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Lepton Mixing and charged Lepton Flavour Violation from Inverse Seesaw

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We consider two possible realizations of the inverse seesaw mechanism with 3+3 sterile states to generate light neutrino masses. Flavor symmetries combined with CP are used for predicting lepton mixing. Prospective bounds on different cLFV processes are shown to constrain the parameter space of this scenario.

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1. Introduction

The origin of neutrino masses and the flavor structure in the lepton sector represent some of the most relevant phenomena not addressed by the Standard Model (SM). Several Beyond SM (BSM) solutions, such type I-II-III seesaw models require new particles with masses much larger than the electroweak scale if couplings are of order one. On the other hand, alternative mechanisms such as the Inverse Seesaw (ISS)[1] can successfully accommodate small neutrino masses with new particles in the TeV-range. A realization of this mechanism is considered in the following: $3 + 3$ heavy sterile states $N_i, i = 1, 2, 3, S_j, j = 1, 2, 3$ are added to SM. A flavor symmetry G_f, belonging to the series of groups $\Delta(3n^2)$ and $\Delta(6n^2)$ [2], and a generalized CP symmetry are imposed. This is broken non-trivially to a residual $G_l = Z_3$ group in the charged lepton sector and to to $G_\nu = Z_2 \times CP$ among the neutral states. Two different realizations of the framework, corresponding to different choices of the representations under the flavor group of the fields, are considered.

2. Scenario

The following lagrangian grants mass to the neutral states:

$$-(y_D)_{\alpha i}\bar{L}^c_\alpha H N^c_i - (M_{NS})_{ij}\bar{N}_i S_j - \frac{1}{2}(\mu_S)_{kl}\bar{S}^c_k S_l + h.c. \tag{1}$$

where L_α are the left-handed lepton doublets, H the Higgs field, $m_D = y_D\langle H\rangle$ (with $\langle H\rangle \approx$ 174GeV) is the Dirac neutrino Yukawa matrix, M_{NS} connects the gauge singlets N_i and S_j, μ_S is the Majorana mass matrix of S_j. The latter constitutes a source of lepton number violation. In the basis $(\nu_{\alpha L}, N^c_i, S_j)$ the following nine-by-nine mass matrix has to be considered:

$$\mathcal{M}_{Maj} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_{NS} \\ 0 & M_{NS}^T & \mu_S \end{pmatrix} \tag{2}$$

With $|\mu_S| \ll |m_D| \ll |M_{NS}|$ the light neutrino mass matrix reads [3]:

$$m_\nu \approx m_D \left(M_{NS}^{-1}\right)^T \mu_s M_{NS}^{-1} m_D^T \tag{3}$$

Lepton mixing is determined by $\tilde{U}_\nu$, the upper-left 3×3 sub-matrix of the unitary matrix $\mathcal{U}$ that diagonalizes $\mathcal{M}_{Maj}$. Choosing the basis in which the charged lepton mass matrix is diagonal, the non-unitary PMNS matrix is written as:

$$\tilde{U}_{PMNS} = \tilde{U}_\nu = (1-\eta)\,U_0 \qquad \text{with} \qquad \eta = \frac{1}{2} m_D^* \left(M_{NS}^{-1}\right)^\dagger M_{NS}^{-1} m_D^T \tag{4}$$

with U_0 unitary and η hermitian.

Different choices of the representations assigned to the fields $L,\ N,\ S$ can have different phenomenology [4, 5]. Option 1 for example ($L, N, S \sim \mathbf{3}$, with $\mathbf{3}$ an irreducible complex and faithful representation of G_f) was shown to lead to highly suppressed rates of cLFV processes [6]. We present here results for Option 2 ($L \sim \mathbf{3}$; $N, S \sim \mathbf{3}'$ with $\mathbf{3}'$ irreducible, real and unfaithful) and Option 3 ($L, N \sim \mathbf{3}$, $\ S \sim \mathbf{3}'$). For the two, different terms in Eq.1 are responsible for the explicit breaking of the symmetry (respectively, the first and second terms explicitly break the flavor symmetry, while the remaining ones are invariant under the whole group), and could thus correspond to different mechanisms that lead to the symmetry breaking.

Mass matrices are constrained by symmetry. For both options here considered, μ_S has trivial structure:

$$\mu_S = \mu_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \tag{5}$$

with $\mu_0 > 0$. For Option 2, M_{NS} is also trivial, and all the flavor information and the symmetry breaking is carried by y_D:

$$M_{NS} = M_0 \mathbb{1}_3 \qquad y_D = \Omega(\mathbf{3})^* R_{ij}(\theta_L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} P^{ij}_{kj} R_{kl}(-\theta_R) \Omega(\mathbf{3}') \tag{6}$$

with $M_0 > 0$. Heavy sterile states form three pairs of almost-degenerate pseudo-Dirac neutrinos of mass $M_0 \pm \frac{\mu_0}{2}$. Option 2 is thus described by two mass scales, M_0 (setting the mass of the heavy sterile states and scanned in a range $150\text{GeV} \leq M_0 \leq 10\text{TeV}$) and μ_0 (varied between $100\text{eV} \leq \mu_0 \leq 100\text{keV}$), three Yukawas y_i, $i = 1, 2, 3$, ajusted to reproduce light neutrino masses, and two real angles θ_L (fitted to accommodate lepton mixing angles) and θ_R, varied between 0 and 2π.

