Constraining the cogenesis of visible and dark matter with AMS-02 and Xenon-100

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We study a nonthermal scenario in a two-Higgs doublet extension of the standard model (SM), augmented by a $U(1)_{\mathrm{B-L}}$ gauge symmetry. In this setup, it is shown that the decay product of a weakly coupled scalar field just above the electroweak scale can generate visible and dark matter (DM) simultaneously. DM is unstable because of the broken $B-L$ symmetry. The lifetime of DM ($\approx 5\times 10^{25}$ sec) is found to be much longer than the age of the Universe, and its decay to the SM leptons at the present epoch can explain the positron excess observed at the AMS-02. The relic abundance and the direct detection constraint from Xenon-100 can rule out a large parameter space, just leaving the $B-L$ breaking scale around $\approx$ 2–4 TeV.

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I. INTRODUCTION

The observed cosmic ray anomalies at PAMELA [1,2], Fermi [3,4], H.E.S.S. [5], and recently at AMS-02 [6,7] (see also [8]) conclusively hint towards a primary source of positrons in our Galaxy.[1] This gives rise to enough motivation to consider particle physics based dark matter (DM) models, such as annihilation [11–16] or decay [12,16–22] of DM, as the origin of positron excess in cosmic rays.[2]

At present, the relic abundance of DM, $\Omega_{\mathrm{DM}}h^2 \sim 0.12$, is well measured by the Planck satellite [27]. However, the mechanism that provides its relic abundance is not yet established. Moreover, the origin of tiny amounts of visible matter in the Universe, which is in the form of baryons with $\Omega_{\mathrm{b}}h^2 \sim 0.022$, arising from a baryon asymmetry $n_B/n_\gamma \sim 6.15\times 10^{-10}$, has been established by the Planck [27] and big-bang nucleosynthesis measurements [28]. The fact that the DM abundance is about a factor of 5 with respect to the baryonic one might hint towards a common origin behind their genesis.

In fact, both baryon and DM abundances could be produced at the end of inflation, whose origin is usually linked to a scalar field called inflaton [29]. A visible sector inflaton which carries the Standard Model (SM) charges [30] can naturally create a weakly interacting DM, as it happens in the case of minimal supersymmetric SM scenarios; see [31]. However, if the inflaton belongs to a hidden sector, such as a SM singlet inflaton, which might also couple to other hidden sectors, then it becomes a challenge to create the right abundance for both DM and visible matter.

In this paper we will consider a simple example of any generic hidden sector inflaton, which first decays into scalar fields charged under a $U(1)_{B-L}$ gauge group. The subsequent decay of these scalar fields to DM and SM charged leptons generates asymmetry in the visible matter and DM sectors, which has to be matched with the observed data [27]. The stability to DM is provided by the $B-L$ gauge symmetry. We assume that all of the above phenomena happen in a nonthermal scenario just above the electroweak scale.

If we assume that $B-L$ is broken above the TeV scale, then the resulting DM lifetime comes out to be longer than the age of the Universe, i.e., $\approx 5\times 10^{25}$ sec, and its decay into charged leptons can explain the rising positron spectrum as shown by the AMS-02 data, provided that the DM mass is around 1 TeV. Furthermore, we are able to put constraints on the model parameters by the direct detection experiments, such as Xenon-100 [32]. The null detection of DM at Xenon-100 constrains the $B-L$ breaking scale to be around 2–4 TeV. The model can be further constrained by the LHC if there is a discovery of an extra Z' gauge boson.

The paper is organized as follows. In Sec. II, we briefly discuss the model. In Sec. III, we provide the mechanism of generating visible matter and DM simultaneously in a nonthermal setup. In Sec. IV we discuss positron anomalies from decaying DM. In Sec. V, we discuss compatibility of DM with the direct detection limits. In Sec. VI, we conclude our main results.

II. THE MODEL

The positron excess seen in PAMELA [1,2], Fermi [3,4], and AMS-02 [6,7] experiments hints towards a leptophilic origin of DM [18,33]. A simple nonsupersymmetric origin of this DM can be explained in a two-Higgs doublet

[1]In fact it has been shown earlier that there is a clean excess of absolute positron flux in the cosmic rays at an energy $E \gtrsim$ 50 GeV [9], even if the propagation uncertainty [10] in the secondary positron flux is added to the Galactic background.

