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Citation of published version:

Contents lists available at ScienceDirect

Physics Letters B

PHYSICS LETTERS B

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A R T I C L E   I N F O

A B S T R A C T

We discuss how the cosmic ray signals reported by the PAMELA and ATIC/PPB-BETS experiments may be understood in a Standard Model (SM) framework supplemented by type II seesaw and a stable SM singlet scalar boson as dark matter. A particle physics explanation of the 'boost' factor can be provided by including an additional SM singlet scalar field.

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The PAMELA experiment has reported a significant positron excess over the expected background without a corresponding increase in the flux of anti-protons [1]. Their measurement seems to be consistent within the error bars with results previously reported by HEAT [2] and AMS [3]. More recently, the ATIC experiment [4] (see also PPB-BETS [5]) has reported an appreciable flux of electrons and positrons at energies of around 100–800 GeV, which also appears to be significantly higher than the expected background at these energies. While pulsars and/or other nearby astrophysical sources may account for the PAMELA results alone [6], a unified understanding of both the PAMELA and ATIC/PPB-BETS measurements based on such sources appears to be more challenging.

A particle physics inspired explanation of both the PAMELA and ATIC/PPB-BETS results in terms of dark matter physics necessitates a suitable extension of the SM framework. For instance, the dark matter could be a stable elementary particle with suitably chosen mass which primarily self annihilates into leptons (leptophilic) through new interactions [7]. Depending on the details, this scenario may, in addition, invoke a 'boost' factor which could either have an astrophysical origin (large inhomogeneities in the dark matter distribution), or have a particle physics origin such as Sommerfeld enhancement [8]. Alternatively, one could assume that the dark matter is not entirely stable but extremely long-lived, with a lifetime $\sim 10^{26}$ s [9].

In this Letter we offer what we believe is a very simple extension of the SM according to which stable dark matter annihilates

primarily into leptons. The dark matter particle in our scheme is a SM singlet boson D [11,12], and its stability comes from an unbroken Z_2 symmetry under which it carries negative parity. The leptophilic nature of D arises from its interactions with the SU(2) triplet scalar fields which are introduced to accommodate the observed neutrino oscillations [13] via the type II seesaw mechanism [14]. In the minimal version the model requires a 'boost' factor, of order 10^3 or so, which should have an astrophysical origin [15]. We then proceed to show how the presence of an additional SM singlet scalar field can provide a particle physics origin for this 'boost' factor based on the Breit–Wigner enhancement of dark matter annihilation [16].

The particle content relevant for our discussion in this Letter is summarized in Table 1. The SM singlet scalar is assigned an odd Z_2 parity which makes it stable and a suitable dark matter candidate. It is often useful to explicitly express the triplet scalar by three complex scalars (electric charge neutral, singly charged and doubly charged scalars):

$$\Delta = \frac{\sigma^i}{\sqrt{2}} \Delta_i = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}. \qquad (1)$$

The scalar potential relevant for the type II seesaw is given by

$$\begin{aligned} V(H, \Delta) &= -m_H^2 \left(H^\dagger H \right) + \frac{\lambda}{2} \left(H^\dagger H \right)^2 + M_\Delta^2 \operatorname{tr}\left(\Delta^\dagger \Delta \right) \\ &\quad + \frac{\lambda_1}{2} \left(\operatorname{tr} \Delta^\dagger \Delta \right)^2 + \frac{\lambda_2}{2} \left[\operatorname{tr}\left(\Delta^\dagger \Delta \right)^2 - \operatorname{tr}\left(\Delta^\dagger \Delta \Delta^\dagger \Delta \right) \right] \\ &\quad + \lambda_4 H^\dagger H \operatorname{tr}\left(\Delta^\dagger \Delta \right) + \lambda_5 H^\dagger \left[\Delta^\dagger, \Delta \right] H \\ &\quad + \left[2\lambda_6 M_\Delta H^T i\sigma_2 \Delta^\dagger H + \text{h.c.} \right], \end{aligned} \qquad (2)$$

where the coupling constants λ_i are taken to be real without loss of generality. The triplet scalar has a Yukawa coupling with the lepton doublets given by

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Table 1

Particle content relevant for our discussion in this Letter. In addition to the SM lepton doublets ℓ_L^i (i is the generation index) and the Higgs doublets H, a complex scalar Δ and a real scalar D are introduced. The triplet scaler Δ plays the key role in type II seesaw mechanism, while D is the dark mater candidate.

