Physics Letters B 695 (2011) 242–246

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Dark matter signals and cosmic ray anomalies in an extended seesaw model

H. Sung Cheon [a], Sin Kyu Kang [b], C.S. Kim [a,*]

[a] Department of Physics and IPAP, Yonsei University, Seoul 120-749, Republic of Korea
[b] School of Liberal Arts, Seoul National University of Technology, Seoul 121-742, Republic of Korea

ARTICLE INFO

Article history:
Received 12 August 2010
Received in revised form 11 October 2010
Accepted 4 November 2010
Available online 12 November 2010
Editor: M. Cvetič

Keywords:
Extended seesaw model
Leptogenesis
Dark matter
Cosmic ray anomalies

ABSTRACT

An extended seesaw model proposed to achieve low scale leptogenesis can resolve the excess positron and electron fluxes observed from PAMELA, ATIC and/or Fermi-LAT, and *simultaneously* accommodate some of recent experimental results for dark matter (DM) signals. In this approach, in addition to $SU(2)_L$ doublet and the (light) singlet Higgs fields, an extra vector-like singlet neutrino and a singlet scalar field, which are coexisting two-particle dark matter candidates, are responsible for the origin of the excess positron and electron fluxes to resolve the PAMELA, ATIC and/or Fermi-LAT anomalies, as well as for the DM signals observed from direct searches in low mass scale.

1. Introduction

The quest for identification of the missing mass of our universe is one of the most fundamental issues in astroparticle physics and cosmology. The evidence for non-baryonic dark matter (DM) inferred from a combination of cosmological and astrophysical phenomena becomes more and more convincing, which alludes the existence of new physics beyond the standard model (SM). Very recently, several new exciting data on DM have been released, which may open up new era to search for DM in a low mass region of a few GeV. CDMS II Collaboration reported the two DM candidate events with a 77% C.L. and the upper bound of null result [1]. DAMA Collaboration confirmed the model independent evidence of the presence of DM on the basis of the DM annual modulation signature with 8.9σ significance [2]. The CoGeNT experiment reported a possible signal of a light DM candidate with $m_{\rm DM} = 7$–11 GeV, and provided 90% C.L. WIMP exclusion plots as well [3]. Those three independent experimental results may be interpreted as signals of the existence of DM with a low mass around a few GeV [4]. Contrary to the results from CDMS II, DAMA and CoGeNT, XENON100 Collaboration announced that they have not observed any DM signal for the similar parameter ranges searched by those three experiments [5]. Therefore, we need further experimental results to judge if there really exists a DM candidate with a low mass or not.

On the other hand, the PAMELA experiment has presented a significant positron flux excess over the expected background with no excess in the corresponding anti-proton flux [6]. The ATIC/PPB-BETS experiment has shown significant excess of electron and positron flux at energies around 300–800 GeV [7,8]. More recently, Fermi-LAT experiment have also shown an excessive electron and positron flux in the same energy range as in ATIC but its strength was not strong compared to ATIC [9]. So, it is likely that the experimental evidences for the signals of DM with a low mass scale are not reconciled with the cosmic ray positron and electron excess in the framework of one and only one DM scenarios.

Recently, we have proposed an extended seesaw model to simultaneously and naturally accommodate tiny neutrino masses, low scale leptogenesis and dark matter candidate by introducing extra singlet neutrinos and singlet scalar particles on top of the canonical seesaw model [10,11]. Furthermore, we have proposed a coexisting two-particle DM scenario [12] by allowing both an extra singlet Majorana neutrino and a light singlet scalar particle as two DM candidates. Such a scenario containing more than one DM may be desirable in the case that there exist a few incompatible phenomena which are very hard to reconcile in the scenarios with only one DM.

The purpose of this Letter is to investigate how both the low mass DM signals observed from direct DM searches and the cosmic ray positron and electron excess observed from PAMELA, ATIC and/or Fermi-LAT experiments are simultaneously explained in the extended seesaw model with coexisting two-particle DM proposed in [12]. Due to the tension among the experimental results of direct search for DM in low mass scale, we first consider the case that lighter DM candidate in our model has mass around 3 GeV

* Corresponding author.
E-mail addresses: hscheon@gmail.com (H. Sung Cheon), skkang@snut.ac.kr (S.K. Kang), cskim@yonsei.ac.kr (C.S. Kim).

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2010.11.028

allowed by DAMA experiment, which is not in conflict with other null results from direct searches but is inconsistent with the DM signals observed from CoGeNT. The other case we consider is to accept DAMA and CoGeNT signals for DM candidate whose overlapped mass range lies between 7 GeV and 11 GeV while ignoring XENON100 results. In this work, we slightly modify the model proposed in [12] by replacing extra singlet Majorana neutrino with singlet vector-like neutrinos so as to simply resolve the cosmic ray anomaly while keeping to accommodate tiny neutrino masses and low scale leptogenesis of order 1–10 TeV [10,11].