[2]For astrophysical origins, see Refs. [15,23–26] and references therein.

extension of the SM with an introduction of a $U(1)_{\rm B-L}$ gauge symmetry [18,34]. We also add three singlet fermions $N_L(1,0,-1)$, $\psi_R(1,0,-1)$, and $S_R(1,0,-1)$ per generation, where the numbers inside the parentheses indicate their quantum numbers under the gauge group $SU(2)_L \times U(1)_Y \times U(1)_{\rm B-L}$. We need to check the axial-vector anomaly [35], which requires the following conditions to be satisfied for its absence:

$$\begin{aligned}
SU(3)_C^2 U(1)_{\rm B-L}&: 3\left[2\times\frac{1}{3}-\frac{1}{3}-\frac{1}{3}\right]=0\\
SU(2)_L^2 U(1)_{\rm B-L}&: 2\left[\frac{1}{3}\times 3+(-1)\right]=0\\
U(1)_Y^2 U(1)_{\rm B-L}&: 3\left[2\times\left(\frac{1}{3}\right)^2\times\frac{1}{3}\right]-3\left[\left(\frac{4}{3}\right)^2\times\frac{1}{3}+\left(\frac{-2}{3}\right)^2\times\frac{1}{3}\right]+[2(-1)^2(-1)-1(-2)^2(-1)]=0\\
U(1)_Y U(1)_{\rm B-L}^2&: 3\left[2\times\frac{1}{3}\times\left(\frac{1}{3}\right)^2\right]-\left[\frac{4}{3}\times\left(\frac{1}{3}\right)^2+\left(\frac{-2}{3}\right)\times\left(\frac{1}{3}\right)^2\right]+[2(-1)(-1)^2-1(-2)(-1)^2]=0\\
U(1)_{\rm B-L}^3&: 3\left[2\times\left(\frac{1}{3}\right)^3-\left(\frac{1}{3}\right)^3-\left(\frac{1}{3}\right)^3\right]+[2\times(-1)^3-(-1)^3]+[(-1)^3-(-1)^3-(-1)^3]=0,
\end{aligned}$$

where the number 3 in front is the color factor. Thus, the model is shown to be free from a $B-L$ anomaly and hence can be gauged by introducing an extra gauge boson Z'. Since N_L is a singlet under $SU(2)_L$, and it does not carry any charge under $U(1)_Y$, its electromagnetic charge is zero. As a result, the lightest one can be a viable candidate of DM. The stability to DM is provided by the gauged $B-L$ symmetry.

However, we also add two massive charged scalars, $\eta^-(1,-2,0)$ and $\chi^-(1,-2,-2)$, in the particle spectrum such that their interaction in the effective theory breaks lepton number by two units and hence introduces a prolonged lifetime for the lightest N_L, which is the candidate for DM. As we show later, the extremely slow decay of DM can explain the positron excess observed at PAMELA [1], Fermi [4], and recently at AMS-02 [6]. Furthermore, we assume that these particles are produced nonthermally from the cascade decay of the hidden sector inflaton field $\phi(1,0,0)$ just above the electroweak (EW) scale as pictorially depicted in Fig. 1. The particle content and their quantum numbers are summarized in Table I.

The main interactions are given by the effective Lagrangian:

$$\begin{aligned}
\mathcal{L}_{\rm eff} \supseteq\ & \frac{1}{2}(M_N)_{\alpha\beta}\overline{(N_{\alpha L})^c}N_{\beta L}+\frac{1}{2}(M_\psi)_{\alpha\beta}\overline{(\psi_{\alpha R})^c}\psi_{\beta R}\\
&+\frac{1}{2}(M_S)_{\alpha\beta}\overline{(S_{\alpha R})^c}S_{\beta R}+(g_S)_{\alpha\beta}(\overline{S_{\alpha R}}H\ell_{\beta L})\\
&+(g_\psi)_{\alpha\beta}(\overline{\psi_{\alpha R}}H\ell_{\beta L})+\mu\eta H_1H_2+m^2\eta^\dagger\chi\\
&+h_{\alpha\beta}\eta^\dagger\overline{N_{\alpha L}}\ell_{\beta R}+f_{\alpha\beta}\chi^\dagger\ell_{\alpha L}\ell_{\beta L}+\text{H.c.}, \qquad (1)
\end{aligned}$$

where

$$m^2=\mu' v_{\rm B-L}, \qquad M_i=F_i v_{\rm B-L}, \qquad (2)$$

with "$v_{\rm B-L}$" as the vacuum expectation value (VEV) of the $U(1)_{\rm B-L}$ breaking scalar field which carries $B-L$ charges by two units and F_i is the coupling between $B-L$ breaking scalar field and the singlet fermions. In Eq. (1), H_1, H_2 are two-Higgs doublets and $\ell_L(2,-1,-1)$, $\ell_R(1,-2,-1)$ are the SM lepton doublet and singlet, respectively.

