PAMELA/ATIC anomaly from the meta-stable extra dark matter component and the leptophilic Yukawa interaction

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Abstract. We present a supersymmetric model with two dark matter (DM) components explaining the galactic positron excess observed by PAMELA/HEAT and ATIC/PPB-BETS: One is the conventional (bino-like) lightest supersymmetric particle (LSP) \( \chi \), and the other is a TeV scale meta-stable neutral singlet \( N_D \), which is a Dirac fermion \( (N, N^c) \). In this model, \( N_D \) decays dominantly into \( \chi e^+e^- \) through an \( R \) parity preserving dimension 6 operator with the lifetime \( \tau_N \sim 10^{26} \) sec. We introduce a pair of vector-like superheavy SU(2) lepton doublets \( (L, L^c) \) and lepton singlets \( (E, E^c) \). The dimension 6 operator leading to the \( N_D \) decay is generated from the leptophilic Yukawa interactions by \( W \supset N e^c E + L h_d E^c + m_{3/2} l_1 L^c \) with the dimensionless couplings of order unity, and the gauge interaction by \( L \supset \sqrt{2} g' \tilde{e}^c e^c \chi + \text{h.c.} \). The superheavy masses of the vector-like leptons \( (M_L, M_E \sim 10^{16} \text{ GeV}) \) are responsible for the longevity of \( N_D \). The low energy field spectrum in this model is just the MSSM fields and \( N_D \). Even for the case that the portion of \( N_D \) is much smaller than that of \( \chi \) in the total DM density \( [O(10^{-10}) \lesssim n_{N_D}/n_{\chi}] \), the observed positron excess can be explained by adopting relatively lighter masses of the vector-like leptons \( (10^{13} \text{ GeV} \lesssim M_{L,E} \lesssim 10^{16} \text{ GeV}) \). The smallness of the electron mass is also explained. This model is easily embedded in the flipped SU(5) grand unification, which is a leptophilic unified theory.

Keywords: supersymmetry and cosmology, dark matter theory, cosmic ray theory

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1 Introduction

Although the existence of dark matter (DM) is advocated through several cosmological observations, we don’t know yet its identity. The lightest supersymmetric particle (LSP) in the minimal supersymmetric standard model (MSSM) has been believed to be one of the most promising DM candidates over last two decades. Not only it is well-motivated from the promising particle physics model i.e. the MSSM, but also it naturally carries the features required for a weakly interacting massive particle (WIMP).

However, recently the PAMELA group reported very challenging observational results on excess of high energy positrons coming from the galactic halo \cite{1}. It has confirmed the previous similar observations of HEAT \cite{2} with the improved precisions. The PAMELA data shows a rising positron flux \( e^+/ (e^+ + e^-) \) from 10 to 100 GeV, which gives rise to considerably big deviations (\( \sim 0.1 \)) from the theoretically expected values \cite{3}. On the other hand, any significant anti-proton excess was not observed. Indeed, these observations would be quite hard to explain in large classes of models only with one DM component of the Majorana fermion such as the MSSM. Moreover, the ATIC and PPB-BETS collaborations also reported recently their observations that the flux of \( (e^+ + e^-) \) keeps rising upto around 800 GeV \cite{4, 5}. It might imply that if such deviations result from the DM’s annihilation or decay, the mass of the DM would be in a TeV range.

Various scenarios beyond the conventional DM models have been suggested so far, including new scenarios of DM annihilation \cite{6–8}, DM decay \cite{9–11}, and nearby pulsars producing charged leptons \cite{12}. However, if the mass of DM is above TeV, and if we keep the galactic profile of NFW and Einasto \cite{13}, the annihilation scenario would be disfavored \cite{14} due to the bound of the \( \gamma \) ray flux by the HESS observations of the galactic ridge \cite{15}. (See also the recent discussions on DM annihilation in refs. \cite{16}.)

In refs. \cite{6, 7}, the PAMELA/HEAT anomaly could be explained by co-annihilations of the LSP and another DM component \( N_D \), which is a Dirac fermion \( (N, N^c) \) with a weak scale mass. It turns out that in this case, introductions of a pair of extra vector-like lepton singlets \( (E, E^c) \), and a leptophilic coupling of the DM, \( N e^c E \) are indispensable to explain the PAMELA/HEAT’s observations. The relatively small masses of \( (N, N^c) \) and \( (E, E^c) \) \( [\sim O(100) \text{ GeV}] \) and the needed \( N^3 \) coupling in the superpotential for decay of \( E \) and \( E^c \) into the DM can be guaranteed by the \( U(1)_R \) symmetry. This model (\( “N_{DM\text{MSSM}}” \)) is easily
embedded in the flipped SU(5) grand unified theory (GUT), which is assumed to be broken to the MSSM at the GUT scale [7, 17].

