_i \mathcal{U}_{ei}^2 m_i = 0$, this contribution provides a more favourable $\sim m_i^4$ scaling to the rate, compared to the $\sim m_i^6$ scaling given by the parametrised amplitude in eq. (2).

With this in mind, one may divide the mass-dependent amplitude in the following way:

$$\mathcal{A}(m_i) = \begin{cases} \mathcal{A}^{(\mathrm{p},<)}(m_i) + \mathcal{A}^{(\mathrm{h})}(m_i) + \mathcal{A}^{(\mathrm{us})}(m_i) & \text{for} \quad m_i < 100\text{ MeV}\,, \\ \mathcal{A}^{(\mathrm{p})}(m_i) + \mathcal{A}^{(\mathrm{h})}(m_i) & \text{for} \quad 100\text{ Mev} \leq m_i < 2\text{ GeV}\,, \\ \mathcal{A}^{(9)}(m_i) & \text{for} \quad 2\text{ Gev} \leq m_i\,, \end{cases} \tag{3}$$

where at large neutrino masses, the amplitude comes from a dimension-9 operator for $0\nu\beta\beta$ with the neutrino being integrated out. At lower masses, the momentum regions discussed above applies, with the superscripts denoting the contribution from potential (p), hard (h), and ultrasoft (us) exchanges. The superscript (p, <) refers to a modified potential contribution to avoid double-counting of the $O(m_i^1)$ terms when the ultrasoft corrections are included. The explicit forms of these amplitudes can be found in refs. [8–10].

3. The minimal seesaw model with two right-handed neutrinos

In the minimal extension of the SM to account for the neutrino masses, two right-handed gauge singlet neutrinos are added to effectively give the neutrino mass matrix

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}, \tag{4}$$

where m_D is the Dirac mass for neutrinos, and the RHN mass matrix is given by

$$M_M = \begin{pmatrix} \overline{M}\left(1 - \frac{\mu}{2}\right) & 0 \\ 0 & \overline{M}\left(1 + \frac{\mu}{2}\right) \end{pmatrix}, \tag{5}$$

for the average Majorana mass $\overline{M}$ and a small degeneracy-breaking parameter μ. The absence of any other new physics contributing to the Weinberg operator leaves the top-left component of M_ν zero.

Assuming $(M_M)_{ij} \gg y_{ij} v$, where v is the electroweak symmetry breaking scale and y_{ij} refers to the Yukawa couplings, the diagonalisation of M_ν gives the eigenvalues

$$m_\nu \simeq -m_D M_M^{-1} m_D^T, \quad M_N \simeq M_M\,, \tag{6}$$

where m_ν gives the light active neutrino masses, and M_N gives the HNL masses. The largeness of M_M makes the active neutrinos light in this so-called "seesaw" mechanism.

The relevant combination for $0\nu\beta\beta$ is [11]

$$\begin{aligned} \mathcal{A}_{\mathrm{eff}} &\equiv \sum_{i=1}^{5} \mathcal{U}_{ei}^2 m_i \mathcal{A}(m_i) \\ \Rightarrow |\mathcal{A}_{\mathrm{eff}}| &\simeq \left| \sum_{i=1}^{3} m_i \mathcal{U}_{ei}^2 \left(\mathcal{A}(0) - \mathcal{A}(\overline{M})\right) + e^{i\lambda} \mu U_e^2 \frac{\overline{M}^2}{2} \mathcal{A}'(\overline{M}) \right|, \end{aligned} \tag{7}$$

where λ is a completely free phase. As a result, HNLs can either enhance or reduce the $0\nu\beta\beta$ decay rate, depending on the value of their masses, their mixing with SM neutrinos, and the phase λ.

Non-observation of $0\nu\beta\beta$ puts an upper limit on μU_e^2. U_e^2 is an experimentally relevant parameter for colliders and other searches, and can also be constrained from below from cosmological considerations such as Big Bang Nucleosynthesis (BBN) and the seesaw limit. Demanding that this model sufficiently explains the matter-antimatter asymmetry via leptogenesis excludes more chunks of the parameter space (see, e.g., refs. [12, 13] for earlier studies combining $0\nu\beta\beta$ and leptogenesis).

3.1 Probing the inverted hierarchy

Since the inverted hierarchy (IH) band for three light neutrinos will be probed completely by the upcoming generation of experiments, we will focus on the $3 + 2$ scenario in the IH.

Figure 1 shows the current limits on the minimal model for different values of μ. The bounds from leptogenesis are shown in orange, and the limit from $0\nu\beta\beta$ is in blue. We see that as μ decreases, the allowed region gets bigger, and both $0\nu\beta\beta$ and leptogenesis constraints weaken.

