



Decaying dark matter baryons in a composite messenger model

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ABSTRACT

A baryonic bound state with a mass of $\mathcal{O}(100)$ TeV, which is composed of strongly interacting messenger quarks in the low scale gauge mediation, can naturally be the cold dark matter. Interestingly, we find that such a baryonic dark matter is generically metastable, and the decay of this dark matter can naturally explain the anomalous positron flux recently observed by the PAMELA Collaboration.

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1. Introduction

The origin and nature of the dark matter (DM) are one of the most challenging problems in the particle physics and cosmology. If the DM is in thermal equilibrium in the early universe, the present abundance of the DM is determined by its annihilation cross section σv_{rel} . Here, v_{rel} is the relative velocity of the DM at the freeze out time. The observed DM density requires $\sigma v_{\text{rel}} \simeq 2 \times 10^{-9} \text{ GeV}^{-2}$. From this result one may derive the upper bound on the mass of the DM as $m_{\text{DM}} \lesssim 100 \text{ TeV}$ [1]. This is because the (s -wave) annihilation cross section never violates the unitarity limit given by

$$\sigma v_{\text{rel}} \lesssim \frac{4\pi}{m_{\text{DM}}^2 v_{\text{rel}}} \quad (1)$$

The upper-bound value, $m_{\text{DM}} \simeq 100 \text{ TeV}$, is obtained when the annihilation cross section saturates the unitarity limit and hence the DM is subject to a new strong interaction at the energy scale of 100 TeV. Interestingly, the scale 100 TeV coincides with the supersymmetry (SUSY) breaking scale in the low scale gauge mediation. Therefore, it is intriguing that the DM is one of composite bound states in hidden quarks Q 's in the dynamical SUSY-breaking hidden sector [2,3].

In a recent article [4], we proposed DM baryons composed of the messenger quarks P 's, instead of the hidden quarks Q 's responsible for the SUSY breaking. Here, the messenger quarks P_α^i and \bar{P}_i^α are assumed to transform as $\mathbf{5}$ and $\mathbf{5}^*$ under the GUT gauge group, and as anti-fundamental and fundamental representations of a new strongly interacting gauge group $SU(N)$, respectively. Here, the subscript i (α) represents the GUT ($SU(N)$) index. The DM baryons are expressed as $B^{i_1 i_2 \dots i_N} = \epsilon^{\alpha_1 \alpha_2 \dots \alpha_N} \times$

$P_{\alpha_1}^{i_1} P_{\alpha_2}^{i_2} \dots P_{\alpha_N}^{i_N}$ and $\bar{B}_{i_1 i_2 \dots i_N} = \epsilon_{\alpha_1 \alpha_2 \dots \alpha_N} \bar{P}_{i_1}^{\alpha_1} \bar{P}_{i_2}^{\alpha_2} \dots \bar{P}_{i_N}^{\alpha_N}$. The requirement that these baryons are neutral under the GUT gauge group dictates $N = 5$.

If the new gauge group is indeed $SU(5)$, the baryon-number violating operators in the superpotential are allowed, $W = (1/M_P^2) P^5 + (1/M_P^2) \bar{P}^5$, and the composite baryons become metastable. Here, $M_P = 2.4 \times 10^{18} \text{ GeV}$ is the reduced Planck scale. We find that the lifetime of the baryon DM is $\mathcal{O}(10^{24-26}) \text{ s}$. It is much longer than the age of the universe and assures the stability of the DM, while it is short enough to leave observable signatures in cosmic rays. Especially, the anomalous positron flux recently observed by the PAMELA Collaboration [5] is naturally explained by the decay of the composite DM with the above mass and lifetime.

2. Strongly interacting messenger model and composite baryons

We consider a SUSY extension of the standard model (SM) in which a SUSY-breaking effect of a hidden sector is communicated to the visible minimal supersymmetric standard model (MSSM) sector by the gauge mediation mechanism [6]. We represent the SUSY-breaking effect of the hidden sector as nonzero vacuum expectation values of scalar and F components of a singlet field Φ_S belonging to the hidden sector: $\langle \Phi_S \rangle = \langle \varphi_S \rangle + \theta^2 \langle F_S \rangle$. We introduce messengers $P_\alpha^i = (L_\alpha, D_\alpha)$ and $\bar{P}_i^\alpha = (\bar{L}^\alpha, \bar{D}^\alpha)$ which are in the fundamental ($\mathbf{5}$) and anti-fundamental ($\mathbf{5}^*$) representations of the SM gauge group $SU(5)_{\text{GUT}} \supset SU(3) \times SU(2) \times U(1)$. Here, $i = 1, \dots, 5$ is the index for $SU(5)_{\text{GUT}}$. We assume that the messengers are also in anti-fundamental ($\mathbf{5}^*$) and fundamental ($\mathbf{5}$) representations of an additional gauge group $SU(5)$ as explained in the Introduction (see also Ref. [4]). The above introduced subscript $\alpha = 1, \dots, 5$ represents the index for this gauge group. A crucial assumption here is that this additional gauge group is strongly coupled at the messenger mass scale.

