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# eV-scale sterile neutrinos from 331-model with Froggatt-Nielsen and linear seesaw mechanisms

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*Abstract.* We consider the properties of sterile neutrino sector of an extension of the Standard Model, (SM) based on $\mathrm{SU}(3)_\mathrm{C}\times\mathrm{SU}(3)_\mathrm{L}\times\mathrm{U}(1)_X$ gauge symmetry (331-model). Our model has built-in Froggatt-Nielsen mechanism (FN) for generating the Yukawa terms as effective operators and subsequently the correct fermion mass hierarchies, unexplained in the Standard Model. In addition, it has another built-in property, the linear seesaw mechanism. The model is very economical, containing three scalar triplets and and six sterile neutrinos. The medium-heavy eV-scale sterile neutrinos mix with the active neutrinos, and the disappearance of active flavours would be a "smoking gun" of this model, among many others. New physics scale is assumed to be $\sim 7$ TeV.

## 1 Introduction

The SM does not explain the neutrino masses and oscillations, number of generations or their hierarchical fermion masses. 331-models have been advocated to explain the number of fermion families in nature [1], and the FN mechanism is one of the most popular explanations of the charged fermion mass hierarchy [2]. It can be incorporated into 331-models (FN331), as was shown in [4]. Here we show that FN331 can be extended to also explain the neutrino sector via linear seesaw mechanism [3], by introducing three extra right-handed eV-scale singlet neutrinos to the model presented in [5].

## 2 Fields and symmetry breaking

In 331-models, the electric charge in our model is defined as

$$Q = T_3 + \beta T_8 + X. \tag{1}$$

We assign $\beta = -\frac{1}{\sqrt{3}}$, which produces minimal scalar sector with effective flavon. The left-handed leptons are assigned into $\mathrm{SU}(3)_\mathrm{L}$-triplets and the right-handed leptons into $\mathrm{SU}(3)_\mathrm{L}$-singlets. See Table 1 for quantum number assignments and representations. The fields $\nu_i'$ and $N_{R,i}$ are new neutrino-like fields.

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| **Field** $(i=1,2,3)$ | $\mathrm{SU}(3)_C$ | $\mathrm{SU}(3)_L$ | $\mathrm{U}(1)_X$ | $Q_{\mathrm{FN}}$ |
|---|---|---|---|---|
| $L_{L,i} = \begin{pmatrix} \nu_i \\ e_i \\ \nu'_i \end{pmatrix}_L$ | **1** | **3** | $-\frac{1}{3}$ | 9 |
| $e_R$ | **1** | | $-1$ | 1 |
| $\mu_R$ | | | | $-2$ |
| $\tau_R$ | | | | $-4$ |
| $N_{R,i}$ | | | 0 | |
| $\eta$ | **1** | **3** | $\frac{2}{3}$ | $-1$ |
| $\rho$ | | | $-\frac{1}{3}$ | 1 |
| $\chi$ | | | | 0 |

Table 1: Scalar and lepton quantum numbers and representations in our model.

The quark and gauge sectors of our model is presented in [4,5]. The fermions are charged under global $\mathrm{U}(1)_{\mathrm{FN}}$-symmetry, which forbids direct inclusion of fermion Yukawa couplings. See Table 1 for FN-charge assignments. Minimal scalar sector that breaks the gauge symmetry and produces the tree-level masses to fermions and gauge bosons, consists of three scalar triplets,

$$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \\ \eta'^+ \end{pmatrix}, \quad \rho = \begin{pmatrix} \rho^0 \\ \rho^- \\ \rho'^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^0 \\ \chi^- \\ \chi'^0 \end{pmatrix}.$$

Only two triplets would produce two massless quarks. Two of the three scalar triplets are in the same 331-representation. This is a special feature of our choice of electric charge in Eq. (1), and allows us to use the combination $\rho^\dagger\chi$ as the effective flavon. The most general electric charge conserving vacuum is,

$$\langle \eta^0 \rangle = \frac{v'}{\sqrt{2}}, \quad \langle \rho^0 \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle \rho'^0 \rangle = \frac{v_2}{\sqrt{2}}, \quad \langle \chi^0 \rangle = \frac{u}{\sqrt{2}}. \tag{2}$$