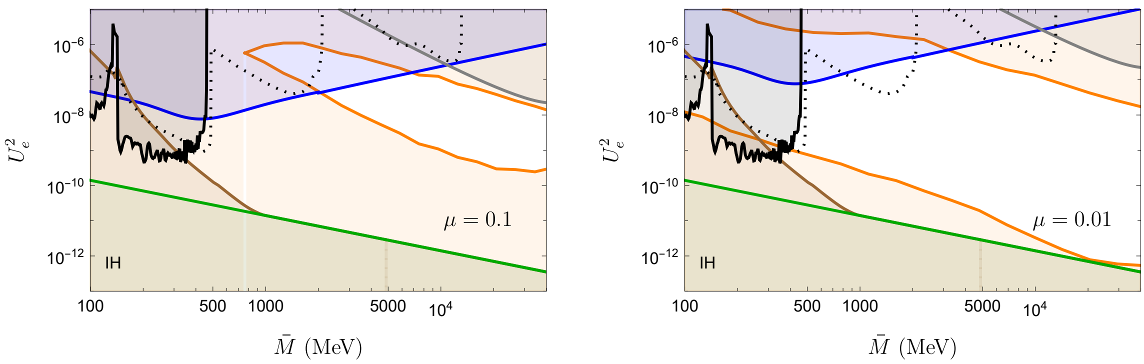

Figure 1: Current limits from leptogenesis (orange), $0\nu\beta\beta$ (blue), BBN (brown), peak searches (black), and displaced vertex searches (dotted) [14, 15], for $\mu = 0.1,\ 0.01$ for IH. The seesaw line is shown in green.

With upcoming $0\nu\beta\beta$ experiments, it is possible to draw also lower limits on U_e^2 if no signal is seen. Combining the constraints as shown in fig. 2, assuming an improvement of two orders of magnitude in the $0\nu\beta\beta$ limits, we find that the $3 + 2$ model will be completely tested in the near future for IH with the help of future searches [16–19]. For normal hierarchy, the next generation of experiments will not be enough to test the entire allowed parameter space.

It is also possible to explore the entire model space with only $0\nu\beta\beta$, using combined exclusions from multiple isotopes. In fig. 3, we show the points that can produce enough matter-antimatter asymmetry, while avoiding current experimental constraints, as a function of their corresponding half-lives for ^{136}Xe and ^{76}Ge. Since the cancellation of rate in one isotope implies a finely tuned set of (physical) parameters, this makes it impossible to sufficiently cancel the rate in other isotopes with the same set of parameters. This explains the two branches at higher values of half-life — by improving the limits by about four orders of magnitude for each isotope, which is rather unrealistic in the near future, the entire model space can be probed.

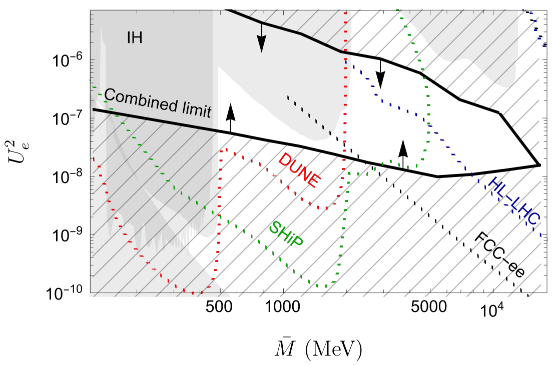

Figure 2: Future prospects for IH in the minimal seesaw model. The black curve is the combined limit from improved $0\nu\beta\beta$ limits and leptogenesis.

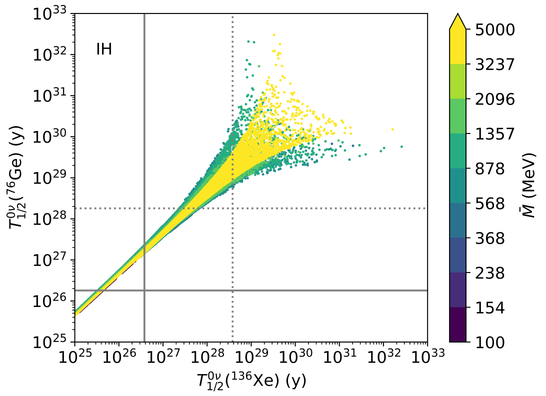

Figure 3: $0\nu\beta\beta$ half-life for different isotopes in models that avoid current constraints and produce sufficient BAU.

4. Conclusions

Neutrinoless double beta decay has the potential to confirm the nature of neutrinos, and provide insight into the matter-antimatter asymmetry. The computation of $0\nu\beta\beta$ amplitudes for neutrinos with arbitrary masses is discussed in the context of predicting $0\nu\beta\beta$ rates in models with sterile neutrinos. A minimal setup with two right-handed neutrinos is studied, and it is seen that for the inverted neutrino mass hierarchy, the next generation of experiments will be able to probe the entire allowed parameter space in this $3 + 2$ benchmark model.

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