Dark matter from baryon asymmetry

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The measured densities of dark and baryonic matter are surprisingly close to each other, even though the baryon asymmetry and the dark matter are usually explained by unrelated mechanisms. We consider a scenario where the dark matter S is produced nonthermally from the decay of a messenger particle X, which carries the baryon number and compensates for the baryon asymmetry in the Universe, thereby establishing a connection between the baryonic and dark matter densities. We propose a simple model to realize this scenario, adding only a light singlet fermion S and a colored particle X which could have a mass in the $\mathcal{O}(\text{TeV})$ range and a lifetime to appear long-lived in collider detector. Therefore in hadron colliders the signal is similar to that of a stable or long-lived gluino in supersymmetric models.

I. INTRODUCTION

Our current understanding of the evolution of the Universe is based on the standard cosmology, the Friedman-Robertson-Walker cosmological model, augmented by the standard model of particle physics. It is clear that this understanding is, however, by no means complete, especially after the tremendous increase in both the volume and accuracy of data from cosmological observations. The standard model, while passing very stringent tests from particle physics experiments and by itself is capable of describing fundamental interactions in energies all the way up to the Planck scale, comes up short in several ways when trying to explain the cosmological data. The data now supports, for example, a dark energy responsible for the accelerating expansion of the Cosmos, a solid case for the nonbaryonic dark matter, a nearly scale-invariant, adiabatic, and Gaussian density fluctuations favored by inflation, and a baryon-asymmetric Universe, all of which cannot be accommodated by the standard model alone.

Brought upon us by the observations, these new insights in turn provide many directions to ponder physics beyond the standard model. In most scenarios, different shortcomings of the standard model are rectified by different and unrelated mechanisms, which makes it a wonder when some observed values from seemingly different physical origins are close to each other. An example is the ratio of the baryon and dark matter densities. Sakharov [1] pointed out that baryogenesis can be achieved by three ingredients: baryon number violation, C and CP violation, and a departure from thermal equilibrium. On the other hand, dark matter is usually proposed to explain the observed galaxy rotation curves, distributions and clustering of galaxies, gravitational lensing effects, the power spectrum of the cosmic microwave background, and so on [2], none of which seem directly relevant to the baryon asymmetry. Nevertheless, the measured dark matter density turns out to be quite close to the baryonic matter density [2,3]: $\Omega_{\text{DM}}/\Omega_b \sim 5$.

Therefore it is natural to look for models in which these two densities have a common origin, and thereby explain the proximity of the two numbers. In this case, the mass of the dark matter particle is predicted from the ratio of $\Omega_{\text{DM}}/\Omega_b$ to be several GeV if the two number densities are comparable. This is an interesting value, being not far from the electroweak scale at which we suspect new physics may appear. There have been a number of attempts in this regard over the years [4–10]. The central idea remains that the dark matter abundance comes from an asymmetry in some new quantum number generated at the same time as the baryogenesis, thus providing the link between the baryon density, or more accurately the nucleonic density we observed, and the dark matter density. Also note that there are proposals based on ideas from different directions [11–16].

Here we consider a simple mechanism discussed in Ref. [8], where dark matter is remnant of an asymmetry of a quantum number in a separate sector, in which all the particles are charged under a new symmetry while the standard model particles are neutral. The lightest particle charged under this new symmetry is stable and a natural dark matter candidate. At the time of baryogenesis, the $B - L$ number is split between the standard model and the dark sector, the sector charged under the new symmetry. If subsequently the interactions between the standard model and the dark sector are switched off or negligible, the $B - L$ number is separately conserved in the two sectors. The excess of the $B - L$ number in the standard model, which results in the baryon asymmetry in the Universe, is then compensated by the dark sector, establishing the link between the dark matter and baryonic matter densities. Such an idea, when applied to the minimal supersymmetric standard model [8], suffers from various phenomenological difficulties; among others, the asymmetries in both sectors will be washed out by scattering processes through the gaugino-exchange diagrams.