We demand $M_i = F_i v_{\rm B-L}$, with $i = N, S, \psi$, to be of the order of TeV scale in order to explain the cosmic ray anomalies, as discussed in Sec. IV. Since the interactions of S and ψ break $B-L$ by two units, the neutrino mass, after the electroweak phase transition, can be generated via the

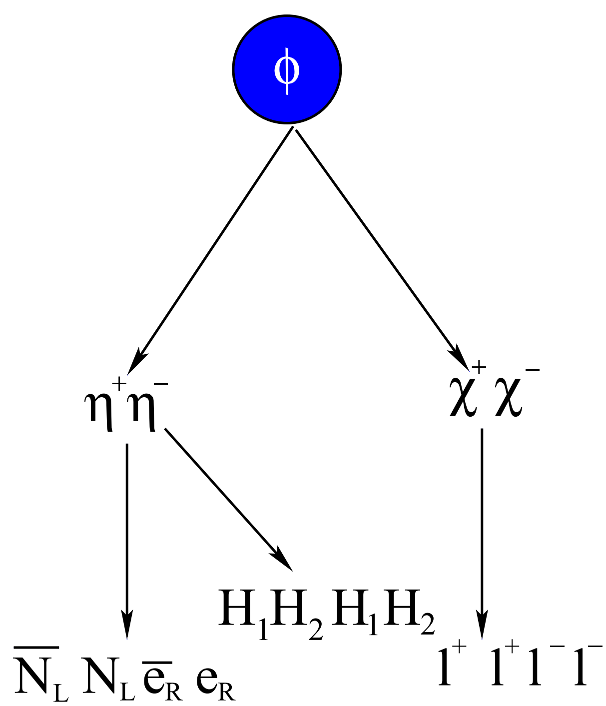

FIG. 1 (color online). Decay of hidden sector inflaton to SM degrees of freedom through η and χ fields.

TABLE I. Particle content and their quantum numbers.

Particle	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$	Mass range
ℓ_L	(2, −1)	−1	MeV to GeV
ℓ_R^-	(1, −2)	−1	MeV to GeV
H_1, H_2	(2, 1)	0	100 GeV → $\mathcal{O}$(TeV)
ϕ	(1, 0)	0	$\mathcal{O}(10^3$ TeV)
χ^-	(1, −2)	−2	$\mathcal{O}(10^3$ TeV)
η^-	(1, −2)	0	$\mathcal{O}(10^3$ TeV)
N_L	(1, 0)	−1	$\mathcal{O}$(TeV)
ψ_R, S_R	(1, 0)	−1	$\mathcal{O}$(TeV)

dimension-five operators $\ell\ell HH/M_S$ and $\ell_L\ell_L HH/M_\psi$, and it is given by

$$M_\nu = \frac{g_S^2\langle H\rangle^2}{M_S} + \frac{g_\psi^2\langle H\rangle^2}{M_\psi}. \quad (3)$$

Taking M_S, $M_\psi \sim \mathcal{O}$(TeV), the sub-eV neutrino mass implies g_S, $g_\psi \sim \mathcal{O}(10^{-5})$. Therefore, the decay of S and ψ cannot produce any lepton asymmetry even though their interactions break $B - L$ by two units. Moreover, the number density of these particles is Boltzmann suppressed as the reheat temperature is around 100 GeV.

As we will show in Sec. III, the lepton number conserving decay, $\eta \to N_L + \ell_R$, generates visible matter and DM (N_L) simultaneously. However, note that the interaction between η and χ violates the lepton number by two units. Therefore, DM is no longer stable and decays slowly to SM fields. Since DM carries a net leptonic charge, it only decays to leptons without producing any quarks. As we will discuss in Sec. IV the lifetime of DM is much longer than the age of the Universe. As a result it could explain the observed positron anomalies at PAMELA [1,2], Fermi [3,4], and AMS-02 [6,7] without conflicting with the anti-proton data.

III. COGENESIS OF VISIBLE AND DARK MATTER

A. Baryon asymmetry

In this section we explain the details of simultaneously creating the observed baryon asymmetry and the relic abundance of DM in our model. We assume that the hidden sector inflaton ϕ with mass m_ϕ decays into the SM degrees of freedom through η and χ, as depicted in Fig. 1. We further assume this gives rise to a reheat temperature:

$$T_R \sim 0.1\sqrt{\Gamma_\phi M_{\rm Pl}} \gtrsim 100 \text{ GeV}. \quad (4)$$

To generate baryon asymmetry we need CP violation, for which we assume that there exist two η fields: η_1 and η_2 of masses M_1 and M_2. Since their couplings with N_L and ℓ_R are in general complex, the $B - L$ conserving decay of the lightest one can give rise to CP violation through the interference of tree-level and self-energy correction diagrams, as shown in Fig. 2. The CP violation due to the decay of the lightest η can be estimated to be [36]

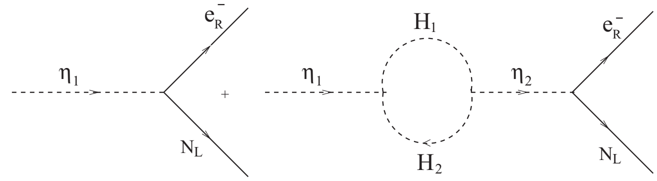

FIG. 2. The interference of tree-level and self-energy correction diagrams which give rise to CP violation.