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The messengers interact with the hidden sector via a Yukawa interaction¹

$$W = y \Phi_S P_\alpha^i \bar{P}_i^\alpha, \quad (2)$$

while they interact with the MSSM sector via the SM gauge interaction. The nonzero scalar and F components of the Φ_S yield a mass term for the messengers. This setup is a standard form of the gauge mediation [6].

We now turn to the strongly interacting SU(5) sector. This sector is a SUSY QCD with the number of fundamentals equal to the rank of the gauge group SU(5) (i.e., $N_f = N = 5$). The low energy effective theory of this gauge theory is described by a confined theory with a deformed moduli space [7]. This theory can be described by SU(5) gauge invariant operators made up of messenger quarks. They are mesons

$$M_j^i = P_\alpha^i \bar{P}_j^\alpha \quad (3)$$

and baryons

$$B = P^5 = \frac{1}{5!} \epsilon_{ijklm} \epsilon^{\alpha\beta\gamma\delta\epsilon} P_\alpha^i P_\beta^j P_\gamma^k P_\delta^l P_\epsilon^m, \\ \bar{B} = \bar{P}^5 = \frac{1}{5!} \epsilon^{ijklm} \epsilon_{\alpha\beta\gamma\delta\epsilon} \bar{P}_i^\alpha \bar{P}_j^\beta \bar{P}_k^\gamma \bar{P}_l^\delta \bar{P}_m^\epsilon. \quad (4)$$

The effective superpotential is given by (with a Lagrange's multiplier field X) [7],

$$W = X(\det M - B\bar{B} - \Lambda^{10}) + m_i^j M_j^i, \quad (5)$$

where, for simplicity, we consider a supersymmetric mass term for messengers. This term and non-supersymmetric mass terms for messengers are generated by the Yukawa term with the vacuum expectation value of Φ_S . This superpotential yields a SUSY invariant vacuum at

$$\langle M_j^i \rangle = [m^{-1}]_j^i (\Lambda^{10} \det m)^{1/5}, \quad (6)$$

$$\langle B \rangle = \langle \bar{B} \rangle = 0, \quad (7)$$

$$\langle X \rangle = -\frac{(\Lambda^{10} \det m)^{1/5}}{\Lambda^{10}}. \quad (8)$$

We can also estimate the masses of the baryons and mesons of the confined theory. For this purpose, however, we must know the form of the Kähler potential, in particular, the normalization of the kinetic terms. We estimate this by using the Naive Dimensional Analysis (NDA) method [8], which assumes that the confined theory is strongly coupled. The NDA method gives the above superpotential in terms of canonically normalized fields \hat{B} , $\hat{\bar{B}}$, \hat{M} and \hat{X} as

$$W = \frac{1}{g^2} \left[\frac{g\hat{X}}{\Lambda^8} (\det(g\Lambda\hat{M}) - g^2 \Lambda^8 \hat{B}\hat{\bar{B}} - \Lambda^{10}) + m_i^j (g\Lambda\hat{M}_j^i) \right] \quad (9)$$

$$= \hat{X} \left(\frac{g^4}{\Lambda^3} \det \hat{M} - g\hat{B}\hat{\bar{B}} - \frac{1}{g} \Lambda^2 \right) + \frac{\Lambda}{g} m_i^j \hat{M}_j^i, \quad (10)$$

where g is a constant of order 4π . The corresponding vacuum expectation values are

$$\langle \hat{M}_j^i \rangle = [m^{-1}]_j^i \frac{(\Lambda^5 \det m)^{1/5}}{g}, \quad (11)$$

$$\langle \hat{B} \rangle = \langle \hat{\bar{B}} \rangle = 0, \quad (12)$$

$$\langle \hat{X} \rangle = -\frac{(\Lambda^5 \det m)^{1/5}}{g\Lambda}. \quad (13)$$

¹ In general the Yukawa couplings of D and L can be different, i.e., $W = y_L \Phi_S L_\alpha \bar{L}^\alpha + y_D \Phi_S D_\alpha \bar{D}^\alpha$.

