

# Lepton number violation in tau lepton decays

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## Abstract

Recent studies of novel four-body lepton number violating decays of  $\tau$  leptons and neutral  $B$  mesons are summarized and updated. These decays are assumed to be enhanced by the exchange of resonant Majorana neutrinos. It is shown that the  $\tau^- \rightarrow \pi^+ l^- l^- \nu_\tau$  decay channels, with  $l = e$  or  $\mu$ , can provide stronger constraints on the mixing vs. mass parameter space of resonant Majorana neutrinos than analogous three-body decays of charged  $B$  mesons.

**Keywords:**

Lepton number violation, Majorana neutrinos, heavy flavor decays, tau lepton

## 1. Introduction

Total lepton number  $L = L_e + L_\mu + L_\tau$  is an absolutely conserved quantum number in the Standard Model (SM). Some extensions of the SM include interactions that can induce  $L$  non-conservation [1]. Minimal extensions of the SM aiming to include massive neutrinos can contain Majorana mass terms, like  $\mathcal{L}_M = \bar{\nu}_R^c M_M \nu_R + \text{h.c.}$ , which provides an appealing mechanism that violates lepton number by two units ( $\Delta L = 2$ ) [2]. A clear signal of Majorana mass terms are  $L$ -number violating processes that involve the production of two equal-sign charged leptons, the most well known and widely studied example being neutrinoless double beta decay in nuclei [3].

In this contribution we consider the exchange of Majorana neutrinos as a source of  $\Delta L = 2$  lepton number violation (LNV) in decays of heavy flavors, and more specifically in four-body decays of the  $\tau$  lepton. These Majorana neutrinos are assumed to be sterile, such that their coupling to the weak charged current are very suppressed by tiny mixings with active neutrinos. Typical neutrino-exchange diagrams contributing to LNV in decays of the  $\tau$  lepton are shown in Figure 1.

Under this scheme, the sensitivity of different heavy flavor LNV decays ( $M$  denotes a vector or pseudoscalar meson and  $l, l' = e, \mu, \tau$  whenever they are allowed by kinematics)

$$\begin{aligned} D_{(s)}^+, B^+, B_c^+ &\rightarrow l^+ l'^+ M^- \\ D^0, B^0, B_s &\rightarrow l^- l'^- M_1^- M_2^- \\ \tau^- &\rightarrow l^+ M_1^- M_2^- \\ \tau^- &\rightarrow \nu_\tau l^- l'^- M^+ \end{aligned}$$

is determined by comparing the mass scale of the exchanged Majorana neutrinos with typical energies of the decay process. Thus, we distinguish three cases [4]:

- If neutrinos are very light compared to their four-momenta in the propagator (actually,  $m_\nu^2 \ll q^2$ ), the decay rates become sensitive to the *effective* Majorana mass defined by  $\langle m_{ll'} \rangle \equiv \sum_i U_{li} U_{l'i} m_i$ , where  $U_{li}$  denote the mixings of light (active) neutrinos described by the PMNS matrix;
- If neutrinos are heavy compared to the mass of the decaying state, the rate is sensitive to  $\sum_N V_{lN} V_{l'N} / m_N$ , where  $V_{lN}$  are the mixings of light (active) and heavy (sterile) neutrinos of type  $N$  (see definition in Section 2).
- Finally, if heavy neutrinos are of the order of the heavy flavor mass scale such that they can be pro-

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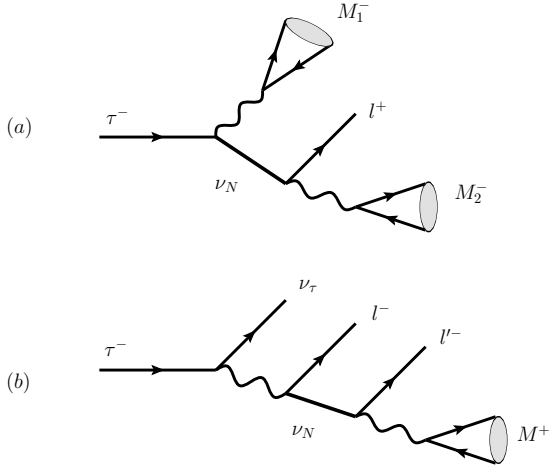


Figure 1: Neutrino-exchange diagrams induced by crossings of the  $W^- W^- \rightarrow l^- l'^- \Delta L = 2$  kernel leading to LNV in (a) three- and (b) four-body tau decays.

duced on their mass-shell ( $q^2 = m_N^2$ ), the rates are largely enhanced due to the resonant effect associated to their decay widths  $\Gamma_N$ , with their decay amplitudes proportional to  $\sum_N V_{lN} V_{l'N} / \Gamma_N$ . This is the so-called *resonant enhancement mechanism* [4] for LNV decays and can occur only for time-like neutrino momenta as in the case of mesons and  $\tau$  lepton decays.