Note that the vacuum expectation value (VEV) of $\chi'^0$ can be rotated away due to residual vacuum symmetry. The symmetry breaking pattern of our model is

$$\mathrm{SU}(3)_\mathrm{L} \times \mathrm{U}(1)_X \xrightarrow{u,v_2} \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \xrightarrow{v_1,v'} \mathrm{U}(1)_{\mathrm{em}},$$

where $v_2, u \gg v_1, v'$. The new scalars and gauge bosons acquire masses that are of the order of $\mathrm{SU}(3)_\mathrm{L} \times \mathrm{U}(1)_X$ breaking scale. We have chosen $v_2 = 7.5$ TeV, $u = 7$ TeV, $v_1 = v' = 203.205$ GeV.

## 3 Emergence of neutrino masses

The combination $\rho^\dagger\chi$ is a gauge singlet, having a non-zero $\mathrm{U}(1)_{\mathrm{FN}}$ charge. We choose it to be the flavon in FN mechanism. The Yukawa couplings are forbidden by the $\mathrm{U}(1)_{\mathrm{FN}}$ charge assignment, but the effective operators

$$\Delta\mathcal{L} = \sum_{s,f} \left(c_s^f\right)_{ij} \left(\frac{\rho^\dagger\chi}{\Lambda_{\mathrm{FN}}^2}\right)^{\left(n_f^s\right)_{ij}} \bar{\psi}_{L,i}^f s f_{R,j} + \text{h.c.} \tag{3}$$

are allowed. The sum is understood over scalar ($s = \eta, \rho, \chi$) and fermion ($f$) degrees of freedom. The Yukawa-generating matrices (YGM) $\left(c_s^f\right)_{ij}$ are dimensionless and $\mathcal{O}(1)$. The $\bar{\psi}_{L,i}^f$ and $f_{R,j}$ represent here the fermion (anti)triplets and singlets, respectively. $\Lambda_{\mathrm{FN}}$ is the mass scale of the heavy FN messengers that have been integrated out. Powers $\left(n_f^s\right)_{ij}$ are uniquely determined by $\mathrm{U}(1)_{\mathrm{FN}}$ charge conservation. Yukawas are created when $\rho^\dagger\chi$ acquires its VEV:

$$\left(y_s^f\right)_{ij} = \left(c_s^f\right)_{ij} \left(\frac{v_2 u}{2\Lambda_{\mathrm{FN}}^2}\right)^{\left(n_f^s\right)_{ij}} \equiv \left(c_s^f\right)_{ij} \varepsilon^{\left(n_f^s\right)_{ij}} \tag{4}$$

We fix the expansion parameter $\varepsilon \equiv (v_2 u)/\Lambda^2 = \sin\theta_C \approx 0.23$ to be the sine of Cabibbo angle, since with this choice the CKM-matrix is generated naturally [4]. Picking up neutrino Yukawa terms, neutrino masses are generated at tree level via linear seesaw mechanism:

$$\mathcal{L}_{\mathrm{m}}^{\nu} = \frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{\nu'}_L & \overline{(N_R)^c} \end{pmatrix} \begin{pmatrix} \mathbf{0} & 2m^{D\dagger} & m^{N*} \\ 2m^{D*} & \mathbf{0} & m'^{N*} \\ m^{N\dagger} & m'^{N\dagger} & M^* \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_L'^c \\ N_R \end{pmatrix} + \text{h.c.}, \tag{5}$$

where all the submatrices have size $3 \times 3$, and they are given by,

$$m_{ij}'^N = \frac{v_2}{\sqrt{2}} c_{ij}^N \epsilon^{q\left(\bar{L}_{L,i}\right)+q\left(N_{R,j}\right)+q(\rho)} + \frac{u}{\sqrt{2}} c'^N_{ij} \epsilon^{q\left(\bar{L}_{L,i}\right)+q\left(N_{R,j}\right)+q(\chi)}, \tag{6}$$

$$m_{ij}^N = \frac{v_1}{\sqrt{2}} c_{ij}^N \epsilon^{q\left(\bar{L}_{L,i}\right)+q\left(N_{R,j}\right)+q(\rho)}, \quad M_{ij} = \sqrt{\frac{u v_2}{2\epsilon}} c_{ij}^M \epsilon^{q\left(N_{R,i}\right)+q\left(N_{R,j}\right)}, \tag{7}$$

$$\text{and} \quad m_{ij}^D = \frac{v'}{\sqrt{2}} \left(c_{\eta^*}^N\right)_{ij} \epsilon^{q\left(\bar{L}_{L,i}\right)+q\left(\bar{L}_{L,j}\right)-q(\eta)}. \tag{8}$$

