DECAY RATES OF HEAVY NEUTRINOS IN THE GRIMUS–NEUFELD MODEL*

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In this work, we take the Grimus–Neufeld model, which extends the Standard Model by adding a sterile neutrino and a second Higgs doublet. We calculate the decay rates for the heaviest neutrino, and by that the lifetime, in the tiny seesaw scenario. The tree-level decay is mediated by the Z boson and the neutral Higgs bosons. The loop-level decay into a neutrino and a photon can dominate in some parameter regions.

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1. Introduction

It is widely known that neutrinos have mass [1] that is very small compared to other leptons. They oscillate between their flavours. However, in the Standard Model (SM), neutrinos are massless and thus cannot oscillate. This leads to a natural conclusion that there exists physics beyond the Standard Model (BSM). One of the models that attempts to explain neutrino masses and mixings is the Grimus–Neufeld model (GNM) [2].

The GNM is an extension of the SM, adding a fermionic singlet and a second Higgs doublet. In this model, the neutrino masses are given by the well-known seesaw mechanism, *e.g.* [3, 4] and by radiative corrections.

Due to the nature of the sterile neutrino, *i.e.* not coupling to the gauge bosons, it can be considered a dark matter candidate as Refs. [5–8] did. One then requires that the sterile neutrino is a stable particle, meaning its lifetime is longer than the age of the universe. Calculations of decay rates have been done in Refs. [8–10] for several models, however, not for the GNM.

In this paper, we calculate the sterile neutrino decay rate in the tiny seesaw scenario. At tree level, we calculate the $N \to 3\nu$ decay, mediated by the Z-boson and by the neutral Higgs bosons h_0, H_0, and A. h_0 is assumed

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to be the SM-like Higgs boson. The loop-level decay $N \to \nu + \gamma$ is mediated by charged leptons and the W-boson or the charged Higgs boson H^+ coming from the second Higgs doublet.

2. The Lagrangian of the GNM

The GNM Lagrangian adds to the SM Lagrangian a second Higgs doublet and a Majorana neutrino [11–14]. The Higgs sector is that of a general 2HDM [15–17], with the Higgs doublets defined in the Higgs basis

$$H_1 = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}\left(v + h_1 + i\phi^0\right) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix}. \tag{2.1}$$

The Goldstone bosons are $\phi^{\pm,0}$ and $v = \frac{2m_W}{g}$ is the vacuum expectation value. The physical Higgs bosons are h_0, H_0, and A. In the CP-conserving case, A is a pseudoscalar and does not mix with h_1.

The definition of the adjoint Higgs doublet

$$\tilde{H}_a = \epsilon H_a^* \tag{2.2}$$

is needed to write the Yukawa sector

$$\mathcal{L}_{\text{Yuk}} = \bar{L}_k \left(Y_L^{(a)}\right)_{k\ell} H_a P_{\text{R}} \ell_\ell^{\text{R}} + \bar{L}_k \left(Y_N^{(a)}\right)_k \tilde{H}_a P_{\text{R}} N + \text{h.c.} \tag{2.3}$$

The indices k and ℓ are flavour indices, while the index a runs over the Higgs doublets. The lepton doublet L_k contains the neutrino fields ν_k and the charged leptons ℓ_k. The right-handed lepton ℓ_k^{R} is a SU(2) singlet. N is the right-handed sterile neutrino. Sums over indices are implicit.

The Majorana Lagrangian

$$\mathcal{L}_{\text{Majorana}} = \frac{1}{2}\bar{\hat{N}} i\partial\!\!\!/ N - \frac{1}{2} M \bar{\hat{N}} P_{\text{R}} N + \text{h.c.} \tag{2.4}$$

has the complex Majorana mass term M. The hat symbol in the field $\bar{\hat{N}}$ stands for the Lorentz Covariant Conjugate [18].