$$\epsilon_L = \frac{\mathrm{Im}[(\mu_1\mu_2^*)\sum_{\alpha\beta} h^1_{\alpha\beta}h^{2*}_{\alpha\beta}]}{16\pi^2(M_2^2 - M_1^2)}\left[\frac{M_1}{\Gamma_1}\right] = -\epsilon_{N_L}, \quad (5)$$

where

$$\Gamma_1 = \frac{1}{8\pi M_1}\left(\mu_1\mu_1^* + M_1^2\sum_{i,j} h^1_{\alpha\beta}h^{1*}_{\alpha\beta}\right). \quad (6)$$

Now assuming $\mu_1 \sim \mu_2 \sim M_1 \sim M_2$ and $h^1_{\alpha\beta} \sim h^2_{\alpha\beta} \sim \mathcal{O}(10^{-2})$ we get from Eqs. (5) and (6) the CP asymmetry $|\epsilon_L| = |\epsilon_{N_L}| \simeq 10^{-5}$.

Since the decay of the lightest η does not violate lepton number, it cannot produce a net $B - L$ asymmetry. But it will produce an *equal and opposite* $B - L$ asymmetry between N_L and ℓ_R [34,37,38]. The two asymmetries, which remain isolated from each other before the electroweak phase transition, can be given by

$$Y_{\rm B-L} = B_\eta \epsilon_L \frac{n_\phi}{s}\bigg|_{T=T_R} = -Y^{\rm asy}_{N_L}, \quad (7)$$

where $n_\phi = \rho_\phi/m_\phi$ is the inflaton density and $s = (2\pi^2/45)g_* T^3$ is the entropy density. The branching fraction in the above equation is defined by

$$B_\eta = \frac{\Gamma(\phi \to \eta^+\eta^-)}{\Gamma(\phi \to \text{all})}. \quad (8)$$

Using $\rho_\phi|_{T=T_R} = (\pi^2/30)g_* T_R^4$ in Eq. (7), we get

$$Y_{\rm B-L} = \frac{3}{4}B_\eta \epsilon_L \frac{T_R}{m_\phi} = -Y^{\rm asy}_{N_L}. \quad (9)$$

The $B - L$ asymmetry in ℓ_R can be transformed to ℓ_L through the lepton number conserving process $\ell_R\ell_R^c \leftrightarrow \ell_L\ell_L^c$, mediated via the SM Higgs as it remains in equilibrium above the electroweak phase transition. As a result, the $B - L$ asymmetry in the lepton sector can be converted to baryon asymmetry through the $SU(2)_L$ sphalerons while leaving an equal and opposite $B - L$ asymmetry in N_L. The conversion of $B - L$ asymmetry to the baryon asymmetry is obtained by

$$\mathcal{Y}_B = \frac{24}{92} B_\eta \epsilon_L \frac{T_R}{m_\phi}. \quad (10)$$

For $T_R/m_\phi \approx 10^{-4}$ and $\epsilon_L \approx 10^{-5}$, we can achieve the observed baryon asymmetry $Y_B \approx \mathcal{O}(10^{-10})$. This leads to the DM to baryon abundance:

$$\frac{\mathcal{Y}^{\rm asy}_{N_L}}{\mathcal{Y}_B} = \frac{92}{32}. \quad (11)$$

A crucial point to note here is that the asymmetric component of DM and baryon asymmetry is produced by a nonthermal decay of the ϕ decay products, η and χ. An obvious danger of washing out this asymmetry comes from the $B-L$ violating process $N_L \ell_R \to \ell_L \ell_L$ through the mixing between η and χ. However, this process is suppressed by a factor $(m^2/M_\eta^2 M_\chi^2)^2$ for $m \ll M_\eta, M_\chi$, and hence it cannot compete with the Hubble expansion parameter at $T_R \sim 100$ GeV. Another lepton number violating process is $\ell_L \ell_L \to HH$, mediated by S and ψ. However, the rate of this process, $\Gamma \sim M_\nu^2 T_R^3/\langle H \rangle^4$, is much less than the Hubble expansion parameter at $T_R \sim 100$ GeV. As a result, the net $B-L$ asymmetry produced by the decay of η will be converted to the required baryon asymmetry without suffering any washout.

B. Dark matter abundance

Let us now calculate the required DM to baryon ratio:

$$\frac{\Omega_{N_L}}{\Omega_{\rm B}} = \frac{\mathcal{Y}^{\rm asy}_{N_L}}{\mathcal{Y}_B} \frac{M_N}{m_n}, \quad (12)$$

where m_n is the mass of a nucleon, and M_N is the Majorana mass of the DM candidate N_L.