For Option 3, μ_S and y_D are trivial, while M_{NS} carries all the flavor information:

$$y_D = y_0 \mathbb{1}_3 \qquad M_{NS} = \Omega(\mathbf{3}) R_{ij}(\theta_N) \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix} P^{ij}_{kl} R_{kl}(-\theta_S) \Omega(\mathbf{3}^\dagger) \tag{7}$$

heavy sterile states again form three pairs of pseudo-Dirac neutrinos, now non-degenerate and with masses $M_i \pm \frac{\mu_0}{2}$. Option 3 is described by four mass scales M_i, $i = 1, 2, 3$, adjusted to reproduce the light neutrino masses, and μ_0 ($100\text{eV} \leq \mu_0 \leq 10^3\text{keV}$), one real Yukawa y_0 varied in the range $10^{-5} \leq y_0 \leq 1$ and two real angles θ_N (fitted to accommodate lepton mixing angles) and θ_R (again in $0 \leq \theta_R \leq 2\pi$).

Above, the matrices $\Omega(\mathbf{3})$ and $\Omega(\mathbf{3}')$ are determined by the CP transformation, and the planes of the rotation matrices R_{ij}, R_{ik} are given by the plane of the two degenerate eigenvalues of the Z_2 generators $Z(\mathbf{3})$ and $Z(\mathbf{3}')$ in the basis transformed by $\Omega(\mathbf{3})$ and $\Omega(\mathbf{3}')$. The permutation matrix P^{ij}_{kl} is necessary whenever the two planes do not coincide. The form of these matrices depends on the choice of the residual symmetry, the different choices being labeled Case 1) thorugh Case 3b.1) [6–8]. For all cases, we performed an analytical and numerical study of lepton mixing and cLFV.

Only the prospective bounds on the $\mu - e$ transitions are considered, as current bounds are non-constraining. We employ the bounds on $\mu \to e\gamma$ from MEG II [10], on $\mu \to 3e$ from Mu3E Phase II [11], on $\mu - e$ conversion from COMET [12].

Both Options lead to similar predictions of the observables considered, the upper and lower values obtained in the scanned ranges always differing by at most a factor of order unity. We show in Fig.1 the predictions for the mentioned processes for Option 3 (Results for Option 2 are found in