Generally speaking, in order for such an idea to work, the dark matter candidate needs to have a large enough

annihilation cross section so that the dark matter number density, which is the sum of the dark matter candidate and its antiparticle, can be linked to the baryon number density, which is proportional to the difference in the dark matter candidate and its antiparticle. Since we need the dark matter to be neutral, this implies the annihilation process has to rely on either the Z boson exchange or extra gauge/Yukawa interactions. For the Z exchange, it is severely constrained by the invisible Z decay width as well as the direct detection searches. For extra gauge/Yukawa interactions, obviously additional model buildings are needed which are likely to be complicated.

In this article, we adopt a minimalist approach, in a similar fashion as in [17], and propose a very simple yet realistic model in which dark matter is produced *nonthermally* by the late-time decay of heavy particles. In addition to the standard model, we introduce the smallest possible new symmetry, a Z_2 symmetry, along with two new particles S and X, both of which are odd under the Z_2 symmetry and comprise the dark sector. The dark matter S is a gauge-singlet fermion that interacts with the standard model sector through the messenger particle X. By the interaction between the standard model and the messenger particle, the baryon (or $B - L$) number is split between the two sectors. The asymmetry in the messenger particle is then converted into the dark matter by the nonthermal decay into S, giving a dark matter number density similar to that of the baryon. Such a simple model turns out to have interesting collider phenomenology, which will be discussed later.

In the next section, we discuss the scenario mentioned above in general terms, followed by a section considering the cosmological constraints on various aspects of the scenario. After that we explicitly write down a simple model realizing the scenario by introducing the dark matter as a gauge-singlet fermion and the messenger as a heavy, colored particle. Then we study the collider phenomenology of our simple model. The lifetime of the messenger particle can be as long as 10^{-2} sec, resulting in collider signals very similar to that of a long-lived gluino in split supersymmetry [18] in the Large Hadron Collider (LHC). In the end we summarize and conclude.

II. THE GENERAL SCENARIO

The basic ingredients of the scenario are simply the standard model plus the dark matter S and the messenger particle X, as well as a new Z_2 symmetry which we call T-parity.[1] All the standard model particles have even T-parity, whereas S and X are odd. The fermion S is an electroweak singlet and the lightest T-odd particle (LTP), but we do not specify the quantum numbers of X here since

there are a wide range of possibilities. Then the scenario proceeds in three stages as follows.

During the first stage, the baryogenesis is made possible without $B - L$ violation by distributing the $B - L$ number between the standard model (T-even) and the dark sector (T-odd). A simple, but not unique, way to achieve this is through the out-of-equilibrium and CP violating decay of a heavy T-odd particle P into a quark and the messenger particle X. An asymmetry in $B - L$ is generated in each sector even though the net $B - L$ number is vanishing. (However the heavy particle P is not necessary; see later section for an alternative scenario without having to introduce it.) Furthermore, we assume that the interactions between the standard model and the dark sector are decoupled below the temperature of the baryogenesis. Thus effectively we have two separately conserved $B - L$ numbers in the two sectors. There may be interactions which preserve both the $B - L$ symmetry and the T-parity such as $X\bar{X}HH^\dagger$, where $\bar{X}$ refers to the antiparticle of X. Such interactions, however, do not redistribute the $B - L$ numbers. As such, T-parity and gauge symmetry can guarantee the $B - L$ numbers to be conserved separately by appropriately choosing the quantum number of X, which result in the following relation:

$$n^{\text{SM}}_{B-L} = -n^X_{B-L} = -q_{B-L}(n_X - n_{\bar{X}}), \qquad (1)$$

where q_{B-L} is the $B - L$ charge of the messenger X, and n^{SM}_{B-L} and n^X_{B-L} are the $B - L$ number densities in the standard model and the dark sector, respectively.