As we discuss in Sec. IV, N_L mass is required to be $\mathcal{O}$(TeV) to explain the observed cosmic ray anomalies at PAMELA [1,2], Fermi [3,4], and recently at AMS-02 [6,7]. However, for $\mathcal{O}$(TeV) mass of N_L, Eq. (12) gives $\Omega_{N_L} \gg \Omega_B$. Fortunately this is not the case, because of the Majorana mass of N_L, which gives rise to rapid oscillation between N_L and N_L^c [39]. As a result, the N_L asymmetry can be further reduced through the annihilation process: $N_L N_L^c \to Z_{\rm B-L} \to f\bar{f}$, where f is the SM fermion.

Note that the decay of η also gives rise to a dominant $B-L$ symmetric abundance of N_L and is given by

$$\mathcal{Y}^{\rm sym}_{N_L} = \frac{3}{4} B_\eta \frac{T_R}{m_\phi}, \quad (13)$$

which is larger than the asymmetric component $\mathcal{Y}^{\rm asy}_{N_L}$ by 5 orders of magnitude and hence requires further depletion to match with the observed DM abundance.

The total N_L abundance $\mathcal{Y}_{N_L} = \mathcal{Y}^{\rm sym}_{N_L} + \mathcal{Y}^{\rm asy}_{N_L} \approx \mathcal{Y}^{\rm sym}_{N_L}$, thus produced nonthermally, can be matched with the observed DM abundance by requiring that the annihilation cross section,

$$\langle \sigma |v| \rangle_{\rm ann} \equiv \langle \sigma |v| \rangle_{(N_L \overline{N_L} \to Z_{\rm B-L} \to \sum_f f\bar{f})} \approx \frac{1}{4\pi} \frac{M_N^2}{v_{\rm B-L}^4}, \quad (14)$$

be larger than the freeze-out value $\langle \sigma |v| \rangle_F = 2.6 \times 10^{-9}\ {\rm GeV}^{-2}$. Note that in the above equation we have used the mass of the $Z_{\rm B-L}$ boson to be

$$M_{Z'} = g_{\rm B-L} v_{\rm B-L}, \quad (15)$$

with $v_{\rm B-L}$ as the $B-L$ symmetry breaking scale. In an expanding Universe, the annihilation cross section (14) has to compete with the Hubble expansion parameter,

$$H = 1.67 g_*^{1/2} \frac{T^2}{M_{\rm pl}}, \quad (16)$$

and the details of dynamics can be obtained by solving the relevant Boltzmann equations:

$$\frac{dn_\eta}{dt} + 3n_\eta H = -\Gamma_\eta n_\eta,$$
$$\frac{dn_{N_L}}{dt} + 3n_{N_L} H = -\langle \sigma |v| \rangle_{\rm ann} n_{N_L}^2 + \Gamma_\eta n_\eta. \quad (17)$$

If we omit the production term from the thermal bath, i.e., $\Gamma_\eta n_\eta \to 0$ in Eq. (17), then $\frac{dn_{N_L}}{dt} \ll 3n_{N_L} H$. In this approximation we obtain

$$\mathcal{Y}_{N_L} \equiv \frac{n_{N_L}}{s} \simeq \frac{3H}{\langle \sigma |v| \rangle_{\rm ann} s}, \quad (18)$$

where s is the entropy density. In the above equation $\mathcal{Y}_{N_L}$ has to be matched with the observed DM abundance:

$$(\mathcal{Y}_{N_L})_{\rm obs} = 4 \times 10^{-13} \left(\frac{1\ {\rm TeV}}{M_N}\right)\left(\frac{\Omega_{\rm DM} h^2}{0.11}\right). \quad (19)$$

The matching of Eqs. (18) and (19) at $T = T_R$ gives a constraint on the annihilation cross section:

$$\frac{\langle \sigma |v| \rangle_{\rm ann}}{\langle \sigma |v| \rangle_F} = 2.74 \left(\frac{M_N}{3\ {\rm TeV}}\right)\left(\frac{0.11}{\Omega_{\rm DM} h^2}\right)\left(\frac{100\ {\rm GeV}}{T_R}\right). \quad (20)$$

The above equation implies that the annihilation cross section (14) is a few times larger than the freeze-out value for a reheat temperature of 100 GeV. Now combining Eqs. (14) and (20), we can get a constraint on the $B-L$ breaking scale:

$$v_{\rm B-L} = 3.16\ {\rm TeV} \left(\frac{\Omega_{\rm DM} h^2}{0.11}\right)^{1/4}\left(\frac{M_N}{3\ {\rm TeV}}\right)^{1/4}\left(\frac{T_R}{100\ {\rm GeV}}\right)^{1/4}. \quad (21)$$

IV. DECAYING DM AND COSMIC RAY ANOMALIES

The lepton number is violated through the mixing between η and χ, as defined by $m^2 \eta^\dagger \chi$. Therefore, the lightest N_L, which is the candidate of DM, is not stable. We assume that $m \ll M_\eta, M_\chi$. This gives a suppression in the