	$SU(2)_L$	$U(1)_Y$	Z_2
Δ	**3**	$+1$	$+$
ℓ_L^i	**2**	$-1/2$	$+$
H	**2**	$+1/2$	$+$
D	**1**	0	$-$

$$\mathcal{L}_\Delta = -\frac{1}{2}(Y_\Delta)_{ij}\ell_L^{Ti}Ci\sigma_2\Delta\ell_L^j + \text{h.c.}$$

$$= -\frac{1}{2}(Y_\Delta)_{ij}\nu_L^{Ti}C\Delta^0\nu_L^j + \frac{1}{\sqrt{2}}(Y_\Delta)_{ij}\nu_L^{Ti}C\Delta^+e_L^j$$

$$+ \frac{1}{2}(Y_\Delta)_{ij}e_L^{Ti}C\Delta^{++}e_L^j + \text{h.c.}, \tag{3}$$

where C is the Dirac charge conjugate matrix and $(Y_\Delta)_{ij}$ denotes elements of the Yukawa matrix.

A non-zero vacuum expectation value (VEV) of the Higgs doublet induces a tadpole term for Δ through the last term in Eq. (2). A non-zero VEV of the triplet Higgs is thereby generated, $\langle\Delta_0\rangle = v_\Delta/\sqrt{2} \sim \lambda_6 v^2/M_\Delta$ ($v = 246$), which leads to the neutrino mass from Eq. (3):

$$M_\nu = (Y_\Delta)_{ij}\langle\Delta_0\rangle. \tag{4}$$

Note that the triplet Higgs VEV contributes to the weak boson masses and alters the ρ-parameter from the SM prediction, $\rho \approx 1$, at tree level. The current precision measurement [17] constrains this deviation to be in the range $\Delta\rho = \rho - 1 \simeq \langle\Delta\rangle/v \lesssim 0.01$, so that $\lambda_6 \lesssim 0.01M_\Delta/v$. This constraint is especially relevant if we take $M_\Delta = \mathcal{O}(100$ GeV$)$, in which case the region $\lambda_6 \gtrsim 0.01$ is excluded.

The scalar potential relevant for dark matter physics is given by

$$V(H,\Delta,D)$$

$$= \frac{1}{2}m_0^2 D^2 + \lambda_D D^4 + \lambda_H D^2(H^\dagger H) + \lambda_\Delta D^2\,\text{tr}(\Delta^\dagger\Delta)$$

$$= \frac{1}{2}m_D^2 D^2 + \lambda_D D^4 + \lambda_H v D^2 h + \frac{\lambda_H}{2}D^2 h^2$$

$$+ \lambda_\Delta D^2\big(\sqrt{2}v_\Delta\Re[\Delta_0] + |\Delta_0|^2 + |\Delta^+|^2 + |\Delta^{++}|^2\big), \tag{5}$$

where $m_D^2 = m_0^2 + \lambda_H v^2 + \lambda_\Delta v_\Delta^2$, and in the last equality the potential is expressed in terms of physical Higgs bosons (h). Since the D particle is weakly interacting dark matter its mass scale is determined by the requirement that its energy density is consistent with the constraints provided by the WMAP five year analysis.