We go to the neutrino mass basis n_b by the transformations

$$\nu_k = U_{kb} P_{\text{L}} n_b \quad \text{and} \quad P_{\text{R}} N = U_{Nb}^* P_{\text{R}} n_b\,. \tag{2.5}$$

The sum over the mass eigenstate index $b = 1, 2, 3, 4$ is implied. In these transformations, U is a 4×4 unitary matrix that transforms neutrinos between bases. It can be expressed as[1]

$$U_{kb} = \tilde{V}_{kb} + \left(\tilde{V}_{k3}\delta_{3b} + \tilde{V}_{k4}\delta_{4b}\right)(c-1) - is\left(\tilde{V}_{k3}\delta_{4b} + \tilde{V}_{k4}\delta_{3b}\right), \tag{2.6}$$

[1] This is done for normal ordering of the neutrino masses; for inverted ordering, we would have $3 \leftrightarrow 1$.

where $\tilde{V}$ is the extension of the usual 3×3 PMNS matrix V [19] to 4×4 by

$$\tilde{V}_{kb} = V_{kb} \quad \text{for} \quad k,b \leq 3\,, \qquad \tilde{V}_{k4} = \tilde{V}_{4b} = 0\,, \qquad \tilde{V}_{44} = 1\,. \tag{2.7}$$

$s(c)$ is sine(cosine) of the seesaw angle θ

$$s^2 \equiv \sin^2\theta = \frac{m_3}{m_3+m_4} \quad \text{and} \quad c^2 \equiv \cos^2\theta = \frac{m_4}{m_3+m_4}\,, \tag{2.8}$$

which implements the seesaw relations Eqs. (2.10) and (2.11).

The PMNS matrix V also appears in the Yukawa couplings

$$\left(Y_N^{(1)}\right)_k = -iyV_{k3} \quad \text{and} \quad \left(Y_N^{(2)}\right)_k = d\,V_{k2} + d'\,V_{k3}\,, \tag{2.9}$$

where $y, d > 0 \in \mathbb{R}$ and $d' \in \mathbb{C}$ parameterize the Yukawa couplings. m_3 is the tree-level seesaw mass, generated by the seesaw mechanism, and m_4 is the mass of the heaviest neutrino, typically associated with the sterile neutrino mass by

$$m_4 = |M| - m_3\,. \tag{2.10}$$

The Yukawa coupling to the first Higgs doublet is responsible for the seesaw

$$y^2 = \sum_k \left|\left(Y_N^{(1)}\right)_k\right|^2 = \frac{2m_3m_4}{v^2}\,. \tag{2.11}$$

The Yukawa coupling of neutrinos to the second Higgs doublet allows for mass generation at the loop level for the n_2 state. The Yukawa couplings for neutrinos can also be parametrized as written in [20].

In the mass basis of the charged leptons, the Yukawa couplings that connect the lepton doublets and charged lepton singlets to the first Higgs doublet are diagonal

$$\left(Y_L^{(1)}\right)_{jk} \equiv \delta_{jk}\frac{\sqrt{2}m_{\ell_k}}{v}\,, \tag{2.12}$$

and proportional to the charged lepton's mass m_{ℓ_k}. The Yukawa couplings to the second Higgs doublet $(Y_L^{(2)})_{jk}$ are completely general and not restricted by neutrino data at one loop.

Since n_1 does not couple to any neutral boson, it stays massless even at one loop. That allows us to set the light neutrino masses as

$$m_1 = 0\,, \qquad m_2 = \sqrt{\Delta m^2_{\text{sol}}}\,, \qquad m_3 = \sqrt{\Delta m^2_{\text{atm}}}\,. \tag{2.13}$$

From Eq. (2.11) one sees: when $m_4 \ll v$, then y becomes very small, comparable to the electron Yukawa coupling $(Y_L^{(1)})_{ee}$, defining the tiny seesaw scenario with $y \leq 10^{-6}$. In this case, $Y_N^{(2)} \gg Y_N^{(1)}$ becomes a large coupling, see Ref. [13].

When $y \to 0$, $\mathcal{L}_{\rm GNM}$ gains an additional Z_2 symmetry in the form

$$\phi_2 \leftrightarrow -\phi_2 \,, \qquad N \leftrightarrow -N \,, \tag{2.14}$$

showing that the tiny seesaw scenario has an approximate Z_2 symmetry.