We can see from the above expressions that both the baryon and meson masses are of order m .

The baryon and anti-baryon in this theory are neutral under the SM gauge group. Note also that the baryon number is automatically conserved by the superpotential and the vacuum expectation values. Assuming the baryon number conservation in the Kähler potential, the (anti-)baryons become stable and can be candidates for the DM. Now if the baryons and mesons are really strongly coupled, the annihilation cross sections of the (anti-)baryons nearly saturate the unitarity limit, and we must have $m \sim 100$ TeV to explain the observed DM density of the universe as discussed in the Introduction. It is very interesting that this mass scale coincides with the messenger mass scale appearing in the gauge mediation, and we have a good reason to identify these baryons of the messenger sector as a candidate for the DM.

3. Possible baryon-number violating operators and decays of the DM baryons

Although we have baryon number conservation to leading order in the messenger sector, it can be violated by higher-dimensional operators. These baryon-number violating effects can be represented by Planck-suppressed higher-dimensional operators in the superpotential. The leading terms are

$$\Delta W = \frac{1}{M_P^2} P^5 + \frac{1}{M_P^2} \bar{P}^5 \rightarrow \frac{1}{M_P^2} \frac{\Lambda^4 \hat{B}}{g} + \frac{1}{M_P^2} \frac{\Lambda^4 \hat{\bar{B}}}{g}, \quad (14)$$

where we omit unknown coefficients of order unity. In the confined description, these terms are linear in \hat{B} and $\hat{\bar{B}}$, and therefore produce a slight shift in the vacuum expectation values of them. We have, instead of Eq. (12),

$$\langle \hat{B} \rangle \simeq \langle \hat{\bar{B}} \rangle \simeq -\frac{\Lambda^5}{gM_P^2 (\Lambda^5 \det m)^{1/5}}. \quad (15)$$

There are interactions between baryons and mesons coming from solving the constraining equation. Upon integrating \hat{X} and expanding around the vacuum expectation values,

$$W \ni \frac{gm}{\Lambda} \hat{B}\hat{\bar{B}}\hat{M}, \quad \frac{g^2 m}{\Lambda^2} \hat{B}\hat{\bar{B}}\hat{M}^2, \quad \text{etc.} \quad (16)$$

There may also be contribution coming from the Kähler potential, e.g.,

$$K \ni \frac{g^2}{\Lambda^2} \hat{B}^\dagger \hat{B} \hat{M}^\dagger \hat{M}, \quad \frac{g^2}{\Lambda^2} \hat{\bar{B}}^\dagger \hat{\bar{B}} \hat{M}^\dagger \hat{M}. \quad (17)$$

These terms and the above baryon-number violating effects induce the baryons to decay into mesons, which in turn decay into MSSM particles by the gauge interaction or higher-dimensional terms in the superpotential (see Ref. [4]). Assuming that the messenger mass m is of the same order as Λ , the lifetime of the baryons are estimated as

$$\tau \sim 16\pi \frac{M_P^4}{g^2 \Lambda^5} \sim \frac{M_P^4}{\pi \Lambda^5}, \quad (18)$$

where the factor 16π comes from the phase space integral. With $m \sim \Lambda \sim (30\text{--}100)$ TeV, this yields numerically $\tau \sim 10^{24\text{--}26}$ s. Note that the theory with $N_f = N = 4$ or 6 , instead of 5 , would lead to a lifetime of $10^{-(1\text{--}3)}$ s or $10^{51\text{--}54}$ s, respectively, which shows that the prediction $\tau \sim 10^{24\text{--}26}$ s for $N = 5$ is quite nontrivial. As we will see, this lifetime together with the DM mass can naturally explain the anomalous positron excess observed by the PAMELA Collaboration.