We first investigate the relic abundance of the singlet dark matter, which is obtained by solving the following Boltzmann equation [18],

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle}{Hx}s(Y^2 - Y_{eq}^2), \tag{6}$$

where $Y = n/s$ is the ratio of the dark matter number density (n) to the entropy density of the universe ($s = 0.439g_*m_D^3/x^3$), $g_* \sim 100$, and $x \equiv m_D/T$ (T is the temperature of the universe). The Hubble parameter is given by $H = 1.66g_*^{1/2}m_D^2 m_{PL}/x^2$, where $m_{PL} = 1.22 \times 10^{19}$ GeV is the Planck mass, and the dark matter yield in equilibrium is $Y_{eq} = (0.434/g_*)x^{3/2}e^{-x}$. Solving the Boltzmann equation with the thermal averaged annihilation cross section $\langle\sigma v\rangle$, we obtain the relic abundance of dark matter (Y_∞).

To a good accuracy, the solution of Eq. (6) is approximately given by [18]

$$\Omega h^2 = \frac{1.07 \times 10^9 x_f \text{GeV}^{-1}}{\sqrt{g_*}m_{PL}\langle\sigma v\rangle}, \tag{7}$$

where $x_f = m_D/T_f$, the freeze-out temperature for dark matter, is given by $x_f = \ln(X) - 0.5\ln(\ln(X))$, with $X = 0.038(1/g_*^{1/2})m_{PL} \times m_D\langle\sigma v\rangle$. If the dark matter annihilation occurs in the s-wave at the non-relativistic limit, the thermal averaged annihilation cross section $\langle\sigma v\rangle$ is simply replaced by non-averaged one, $\langle\sigma v\rangle = \sigma v$.

In the following we consider the case $m_D > M_\Delta$, m_h, where m_h is the SM Higgs boson mass. In this case, we find that the dominant dark matter annihilation process is $DD \to hh, \Delta^\dagger\Delta$ through the quartic coupling λ_H and λ_Δ in Eq. (5). In the non-relativistic limit the cross section is given by

$$\sigma v = \frac{1}{16\pi m_D^2}\big(\lambda_H^2 + 6\lambda_\Delta^2\big). \tag{8}$$

For a given m_D, the annihilation cross sections is determined so as to satisfy the observed relic density of dark matter [19],

$$\Omega_{DM}h^2 \simeq 0.1131. \tag{9}$$

For example, the following parameter set can reproduce the observed dark matter relic density:

$$m_D = 1.3 \text{ TeV},$$

$$\lambda_H^2 + 6\lambda_\Delta^2 = 0.16, \tag{10}$$

which leads to $\langle\sigma v\rangle = 1.85 \times 10^{-9}$ GeV$^{-2} = 0.72$ pb.

A variety of experiments are underway to directly detect dark matter particles through elastic scattering off nuclei. The most stringent limit on the (spin-independent) elastic scattering cross section has been obtained by the recent XENON10 [20] and CDMS II [21] experiments: σ_{el}(cm^2) $\lesssim 7 \times 10^{-44} - 5 \times 10^{-43}$, for a dark matter mass of 100 GeV $\lesssim m_{DM} \lesssim 1$ TeV. Since the singlet D can scatter off a nucleon through processes mediated by the SM Higgs boson in the t-channel, a parameter region of our model is constrained by this current experimental bound. The elastic scattering cross section for this process is estimated to be [12]

$$\sigma_{el} \sim \big(1.4 \times 10^{-45} \text{ cm}^2\big)\left(\frac{\lambda_H^2}{0.1}\right)\left(\frac{1.3 \text{ TeV}}{m_D}\right)^2\left(\frac{120 \text{ GeV}}{m_h}\right)^4. \tag{11}$$

For the parameter set in Eq. (10), this cross section is two orders of magnitude smaller than the current bound, but could be within the reach of future experiments if $\lambda_H^2 = \mathcal{O}(0.1)$.

