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# Phenomenology of TeV Scale See-Saw Mechanism

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We review the low energy constraints on type I see-saw extensions of the Standard Model in which the scale of new physics, associated to lepton number violation, can be probed at current collider searches. In such scenarios, the flavour structure of the charged current an neutral current weak interactions of the Standard Model leptons with the heavy right-handed neutrinos, which provide the contribution of new physics, is essentially determined by the neutrino oscillation parameters. Correlations among different low energy observables in the lepton sector emerge, which may provide a striking indirect evidence of low energy (TeV scale) see-saw mechanism.

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The measurement of the neutrino mixing pattern as well as the solar and atmospheric neutrino mass scales in neutrino oscillation experiments, has provided compelling evidence for physics beyond the Standard Model (SM) of elementary particles. Massive active neutrinos can be naturally accounted for in see-saw type extensions of the SM, where new fermion or scalar representations are introduced in the theory with suitable Yukawa couplings to the SM lepton doublets. The mass of the new physical states is in general unrelated to the electroweak (EW) symmetry breaking scale and, therefore, can assume arbitrary large values up to the Planck scale.

On the purely phenomenological side, it is interesting to study see-saw scenarios in which new physics is manifest at the TeV scale and can be in principle accessible in current collider searches, LHC included. In this physical context, the phenomenology of type I see-saw extensions has been studied in detail in [1, 2], in a model independent way. The new particle states in such scenarios consist of at least two heavy SM-singlet fermions, which are conventionally denoted as right-handed (RH) neutrinos, $\nu_{aR}$ ($a > 2$), and give rise, when EW symmetry is broken, to the full mass Lagrangian in the neutrino sector:

$$\mathscr{L}_\nu \;=\; -\,\overline{\nu_{\ell L}}\,(M_D)_{\ell a}\,\nu_{aR} - \frac{1}{2}\,\overline{\nu^C_{aL}}\,(M_N)_{ab}\,\nu_{bR} \;+\; \text{h.c.}\,, \tag{1}$$

where $\nu^C_{aL} \equiv C\overline{\nu_{aR}}^T$ ($a = 1,2,\ldots,K$), $M_N = (M_N)^T$ is the $K \times K$ Majorana mass matrix of the RH neutrinos and $M_D$ provides the $3 \times K$ neutrino Dirac mass term. The Majorana mass $m_\nu$ for the active left-handed neutrinos is given by the renowned see-saw relation: $m_\nu \cong -M_D M_N^{-1}(M_D)^T$. After the diagonalization of the full mass matrix given in (1), the charged current (CC) and neutral current (NC) weak interactions involving the heavy Majorana mass eigenstates $N_j$ ($j = 1,2,\ldots,K$) can be expressed as [1]:

$$\mathscr{L}^N_{CC} \;=\; -\,\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha \;+\; \text{h.c.}\,, \tag{2}$$

$$\mathscr{L}^N_{NC} \;=\; -\frac{g}{2c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}\,N_{kL}\,Z^\alpha \;+\; \text{h.c.}\,, \tag{3}$$

with $R^* \cong M_D M_N^{-1}$ at leading order in the see-saw expansion and $V^T M_N V \cong \text{diag}(M_1, M_2, \ldots, M_K)$. The couplings $|(RV)_{\ell j}|$ can in principle be sizable, typically $|(RV)_{\ell j}| \sim 10^{-(3\div 2)}$ if the RH neutrino mass is taken in the TeV range. Then, in order to reproduce small neutrino masses via the see-saw mechanism, a “large” contribution to $m_\nu$ from $N_1$ is *exactly* cancelled by a negative contribution from a second RH neutrino, say $N_2$, provided:

$$(RV)_{\ell 2} = \pm i\,(RV)_{\ell 1}\sqrt{\frac{M_1}{M_2}}\,, \tag{4}$$

where $M_{1,2}$ is the mass of the RH neutrinos $N_{1,2}$. Barring accidental cancellations, relation (4) is naturally fulfilled in models where an approximately conserved lepton charged exists. In such scenarios *$N_1$ and $N_2$ form a pseudo-Dirac pair and the neutrino oscillation parameters fix the flavour structure of their weak CC and NC couplings to gauge bosons and charged leptons, up to an overall scale* (see [1, 2] for a details).