On the other hand, since both X and $\bar{X}$ eventually decay into the LTP, the dark matter candidate S, its number density is given by the total number of X and $\bar{X}$ particles

$$n_{\text{DM}} = n^{\text{tot}}_X \equiv n_X + n_{\bar{X}}, \qquad (2)$$

which is independent of the n^{SM}_{B-L} in Eq. (1) and would suggest there is *no* connection between the baryonic and dark matter densities, unless $n_X \gg n_{\bar{X}} \sim 0$ or the other way around. This implies the lifetime of X should be long enough so that it does not decay until after most of the $\bar{X}$ particles annihilate with X. Therefore, the second stage of the scenario is the annihilation of the messenger particle in the dark sector. At temperature $T < m_X$, where m_X is the mass of the messenger, particle X starts to annihilate with its antiparticle $\bar{X}$ through gauge interactions and we are left with an abundance of X. Consequently,

$$n^{\text{SM}}_{B-L} = -n^X_{B-L} \simeq -q_{B-L}n^{\text{tot}}_X. \qquad (3)$$

The final step is the decay of X into the dark matter S. We emphasized that, in order to establish the link between the number densities of the dark and baryonic matter, the messenger X needs to have a lifetime long enough to survive until after the annihilation is completed. This will be the case if there is no relevant or marginal operator contributing to the decay of X, which can be achieved

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[1]Incidentally, or perhaps not so much so, the little hierarchy problem strongly suggests a new symmetry at the TeV scale in order to stabilize the electroweak scale naturally, which can be just a Z_2 [19].

easily by choosing the spin and/or the quantum number of X. Then the X decay produces the same number density of the LTP as n_X^{tot} due to T-parity. At this point there are two distinct situations. One is that X decays after the electroweak phase transition. The baryon and the dark matter number densities in this case are given by

$$n_B = \left(\epsilon - \frac{q_B^{\text{decay}}}{q_{B-L}}\right) n_{B-L}^{\text{SM}}, \qquad n_{\text{DM}} = \left| \frac{n_{B-L}^{\text{SM}}}{q_{B-L}} \right|, \quad (4)$$

where q_B^{decay} is the effective baryon number of X defined by the operator which induces the X decay. The efficiency ϵ is the relation between the $B - L$ number and the baryon asymmetry in the presence of the sphaleron process. This may be different from the standard model value of $28/79$ [20] since the $U(1)_Y$ neutrality condition is modified by the asymmetry stored in X which may have a nonvanishing $U(1)_Y$ charge. The second term in the baryon number density is the contribution from the decay products of the X particle. The other possibility is that X decays before the electroweak phase transition. We obtain a different formula from Eq. (4):

$$n_B = \epsilon \left(1 - \frac{q_{B-L}^{\text{decay}}}{q_{B-L}}\right) n_{B-L}^{\text{SM}}, \qquad n_{\text{DM}} = \left| \frac{n_{B-L}^{\text{SM}}}{q_{B-L}} \right|, \quad (5)$$

where q_{B-L}^{decay} is the effective $B - L$ charge of X defined by the operator which induces the X decay. In general, it is different from q_{B-L} which is the charge defined by the operator responsible for the baryogenesis. We will see an example of such a case later, even though the decay in the example occurs after the electroweak symmetry breaking owing to the cosmological constraints to be discussed in the next section.

From Eqs. (4) and (5) and the observed ratio of $\Omega_{\text{DM}}/\Omega_b$, we can determine the mass of the dark matter m_{DM} from m_p, the mass of the proton:

$$\frac{m_{\text{DM}}}{m_p} = \frac{\Omega_{\text{DM}}}{\Omega_B} \left| \frac{n_B}{n_{\text{DM}}} \right| = 5.1 |\epsilon q_{B-L} - q_B^{\text{decay}}|, \quad (6)$$

for X decaying after the electroweak phase transition and

$$\frac{m_{\text{DM}}}{m_p} = 5.1 \epsilon |q_{B-L} - q_{B-L}^{\text{decay}}|, \quad (7)$$

for X decaying before the electroweak phase transition. The mass of the dark matter S is predicted to be of $\mathcal{O}(\text{GeV})$ if its number density is comparable to that of the baryon.

