Physics Letters B 749 (2015) 458–463

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The Higgs seesaw induced neutrino masses and dark matter

Yi Cai [a], Wei Chao [b,c,*]

[a] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Melbourne, Victoria 3010, Australia
[b] Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts-Amherst Amherst, MA 01003, United States
[c] INPAC, Shanghai Jiao Tong University, Shanghai, China

ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 29 June 2015
Accepted 10 August 2015
Available online 12 August 2015
Editor: J. Hisano

ABSTRACT

In this paper we propose a possible explanation of the active neutrino Majorana masses with the TeV scale new physics which also provide a dark matter candidate. We extend the Standard Model (SM) with a local $U(1)'$ symmetry and introduce a seesaw relation for the vacuum expectation values (VEVs) of the exotic scalar singlets, which break the $U(1)'$ spontaneously. The larger VEV is responsible for generating the Dirac mass term of the heavy neutrinos, while the smaller for the Majorana mass term. As a result active neutrino masses are generated via the modified inverse seesaw mechanism. The lightest of the new fermion singlets, which are introduced to cancel the $U(1)'$ anomalies, can be a stable particle with ultra flavor symmetry and thus a plausible dark matter candidate. We explore the parameter space with constraints from the dark matter relic abundance and dark matter direct detection.

1. Introduction

With the discovery of the Higgs-like scalar at the Large Hadron Collider (LHC), the Higgs mechanism of the SM for spontaneous breaking of the $SU(2)_{\rm L} \times U(1)_{\rm Y}$ gauge symmetry appears to be a correct description of the nature. In addition to explaining the spontaneous breaking of the electroweak symmetry, the Higgs boson is also responsible for the origin of fermion masses, via the Yukawa interactions. The minimal Higgs mechanism, however, is not able to address the fermion mass hierarchy problem, where the quark–lepton masses range from the top quark with mass of order electroweak scale, $M_t = 172$ GeV, down to electron of mass, $M_e = 0.511$ MeV, and the first order phase transition which is relevant for baryon asymmetry of the Universe. More precise measurement of Higgs boson properties will help determine whether there are new degrees of freedom that participate in electroweak symmetry breaking or otherwise involve in new Higgs boson interactions.

Furthermore, the discovery of the neutrino oscillation has confirmed the theoretical expectation that neutrinos are massive and lepton flavors are mixed [1], which provided the first piece of evidence for physics beyond the Standard Model (SM). In order to accommodate the tiny neutrino masses, one can extend the SM by introducing several right-handed neutrinos, which are taken to be singlets under the $SU(2)_{\rm L} \times U(1)_{\rm Y}$ gauge group. In this case, the gauge invariance allows right-handed neutrinos to have Majorana mass M_R, which is not subject to the electroweak symmetry breaking scale. Thus the effective mass matrix of three light Majorana neutrinos can be highly suppressed if M_R is much larger than the electroweak scale, which is the so-called canonical seesaw mechanism [2]. Two other types of tree-level seesaw mechanisms have also been proposed [3,4]. Despite its simplicity and elegance, the canonical seesaw mechanism is impossible to be tested in current collider experiments, especially at the LHC, due to its inaccessibility to the high right-handed Majorana mass scale. Heavy Majorana neutrinos can also give large radiative corrections to the SM Higgs mass, which leads to the seesaw hierarchy problem [5]. An alternative way to generate tiny Majorana neutrino masses at the TeV scale is the inverse seesaw mechanism [6,7], in which the neutrino mass m_ν is proportional to a small effective Majorana mass term μ. But there is no dynamical explanation of the smallness of μ. The argument is that neutrinos become massless in the limit of vanishing μ and the global lepton number, $U(1)_{\rm L}$, is then restored, leading to a larger symmetry [8]. This argument, however, only works when we give the left-handed singlets (S_L) the same quantum(lepton) number as that of the right-handed heavy neutrinos (N_R). If the lepton number of S_L is zero, the argument above does not hold up any more. Besides, the lepton number is only an accidental symmetry of the SM and is explicitly broken by anomalies.

