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keV right-handed neutrinos from type II seesaw mechanism in a 3-3-1 model

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ABSTRACT

We adapt the type II seesaw mechanism to the framework of the 3-3-1 model with right-handed neutrinos. We emphasize that the mechanism is capable of generating small masses for the left-handed and right-handed neutrinos and the structure of the model allows that both masses arise from the same Yukawa coupling. For typical values of the free parameters of the model we may obtain at least one right-handed neutrino with mass in the keV range. Right-handed neutrino with mass in this range is a viable candidate for the warm component of the dark matter existent in the universe.

1. Introduction

One of the main puzzles in particle physics concerns the smallness of the neutrino masses. It is considered that the most elegant way of generating small Majorana neutrino masses is through seesaw mechanisms. There are three distinct ways of accomplishing the seesaw mechanism into the standard model. In the so-called type I seesaw mechanism [1], small neutrino masses are induced by three heavy right-handed neutrinos, while in the type II [2] and type III [3] seesaw mechanisms, small neutrino masses are induced by a heavy triplet of scalars and a heavy triplet of leptons, respectively. All these mechanisms were originally developed to induce small masses to the left-handed neutrinos.

Right-handed neutrinos were not detected yet in nature. Nobody knows if they are light or heavy particles. Light right-handed neutrinos are phenomenologically interesting because of their intricate implications in particle physics [4], astrophysics and cosmology [5]. For example, warm dark matter in the form of sterile neutrinos with mass in the keV range has been advocated as a solution to the conflict among cold dark matter and observations of clustering on sub galactic scales [6]. There are many papers devoted to the study of such implications [7–10]. However, as far as we know, there are few ones devoted to the development of mechanisms that could lead to light right-handed neutrinos [11]. Suppose a scenario where the left-handed neutrinos as well as the right-handed ones are all light particles. In a scenario like this, a challenging task to particle physics would be to develop a seesaw mechanism in the framework of some extension of the standard model that could induce the small masses of these neutrinos. In this regard, an even more interesting scenario would be one where the explanation of the lightness of both left-handed and right-handed neutrino masses would have a common origin.

In this Letter we consider a variant of the gauge models based in the $SU(3)_C \otimes SU(3)_L \otimes U(1)_N$ (3-3-1) symmetry called 3-3-1 model with right-handed neutrinos (331νR) [12] and adapt the type II seesaw mechanism in this framework. We proceed as in the implementation of the conventional type II seesaw mechanism in the standard model. Due to the structure of the 331νR, instead of a triplet, we have to add a sextet of scalars to its particle content. As our main result, we will show that this type II seesaw mechanism will induce small masses for the left-handed and right-handed neutrinos. Moreover, both neutrino masses have a common origin. As common origin we mean that both masses arise from the same Yukawa term, or better, the same set of Yukawa couplings are common for both neutrino masses. Another interesting point is that the mechanism can provide right-handed neutrinos much heavier than the left-handed ones. For example, for typical values of the free parameters of the model we can obtain at least one right-handed neutrino with mass in the keV range. This is particularly interesting because right-handed neutrino with mass in this range is a viable candidate for the warm component of the dark matter existent in the universe.

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This work is organized as follow. In Section 2 we present some aspects of the model relevant for the implementation of the mechanism. In Section 3 we implement the mechanism in the model and present an illustrative example. We finish this work with a summary in Section 4.

2. Some aspects of the model

In the 331νR the leptons come in triplet and singlets as follows [12],

$$f_{aL} = \begin{pmatrix} \nu_a \\ e_a \\ \nu_a^c \end{pmatrix}_L \sim (1,3,-1/3), \quad e_{aR} \sim (1,1,-1), \tag{1}$$

with $a = 1,2,3$ representing the three known generations. We are indicating the transformation under 3-3-1 after the similarity sign, "$\sim$".

In the gauge sector, the model recovers the standard gauge bosons and disposes of five more other called $V^\pm$, U^0, $U^{0\dagger}$ and Z' [12].

The scalar sector of the model is composed by three scalar triplets as follows [12]

$$\chi = \begin{pmatrix} \chi^0 \\ \chi^- \\ \chi'^0 \end{pmatrix}, \qquad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho'^+ \end{pmatrix}, \qquad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta'^0 \end{pmatrix}, \tag{2}$$

with η and χ transforming as $(1,3,-\frac{1}{3})$ and ρ transforming as $(1,3,-\frac{2}{3})$. Although the scalar content above involves five neutral scalars, it is just necessary that η^0, ρ^0 and χ'^0 develop vacuum expectation value (VEV) for that all the particles of the model, with exception of the neutrinos, develop their correct mass terms.

In the 331νR neutrino mass terms must, necessarily, involve the product $\bar{f}_L f_L^c$. Considering its transformation by the $SU(3)_L$ symmetry, $\bar{f}_L f_L^c = 3^* \otimes 3^* = 3 \oplus 6^*$, we see that, in order to generate mass terms for the neutrinos, we must couple $\bar{f}_L f_L^c$ to an anti-triplet or to a sextet of scalars. Previous works showed that the first case leads to degenerate Dirac mass terms for the neutrinos [12]. This case is not of interest for us here. In regard to the scalar sextet, recent works have employed it to implement the type I seesaw mechanism into the model [13].