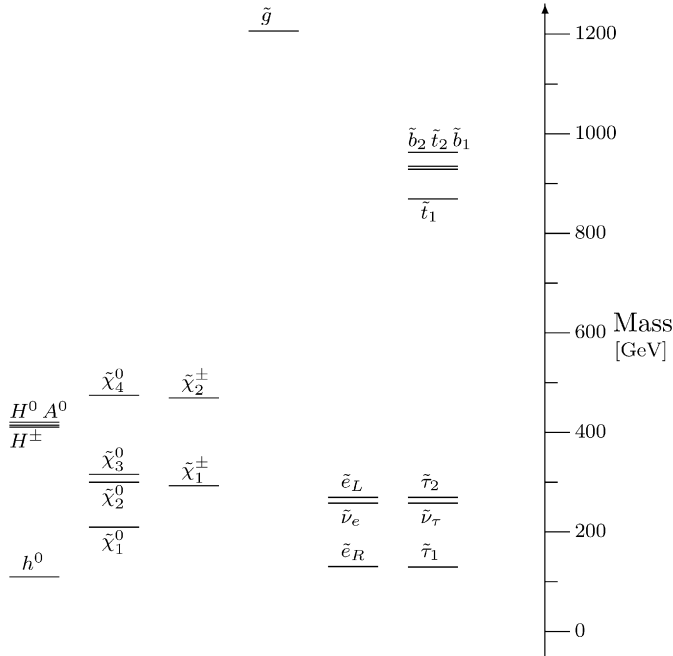


Fig. 1. MSSM mass spectrum. The gravitino mass is 0.3 eV.

4. Positrons from the DM decays

Before discussing the signals of the DM decays, we give a typical SUSY particle spectrum for concreteness. In our model, it is not easy to calculate the low-energy mass spectrum, since the messenger sector is strongly interacting. We expect that, from the viewpoint of effective theory, the $SU(5)_{\text{GUT}}$ adjoint messenger mesons (such as $L\bar{L}$, $D\bar{D}$, $L\bar{D}$, $D\bar{L}$) generate the MSSM sparticle masses. Thus, for simplicity, we adopt a minimal gauge mediated SUSY breaking (mGMSB) model with $N_5 = 5$. From now on, we take mGMSB parameters as

$$\Lambda_{\text{SUSY}} = 30 \text{ TeV}, \quad M = 40 \text{ TeV}, \quad N_5 = 5, \\ \tan \beta = 5, \quad \text{sgn}(\mu) = +1 \quad \text{and} \quad C_{\text{grav}} = 1. \quad (19)$$

The mass spectrum is shown in Fig. 1, which is calculated by ISAJET 7.72 [9]. It also predicts an ultralight gravitino with mass 0.3 eV.

Now let us discuss the signals of the DM decays. For simplicity, we assume that the DM baryon decays to only two lightest $L\bar{L}$ mesons.² This meson decays to a pair of gauginos or gauge bosons through triangle anomaly-like diagrams. A precise calculation of mesons' branching fractions is difficult, because of the strong dynamics as well as the SUSY breaking effects. Here, for simplicity, we assume that the mesons decay into a pair of gauge bosons or a pair of gauginos with the same branching fraction, as in the SUSY conserving limit.

These decay products emit high energy positrons, and these positron are detected as cosmic rays. Especially, the decays into the gaugino are rich positron source, since almost all of the gauginos decay into the next-to-lightest SUSY particle (NLSP) slepton emit-

² Because of the renormalization effect from $SU(5)_{\text{GUT}}$, the leptonic messenger tends to be light. Therefore, it would be reasonable to assume that the baryon DM dominantly decays to $L\bar{L}$ mesons because of kinematical reason. Here, for simplicity, we assume that the baryon DM decays into a pair of $SU(2)$ singlet $L\bar{L}$'s, neglecting the effects of the $D\bar{D}$ component in the singlet as well as the decay into the $SU(2)$ triplet $L\bar{L}$'s.

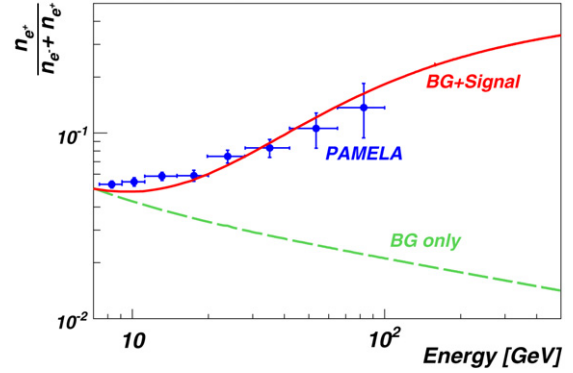


Fig. 2. Positron fraction from decay of the baryon with $m_B = 100 \text{ TeV}$ and $m_M = 40 \text{ TeV}$. The lifetime of the DM is $1.1 \times 10^{25} \text{ s}$. The red solid line represents the signal plus background and the green dashed line the background only. The blue points represent the current PAMELA data [5]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

ting lepton(s), and subsequently the slepton decays into a gravitino and a lepton. To evaluate the positron spectrum from the decay of the baryon, we have used the program PYTHIA [10]. We estimate the positron fraction following Refs. [11–13]. In Fig. 2, we show the positron fraction in our model. Here we take $m_B = 100 \text{ TeV}$, $m_M = 40 \text{ TeV}$ and the lifetime of the DM is $1.1 \times 10^{25} \text{ s}$. Interestingly, the positron flux from the baryonic DM decay can naturally explain the positron excess for $\gtrsim 10 \text{ GeV}$ recently reported by the PAMELA Collaboration [5].