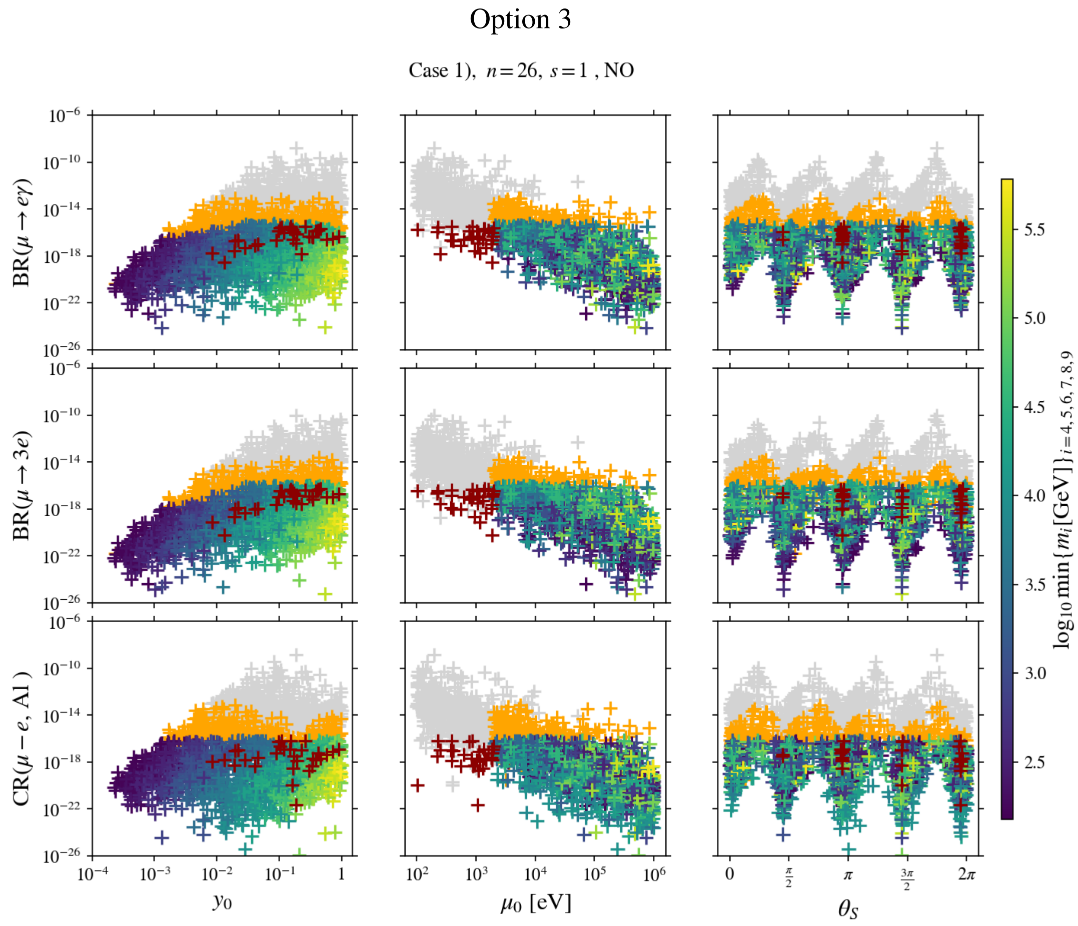

Figure 1: Results for cLFV observables for Option 3, Case 1). Details in [5].

[5]) Case 1) with $n = 26$ and $s = 1$ and normal ordering (NO) with the mass of the lightest neutrino mass set to $m_0 = 0.03$eV. Gray points correspond to parameter values for which at least one of the prospective bound on the considered processes as well as the current bounds on at least one of the matrix elements of η are violated [13]. Orange point correspond to parameter values for which at least one of the bounds on the rates is violated while the bounds on η are respected. Red points correspond to parameter values which comply with the bounds on the rates but violate bounds on η. Finally, the points in the Green-Yellow-Blue colormap comply with all bounds. On the color bar we can read to which value of the average Yukawa for Option 2 (or the smallest mass of the heavy sterile states for Option 3) each point corresponds. A lower limit $\mu_0 \gtrsim 2$keV is observed for all cases analyzed, the bounds on BR($\mu \to 3e$) and CR($\mu - e$, Al) are reached for both Options, while the predictions for BR($\mu \to e\gamma$) always remain about two order of magnitudes below the prospective bound, thus only mildly constraining the model. A modulation of the points for varying $\theta_{R(S)}$ is observed, showing an enhancement of the rates for $\cos 2\theta_{R(S)} \approx 0$ and a suppression for $|\cos 2\theta_{R(S)}| \approx 1$ (For Case 2) the cosine is replaced by a sine). Other cases, e.g. Case 2) with $n = 14$, $s = 1$, $t = 2$ shows no such dependence from this angle. Similar results are also obtained for Inverted Ordering (IO) and smaller values of m_0 [5]. Similar predictions are obtained

for both Options and for all cases considered, the best possibility of discerning between different residual symmetries residing in the possible enhancements of the rates for particular ranges of $\theta_{R(S)}$. Additionally, direct searches for fermionic states could eventually shed light on the couplings of these with charged leptons, thus possibly constraining the particular residual symmetry and the mass scales of such particles.

The two options show nonetheless several differences, asides from the different spectrum of the heavy sterile states. For Option 2, one can show that the analytical expressions of the branching ratios and the conversion rate are mostly proportional to $\eta_{\alpha\beta}$ (carrying all the dependence on the choice of the residual symmetry) as the various heavy states contribute equally to the processes. An interesting consequence is that CR$(\mu - e)$ features a cancellation among its contributions for a certain value of M_0 depending on the particular nucleus considered. Such is also independent of the choice of the residual symmetry (for Aluminum we find $M_0 \approx 6.5$TeV, see also [9]), as due to the almost-degenerate nature of the heavy sterile states, all the dependence of the rates on the former is factorized in an overall $|\eta_{e\mu}|^2$ factor. The cancellation is between the up and down quarks contributions.

For Option 3, the dependence on the Case considered is less trivial, as the non-degenerate nature of the heavy states doesn't allow to disentangle the $\mathcal{U}$ matrix elements from the loop functions. A cancellation of CR$(\mu - e)$ can still be observed for some Cases, such as per Case 1) and Cases 3a) and 3 b.1) (the latter two only for $s = 0$). For the remaining cases, the cancellation is replaced by a local minima. The position of either the cancellation or the local minima is also dependent on the value of θ_S. The origin of this effect is still traced to the different signs of the up and down quarks.

No further bounds are obtained from cLFV τ decays ($\tau \to \mu\gamma,\ \tau \to e\gamma,\ \tau \to 3\mu,\ \tau \to 3e$) as the predicted branching ratios are much below current and future limits.

Direct searches of additional fermionic states (CMS, ATLAS) in the TeV-range have the best chance of distinguishing among the two Options by the degenerate or not nature of their spectrum.

3. Conclusions

The ISS is a viable mechanism to generate neutrino masses and keep the masses of the heavy sterile states in an interesting TeV-range, while fermion mixing can then be addressed by imposing Flavor and CP symmetries on the model. The different choices of the fields representation under the flavor group G_f (different Options) and of the residual symmetry group among neutral states G_ν (different Cases) result in distinct phenomenological signatures. We have here considered Options 2 and 3 which lead to sizable signals of cLFV processes ($\mu - e$ transitions), thus allowing us to constrain the model's parameter space.

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