3. The decay rates

Since the GNM has no symmetry that prevents neutrino decays, we can calculate the decay rates. Figure 1 shows the diagrams for the decays $N \to \nu_k + \bar{\nu}_j + \nu_l$ and $N \to \nu + \gamma$. For the tree-level decays, (a) and (c), we focus on the decay channels where $f(\bar{f})$ is $\nu(\bar{\nu})$ and it happens iff $m_{\nu_j} > m_{\nu_k} + m_{\nu_{\bar{\ell}}} + m_{\nu_\ell}$, while the loop, (b) and (d), happens iff $m_{\nu_j} > m_{\nu_k}$.

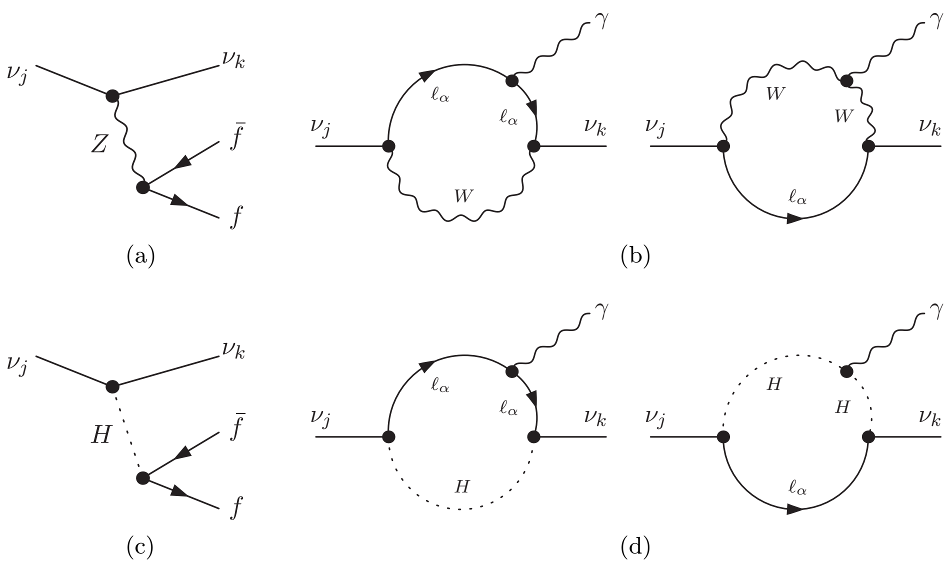

Fig. 1. Sterile neutrino decays: into a neutrino and two other fermions with the Z-boson as the mediating particle in (a), and the neutral Higgs bosons as mediating particles in (c); into a neutrino and a photon via a loop with W-bosons and charged leptons in (b), and charged Higgs bosons and charged leptons in (d).

For the kinematics, we set $m_{\nu_{\rm final}} \to 0$. For the tiny seesaw, we assume $m_4 \ll m_Z < m_H$, simplifying the propagators in the diagrams to

$$\frac{1}{p^2 - m^2} \approx -\frac{1}{m^2} \,, \tag{3.1}$$

where m is the mass of the mediating boson.

The three processes $n_4 \to 2n_1 + n_3$, $n_4 \to 2n_2 + n_3$, and $n_4 \to 3n_3$ contribute to the Z-boson-mediated decay with the decay rate

$$\Gamma^{Z}_{n_4\to 3\nu} = \frac{G_{\mathrm{F}}^2 m_4^5 s^2}{96\pi^3}\,, \tag{3.2}$$

which matches the result of Ref. [8]. If we express s by Eq. (2.8), we see the scaling of the decay rate with the 4$^{\text{th}}$ power of the mass of the sterile neutrino

$$\Gamma^{Z}_{n_4\to 3\nu} \sim s^2 m_4^5 = \frac{m_3 m_4^5}{m_3+m_4} \sim m_4^4\,. \tag{3.3}$$