## 1. Neutrinoless double beta decay in TeV scale see-saw scenarios

The mass splitting of the two RH neutrinos is highly constrained from the experimental upper limits set in neutrinoless double beta ($(\beta\beta)_{0\nu}$-) decay experiments. Indeed, in this case the effective

Majorana mass $| < m > |$, which controls the $(\beta\beta)_{0\nu}$-decay rate, receives an additional contribution from the exchange of the heavy Majorana neutrinos $N_k$, which may be sizable/dominant for "large" couplings $(RV)_{\ell j}$. For $K = 2$, given a nucleus $(A,Z)$, one has (see [1, 2] for details):

$$|{<}m{>}| \cong \left| \sum_{i=1}^{3} U_{ei}^2 m_i - \sum_{k=1}^{2} F(A, M_k)\,(RV)_{ek}^2 M_k \right| , \tag{1.1}$$

where for $M_k = (100 \div 1000)$ GeV: $F(A,M_k) \cong (M_a/M_k)^2 f(A)$, $M_a \approx 0.9$ GeV and $f(A) \approx 10^{-(2\div 1)}$. Using eq. (4), the $N_k$ exchange contribution to $|{<}m{>}|$ takes the simple form:

$${<}m{>}^{\rm N} \cong -\,\frac{2z+z^2}{(1+z)^2}\,(RV)_{e1}^2\,\frac{M_a^2}{M_1}\,f(A)\,, \tag{1.2}$$

where $z \equiv |M_2 - M_1|/M_1$ is the relative mass splitting. In the case of *sizable* couplings of RH neutrinos to the charged leptons, *i.e.* $|(RV)_{\ell 1}| \approx 10^{-2}$, this contribution can be even as large as $|{<}m{>}^N| \sim 0.2$ (0.3) eV for $z \cong 10^{-3}\,(10^{-2})$ and $M_1 \cong 100\,(1000)$ GeV [1, 2]. [1] An effective Majorana mass of this order of magnitude may take place in both types of neutrino mass spectrum and can be accessible in outgoing experiments looking for $(\beta\beta)_{0\nu}$-decay (*e.g.* the GERDA experiment [3], which can probe values of $|{<}m{>}| \sim 0.03$ eV).

## 2. Charged lepton radiative decays in TeV scale see-saw scenarios

In the scenario under discussion, lepton flavour radiative decays allow to put strong constraints on the size of the mixing between light and heavy Majorana neutrinos. The most relevant bounds are obtained from the current experimental upper limit on $\mu \to e+\gamma$ branching ratio [2]:

$$B(\mu \to e+\gamma) = \frac{\Gamma(\mu \to e+\gamma)}{\Gamma(\mu \to e+\nu_\mu+\overline{\nu}_e)} = \frac{3\alpha_{\rm em}}{32\pi}\,|T|^2 , \tag{2.1}$$

$$\begin{aligned} T &= \sum_{j=1}^{3} [(1+\eta)U]^*_{\mu j}\,[(1+\eta)U]_{ej}\,G\!\left(\frac{m_j^2}{M_W^2}\right) + \sum_{k=1}^{2} (RV)^*_{\mu k}\,(RV)_{ek}\,G\!\left(\frac{M_k^2}{M_W^2}\right) \\ &\cong\; 2\left[(RV)^*_{\mu 1}\,(RV)_{e1}\right]\,[G(X) - G(0)]\,, \end{aligned} \tag{2.2}$$

where $\eta \equiv -RR^\dagger/2$. The last relation arises from (4) and taking into account the further constraint $z \ll 1$, derived from $(\beta\beta)_{0\nu}$-decay rate upper bound. Therefore, taking $B(\mu \to e+\gamma) < 2.4\times 10^{-12}$ at 90% C.L. from MEG experiment [4], the following constraint for $M_1 = 100$ GeV ($M_1 = 1$ TeV) is derived [2]

$$\left|(RV)^*_{\mu 1}\,(RV)_{e1}\right| < 0.8\times 10^{-4}\,(0.3\times 10^{-4})\,. \tag{2.3}$$

## 3. Interplay between lepton flavour and lepton number violating observables

Since the flavour structure of the neutrino Yukawa couplings is fixed in the present scenarios [2], correlations among different low energy leptonic observables may be a relevant signature of

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[1] Therefore, in this scenario the two RH neutrinos $N_1$ and $N_2$ form a pseudo-Dirac pair. Notice that this conclusion is valid even in the case in which there is no conserved lepton charge in the limit of zero splitting at tree level between the masses of the pair [1, 2].

