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NEUTRINOLESS DOUBLE BETA DECAY AND LEPTON FLAVOR VIOLATION

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I argue that muon lepton flavor violating (LFV) processes (such as $\mu \to e\gamma$ and $\mu \to e$ conversion in nuclei) provide a useful diagnostic tool to determine whether or not the effective neutrino mass can be safely extracted from the rate of neutrinoless double beta decay.

In the past few years convincing experimental evidence for neutrino oscillations has been collected [1], implying that neutrinos are massive particles, with masses much smaller than those of other known fermions. Among the most urgent open questions [2] in neutrino physics are the determination of (i) neutrino charge conjugation properties (Dirac or Majorana) and (ii) the absolute mass scale in the spectrum. The study of neutrinoless double beta decay ($0\nu\beta\beta$) can help addressing these issues. For one, observation of this $\Delta L = 2$ process would establish the existence of total lepton number violation (LNV), thereby implying that neutrinos are massive Majorana particles [3]. Ideally, the observation of $0\nu\beta\beta$ would also help determine the absolute scale of neutrino mass, since the total decay rate ($\Gamma_{0\nu\beta\beta}$) arising from light Majorana neutrinos is proportional to the square of the effective mass, $m_{\beta\beta}$ (defined precisely below).

It has long been recognized, however, that the extraction of $m_{\beta\beta}$ from $\Gamma_{0\nu\beta\beta}$ is problematic. In general, $0\nu\beta\beta$ can be generated by (i) light Majorana ν exchange (helicity flip and non-flip) or (ii) heavy particle exchange (see, e.g., [6]), resulting from LNV dynamics at some scale above the electroweak one. The relative size of heavy (A_H) versus light particle (A_L) exchange contributions to the decay amplitude can be crudely estimated as follows [7]:

$$A_L \sim G_F^2 \frac{m_{\beta\beta}}{\bar{k}^2}, \; A_H \sim G_F^2 \frac{M_W^4}{\Lambda^5}, \; \frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}} \, , \tag{1}$$

where $m_{\beta\beta} = \sum_i U_{ei}^2 m_{\nu_i}$ is the effective Majorana mass ($U_{\ell n}$ being the light neutrino mixing matrix), $\bar{k}^2 \sim (50 \text{ MeV})^2$ is the typical light neutrino virtuality, and Λ is the heavy scale relevant to the LNV dynamics. Therefore, $A_H/A_L \sim O(1)$ for $m_{\beta\beta} \sim 0.1 - 0.5$ eV and $\Lambda \sim 1$ TeV, and thus the LNV dynamics at the TeV scale leads to similar $0\nu\beta\beta$ decay rate as the exchange of light Majorana neutrinos with effective mass $m_{\beta\beta} \sim 0.1 - 0.5$ eV. While spin-flip and non-flip exchange can be, in principle, distinguished by the measurement of the single-electron spectra or polarization (see e.g. [8]), in most cases the observation of the emitted electrons does not distinguish between light Majorana or heavy particle exchange. Thus, one must look for phenomenological consequences of the different mechanisms other than observables directly associated with $0\nu\beta\beta$.