The tree-level decay mediated by the Higgs bosons of the first doublet is

$$\Gamma^{H_1}_{n_4\to 3n_3} = \frac{G_{\mathrm{F}}^2 m_4^5 s^2 c^2 \left(c^2 - s^2\right) m_3^2 m_4^2}{768\pi^3 m_{H_1}^4}\,, \tag{3.4}$$

where

$$\frac{1}{m_{H_1}^2} = \frac{c_{12}^2}{m_{h_0}^2} + \frac{s_{12}^2}{m_{H_0}^2} \tag{3.5}$$

is the effective mass for the combination of both neutral scalar Higgs bosons and $s_{12}^2 = 1 - c_{12}^2$ is their mixing angle [17]. The scaling of this decay rate is

$$\Gamma^{H_1}_{n_4\to 3n_3} \sim m_4^5 s^2 c^2 \left(c^2 - s^2\right) m_3^2 m_4^2 \sim m_4^5\,. \tag{3.6}$$

Comparing to Eq. (3.2)

$$\frac{\Gamma^{H_1}_{n_4\to 3n_3}}{\Gamma^{Z}_{n_4\to 3\nu}} = \frac{c^2\left(c^2 - s^2\right) m_3^2 m_4^2}{8 m_{H_1}^4} \sim \frac{m_3^2 m_4^2}{8 m_{H_1}^4} \ll 1\,, \tag{3.7}$$

we see its suppression.

The tree-level decay rate contributions coming from the second Higgs doublet are

$$\Gamma^{H_2}_{n_4\to 2n_2+n_3} = \frac{5 d^4 m_4^5 s^2}{8192\pi^3}\frac{1}{m_{H_2}^4}\,, \tag{3.8}$$

$$\Gamma^{H_2}_{n_4\to n_2+2n_3} = \frac{5 d^2 |d'|^2 m_4^5 s^2}{8192\pi^3}\left(\frac{1}{m_{H_2}^4} - \frac{s_{12}^2}{m_A^2 m_{h_0}^2}\right)\,, \tag{3.9}$$

and $$\Gamma^{H_2}_{n_4\to 3n_3} = \frac{|d'|^4 m_4^5 s^2}{6144\pi^3}\frac{1}{m_{H_2}^4}\,, \tag{3.10}$$

where

$$\frac{1}{m_{H_2}^2} = \frac{s_{12}^2}{m_{h_0}^2} + \frac{c_{12}^2}{m_{H_0}^2} + \frac{1}{m_A^2} \tag{3.11}$$

is the effective mass for the second Higgs doublet. The full contribution is

$$\Gamma^{H_2}_{n_4\to 3\nu} = \Gamma^{H_2}_{n_4\to 2n_2+n_3} + \Gamma^{H_2}_{n_4\to n_2+2n_3} + \Gamma^{H_2}_{n_4\to 3n_3} \tag{3.12}$$

with the scaling

$$\Gamma^{H_2}_{n_4\to 3\nu} \sim m_4^2\,, \tag{3.13}$$

coming from the $1/\sqrt{m_4}$ scaling of d and d'.

The loop-level decay rates can be mediated by the W boson

$$\Gamma^{W}_{n_4\to\nu+\gamma} = \frac{9\alpha G_{\rm F}^2 m_4^5 s^2}{512\pi^4} \sum_{j,k}^{3} \left[\left(|V_{j3}|^2\delta_{jk} - s^2|V_{j3}|^2|V_{k3}|^2\right) f_j^W f_k^W\right]\,, \tag{3.14}$$

where

$$f_j^W = \frac{2-7x_j-2x_j^2[\ln(x_j)-3]-x_j^3}{(1-x_j)^3}\,, \quad \text{with} \quad x_j := \frac{m_{\ell_j}^2}{m_W^2}\,, \tag{3.15}$$

and the charged Higgs boson H^+

$$\Gamma^{H^+}_{n_4\to\nu+\gamma} = \frac{\alpha m_4^3}{512\pi^4 m_{H^+}^4} \sum_{j,k,b}^{3} \left[F_{jb}F_{kb}^* + F_{jb}^*F_{kb}\right]\,, \tag{3.16}$$

where

$$F_{jb} = \sum_{k=1}^{3} m_{\ell_j} f_j^H \left(Y_N^{(2)}\right)_j \left(Y_L^{(2)}\right)_{jk} \left[U_{kb}^*U_{44}^* - U_{k4}^*U_{4b}^*\right]\,, \tag{3.17}$$

and

$$f_j^H = \frac{1+\log(x_j)-x_j}{(1-x_j)^2}\,, \quad \text{with} \quad x_j := \frac{m_{\ell_j}^2}{m_{H^+}^2}\,. \tag{3.18}$$

α is the fine structure constant.