III. COSMOLOGICAL CONSTRAINTS

There are only two model parameters in this scenario after fixing m_{DM} to give the correct ratio of $\Omega_{\text{DM}}/\Omega_b$. One is the scale M that suppresses the operator for the decay of X, while the other is the mass of the messenger particle m_X. Several constraints on these two parameters arise from cosmological observations. The first requirement, if X decays after the electroweak phase transition,

is the decay should happen before the big-bang nucleosynthesis, $\tau \lesssim 10^{-2}$ s, in order not to tamper with this very stringent test of the standard cosmology. Suppose X decays through a dimension D operator with $D > 4$, $\mathcal{O}_{\text{decay}} = \mathcal{O}_{\text{SM}}(XS)/M^{D-4}$, an upper bound on M is given by the following

$$M \lesssim 10^{15} \text{ GeV}\left(\frac{m_X}{1 \text{ TeV}}\right)^{3/2}, \quad (8)$$

for $D = 5$ and

$$M \lesssim 10^9 \text{ GeV}\left(\frac{m_X}{1 \text{ TeV}}\right)^{5/4}, \quad (9)$$

for $D = 6$. If instead we require the decay to occur before the electroweak phase transition,

$$M \lesssim 10^{11} \text{ GeV}\left(\frac{m_X}{1 \text{ TeV}}\right)^{3/2}, \quad (10)$$

for $D = 5$ and

$$M \lesssim 10^7 \text{ GeV}\left(\frac{m_X}{1 \text{ TeV}}\right)^{5/4}, \quad (11)$$

for $D = 6$.

On the other hand, a lower bound on M can be obtained from the requirement that the decay of X should occur after the completion of the annihilation, which results in

$$M \gtrsim m_X \left(\frac{M_{\text{Pl}} x_f^2}{m_X}\right)^{1/(2D-8)}, \quad (12)$$

where x_f is defined as $x_f \equiv m_X/T_f$, with T_f being the freeze-out temperature of the annihilation, and is evaluated to be $\mathcal{O}(20)$ [21].

As for the mass of the messenger particle X, it is constrained by the requirement that there are sufficient annihilations so that the symmetric component of X (the total abundance minus asymmetry) becomes much less significant than asymmetry. Within the standard model gauge interactions, the cross section from the strong interaction is estimated to be $0.2/m_X^2$ for s-wave annihilation which gives an upper bound on m_X:

$$m_X \ll 2 \times 10^4 \text{ TeV}\left(\frac{5 \text{ GeV}}{m_S}\right). \quad (13)$$

For the case where X is a scalar particle, the annihilation through the gluon-exchange diagram is p-wave, which gives a stronger bound than above:

$$m_X \ll 8 \times 10^2 \text{ TeV}\left(\frac{5 \text{ GeV}}{m_S}\right). \quad (14)$$

These bounds are larger than the unitarity bound of 350 TeV [22] derived for a stable massive particle which was once in thermal equilibrium. This is because our messenger particle eventually decays into the dark matter S which is much lighter than X, resulting in a much smaller

mass density. Hence m_X can be much larger than 350 TeV without overclosing the Universe. We stress that the values given here are simply upper bounds on the mass of the messenger, which are saturated when the symmetric component of the messenger X is equal to the asymmetric component. In order to establish the connection between the baryon and dark matter number densities, $n_{B-L}^{\mathrm{SM}} \sim -q_{B-L} n_X^{\mathrm{tot}}$, it is preferred to have m_X much lower than the upper bounds. On the other hand, the lower bounds on m_X simply come from direct searches of new particles which is less than 500 GeV. Therefore it is quite natural for the messenger particle to have a mass in the $\mathcal{O}(\mathrm{TeV})$ range, which raises the interesting possibility that it could be observed at future collider experiments.