We notice that to achieve our coexisting two-particle DM scenario in the renormalizable framework as shown in [12], an extra singlet Higgs scalar field Φ is necessarily introduced, which may open up new channels of DM annihilations. As will be shown later, in this scenario, this scalar field Φ may play an essential role in resolving the unexpected electron and positron fluxes measured at PAMELA, ATIC and/or Fermi-LAT if the mass of Φ has rather small around just below 1 GeV so as for the annihilation cross section to be enhanced via a mechanism first described by Sommerfeld [13–15]. Once this new force carrier Φ is included, the possibility of a new dominant annihilation of singlet vector-like neutrinos into a fair of Φ opens up. The Φ mixes with the Higgs allowing it to decay into the final state fermions, and if the Φ is taken to be light, it is kinematically constrained to decay to mostly lepton pairs preventing from producing anti-protons, so that the excess of positron and/or electron observed can be accounted for. In addition, the low mass DM signals will be explained by considering the singlet scalar ψ as the lightest DM candidate with mass of order a few GeV. Thus, the low mass DM signals, the excess positron and electron fluxes produced from the cosmic rays, low scale leptogenesis and light neutrino masses can be *simultaneously* accommodated in our model proposed.

To see how the coexisting two-particle DM scenario is achieved, let us consider the following Lagrangian

$$\begin{aligned}\mathcal{L} = {} & \mathcal{L}_0 + (Y_D \bar{L} H N + Y_S \bar{N}\psi S + \text{h.c.}) + M_N N^T N \\ & + Y_\Phi \bar{S}\Phi S - m_{S^0}\bar{S}S \\ & + \frac{1}{2}m_{\psi^0}^2\psi^2 - \frac{\lambda_s}{4}\psi^4 - \lambda H^\dagger H \psi^2 + \frac{1}{2}m_{\Phi^0}^2\Phi^2 \\ & - \frac{\lambda_2}{4}\Phi^4 - \lambda_3\psi^2\Phi^2 - \lambda_4 H^\dagger H \Phi^2, \end{aligned} \tag{1}$$

where the first term is the Lagrangian of the SM and kinetic terms of the singlet fields, and L, N, S and ψ stand for $SU(2)_L$ lepton doublet, singlet heavy Majorana neutrino, singlet vector-like neutrino composed of two Weyl fermions, and light singlet scalar, respectively. Note that S and ψ are our coexisting two-particle dark matter candidates. Finally H and Φ denote the $SU(2)_L$ doublet and singlet (Higgs) scalar fields, and m_Φ is assumed to be smaller than 1 GeV to realize the Sommerfeld enhancement in indirect detection [13–15]. The effective scalar potential including one-loop corrections is given by

$$\begin{aligned}V_{\text{eff}} = {} & -\frac{1}{2}m_\psi^2\psi^2 + \frac{\lambda_s}{4}\psi^4 + \lambda H^\dagger H\psi^2 - \frac{1}{2}m_H^2 H^\dagger H \\ & + \frac{\lambda_1}{4}H^\dagger H H^\dagger H - \frac{1}{2}m_\Phi^2\Phi^2 + \frac{\lambda_2}{4}\Phi^4 \\ & + \lambda_3\psi^2\Phi^2 + \lambda_4 H^\dagger H\Phi^2 + \frac{1}{64\pi^2}\left[m_H^4\left(\ln\frac{m_H^2}{\mu^2} - \frac{3}{2}\right)\right. \\ & + 2m_Z^4\left(\ln\frac{m_Z^2}{\mu^2} - \frac{5}{6}\right) + 4m_W^4\left(\ln\frac{m_W^2}{\mu^2} - \frac{5}{6}\right) \\ & - 12m_t^4\left(\ln\frac{m_t^2}{\mu^2} - \frac{3}{2}\right) + m_\psi^4\left(\ln\frac{m_\psi^2}{\mu^2} - \frac{3}{2}\right) \\ & \left. + m_\Phi^4\left(\ln\frac{m_\Phi^2}{\mu^2} - \frac{3}{2}\right) - 4m_S^4\left(\ln\frac{m_S^2}{\mu^2} - \frac{3}{2}\right)\right], \end{aligned} \tag{2}$$

where we have adopted $\overline{MS}$ renormalization scheme and the field-dependent masses are

$$\begin{aligned} & m_t^2 = y_t^2 h^2/2, \qquad m_Z^2 = (g^2 + g'^2)h^2/4, \qquad m_W^2 = g^2h^2/4, \\ & m_\psi^2 = m_{\psi^0}^2 - 2\lambda H^\dagger H - 2\lambda_3\Phi^2, \\ & m_\Phi^2 = m_{\Phi^0}^2 - \lambda_2\Phi^2 - 2\lambda_4 H^\dagger H, \\ & m_H^2 = m_{H^0}^2 - \lambda_1 H^\dagger H - 2\lambda_4\Phi^2, \qquad m_S^2 = Y_\Phi^2\Phi^2, \end{aligned}$$