5. Discussion and conclusions

A baryonic bound state of strongly interacting sector in low scale gauge mediation, which have mass of $\mathcal{O}(100) \text{ TeV}$ and annihilation cross section close to the unitarity bound, can naturally be the cold dark matter. Such a scenario predicts an ultralight gravitino with a mass of $\mathcal{O}(1) \text{ eV}$, which is attractive since it circumvents all the notorious cosmological gravitino problems.

If the baryonic DM is composed of messenger quarks charged under strongly interacting $SU(N)$, the neutrality of the DM requires $N = 5$. In this Letter, we pointed out that such a baryonic DM is in general metastable due to the higher-dimensional, baryon-number violating operators, and showed that its lifetime becomes $\mathcal{O}(10^{24-26}) \text{ s}$. Interestingly enough, the products of the baryonic DM decay can be observed, opening the possibility of its indirect detection. We have shown that the positron flux from the baryonic DM decay can naturally explain the anomalous positron flux recently observed by the PAMELA Collaboration [5]. We should emphasize that, as shown in Fig. 2, the heavy baryonic DM decay predicts that the positron excess continues up to higher energy, which can be tested by the near future PAMELA data up to about 300 GeV.

In the MSSM LSP DM scenario, the positron flux anomaly stretching up to higher energy indicates the heavier LSP, which may imply the difficulty of the SUSY discovery at the LHC. However, our present model is free from this difficulty.

In addition to the positron signal, this model also predicts high energy cosmic rays such as gamma rays and neutrinos, which are tested by the current of future experiments. A more detailed study along this line will be given elsewhere.

Note added

Recently the ATIC Collaboration reported an excess in the total $e^- + e^+$ flux [14], in consistent with the PPB-BETS experiment [15]. This excess may also be explained by the composite DM decay if its mass is $\mathcal{O}(1) \text{ TeV}$, which can be realized in our GMSB model by using the SUSY breaking effects to lower the messenger scalar masses [16].

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References

- [1] K. Griest, M. Kamionkowski, Phys. Rev. Lett. 64 (1990) 615.
- [2] S. Dimopoulos, G.F. Giudice, A. Pomarol, Phys. Lett. B 389 (1996) 37, arXiv:hep-ph/9607225.
- [3] M. Ibe, H. Murayama, Y. Nakayama, T.T. Yanagida, arXiv:0902.2914 [hep-ph].
- [4] K. Hamaguchi, S. Shirai, T.T. Yanagida, Phys. Lett. B 654 (2007) 110, arXiv:0707.2463 [hep-ph].
- [5] O. Adriani, et al., arXiv:0810.4995 [astro-ph].
- [6] See for a general review of gauge mediation, G.F. Giudice, R. Rattazzi, Phys. Rep. 322 (1999) 419, arXiv:hep-ph/9801271.
- [7] N. Seiberg, Phys. Rev. D 49 (1994) 6857, arXiv:hep-th/9402044.
- [8] M.A. Luty, Phys. Rev. D 57 (1998) 1531, arXiv:hep-ph/9706235; A.G. Cohen, D.B. Kaplan, A.E. Nelson, Phys. Lett. B 412 (1997) 301, arXiv:hep-ph/9706275.
- [9] F.E. Paige, S.D. Protopopescu, H. Baer, X. Tata, arXiv:hep-ph/0312045.
- [10] T. Sjostrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, arXiv:hep-ph/0603175.
- [11] J. Hisano, S. Matsumoto, O. Saito, M. Senami, Phys. Rev. D 73 (2006) 055004, arXiv:hep-ph/0511118.
- [12] A. Ibarra, D. Tran, JCAP 0807 (2008) 002, arXiv:0804.4596 [astro-ph].
- [13] C.R. Chen, F. Takahashi, T.T. Yanagida, arXiv:0809.0792 [hep-ph].
- [14] J. Chang, et al., Nature 456 (2008) 362.
- [15] S. Torii, et al., arXiv:0809.0760 [astro-ph].
- [16] K. Hamaguchi, E. Nakamura, S. Shirai, T.T. Yanagida, in preparation.