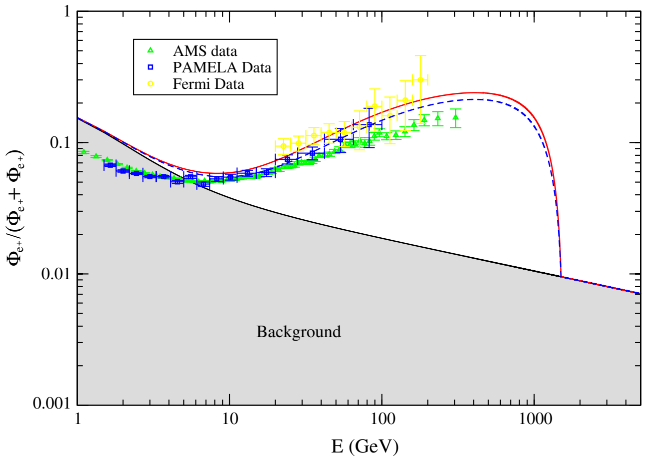

FIG. 3 (color online). Positron excess from lightest $N_L \to \tau^- \tau^+ \bar{\nu}$ with $M_N = 3$ TeV. The red solid (top) and blue dashed (bottom) lines are shown for $\tau_N = 4 \times 10^{25}$ sec and $\tau_N = 5 \times 10^{25}$ sec, respectively. The fragmentation function has been calculated using PYTHIA [45].

decay rate of DM. In other words the lifetime of DM is longer than the age of the Universe. The only available channel for the decay of lightest N_L is three-body decay:

$$N_L \to e^-_{\alpha R} e^+_{\beta L} \bar{\nu}_{\gamma L}, \tag{22}$$

with $\beta \neq \gamma$. Since the coupling of χ to two lepton doublets is antisymmetric, i.e., $\beta \neq \gamma$, the decay of N_L is not necessarily flavor conserving. In particular, the decay mode $N_L \to \tau^-_R \tau^+_L \bar{\nu}_{eL}(\bar{\nu}_{\mu L})$ violates L_e (L_μ) by one unit while it violates $L = L_e + L_\mu + L_\tau$ by two units.

In the mass basis of N_L, the lifetime can be estimated to be

$$\tau_N = 8.0 \times 10^{25}\ \mathrm{s} \left(\frac{10^{-2}}{h}\right)^2 \left(\frac{10^{-8.5}}{f}\right)^2 \left(\frac{50\ \mathrm{GeV}}{m}\right)^4 \times \left(\frac{m_\phi}{10^6\ \mathrm{GeV}}\right)^8 \left(\frac{3\ \mathrm{TeV}}{M_N}\right)^5, \tag{23}$$

where we assume that $M_\eta \simeq M_\chi \approx m_\phi$ in order to get a lower limit on the lifetime of N_L. The prolonged lifetime of N_L may explain the current cosmic ray anomalies observed by PAMELA [1,2], Fermi [3,4], and recently at AMS-02 [6,7]. The electron and positron energy spectra can be estimated by using the same setup as in Ref. [17]. In Figs. 3 and 4, we have shown the integrated electron and positron fluxes in a typical decay mode, $N_L \to \tau^- \tau^+ \bar{\nu}$, up to the maximum available energy $M_N/2$ for two values of the decay lifetime, namely, $\tau_N = 4 \times 10^{25}$ sec and $\tau_N = 5 \times 10^{25}$ sec.[3] From there, it can be seen that the

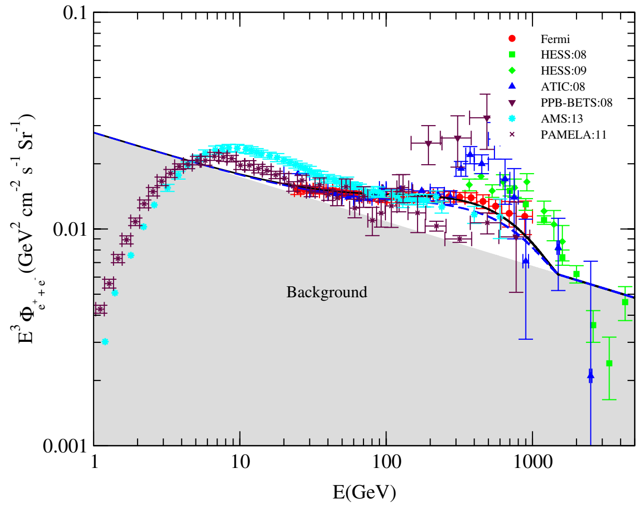

FIG. 4 (color online). Total electron plus positron flux from lightest $N_L \to \tau^- \tau^+ \bar{\nu}$ with $M_N = 3$ TeV. The black solid (top) and blue dashed (bottom) lines are shown for $\tau_N = 4 \times 10^{25}$ sec and $\tau_N = 5 \times 10^{25}$ sec, respectively. The fragmentation function has been calculated using PYTHIA [45].

decay of N_L can nicely explain the observed cosmic ray excesses at PAMELA, Fermi, and AMS-02. While doing so, we assume that the branching fraction in the decay of N_L to $\tau^- \tau^+ \bar{\nu}$ is significantly larger than the other viable decay modes: $N_L \to \mu^- \mu^+ \bar{\nu}$ and $N_L \to e^- e^+ \bar{\nu}$.