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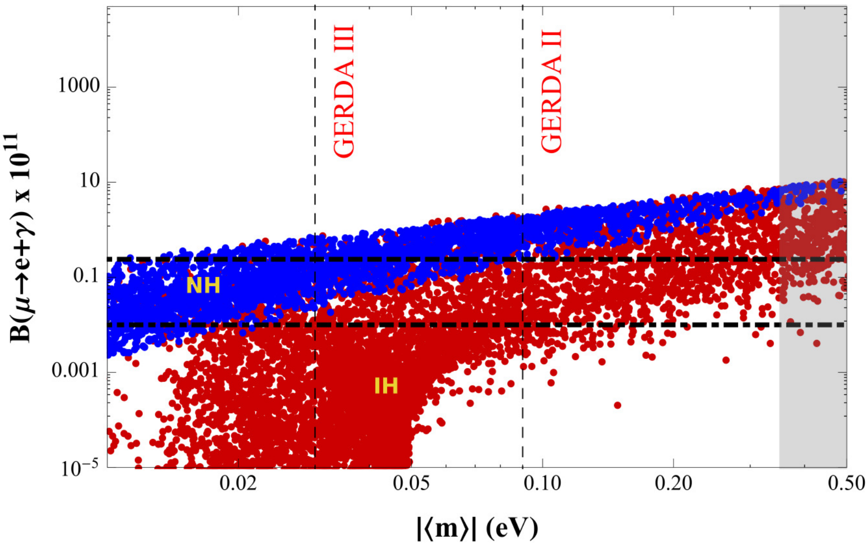

**Figure 1:** $B(\mu \to e+\gamma)$ vs $|<m>|$ for $M_1 = 100$ GeV and $|M_2 - M_1|/M_1 = 10^{-3}$.

TeV scale type I see-saw mechanism. Indeed, in the simple extension of the Standard Model considered, with the addition of two heavy RH neutrinos $N_1$ and $N_2$ at the TeV scale, which behave as a pseudo-Dirac particle, *a sizable (dominant) contribution of* $N_1$ *and* $N_2$ *to the* $(\beta\beta)_{0\nu}$*-decay rate would imply a "large" enhancement of the muon radiative decay rate*. In fact, if $|<m>| \cong |<m>^{\rm N}|$, where $<m>^{\rm N}$ is given in eq. (1.2), it is easy to show that [2]

$$B(\mu \to e+\gamma) \;\cong\; \frac{3\alpha_{\rm em}}{64\pi}\,|G(0)-G(X)|^2\,|r|^2\,\frac{M_1^2}{M_a^4}\,\frac{|<m>^{\rm N}|^2}{z^2(f(A))^2}\,, \qquad (3.1)$$

where $0.5 \lesssim |r| \lesssim 30$ ($0.01 \lesssim |r| \lesssim 5$) for the normal (inverted) hierarchical light neutrino mass spectrum. The analytic relation in eq. (3.1) is confirmed by the results of the numerical computation reported in Figure 1, where it is shown the correlation between the $\mu \to e+\gamma$ branching ratio and the effective Majorana mass in the case of "large" couplings between the RH (pseudo-Dirac pair) neutrinos and charged leptons. In general, a lower bound on $B(\mu \to e+\gamma)$ within the MEG experiment sensitivity reach is set for both light neutrino mass hierarchies (normal and inverted) if a positive signal is detected by GERDA, *i.e.* for $|<m>| \sim 0.1$ eV.

In conclusion, the observation of $(\beta\beta)_{0\nu}$-decay in the next generation of experiments, under preparation at present, and of the $\mu \to e+\gamma$ decay in the MEG experiment, could be the first indirect evidence for the TeV scale type I see-saw mechanism of neutrino mass generation.

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