where $\sqrt{2}H^T = (h, 0)$. In order to guarantee the stability of the 2DM candidates, we impose the discrete symmetry $Z_2 \times Z_2'$ under which all SM bosons (photon, Higgs, $W^\pm$ and Z) and Φ are $(+,+)$, all SM fermions are $(-,-)$, the singlet neutrino S is $(-,+)$ and the singlet scalar boson ψ is $(+,-)$. Now, we demand that the minimum of the scalar potential is bounded from below so as to guarantee the existence of vacuum and the minimum of the scalar potential must spontaneously break the electroweak gauge group, $\langle H^0\rangle$, $\langle\Phi\rangle \neq 0$, but must not break $Z_2 \times Z_2'$ symmetry imposed above.

Since Eq. (2) depends on the renormalization scale μ, it must be RG-improved and this can be simply done by repeatedly decoupling all singlet particles and top quark at their mass scales [16]. After spontaneous symmetry breaking, the low energy effective scalar potential becomes

$$\begin{aligned}V_{\text{eff}} = {} & -\frac{1}{2}\bar{m}_\psi^2\psi^2 - \frac{1}{2}\bar{m}_h^2h^2 - \frac{1}{2}\bar{m}_\phi^2\phi^2 + 2\bar{\lambda}_4 v_h v_\phi h\phi + \frac{\lambda_s}{4}\psi^4 \\ & + \frac{\bar{\lambda}_1}{4}v_h h^3 + \frac{\bar{\lambda}_1}{16}h^4 + \frac{\bar{\lambda}_2}{4}\phi^4 + \bar{\lambda}_2 v_\phi\phi^3 + \frac{\lambda}{2}\psi^2h^2 \\ & + \lambda v_h h\psi^2 + \lambda_3\psi^2\phi^2 + 2\lambda_3 v_\phi\phi\psi^2 + \frac{\bar{\lambda}_4}{2}h^2\phi^2 \\ & + \bar{\lambda}_4 v_\phi h^2\phi + \bar{\lambda}_4 v_h h\phi^2 + \text{h.c.}, \end{aligned} \tag{3}$$

where $\bar{m}_\psi^2 = m_{\psi^0}^2 + \lambda v_h^2 + 2\lambda_3 v_\phi^2$, $\bar{m}_h^2 = \frac{1}{2}m_{H^0}^2 - \frac{3}{4}\bar{\lambda}_1 v_h^2 - \bar{\lambda}_4 v_\phi^2$, $\bar{m}_\phi^2 = m_{\phi^0}^2 - 3\bar{\lambda}_2 v_\phi^2 - \bar{\lambda}_4 v_h^2$. Here, we have shifted the Higgs boson H and the singlet Higgs scalar Φ by $H \to h + v_h$ and $\Phi \to \phi + v_\phi$, respectively, and

$$\begin{aligned} & \bar{\lambda}_1 = \lambda_1 - \frac{3}{32\pi^2}\lambda_1^2 + \frac{9}{32\pi^2}y_t^4 - \frac{3}{8\pi^2}\lambda^2 - \frac{3}{8\pi^2}\lambda_4^2, \\ & \bar{\lambda}_2 = \lambda_2 - \frac{3}{32\pi^2}\left(4\lambda_4^2 + 4\lambda_3^2 + \lambda_2^2 - 4Y_\Phi^4\right), \end{aligned}$$

and

$$\bar{\lambda}_4 = \lambda_4 - \frac{3}{128\pi^2}(4\lambda_4\lambda_1 + 8\lambda\lambda_3 + 4\lambda_2\lambda_4).$$

Since there exists a mixing mass term between h and ϕ, we rotate them with $\phi = sh' + c\phi'$ and $h = ch' - s\phi'$, where s and c are $\sin\theta$ and $\cos\theta$, respectively.

For $m_\phi \lesssim 1$ GeV and $m_S \gg m_\phi$, the singlet neutrinos S annihilate into mostly $\phi\phi$. Other annihilation channel like $\bar{S}S \to \psi\psi$ is negligible due to its very small coupling of the process. The ϕ's can then subsequently decay into SM particles, which arises due to their mixing with the Higgs field h. For the case of $m_\phi = 0.25$ GeV, the ϕ mostly decays to muon pairs, which in turn produce electrons and positrons, and thus the resulting spectra for the electrons and positrons are much harder than typical e^+e^- spectra coming from weak-scale WIMP annihilation as shown in [14,15].

The amount of cold dark matter in the Universe, which has been determined precisely from 5 year WMAP data [17], is given