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Common radiative origin of active and sterile neutrino masses

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ABSTRACT

Sterile neutrinos with sub-electron volt (eV) masses have recently received serious attention due to the tantalizing hints from reactor neutrino experiments as well as cosmology. While the nine year old Wilkinson Mass Anisotropy Probe experiment suggests the effective number of relativistic degrees of freedom to be $N_{\text{eff}} = 3.84 \pm 0.40$, recently reported Planck Collaboration results show more preference towards the standard three light neutrino scenario $N_{\text{eff}} = 3.30^{+0.54}_{-0.51}$. Keeping in mind that the issue of existence or non-existence of sub-eV scale sterile neutrinos is not yet settled, here we outline a mechanism to generate sub-eV scale masses for three active and one sterile neutrinos simultaneously. The model is based on an abelian extension of Standard Model where the fermion and scalar fields are charged under the additional $U(1)$ gauge group in such an anomaly free way that it allows one eV scale neutrino and three massless neutrinos at tree level. However, at one loop level, this model naturally allows three active and one sterile neutrino with mass at the sub-eV scale. The model also allows for mixing between active and sterile neutrinos at one loop level which can have interesting signatures in reactor neutrino experiments.

1. Introduction

The Standard Model (SM) of particle physics has turned out to be the most successful low energy theory, specially after the 2012 discovery of its last missing piece: the Higgs boson. Despite its phenomenological success, the Standard Model neither addresses some theoretical issues like gauge hierarchy problem, nor provides a complete understanding of various observed phenomena like non-zero neutrino masses, dark matter etc. A significant amount of works have been carried out so far on various possible extensions of the Standard Model, although none of them can be called a complete phenomenological model. Such extensions usually involve incorporating some additional symmetries (gauged or global) into the Standard Model or inclusion of additional fields. We know that the smallness of three Standard Model neutrino masses [1,2] can be naturally explained via seesaw mechanism. Such seesaw mechanism can be of three types: type I [3], type II [4] and type III [5]. All these mechanisms involve the inclusion of additional fermionic or scalar fields to generate tiny neutrino masses at tree level. However, it could well be true that the gauge symmetry as well as the field content of the theory do not allow neutrino masses at tree level and tiny neutrino masses appear only at the loop level. Here we are interested in a model which gives rise to such radiative neutrino mass in the manner proposed in [6,7].

In addition to additional scalar and fermionic fields, the model we study also has an enhanced gauge symmetry: an additional $U(1)_X$ gauge symmetry. It is worth mentioning that abelian gauge extension of Standard Model is one of the best motivating examples of beyond Standard Model physics [8]. Such a model is also motivated within the framework of GUT models, for example E_6. The supersymmetric version of such models can also provide a solution to the MSSM μ problem, among many other advantages. An abelian gauge extension of SM was studied recently by one of us in the context of four fermion generations [9] which explains the origin of three light and one heavy fourth generation neutrino masses and at the same time provides a way to avoid the strict bounds put by Large Hadron Collider (LHC) on a SM like Higgs boson mass in the presence of a fourth family.

Recently, a similar abelian gauge extension of Standard Model was studied in the context of radiative neutrino mass and dark matter in [10]. Here we study the same model with little modification to take into account light sterile neutrinos. Light sterile neutrino of mass of the order of electron volts (eV) have recently got lots of attention due to some experimental evidence suggesting additional light degrees of freedom beyond the three active neutrino species. For a review, please see [11]. The nine year Wilkinson Mass Anisotropy Probe (WMAP) data are pointing towards the existence of additional light degrees of freedom