The dark matter in the halo of our galaxy can annihilate and produce high energy SM particles. In the case of D we obtain the triplet (Δ) and the SM Higgs bosons through the same processes as in the early universe with the same annihilation cross section. Thus, pairs of the Higgs triplet and the SM Higgs bosons are produced which eventually decay into the lighter SM particles, and thus provide additional contributions to cosmic ray fluxes. In this Letter we assume $\lambda_H < \lambda_\Delta$ so that the dark matter pair dominantly annihilates into the Higgs triplet of type II seesaw. There are two types of decay modes of the triplet Higgs boson. One is into lepton pairs through the Yukawa coupling Y_Δ which has a direct relation to the neutrino oscillation data through the type II seesaw mechanism. The second decay mode contains gauge bosons and SM Higgs boson pairs and proceeds through the gauge interactions and the couplings $\lambda_{4,5,6}$. Note that the decay amplitudes in the latter case are proportional to the small VEV of the triplet scalars, and hence the Higgs triplet dominantly decay into lepton pairs unless the Yukawa coupling Y_Δ is very small ($Y_\Delta \lesssim v_\Delta/M_\Delta$
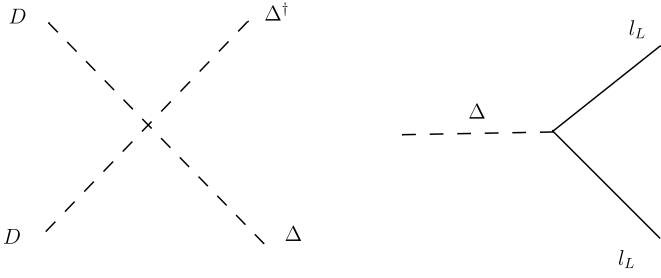
Fig. 1. Dark matter annihilation into pair of Δ's; Δ decay into pair of leptons.

Fig. 2. Dark matter annihilation into Δ's mediated by S; Δ decay into pair of leptons.

as a rough estimate). Therefore, our model predicts that the cosmic rays originating from dark matter annihilation in the halo are primarily leptons. This is a remarkable feature when we consider the experimentally observed cosmic ray positron/electron excess, with no corresponding excess in the cosmic ray anti-proton flux.

It has been argued [22] that the excess in cosmic ray electron/positron fluxes observed by PAMELA and ATIC/PPB-BETS can be simultaneously explained through lepton pairs produced by dark matter annihilation in the halo with suitable energy for the primary leptons; an e^+e^- pair each with 650 GeV of energy produced through pair annihilation with a cross section of about 100 pb, or a $\mu^+\mu^-$ pair or a $\tau^+\tau^-$ pair with about 1 TeV energy each produced by pair annihilation with a cross section of about 1000 pb. Note that in order to explain the excess of cosmic rays, the dark matter annihilation cross section should be two or three orders of magnitude larger than the typical cross section ~ 1 pb which yields the correct relic abundance. We simply assume that the difference is provided by the so-called 'boost' factor originating from the inhomogeneity of the dark matter distribution in the halo. A particle physics explanation for this 'boost' factor will shortly be discussed.

In our model a pair of D's annihilates into a pair of triplet Higgs bosons which, in turn, produce a total of four leptons (see Fig. 1). In order to explain the PAMELA and ATIC/PPB-BETS signals, the dark matter mass should be roughly twice the observed positron energy of 650 GeV.[2]

If the decay product is mainly e^+e^-, the required dark matter mass is around 1.3 TeV, while $m_D \sim 2$ TeV is needed if $\mu^+\mu^-$ pair or $\tau^+\tau^-$ pair dominates the annihilation channel. There is an interesting implication of this because of the underlying type II seesaw mechanism. The primary leptons are produced by the triplet Higgs boson decay, so that the final state lepton flavor has a direct relation with the Yukawa coupling Y_Δ and hence also with the neutrino mass matrix. The normal hierarchical mass spectrum of neutrinos predicts that $\mu^+\mu^-$ and $\tau^+\tau^-$ pairs are the dominant decay channels, while comparable amounts of e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ pairs are produced in the inverted-hierarchical neutrino mass spectrum. A precise measurement of the energy dependence of the positron/electron flux may allow us to distinguish these two neutrino mass spectra because the flux of primary e^+e^- pair shows a sharp drop at the maximum cosmic ray energy (half of the dark matter mass).