Since neutrino is the only neutral matter field in the SM, it is reasonable to conjecture that neutrinos are correlated with

---

* Corresponding author.
E-mail addresses: yi.cai@unimelb.edu.au (Y. Cai), chao@physics.umass.edu (W. Chao).

http://dx.doi.org/10.1016/j.physletb.2015.08.026
0370-2693/

the dark matter, which provides another evidence of the new physics beyond the SM from the precise cosmological observations, through certain dark symmetry. The nature of the dark matter and the way it interacts with ordinary matter are still mysteries. The discovery of the Higgs boson opens up new ways of probing the world of the dark matter. The neutrino flux from the annihilation of the dark matter at the center of the dark matter halo also provides a way of indirect detecting the dark matter.

In this paper, we propose a possible explanation of the smallness of neutrino masses and a possible candidate of the dark matter. The discovery of the Higgs-like boson makes the Higgs mechanism more promising as a possible way to understand the origin of the fermion masses. We study the possibility of generating a small Majorana mass term with the help of the seesaw mechanism in the Higgs sector. We extend the SM with a local $U(1)'$ gauge symmetry, which is spontaneously broken by the vacuum expectation value (VEV) $\langle\varphi\rangle$ of an extra scalar singlet. Furthermore there is a seesaw mechanism in the scalar singlet sector: a second scalar singlet gets a tiny VEV $\langle\Phi\rangle$ in a way similar to that of the Higgs triplet in the type-II seesaw model [3]. $\langle\varphi\rangle$ is responsible for the origin of the dark matter mass and the Dirac neutrino mass term, while $\langle\Phi\rangle$ is responsible for the origin of a small Majorana neutrino mass term. The active neutrino mass matrix arises from the modified inverse seesaw mechanism. Compared with various existed inverse seesaw models [33–42], our studies are new in the following three aspects

- All the mass terms (Dirac and Majorana mass terms) originate from the spontaneous breaking of local gauge symmetries in our model.
- The smallness of the Majorana mass term (μ term in the traditional inverse seesaw model) is naturally explained by the so-called Higgs seesaw mechanism.
- The dark matter phenomenology is closely correlated with the neutrino physics via the $U(1)'$ gauge symmetry in our model.

We study constraints on the parameter space of this model from astrophysical observation and dark matter direct detections.

The paper is organized as follows. In Section 2 we describe our model, including the full Lagrangian, Higgs VEVs and mass spectrum. In Section 3 we study the neutrino masses and the effective lepton mixing matrix of the model. Section 4 is devoted to the study of the dark matter phenomenology. We summarize in Section 5.

2. The model

We extend the SM with three generations of right-handed neutrinos N_R and singlets S_L as in the inverse seesaw mechanism, together with two extra scalar singlets, φ and Φ, as well as a spontaneously broken $U(1)'$ gauge symmetry and a global $U(1)_D$ flavor symmetry. The quantum numbers of the fields are given in Table 1, where ℓ_L is left-handed lepton doublet, E_R is the right-handed charged lepton, H is the SM Higgs doublet, and χ_L and χ_R are the fermion singlet pair carrying the same $U(1)_D$ quantum number. Three generations of gauge singlets $\chi_{L,R}$ are needed to cancel anomalies [9–15] of the $U(1)'$ gauge symmetry. The lightest generation of $\chi_{L,R}$ is stable due to the global $U(1)_D$ flavor symmetry and thus plays the role of dark matter [30–32].

Table 1
Quantum numbers of the relevant fields under the local $U(1)'$ and the global $U(1)_D$ flavor symmetry.

	ℓ_L	E_R	N_R	S_L	χ_R	χ_L	H	φ	Φ
$U(1)'$	0	0	0	1	1	0	0	1	2
$U(1)_D$	0	0	0	0	1	1	0	0	0

The Higgs potential of the model can be written as

$$\begin{aligned} V = & -m^2 H^\dagger H - m_1^2 \varphi^\dagger \varphi + m_2^2 \Phi^\dagger \Phi + \lambda (H^\dagger H)^2 \\ & + \lambda_1 (\varphi^\dagger \varphi)^2 + \lambda_2 (\Phi^\dagger \Phi)^2 \\ & + \lambda_3 (H^\dagger H)(\varphi^\dagger \varphi) + \lambda_4 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_5 (\varphi^\dagger \varphi)(\Phi^\dagger \Phi) \\ & + \sqrt{2}\lambda_6 \left(\Lambda \varphi^2 \Phi^* + \text{h.c.} \right) , \end{aligned} \tag{1}$$