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$N_{\mathrm{eff}} = 3.84 \pm 0.40$ [12]. Recently, the Planck Collaboration have reported a preference towards the standard three light neutrino scenario $N_{\mathrm{eff}} = 3.30^{+0.54}_{-0.51}$ [13]. Nevertheless, the issue of more than three relativistic degrees of freedom is not yet settled. Apart from cosmological hints in support of light sterile neutrino, there have also been evidence from anomalous results in accelerator and reactor based neutrino experiments. The anomalous results in antineutrino flux measurements at the LSND accelerator experiment [14] provided the first hint of light sterile neutrinos. The LSND results have also gained support from the latest data released by the MiniBooNE experiment [15]. Similar anomalies have also been observed at nuclear reactor neutrino experiments [16] as well as gallium solar neutrino experiments [17]. These anomalies suggesting the presence of light sterile neutrinos have led to global short-baseline neutrino oscillation data favoring two light sterile neutrinos within the eV range [18]. Some more interesting discussions on light sterile neutrinos from cosmology as well as neutrino experiments point of view can be found in [19] and references therein. Thus, the hints in favor of sub-eV scale sterile neutrinos have led to a model building challenge to explain the origin of three light active neutrinos together with one or two sterile neutrinos within the same mass range. Some interesting proposals along these lines have appeared recently in [20,21]. A nice review of some of the earlier works can also be found in [22].

In this Letter, we present an abelian extension of the Standard Model where three active and one sterile neutrino masses arise at eV scale. The gauge charges of the field content under the additional $U(1)_X$ gauge group are chosen in such an anomaly free way that only one active neutrino acquires non-zero tree level mass from usual type I seesaw mechanism whereas two other active neutrinos and one sterile neutrino remain massless. However, at one-loop level two other active neutrinos and one sterile neutrino acquire non-zero mass. Due to the loop suppression, the particles in the loop can be around the TeV corner while keeping the neutrino masses at eV scale and hence can have interesting signatures in the colliders. This model also allows non-zero mixing between active and sterile neutrinos at one loop level and hence can have tantalizing consequences in the reactor neutrino experiments. Also, as discussed in one of our earlier works [10], this model also has the provision of breaking the gauge symmetry spontaneously in a way that leaves a remnant Z_2 symmetry at low energy allowing the lightest Z_2 odd particle to be stable and hence a cold dark matter candidate. However, in our minimal setup, to allow nontrivial mixing of light sterile neutrino with the active neutrinos, we have to sacrifice this Z_2 symmetry. Thus, the present work is not aimed at explaining dark matter which may have origin from a different new physics sector.

This Letter is organized as follows. In Section 2 we briefly discuss the model we are interested in. In Section 3 we study the generation of three active neutrino masses in this model. In Section 4, we discuss the origin of one eV scale sterile neutrino in our model. Then in Section 5 we discuss the possibility of active–sterile neutrino mixing at one-loop level and finally conclude in Section 6.

2. The model

The model which we take as a starting point of our discussion was first proposed in [7]. The authors in that Letter discussed various possible scenarios with different combinations of Majorana singlet fermions N_R and Majorana triplet fermions Σ_R. Here we discuss one of such models which we find the most interesting for our purposes. This, so-called model C by the authors in [7], has the following particle content shown in Table 1.

Table 1
Particle content of the model.

Particle	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$U(1)_X$	Z_2
$(u,d)_L$	$(3, 2, \frac{1}{6})$	n_1	$+$
u_R	$(\bar{3}, 1, \frac{2}{3})$	$\frac{1}{4}(7n_1 - 3n_4)$	$+$
d_R	$(\bar{3}, 1, -\frac{1}{3})$	$\frac{1}{4}(n_1 + 3n_4)$	$+$
$(\nu, e)_L$	$(1, 2, -\frac{1}{2})$	n_4	$+$
e_R	$(1, 1, -1)$	$\frac{1}{4}(-9n_1 + 5n_4)$	$+$
N_R	$(1, 1, 0)$	$\frac{3}{8}(3n_1 + n_4)$	$-$
$\Sigma_{1R,2R}$	$(1, 3, 0)$	$\frac{3}{8}(3n_1 + n_4)$	$-$
S_{1R}	$(1, 1, 0)$	$\frac{1}{4}(3n_1 + n_4)$	$+$
S_{2R}	$(1, 1, 0)$	$-\frac{5}{8}(3n_1 + n_4)$	$-$
$(\phi^+, \phi^0)_1$	$(1, 2, -\frac{1}{2})$	$\frac{3}{4}(n_1 - n_4)$	$+$
$(\phi^+, \phi^0)_2$	$(1, 2, -\frac{1}{2})$	$\frac{1}{4}(9n_1 - n_4)$	$+$
$(\phi^+, \phi^0)_3$	$(1, 2, -\frac{1}{2})$	$\frac{1}{8}(9n_1 - 5n_4)$	$-$
χ_1	$(1, 1, 0)$	$-\frac{1}{2}(3n_1 + n_4)$	$+$
χ_2	$(1, 1, 0)$	$-\frac{1}{4}(3n_1 + n_4)$	$+$
χ_3	$(1, 1, 0)$	$-\frac{3}{8}(3n_1 + n_4)$	$-$
χ_4	$(1, 1, 0)$	$-\frac{3}{4}(3n_1 + n_4)$	$+$