As previously stated the dark matter annihilation cross section required to account for the PAMELA and ATIC/PPB-BETS data
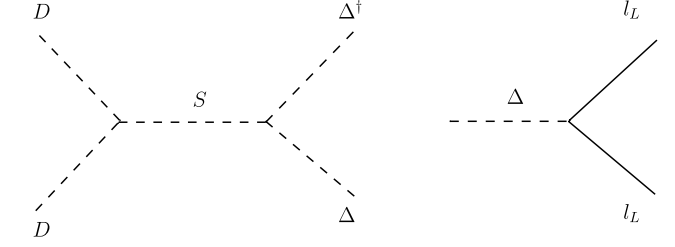
should be a few orders of magnitude larger than the one suitable for obtaining the correct relic abundance. In the above discussion, we simply assumed that the boost factor of astrophysical origin provides the required degree of enhancement of the cross section. It would be more interesting if the boost factor emerges as a result of some mechanism from particle physics. In the following, we show that a simple extension of our model can indeed provide such a boost factor.

We consider the Breit–Wigner enhancement of dark matter annihilation proposed in [16]. In this mechanism, the dark matter pair annihilation in the present universe occurs trough an s-channel process mediated by a state with mass very close to but slightly smaller than twice the dark matter mass. Although the same process is also relevant for dark matter annihilation in the early universe, a relative velocity between annihilating dark matters at the freeze-out time is not negligible, and the total energy of two annihilating D's is pushed away from the s-channel resonance pole. As a result, we can obtain a relatively large suppression of the annihilation cross section at the freeze-out time compared to the one at present.

To implement this scenario we introduce a Z_2-parity even real scalar (S) which is a singlet under the SM gauge group. We focus on the following scalar potential:

$$V(S, D, \Delta) = \frac{1}{2}M_S^2 S^2 + \lambda_1 M_S S D^2 + \lambda_2 M_S S \operatorname{tr}(\Delta^\dagger \Delta). \tag{12}$$

We assume $M_S > M_\Delta$ and also that other couplings involving S are negligibly small. As far as particle S is concerned, we need to tune its mass in order to realize the Breit–Wigner enhancement. In the absence of supersymmetry there is no deeper explanation available for the origin of the mass scales for D and S.

Next consider the annihilation process mediated by the singlet, $DD \to S \to \Delta^\dagger \Delta$ (see Fig. 2). The annihilation cross section times relative velocity in the zero-velocity limit is calculated to be

$$\sigma v|_{v\to 0} = \frac{8\lambda_1^2 M_S^2}{(4m_D^2 - M_S^2)^2 + M_S^2 \Gamma_S^2} \frac{\tilde{\Gamma}_S}{2m_D}, \tag{13}$$

where the total decay width of the S boson is given by $\Gamma_S = (3\lambda_2^2/16\pi)M_S$, and $\tilde{\Gamma}_S = \Gamma_S(M_S \to 2m_D)$. According to Ref. [16], we introduce two small parameters ($0 < \delta \ll 1$ and $\gamma \ll 1$):

$$M_S^2 = 4m_D^2(1 - \delta), \qquad \gamma = \frac{\Gamma_S}{M_S} = \frac{3\lambda_2^2}{16\pi}, \tag{14}$$

so that the cross section formula is rewritten as

$$\sigma v|_{v\to 0} \simeq \frac{2\lambda_1^2}{m_D^2} \frac{\gamma}{\delta^2 + \gamma^2}. \tag{15}$$

For $\delta, \gamma \ll 1$, the parameters are set to be very close to the S-resonance pole, and the relative velocity of annihilating dark matter in the early universe, $v \sim \mathcal{O}(0.1)$, causes a large suppression of the annihilation cross section ($v \gg \delta, \gamma$). In [16], this suppression factor (in other words, the inverse of the boost factor

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[2] The energy distribution of the final state leptons is not monochromatic since they are produced by the decay of the boosted Higgs triplet bosons. Thus, more precisely, the dark matter mass required to fit the PAMELA and ATIC/PPB-BETS data would be slightly larger. The effect of this energy distributions of the final state leptons is reflected in the cosmic ray electron flux which can be a key to sort out dark matter models accounting for the excess reported by PAMELA and ATIC/PPB-BETS [23].