For the loop with the W boson, we have

$$\Gamma^{W}_{n_4\to\nu+\gamma} \ll \Gamma^{Z}_{n_4\to 3\nu}\,, \tag{3.19}$$

both having the same scaling as the fourth power of m_4.

The loop with the charged Higgs scales similarly to the $\Gamma^{H_2}_{n_4\to 3\nu}$, Eq. (3.13), due to the scaling of $Y_N^{(2)}$. There is no seesaw suppression (s^2) for this loop, explaining its large value, as seen in Fig. 2.

We note that the loop-level decay with H^+ dominates the tiny seesaw scenario as long as $Y_L^{(2)}$ does not vanish. However, for larger masses, *i.e.* $m_4 > 0.01$ GeV, the decay $\Gamma^{Z}_{n_4\to 3\nu}$ gives a good lifetime estimate, shorter than the age of the universe.

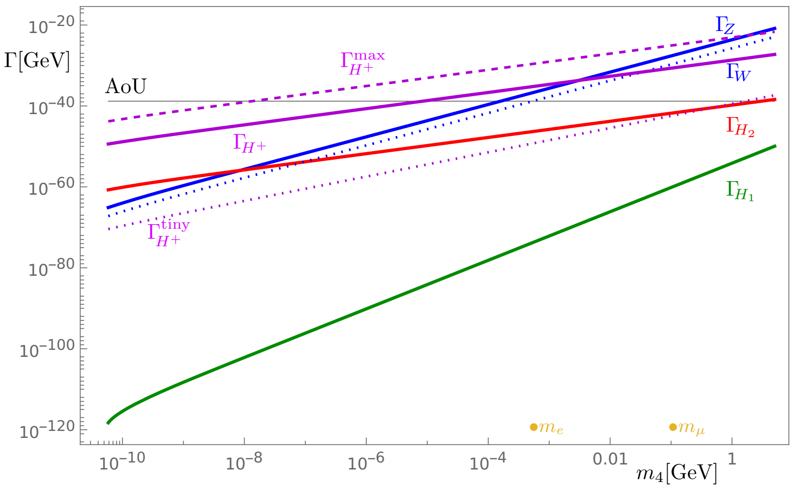

Fig. 2. The decay rates of the sterile neutrino with respect to its mass m_4. Rates using the benchmark point B1 [21], *i.e.* Higgs masses $m_{H_0} = 300$ GeV, $m_A = 441$ GeV, and $m_{H^\pm} = 442$ GeV. AoU describes the rate at which the neutrino has a lifetime as long as the age of the universe. For describing, the Yukawa coupling $Y_N^{(2)}$ were taken $\omega_{22} = \pi/3$ and $r = \pi/6$ as representative model parameters. For definitions, see Ref. [20]. For the charged lepton Yukawa coupling $Y_L^{(2)}$, we took 2π ($\Gamma_{H^+}^{\max}$) as the maximal value, 10^{-2} (Γ_{H^+}) as the "normal" value, and y ($\Gamma_{H^+}^{\text{tiny}}$) as the tiny value.

4. Conclusions

In this paper, we have looked at the sterile neutrino of the GNM and its decays into two channels: the decay into three active neutrinos and the decay into an active neutrino and a photon. We have seen that at tree level, the decay mediated by the Z-boson is the dominant one for masses much smaller than the mass of the Z-boson, which coincides with the results in Ref. [8].

At the loop level, we saw a different scenario. The loops with the W-boson are consistent with the results in Refs. [8–10] up to a factor of 2. This factor comes from the fact that the neutrinos we consider are Majorana. And, as one would expect, this decay rate is lower than the tree-level decay.

However, the loop-level decays mediated by the charged Higgs boson H^+ can be comparable to the tree level and even be dominant, reflecting the spirit of the Grimus–Neufeld construction.

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