Another potential signature of this scenario is the emission of energetic neutrinos from the Galactic center [40], which can be checked by future experiments such as IceCube DeepCore [41] and KM3NeT [42].

V. DIRECT DETECTION OF DARK MATTER AND CONSTRAINTS

The interaction of N_L on the nucleons can give rise to a coherent spin-independent elastic scattering, mediated by the $Z_{\mathrm{B-L}}$ gauge boson, through t-channel process. In the limit of zero-momentum transfer, the resulting cross section is given by

$$\sigma_{N_L n} = \frac{\mu^2_{N_L n}}{64\pi v^4_{\mathrm{B-L}}} (Y^q_{\mathrm{B-L}} Y^{N_L}_{\mathrm{B-L}})^2 \left(Z\frac{f_p}{f_n} + (A - Z)\right)^2 f_n^2, \tag{24}$$

where f_n and f_p introduce the hadronic uncertainties in the elastic cross section and $\mu_{N_L n}$ is the reduced mass of the DM-nucleon system, given by

$$\mu_{N_L n} = \frac{M_N m_n}{M_N + m_n}. \tag{25}$$

Since $M_N \gg m_n$, one gets $\mu_{N_L n} \approx m_n$. In Eq. (24), the symbols $Y^q_{\mathrm{B-L}}$ and $Y^{N_L}_{\mathrm{B-L}}$ represent the $B - L$ charge of the quark and N_L, respectively. The value of f_n varies within a wide range: $0.14 < f_n < 0.66$, as quoted in Ref. [43]. Hereafter we take $f_n \simeq \frac{1}{3}$, the central value.

[3]The constraints on the $\tau^+ + \tau^-$ emission modes by gamma ray emissions from the Galactic center and dwarf spheroidals within the Galaxy depend on the density profile. Since we adopt a cored profile, the constraints are much weaker than those from the Galactic center and dwarf spheroidals [15].

At present, the strongest constraint on the spin-independent DM-nucleon cross section is given by Xenon-100, which assumes $f_p/f_n = 1$ with $Z = 54$, while A varies between 74 and 80. This is the isospin conserving case. For a 3 TeV DM, Xenon-100 gives an upper bound on the DM-nucleon cross section of $\sigma_{N_L n} < \mathcal{O}(10^{-43})$ cm^2 at 90% confidence level [32]. From Eq. (24), we can estimate the DM-nucleon cross section:

$$\sigma_{N_L n} = 2.15 \times 10^{-43}\ \mathrm{cm}^2 \left(\frac{\mu_{N_L n}}{\mathrm{GeV}}\right)^2 \left(\frac{5\ \mathrm{TeV}}{v_{\mathrm{B-L}}}\right)^4. \qquad (26)$$

Thus, the $\sigma_{N_L n}$ cross section is in the right order of magnitude and it is compatible with the latest Xenon-100 limit [32]. However, from Eq. (14) we see that for $v_{\mathrm{B-L}} =$ 5 TeV and $M_N = 3$ TeV, the annihilation cross section $\langle\sigma|v|\rangle_{\mathrm{ann}} < \langle\sigma|v|\rangle_F = 2.6 \times 10^{-9}\ \mathrm{GeV}^{-2}$. This implies that we get more than the observed value of DM abundance and hence $v_{\mathrm{B-L}} \gtrsim 5$ TeV is not allowed. On the other hand, for $v_{\mathrm{B-L}} < 5$ TeV, we can get the right amount of DM abundance. But those values of $v_{\mathrm{B-L}}$ are not allowed by the Xenon-100 constraint, as they give a large DM-nucleon cross section. These features can be easily read from Fig. 5, where we have shown the compatibility of the $B-L$ breaking scale with relic abundance (dashed black line) and the direct detection constraint (solid red line for isospin conserving and dot-dashed blue line for isospin violating) from Xenon-100.