There is also a constraint on the reheating temperature of the Universe by the requirement that the number of thermally produced S particles through $\mathcal{O}_{\mathrm{decay}}$ must be smaller than that of the nonthermal component from the X decay. The bound is given by

$$T_{\mathrm{RH}} \lesssim M \left(10^{-7} \frac{M}{M_{\mathrm{Pl}}} \right)^{1/(2D-9)}. \tag{15}$$

For baryogenesis to work, we need at least $T_{\mathrm{RH}} > m_X$ to generate asymmetry in the X particle. This gives a constraint on M more stringent than the lower bound derived from Eq. (12):

$$M \gtrsim 10^{14} \, \mathrm{GeV} \left(\frac{m_X}{1 \, \mathrm{TeV}} \right)^{1/2}, \tag{16}$$

for $D = 5$ and

$$M \gtrsim 10^{8} \, \mathrm{GeV} \left(\frac{m_X}{1 \, \mathrm{TeV}} \right)^{3/4}, \tag{17}$$

for $D = 6$. Note that, however, if X decays through a dimension six operator, there is a dimension-five operator, $(SS)(H^{\dagger}H)/M_S$, which could contribute to the thermal production of S dominantly unless M_S satisfies the lower bound Eq. (16), which we assume to be the case.

By comparing Eqs. (16) and (17) with the mass bound in Eq. (13), we conclude that the decay always occurs after the electroweak phase transition, and our scenario is very predictive on the mass scale M:

$$10^{14} \, \mathrm{GeV} \left(\frac{m_X}{1 \, \mathrm{TeV}} \right)^{1/2} \lesssim M \lesssim 10^{15} \, \mathrm{GeV} \left(\frac{m_X}{1 \, \mathrm{TeV}} \right)^{3/2}, \tag{18}$$

for $D = 5$ and

$$10^{8} \, \mathrm{GeV} \left(\frac{m_X}{1 \, \mathrm{TeV}} \right)^{3/4} \lesssim M \lesssim 10^{9} \, \mathrm{GeV} \left(\frac{m_X}{1 \, \mathrm{TeV}} \right)^{5/4}, \tag{19}$$

for $D = 6$. The lifetime of X, for $m_X = 1$ TeV, ranges from 10^{-5} (10^{-7}) to 10^{-2} second for $D = 5$ ($D = 6$). For comparison, in the LHC a particle with a lifetime

longer than 10^{-6} sec will decay outside of the detector and appear to be stable.

IV. A SIMPLE MODEL

In this section we present an explicit model and discuss its collider phenomenology in the following section. We will take the quantum numbers of X to be the same as the antiparticle of the right-handed down type quark $X:(\bar{\mathbf{3}}, \mathbf{1})_{1/3}$ with spin $1/2$. Baryogenesis can be achieved by the out-of-equilibrium and CP-violating decay of a singlet T-odd particle P, which can be the inflaton, into $d_R + X$ and $\bar{d}_R + \bar{X}$. The effective $B - L$ number of X is then $q_{B-L} = -1/3$. The annihilation of X is sufficiently effective because of the strong interaction once the bound in Eq. (13) is satisfied.

With this assignment of quantum numbers and spin for X, gauge symmetry and T-parity ensures the lowest dimensional operator contributing to the X decay is a dimension six one:

$$\mathcal{O}_{\mathrm{decay}} = \frac{1}{M^2} u^c d^c X S. \tag{20}$$

Thus the bounds on the scale M are given by Eq. (19). The decay operator breaks the $B - L$ symmetry and defines B and $B - L$ numbers of X to be different from q_{B-L},

$$q_B^{\mathrm{decay}} = q_{B-L}^{\mathrm{decay}} = +\frac{2}{3}. \tag{21}$$

We then obtain the number densities n_B and n_{DM} by applying Eq. (4) as follows:

$$n_B = (\epsilon + 2) n_{B-L}^{\mathrm{SM}}, \qquad n_{\mathrm{DM}} = 3 |n_{B-L}^{\mathrm{SM}}|, \tag{22}$$

where the efficiency ϵ is different from the standard model value, now that the presence of X modifies the charge neutrality condition, and calculated to be $34/79$ with the additional constraint that the total $(B - L)$ number is zero before the decay of X. Therefore the mass ratio m_{DM}/m_p is given by

$$\frac{m_{\mathrm{DM}}}{m_p} = 4.1, \tag{23}$$

from Eq. (6). The observed ratio of $\Omega_{\mathrm{DM}}/\Omega_b$ determines the mass of the dark matter to be 3.9 GeV in this model.

Alternatively, if one were to insist on not introducing the extra heavy particle P, a possibility would be that the baryogenesis generates $B - L$ asymmetry (or asymmetry in X) first and distribute the asymmetry to the T-odd (T-even) sector through an interaction such as $(d_R X) \times (d_R X)$. After the decoupling of the interaction, the $B - L$ asymmetry conserves separately in each sector and the asymmetry in X again becomes the source of the dark matter. The prediction to the ratio m_{DM}/m_p is modified

to be

$$\frac{m_{\rm DM}}{m_p} = 0.89. \qquad (24)$$

We mention in passing that models in which X decays through dimension five operators can also be easily constructed with X being a scalar particle. For example, X can again have the quantum numbers $X:(\bar{\mathbf{3}}, \mathbf{1})_{1/3}$ but with spin 0 this time. It decays through the dimension five operator $\mathcal{O}_5 = (\bar{q}_L H)^*(XS)/M$ with M satisfying the constraint Eq. (18). Note that there is actually a dimension four operator $\mathcal{O}_4 = d^c \bar{X} S$ allowed by the gauge symmetry and the T-parity. However, we can impose a Peccei-Quinn symmetry or its discrete subgroup, under which the singlet fermion S is charged, to allow $\mathcal{O}_5$ but prohibit $\mathcal{O}_4$ at tree level. Then the Peccei-Quinn symmetry is only softly broken by the mass term of S, which would radiatively induce the operator $\mathcal{O}_4$ with a small coefficient $m_S/(16\pi^2 M)$. Then X still decays dominantly through $\mathcal{O}_5$ since $\Gamma_{\mathcal{O}_4}/\Gamma_{\mathcal{O}_5} \sim (m_S/16\pi^2 m_X)^2$ which is only 10^{-10} for $m_S = 1$ GeV and $m_X = 1$ TeV. In the end the mass ratio $m_{\rm DM}/m_p$ is 0.97 or 6.0 for the case with or without the P particle. Or more simply, if one did not insist on standard model quantum numbers, dimension four operators could be forbidden by appropriately choosing quantum number of X.

V. COLLIDER SIGNALS

In spite of the simplicity of this model, the collider signal for the messenger particle turns out to be quite interesting. As discussed before, it is natural for the messenger particle X to have a mass in the $\mathcal{O}(\text{TeV})$ range and a lifetime between 10^{-7} s to 10^{-2} s, which implies its collider phenomenology shares similar features with that of a heavy stable/long-lived particle. Examples of such particles include a heavy gluino as the lightest supersymmetric particle (LSP) [23] and a long-lived gluino in the scenario of split supersymmetry [18]. The phenomenology of such a long-lived/stable gluino has been studied extensively in Refs. [24–29]. Here we very briefly summarize their results and point out differences, if any.