The light neutrino mass matrix is obtained via block diagonalization:

$$m_\nu = 4m^{D\dagger}\left(m'^{N\dagger}\right)^{-1} M^* \left(m'^{N*}\right)^{-1} m^{D*} - \left[m^{N*}\left(m'^{N*}\right)^{-1} 2m^{D*} + 2m^{D\dagger}\left(m'^{N\dagger}\right)^{-1} m^{N\dagger}\right].$$

## 4 Numerical analysis

We used the following values for YGM's, which result in the correct absolute values $|U|$ of the neutrino mixing matrix within the current $3\sigma$ bounds.

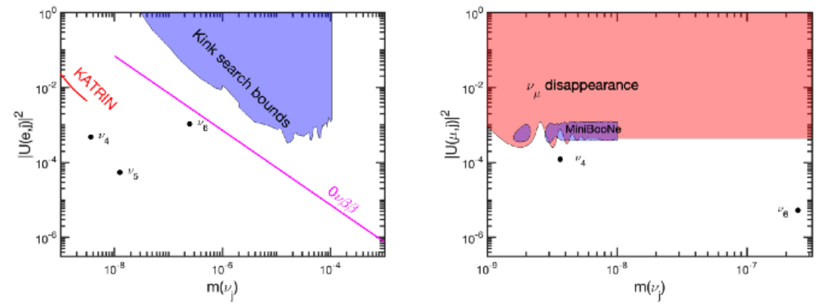


Figure 1: Horizontal axis: sterile neutrino mass in GeV. Vertical axis: sterile neutrino $\nu_i'$ mixing with $\nu_e$ (left) and $\nu_\mu$ (right). Shaded areas are excluded.

$$
c^L = \begin{pmatrix} 2.3096 & -3.6834 & -3.4934 \\ -0.54887 & -3.5671 & -2.3664 \\ -0.97663 & 3.651 & -1.171 \end{pmatrix}, \quad c^N = \begin{pmatrix} 1.0653 & -4.3 & 2.2631 \\ -2.1733 & 2.657 & 0.8052 \\ 2.2396 & -2.5456 & 4.8348 \end{pmatrix},
$$

$$
c^M = \begin{pmatrix} 3.7613 & -1.6919 & 0.9669 \\ -1.6919 & -2.7951 & -3.1256 \\ 0.9669 & -3.1256 & -3.5534 \end{pmatrix}, \quad c^{N\prime} = \begin{pmatrix} 0.89298 & -1.907 & 1.0669 \\ -3.3662 & 4.9836 & -3.163 \\ -1.8707 & -4.2456 & -3.3193 \end{pmatrix},
$$

$$
e = \begin{pmatrix} 0 & -1.1949 & -1.8096 \\ -2.018 & 0 & -1.4684 \\ -4.9797 & -1.306 & 0 \end{pmatrix}, \quad |U| = \begin{pmatrix} 0.82345 & 0.54885 & 0.14381 \\ 0.47676 & 0.53191 & 0.69984 \\ 0.30761 & 0.64485 & 0.69967 \end{pmatrix}.
$$

Note that the $c^M$ is a symmetric and $c^N_{\eta^*} \equiv \frac{1}{2}(e - e^T)$ is an antisymmetric matrix by construction. Our YGM choice provides light neutrino masses $m_i$ and mass squared differences $\Delta m^2_{ij}$ consistent with cosmology and neutrino experiments. See Fig. 1 for expected $\nu$–$\nu'$ mixing and experimental constraints. The sterile neutrino $\nu_4$ has the right mass to produce oscillations anomalies in next-generation oscillation experiments.


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