BF^{-1}) is estimated as $BF^{-1} \sim 10 \, \text{Max}[\delta, \gamma]$. In order to account for the excess in the PAMELA and ATIC/PPB-BETS experiments we impose $\sigma v|_{v \to 0} \sim 1000$ pb, while $BF^{-1} \sim 1000$ to obtain the correct relic abundance of the dark matter, $\langle \sigma v \rangle \sim 1$ pb. It is in fact easy to satisfy these conditions by tuning the model parameters. For example, if we take $\lambda_1 \sim 0.01$ and $\lambda_2 \sim 0.04$, these conditions are satisfied with $\delta \sim \gamma \sim 10^{-4}$. In this case, it is not necessary for the process, $DD \to hh, \Delta^\dagger \Delta$, examined before, to be the dominant annihilation process, so that we take $\lambda_H^2 + 6\lambda_\Delta^2 < 0.16$ (see Eq. (10)).

In summary, we have proposed a simple extension of the SM to accommodate both non-zero neutrino masses and the observed dark matter in the universe. An $SU(2)_L$ triplet scalar with unit hypercharge and a Z_2-parity odd real scalar singlet are introduced. The triplet scalar implements type II seesaw while the singlet scalar D is the dark matter candidate. The relic density of D depends on the annihilation process $DD \to \Delta^\dagger \Delta$, and we have identified the desired parameter region. The singlet dark matter particles in the halo of our galaxy annihilate into the triplet scalars whose subsequent decay produces lepton pairs. Assuming a suitable astrophysical boost factor, these leptons can account for the excess in cosmic-ray positron/electron fluxes with a dark matter mass of around 1 TeV. Because of the nature of type II seesaw, the triplet Higgs bosons have no direct coupling with quarks, so that there is no sizable contribution to the cosmic-ray anti-proton flux. We have also proposed a further extension of the model by introducing a Z_2-parity even real SM scalar singlet S. In this case, the dark matter annihilation into the Higgs triplet bosons proceeds through an s-channel process mediated by the singlet S. With appropriate tuning of parameters, the annihilation cross section of dark matter in the present universe is enhanced through the Breit–Wigner enhancement mechanism [16], while keeping the annihilation cross section in the early universe to be of the right size (~ 1 pb). This extension can account for the cosmic ray positron/electron excess without invoking an astrophysical boost factor.

Finally, we offer some concluding remarks. First, our model has important implications for the SM Higgs boson mass. As shown in [24], the SM Higgs boson mass bounds obtained from imposing vacuum stability and perturbativity of the quartic Higgs coupling can be dramatically altered in the presence of type II seesaw. In particular, the Higgs boson mass window with type II seesaw can encompass mass regions otherwise not allowed. Indeed, the Higgs boson mass can even coincide with the current experimental lower bound of $m_H = 114.4$ GeV [25]. Second, the seesaw Higgs triplet is lighter than the mass ($\sim$ TeV) of the singlet dark matter particle. A Higgs triplet boson this light should be produced in hadron colliders, especially the Large Hadron Collider [26]. In particular, the doubly-charged scalar may provide a clean signature through its decay into a pair of same sign charged leptons [10].

Note added

After this Letter was submitted for publication the Fermi LAT observatory has released a new set of data [27]. According to some very recent papers, for example, see Ref. [28], muons as the primary leptons from dark matter annihilation provide a nice fit to Fermi LAT, while positrons as primary leptons give an energy spectrum which is far too strong. The energy spectrum from the tau leptons turns out to be too weak. Thus, taking the recently released Fermi LAT data [27] into account, we can say that in our model a normal hierarchy for the neutrino mass spectrum is favored, so that the primary leptons from the triplet decay are muons and taus.

Acknowledgements

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