where we define $H = (h^+, (h_0 + iA + v)/\sqrt{2})^T$, $\varphi = (\varphi_0 + i\delta + v_1)/\sqrt{2}$ and $\Phi = (\Phi_0 + i\rho + v_2)/\sqrt{2}$. After imposing the conditions of the global minimum, one has

$$-m^2 v + \lambda v^3 + \frac{1}{2} v (\lambda_3 v_1^2 + \lambda_4 v_2^2) = 0 \, , \tag{2}$$

$$-m_1^2 v_1 + \lambda_1 v_1^3 + \frac{1}{2} v_1 (\lambda_3 v^2 + \lambda_5 v_2^2) + 2\lambda_6 \Lambda v_2 = 0 \, , \tag{3}$$

$$+m_2^2 v_2 + \lambda_2 v_2^3 + \frac{1}{2} v_2 (\lambda_4 v^2 + \lambda_5 v_1^2) + \lambda_6 \Lambda v_1^2 = 0 \, . \tag{4}$$

Then the VEVs can be solved in terms of the parameters

$$\begin{aligned} & v^2 \approx \frac{2m_1^2 \lambda_3 - 4m^2 \lambda_1}{\lambda_3^2 - 4\lambda_1 \lambda} \, , \qquad v_1^2 \approx \frac{2m^2 \lambda_3 - 4m_1^2 \lambda}{\lambda_3^2 - 4\lambda \lambda_1} \, , \\ & v_2 \approx - \frac{2\lambda_6 \Lambda v_1^2}{2m_2^2 + \lambda_4 v^2 + \lambda_5 v_1^2} \, , \end{aligned} \tag{5}$$

where v_2 is proportional to Λ and suppressed by m_2^2. Thus v_2 can be a small value given a large m_2^2 or small Λ.

In the basis $(h_0, \ \phi_0, \ \Phi_0)$, the mass matrix of the CP-even Higgs can be written as

$$M^2_{\text{CP-even}} = \begin{pmatrix} 2v^2\lambda & v v_1 \lambda_3 & v v_2 \lambda_4 \\ v v_1 \lambda_3 & 2\lambda_1 v_1^2 & 2\Lambda v_1 \lambda_6 \\ v v_2 \lambda_4 & 2\Lambda v_1 \lambda_6 & 2v_2^2 \lambda_2 - \lambda_6 \Lambda v_1^2 v_2^{-1} \end{pmatrix} . \tag{6}$$

The mass eigenstates of the CP-even Higgs are then denoted as h_i including the SM-like Higgs h and two exotic Higgs, h_1 and h_2. There is no mixing between the SM CP-odd Higgs A, which is the Goldstone boson eaten by the Z gauge boson, and those of the Higgs singlets, i.e. δ and ρ. The mass matrix of the CP-odd Higgs singlets in the basis of (δ, ρ) is

$$M^2_{\text{CP-odd}} = \begin{pmatrix} -4\Lambda v_2 \lambda_6 & 2\Lambda v_1 \lambda_6 \\ 2\Lambda v_1 \lambda_6 & -\Lambda \lambda_6 v_1^2 v_2^{-1} \end{pmatrix} . \tag{7}$$

The massless eigenstate of the eq. (7) is the Goldstone boson eaten by the Z' and the nonzero mass eigenstate of the CP-odd scalar is then denoted as A', the mass squared of which can be written as $m^2_{A'} = -(4v_2 + v_1^2 v_2^{-1})\Lambda\lambda_6$.

Since the SM particles are not charged under $U(1)'$, there is no experimental constraint on the new symmetry. We assume that there is no kinetic mixing between Z and Z' at the tree level. Thus the mass and coupling of Z' are not constrained by current experiments either. We refer the reader to Ref. [16] for the discussion of Z–Z' mixing at the one-loop level. Notice that the SM Higgs, h, mainly mixes with the CP-even scalar singlet h_1. For the case $m_{h_1} < 1/2 m_h$, where m_h is the mass eigenvalue of the SM Higgs and m_{h_1} is the mass eigenvalue of the CP-even scalar singlet, the SM Higgs can decay into h_1, providing enhancement to the Higgs to invisible decay width, which is thus disfavored by the LHC data. For the region $1/2 m_h < m_{h_1}$, a global χ^2 fit to the current Higgs data from both ATLAS and CMS shows that the present 95% C.L.