From Eqs. (14) and (24), we see that both cross sections $\langle\sigma|v|\rangle_{\mathrm{ann}}$ and $\sigma_{N_L n}$ vary inversely as the fourth power of the $B-L$ breaking scale. Therefore, we need large $\langle\sigma|v|\rangle_{\mathrm{ann}}$ to get the right amount of relic abundance of DM, while small $\sigma_{N_L n}$ is required to be compatible with the direct detection limits from Xenon-100. In other words, we need small $v_{\mathrm{B-L}}$ to get the right amount of relic abundance,

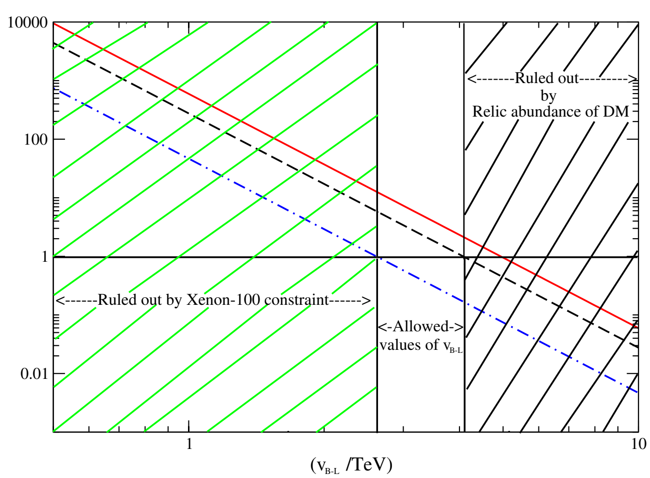

FIG. 5 (color online). $\langle\sigma|v|\rangle_{\mathrm{ann}}/\langle\sigma|v|\rangle_F$, shown by the dashed black line, and $\sigma_{\mathrm{DMn}}/\sigma_{\mathrm{xenon100}}$, shown by solid red (isospin conserving) and blue dot-dashed (isospin violating) lines, as function of $v_{\mathrm{B-L}}$ for a typical value of the DM mass: $M_N = 3$ TeV.

while large $v_{\mathrm{B-L}}$ is required to be compatible with the direct detection limits.

From Fig. 5, we see that for the isospin conserving case (solid red line) we do not get any value of $v_{\mathrm{B-L}}$, which is compatible with the relic abundance and the direct detection constraint on DM. However, these constraints can be evaded by considering an isospin violating DM-nucleon interaction [44], as shown in Fig. 5 by the dot-dashed blue line. From there, we see that a small window of the $B-L$ breaking scale, $v_{\mathrm{B-L}} = (2.5\text{–}4$ TeV) can give $\langle\sigma|v|\rangle_{\mathrm{ann}} \gtrsim \langle\sigma|v|\rangle_F$ and $\sigma_{N_L n} < \sigma_{\mathrm{Xenon100}}$ for $M_N = 3$ TeV.

Thus, we saw that DM satisfies the direct detection constraints from Xenon-100 only in the case of isospin violation and within a small window of the $B-L$ breaking scale: $v_{\mathrm{B-L}} = (2.5\text{–}4$ TeV). It is worth mentioning that the model, however, requires many parameters to explain the cosmic ray anomalies from decaying DM, but the relic abundance and the compatibility with direct detection constraints of the latter involve a single parameter, i.e., the $B-L$ breaking scale: $v_{\mathrm{B-L}}$. On one hand, if $v_{\mathrm{B-L}} >$ 4 TeV, then the annihilation cross section of DM is smaller than the freeze-out value [see Eq. (14)], and hence the model produces large DM abundance. On the other hand, if $v_{\mathrm{B-L}} < 2$ TeV, then DM does not satisfy the direct detection constraints from Xenon-100 [see Eq. (24)]. Note that the above conclusions are independent of other parameters involved in explaining cosmic ray anomalies and baryon asymmetry. Therefore, our scenario is strongly constrained in terms of the model parameter and can be checked in future terrestrial experiments such as Xenon-1T.

VI. CONCLUSIONS

We studied a nonthermal scenario in a gauged $B-L$ extension of the SM to explain a common origin behind DM abundance and baryon asymmetry. The $B-L$ symmetry is broken at a TeV scale which gives a Majorana mass to the DM, while the baryon asymmetry is created via a lepton number conserving leptogenesis mechanism and, therefore, it does not depend on the $B-L$ breaking scale. Since the lepton number is violated, the DM is no longer stable and slowly decays into the lepton sector as it carries a net leptonic charge. Since the decay rate of DM is extremely slow, it could explain the positron excess observed at PAMELA, Fermi, and recently at AMS-02 without conflicting with the antiproton data.

We also checked the compatibility of a TeV scale DM with the spin-independent DM-nucleon scattering at Xenon-100, which at present gives the strongest constraint on the DM-nucleon cross section. We have found that in the case of isospin conservation, the spin-independent DM-nucleon cross section is incompatible with the relic abundance of DM. On the other hand, by assuming the isospin violation interaction, we found a small window of the $B-L$ breaking scale, $v_{\mathrm{B-L}} = (2.5$ TeV–4 TeV), which can yield the right amount of DM abundance while explaining the positron excess. This implies that the corresponding $B - L$ gauge boson (i.e., the Z'-gauge boson) is necessarily at a TeV scale, which can be searched for at the LHC.

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