At the LHC X can be pair-produced from s- and t-channels through gg and $\bar{q}q$ annihilations if it is colored. Because of its long lifetime, X hadronizes into a color-singlet state before decaying. In supersymmetry such particles, resulting from the hadronization of the gluino, are called R-hadrons since they carry one unit of R-parity. In our case, the role of R-parity is played by the T-parity so we may as well call the corresponding color singlets T-hadrons. In the model discussed in the previous section, unlike gluino, X is a fermion in the fundamental representation of $SU(3)_c$ with the quantum numbers of the b-quark, which implies the spectroscopy of T-hadrons should look very much like that of hadrons containing a b-quark. That is, there should be states like Xq, a spin 0 T-meson, and

$X\bar{q}\bar{q}$, a spin $1/2$ T-baryon. It is well known that, in the case of b-quark, heavy quark effective theory [30] is a useful tool in studying the spectroscopy and interactions of B-meson. Since the messenger particle X is 1000 times heavier than the b-quark, we expect that heavy quark effective theory will be extremely useful in studying the spectroscopy and interactions of the T-hadron since all the $1/m_X$ corrections are very small.

In terms of detection at the LHC, with a lifetime longer than 10^{-7} s, X is most likely to decay outside of the detector and appears to be a massive stable particle as far as the collider is concerned. Then the technique for searching for the gluino LSP should be employed. In the scenario where the messenger X hadronizes into neutral particles, interacts very softly with the detector and remain so through out their lifetime, pair-production of X in the collider will become invisible because it interacts very softly with the detector. The detection will rely on pair-production of X plus an additional jet in this case for the event to be triggered as the monojet with missing energies carried away by the neutral T-hadrons [27]. An event easier to observe is a pair-production of X hadronizing into charged T-hadrons, which can be distinguished from light particles by looking at their velocities and the energy loss due to ionization [27]. In the LHC we expect that the T-hadron can be discovered for $m_X \lesssim 2$ TeV, a bound similar to that of a long-lived gluino [26].

There is also an interesting possibility that X and $\bar{X}$ would form a bound state, a quarkonium η_4, in the hadron colliders [31]. For discovery potential at the LHC, studies found that the most promising channel is $\eta_4 \rightarrow \gamma\gamma$ [32]. For luminosity at 100 fb^{-1}, η_4 can be observed up to $m_{\eta_4} = 400$ GeV.

VI. SUMMARY

The origins of baryon asymmetry and dark matter are two cosmological puzzles for which the standard model of particle physics fails to explain; the CP violation in the standard model is too small to explain the baryon asymmetry and there is simply no candidate for dark matter in the particle content of standard model. Conventionally the dark matter is postulated to be a weakly interacting particle whose relic density is determined by the freezing-out of the interactions that keep it in thermal equilibrium, and is independent of the dynamics generating the baryon asymmetry. Therefore it is a mystery that the observed values of the dark and baryonic matter densities are quite close to each other, within a factor of 5.

In this article we study a general scenario where the dark matter is produced nonthermally from the decay of a messenger particle, which carries the $B - L$ number and compensates for the excess of the baryon number in the standard model. The simplest realization of this scenario includes only two new particles, the dark matter S which is

a gauge-singlet fermion with a mass in the $\mathcal{O}(\text{GeV})$ range and the messenger particle X which is a colored particle with possibly a mass in the $\mathcal{O}(\text{TeV})$ range. Moreover, the X particle has a long lifetime, between 10^{-7} s and 10^{-2} s, which makes interesting collider signals and, to the first order approximation, mimics that of a stable/long-lived gluino in supersymmetric models with a gluino LSP or split supersymmetry.

Finally, it seems appropriate to try to implement this idea in more complicated models for physics beyond standard model. Earlier attempts in this regard typically involve the thermal production of sneutrino as the dark matter in supersymmetric versions of the standard model [8,10], and efforts need to be made to make the sneutrino

dark matter much lighter, or its number density much larger, than natural expectations. In this regard the scenario proposed in [33,34], where a dark matter candidate with a baryon number and a mass as low as $\mathcal{O}(\text{GeV})$, seems promising.

ACKNOWLEDGMENTS

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