Note that in the first two cases, the rates of heavy flavor decays turn out to be very suppressed, making uninteresting their searches at flavor factories [5, 6]. Lepton number violation in three-body decays of  $\tau$  leptons and charged ( $D$ ,  $D_s$ ,  $B$ ,  $B_c$ ) mesons have been widely investigated previously, both from the theoretical [4, 5, 6, 7, 8] and experimental [9, 10, 11, 12, 13, 14, 15] points of view. The current best experimental upper bounds available on these decay channels are shown in Figure 2; in addition, very stringent bounds of the order of  $10^{-9}$  have been obtained (see for example [13]) for  $K^+ \rightarrow \pi^- l^+ l'^+$  decays, with  $l, l' = e, \mu$ . The measured upper limits allow to exclude a region in the  $|V_{lN}|^2$  vs.  $m_N$  plane of the parameter space, by assuming that a single resonant neutrino (usually denoted by the subindex  $N$  or 4) dominates the decay amplitude. Such sterile Majorana neutrinos, with masses in the range of 1–10 GeV, can appear in the framework of some minimal extensions of the SM; for instance, it has been suggested that they can play an important role to explain simultaneously the oscillations of neutrinos, the baryon asymmetry of the Universe and the dark matter problem [16].

In this paper we present a summary and update of our

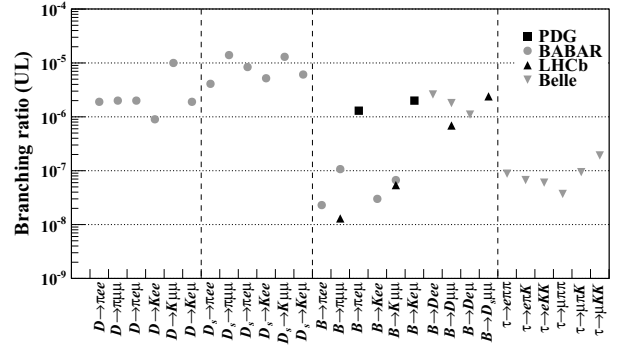


Figure 2: Experimental upper limits on branching ratios of 3-body decays of charged heavy mesons and  $\tau$  lepton [9–15].

recent proposals [17, 18] which consider the four-body decays  $\tau^- \rightarrow \nu_\tau l^- l'^- M^+$  and  $B^0 \rightarrow D^- l^+ l'^+ M^-$ , where  $M$  is a pseudoscalar or vector meson that can be allowed by kinematics (the analogous decay  $\pi^+ \rightarrow e^+ e^+ \mu^- \nu$  was considered in [19]). We illustrate our studies with results on di-muonic channels (results on di-electrons modes can be found in [17, 18]). Searches for these decay channels have not been undertaken by experiments up to now. Here we emphasize that they can provide competitive or even stronger bounds on the parameter space of Majorana neutrinos as compared to three-body decays of heavy flavors.

## 2. Resonant three-body decays

The addition of right-handed singlet neutrinos to the SM leads in a natural way to the appearance of Majorana and Dirac mass terms [2], with Majorana mass terms allowing  $\Delta L = 2$  lepton number violation. The heavier (sterile) neutrinos get involved into charged weak interactions, since after diagonalization of the full neutrino matrix, neutrinos of defined flavor becomes a mixture of light and heavy mass eigenstates, namely,

$$\nu_l = \sum_{i=1}^3 U_{li} \nu_i + \sum_{N=4}^{n+4} V_{lN} \nu_N \quad (1)$$

if  $n$  right-handed singlets are considered. Here,  $U_{li}$  are essentially the entries of the PMNS matrix, and  $V_{lN}$  are the tiny mixings of the active and sterile neutrinos. The charged current interaction Lagrangian in the flavor basis becomes:

$$\mathcal{L}_{cc} = \frac{g}{2\sqrt{2}} \bar{\nu}_l \gamma^\mu (1 - \gamma_5) l \cdot W_\mu^- + \text{h.c.} \quad (2)$$

where  $\nu_l$  is given above.

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