The third column in Table 1 shows the $U(1)_X$ quantum numbers of various fields which satisfy the anomaly matching conditions. The Higgs content chosen above is not arbitrary and is needed, which leads to the possibility of radiative neutrino masses in a manner proposed in [6] as well as a remnant Z_2 symmetry. Two more singlets S_{1R}, S_{2R} are required to be present to satisfy the anomaly matching conditions. In this model, the quarks couple to Φ_1 and charged leptons to Φ_2 whereas $(\nu, e)_L$ couples to N_R, Σ_R through Φ_3 and to S_{1R} through Φ_1. The extra four singlet scalars χ are needed to make sure that all the particles in the model acquire mass. The Lagrangian which can be constructed from the above particle content has an automatic Z_2 symmetry and hence provides a cold dark matter candidate in terms of the lightest odd particle under this Z_2 symmetry. Part of the scalar potential of this model relevant for our future discussion can be written as

$$\begin{aligned} V_s \supset\; & \mu_1 \chi_1 \chi_2 \chi_4^\dagger + \mu_2 \chi_2^2 \chi_1^\dagger + \mu_3 \chi_3^2 \chi_4^\dagger + \mu_4 \chi_1 \Phi_1^\dagger \Phi_2 \\ & + \mu_5 \chi_3 \Phi_3^\dagger \Phi_2 + \lambda_{13} (\Phi_1^\dagger \Phi_1)(\Phi_3^\dagger \Phi_3) + f_1 \chi_1 \chi_2^\dagger \chi_3^2 \\ & + f_2 \chi_2^3 \chi_4^\dagger + f_3 \chi_1 \chi_3^\dagger \Phi_1^\dagger \Phi_3 \\ & + f_4 \chi_2^2 \Phi_1^\dagger \Phi_2 + f_5 \chi_3^\dagger \chi_4 \Phi_3^\dagger \Phi_2 \\ & + \lambda_{23} (\Phi_2^\dagger \Phi_2)(\Phi_3^\dagger \Phi_3) + \lambda_{16} (\Phi_1^\dagger \Phi_1)(\chi_3^\dagger \chi_3) \\ & + \lambda_{26} (\Phi_2^\dagger \Phi_2)(\chi_3^\dagger \chi_3) \end{aligned} \tag{1}$$

Let us denote the vacuum expectation values (vev) of various Higgs fields as $\langle \phi^0_{1,2} \rangle = v_{1,2}$, $\langle \chi^0_{1,2,4} \rangle = u_{1,2,4}$. We also denote the coupling constants of $SU(2)_L$, $U(1)_Y$, $U(1)_X$ as g_2, g_1, g_x respectively. The charged weak bosons acquire mass $M_W^2 = \frac{g_2^2}{2}(v_1^2 + v_2^2)$. The neutral gauge boson masses in the (W_3^μ, Y^μ, X^μ) basis is

$$M = \frac{1}{2} \begin{pmatrix} g_2^2(v_1^2+v_2^2) & g_1 g_2 (v_1^2+v_2^2) & M_{WX}^2 \\ g_1 g_2 (v_1^2+v_2^2) & g_1^2(v_1^2+v_2^2) & M_{YX}^2 \\ M_{WX}^2 & M_{YX}^2 & M_{XX}^2 \end{pmatrix} \tag{2}$$

where

$$M_{WX}^2 = -g_2 g_x \left(\frac{3}{4}(n_1 - n_4) v_1^2 + \frac{1}{4}(9n_1 - n_4) v_2^2 \right)$$

$$M_{YX}^2 = -g_1 g_x \left(\frac{3}{4}(n_1 - n_4) v_1^2 + \frac{1}{4}(9n_1 - n_4) v_2^2 \right)$$