Here we point out a link between $0\nu\beta\beta$ mechanisms and muon LFV processes [9], with emphasis on the processes $\mu \to e\gamma$ and $\mu \to e$ conversion in nuclei that will be studied with unprecedented sensitivity in the forthcoming MEG [4] and MECO [5] experiments, respectively. The relevant branching ratios are $B_{\mu\to e\gamma} = \Gamma(\mu \to e\gamma)/\Gamma_\mu^{(0)}$ and $B_{\mu\to e} = \Gamma_{\rm conv}/\Gamma_{\rm capt}$, where $\mu \to e\gamma$ is normalized to the standard muon decay rate $\Gamma_\mu^{(0)} = (G_F^2 m_\mu^5)/(192\pi^3)$, while $\mu \to e$ conversion is normalized to the capture rate $\Gamma_{\rm capt}$. The new experiments will probe $B_{\mu\to e\gamma}$ and $B_{\mu\to e}$ at levels that would be sensitive to the effects of LFV induced by interactions involving TeV scale particles. Since models for the generation of Majorana neutrino masses typically also imply the existence of such interactions, studies of charged lepton LFV can also provide insight into the mechanism of $0\nu\beta\beta$. Moreover, one expects different models to predict different ratios of branching fractions, as these depend on the relative size of different form factors. For example, $B_{\mu\to e\gamma}$ is determined by a transition magnetic moment form factor. If the same form factor is also the dominant contribution to $B_{\mu\to e}$, then the ratio of the two rates is expected to be $\sim \alpha/\pi$. However, $B_{\mu\to e}$ receives contributions as well from a transition charge radius form factor, Z-penguins, box diagrams, and in some cases by tree level exchange of exotic particles. In light of this, the main discriminating quantity in our analysis is the ratio $\mathcal{R} = B_{\mu\to e}/B_{\mu\to e\gamma}$. We find that:

(1) Observation of both the LFV muon processes $\mu \to e$ and $\mu \to e\gamma$ with relative ratio $\mathcal{R} \sim 10^{-2}$ implies, under generic conditions, that $\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$.
(2) On the other hand, observation of LFV muon processes with relative ratio $\mathcal{R} \gg 10^{-2}$ opens up many possibilities, inlcuding non-trivial LNV dynamics at the TeV scale (whose effect on $0\nu\beta\beta$ has to be analyzed on a case by case basis). Therefore, in this scenario no definite conclusion on $0\nu\beta\beta$ can be drawn based on LFV rates.
(3) Non-observation of LFV in muon processes in forthcoming experiments would imply either that the scale of non-trivial LFV and LNV is above a few TeV, and thus $\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$, or that any TeV-scale LNV is approximately flavor diagonal.

(If only one process is observed, the deduced constraint on $\mathcal{R}$ may still be of use for our analysis.) Below, we explain the basis for the above observations and discuss the requirements on scenarios that might circumvent them.

In order to arrive at the above results, it is useful to formulate the problem in terms of effective field theory. Relevant quantities in this context are the LNV and LFV scales, which in general may be distinct. As long as both scales are well above the weak scale, then $\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$, and one does not expect to observe LFV signals in forthcoming experiments. In scenarios with high scale LNV ($\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$) but possibly low scale LFV, one can have different LFV signatures: in models such as SUSY-GUT [10] or SUSY see-saw [11], one expects $\mathcal{R} \sim 10^{-2}$, while in models based on E_6 or showing non-decoupling effects one expects $\mathcal{R} \gg 10^{-2}$ [12,13]. Finally, the case where the scales of LNV and LFV are both relatively low ($\lesssim$ TeV) is more subtle, as this scenario might lead to observable LFV and at the same time to ambiguities in interpreting a positive signal in $0\nu\beta\beta$. We have shown [9] that in models with TeV scale $|\Delta L| = 1, 2$ interactions the typical LFV signature is $\mathcal{R} \gg 10^{-2}$. These observartions allow one to establish the criteria enumerated above.

The main claim of Ref. [9] is that in models with TeV scale $|\Delta L| = 1, 2$ interactions and generic flavor content of the couplings one finds that a short-distance contribution to $0\nu\beta\beta$ is accompanied by $\mathcal{R} \gg 10^{-2}$. This statement has been illustrated in two explicit cases: the minimal supersymmetric standard model (MSSM) with R-parity violation (RPV-SUSY) and the Left-Right Symmetric Model (LRSM) (for details see Ref. [9]). The basic mechanism at work is that TeV scale LNV interactions ($\Delta L = \pm 1$ and/or $\Delta L = \pm 2$) generate sizable contributions to the transition charge radius form factor and/or to tree level operators mediating $\mu q \to e q$, thus enhancing $\mu \to e$ conversion over $\mu \to e\gamma$ [14,15,16]. These conclusions can be evaded only by fine-tunings in the appropriate Yukawa couplings.

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