In this work we employ the scalar sextet to implement the type II seesaw mechanism into model [14]. The sextet we refer has the following scalar content,

$$S = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^0 & \Delta^- & \Phi^0 \\ \Delta^- & \Delta^{--} & \Phi^- \\ \Phi^0 & \Phi^- & \sigma^0 \end{pmatrix} \sim \left(1, 6, \frac{-2}{3}\right). \tag{3}$$

With the lepton triplet f_L and the sextet S we form the Yukawa coupling $\bar{f}_L f_L^C S$. The sextet S presents three neutral scalars that may develop VEV. The VEVs of the neutral scalars Δ^0 and σ^0 will lead to Majorana mass terms for both the left-handed and right-handed neutrinos respectively, while the VEV of the neutral scalar Φ^0 will generate a Dirac mass term which mix the left-handed neutrinos with the right-handed ones. In order to implement the type II seesaw mechanism the Dirac mass terms must be avoided. For this we assume that Φ^0 does not develop VEV and impose the set of discrete symmetries $(\chi, \rho, e_{aR}) \to -(\chi, \rho, e_{aR})$. The discrete symmetry also helps in avoiding flavor changing neutral currents involving quarks and scalars and is important to obtain a simple potential. In regard to the Dirac mass terms, we think important to emphasize that, in avoiding them, the left-handed neutrinos get decoupled of the right-handed ones. Thus, in this case, we could say that our right-handed neutrinos are, in fact, completely sterile. For this reason, from now on we refer to these neutrinos as the sterile neutrinos.

The mechanism arises in the potential of the model and is communicated to the neutrinos through the Yukawa interaction $\bar{f}_L f_L^C S$. The essence of the mechanism is that lepton number is violated explicitly through some terms in the potential. For this it is necessary to know the lepton number distribution of the scalars: $L(\eta'^0, \sigma^0, \rho'^+) = -2$ and $L(\chi^0, \chi^-, \Delta^0, \Delta^-\Delta^{--}) = 2$. When Δ^0 and σ^0 develop VEVs, automatically the left-handed neutrinos (ν_L) and the sterile ones (ν_R) both develop Majorana mass terms. The masses of ν_L and of ν_R get proportional to v_Δ and v_σ, respectively. The role of the type II seesaw mechanism is to furnish tiny values for v_Δ and v_σ.

The most complete part of the potential that obeys the discrete symmetry discussed above and conserves lepton number is composed by the following terms,

$$\begin{aligned} V = {} & \mu_\chi^2 \chi^2 + \mu_\eta^2 \eta^2 + \mu_\rho^2 \rho^2 + \lambda_1 \chi^4 + \lambda_2 \eta^4 + \lambda_3 \rho^4 \\ & + \lambda_4 (\chi^\dagger \chi)(\eta^\dagger \eta) + \lambda_5 (\chi^\dagger \chi)(\rho^\dagger \rho) + \lambda_6 (\eta^\dagger \eta)(\rho^\dagger \rho) \\ & + \lambda_7 (\chi^\dagger \eta)(\eta^\dagger \chi) + \lambda_8 (\chi^\dagger \rho)(\rho^\dagger \chi) + \lambda_9 (\eta^\dagger \rho)(\rho^\dagger \eta) \\ & + \left(\frac{f}{\sqrt{2}} \epsilon^{ijk} \eta_i \rho_j \chi_k + \text{H.C.}\right) + \mu_S^2 \operatorname{Tr}(S^\dagger S) \\ & + \lambda_{10} \operatorname{Tr}(S^\dagger S)^2 + \lambda_{11} [\operatorname{Tr}(S^\dagger S)]^2 \\ & + (\lambda_{12} \eta^\dagger \eta + \lambda_{13} \rho^\dagger \rho + \lambda_{14} \chi^\dagger \chi) \operatorname{Tr}(S^\dagger S) \\ & + \lambda_{15} (\epsilon^{ijk} \epsilon^{lmn} \rho_n \rho_k S_{li} S_{mj} + \text{H.C.}) \\ & + \lambda_{16} (\chi^\dagger S)(S^\dagger \chi) + \lambda_{17} (\eta^\dagger S)(S^\dagger \eta) \\ & + \lambda_{18} (\rho^\dagger S)(S^\dagger \rho), \end{aligned} \tag{4}$$

while the other part that violates explicitly the lepton number is composed by these terms,

$$\begin{aligned} V' = {} & \lambda_{19} (\eta^\dagger \chi)(\eta^\dagger \chi) + \left(\frac{\lambda_{20}}{\sqrt{2}} \epsilon^{ijk} \eta_m^* S_{mi} \chi_j \rho_k + \text{H.C.}\right) \\ & + \left(\frac{\lambda_{21}}{\sqrt{2}} \epsilon^{ijk} \chi_m^* S_{mi} \eta_j \rho_k + \text{H.C.}\right) \\ & - M_1 \eta^T S^\dagger \eta - M_2 \chi^T S^\dagger \chi. \end{aligned} \tag{5}$$

We think we have presented all the aspects of the model that are relevant to the implementation of the type II seesaw mechanism, which we do next.

3. The implementation of the type II seesaw mechanism

From the Yukawa interaction,

$$\mathcal{L}_\nu^Y = G_{ab} \bar{f}_{aL} S f_{bL}^C + \text{H.C.}, \tag{6}$$

when Δ^0 and σ^0 both develop VEV, the left-handed and the sterile neutrinos develop the following mass terms,

$$\mathcal{L}_\nu^Y = G_{ab} v_\Delta \bar{\nu}_{aL}^C \nu_{bL} + G_{ab} v_\sigma \bar{\nu}_{aR}^C \nu_{bR}. \tag{7}$$

We emphasize here that the mass terms of both neutrinos have as common origin the Yukawa interaction in Eq. (6). In practical terms this means that the same Yukawa couplings G_{ab} are common for the left-handed and sterile neutrino masses. That's a very interesting result because when the masses of the left-handed neutrinos get measured directly, automatically the masses of the sterile neutrinos will be predicted.

The role of the type II seesaw mechanism here is to provide tiny values for v_Δ and v_σ. This is achieved from the minimum condition of the potential $V + V'$. For this it is necessary to select which