In this paper, we attempt to explain the anomalies from PAMELA/HEAT and ATIC/PPB-BETS by decay of the extra DM component \( N_D \). If the observations by PAMELA/HEAT and ATIC/PPB-BETS are caused indeed by DM decay, the data of ATIC/PPB-BETS imply that the mass of the DM matter would be around 2 TeV and its life time \( \sim 10^{26} \) sec. Such a long lifetime is achievable, if the TeV scale DM decays to \( e^\pm \) (+ neutral particles) through a dimension 6 operator suppressed by the mass squared of order the GUT scale [10, 11]. To be consistent with the PAMELA data, the hadronic decay modes of DM should not exceed 10% [10].

This paper is organized as follows: In section 2, we discuss how a dimension 6 operator for DM decay can be naturally dominant in a supersymmetric model extending the MSSM, and in section 3, we propose a specific model realizing the idea discussed in section 2. In section 4, we briefly discuss the implications of the recently observed anomalies in phenomenological model building in string theory, and summarize our conclusions.

2 Dark matter decay

For the case that DM decays to the positrons, the positron flux at the earth is given by a semi-analytic form [10]:

\[
\Phi_{e^+}(E) = \left( \frac{\rho}{m_{DM}} \right) \Gamma_{DM} \times \frac{1}{4b(E)} \int_E^{m_{DM}} dE' \frac{dN_{e^+}}{dE'} I(\lambda_D),
\]

where \( dN_{e^+}/dE' \) is the spectrum of \( e^+ \) produced by DM decay, \( \rho \) the DM energy density at the earth, and \( m_{DM} \) its mass. \( b(E) = E^2/(\text{GeV}\cdot10^{16} \text{ sec.}) \) indicates the energy loss coefficient, and \( I(\lambda_D) \) is the halo function for DM decay, which depends only on the galactic astrophysics.

As mentioned in Introduction, if DM decay causes the observations by ATIC/PPB-BETS, it implies the DM mass \( m_{DM} \) should be about 2 TeV. For \( \rho \approx 0.3 \text{ GeV} \cdot \text{cm}^{-3} \), the decay rate \( \Gamma_{DM} \) should be around \( 10^{-26} \) sec. This value can be achieved if the DM decays to light leptons through a dimension 6 operator mediated by a GUT scale massive field \( \sim 10^{16} \text{ GeV} \) [10]:

\[
\Gamma_{DM} \sim \frac{m_{DM}^3}{192\pi^2 M_G^4} \sim 10^{-26} \text{ sec.}^{-1}
\]

It might imply that the observations of ATIC/PPB-BETS could be interpreted as signals of the GUT scale physics.

If DM with a TeV scale mass was the LSP such as the neutralino or gravitino, and so supersymmetry (SUSY) breaking soft masses of the visible sector fields should be heavier than TeV, then the status of SUSY as a solution of the gauge hierarchy problem in particle physics becomes weak and a considerable fine-tuning for the Higgs mass would be unavoidable. Thus, we introduce a Dirac type extra DM component \( \{N, N^c\} (\equiv N_D) \) with a TeV scale mass apart from the (bino-like) LSP, \( \chi \). If \( N \) and \( N^c \) are the dominant component of DM, the mass of the heavy field mediating DM decay should be around the GUT scale. However, we have one more DM component \( \chi \), which is the absolutely stable particle. If the portion of \( \chi \) in the total DM density is large (and so the portion of \( N \) and \( N^c \) is small), the mass of the heavy field mediating DM decay needs to be adjusted such that the flux needed to explain the positron excess is fixed. That is to say, in eq. (2.1) the smaller DM number density by a
factor \((M_\ast/M_G)^4\) \(< 1\) can be compensated with a larger decay rate by assuming the lighter mediator in eq. (2.2) such that the eq. (2.1) remains the same:

\[
\frac{\rho}{m_{DM}} \to \frac{\rho}{m_{DM}} \times \left(\frac{M_\ast}{M_G}\right)^4 \quad \text{for} \quad M_G \to M_\ast \quad \text{in} \quad \Gamma_{DM}.
\]

However, we should protect the results of the standard big bang nucleosynthesis. For the life time of \(N\) longer than the age of the universe \(1/\Gamma_{DM} \gtrsim 10^{16}\) sec., the ratio of the number density of \(N\) to \(\chi\), \(n_N/n_\chi\) is indeed extremely flexible:

\[
\mathcal{O}(10^{-10}) \lesssim \frac{n_N}{n_\chi} \quad \text{for} \quad 10^{13} \text{ GeV} \lesssim M_\ast \lesssim 10^{16} \text{ GeV}.
\]

Even with an extremely small number density of \(N_D\), thus, the energetic positron excess from the recent experiments can be easily explained.

In fact, how much \(N_D\) was created in the early universe is quite model dependent. In ref. [11], when DM interacts with the standard model particles via a GUT suppressed dimension 6 operator, the reheating temperature to produce DM much enough to explain the energy density \(\rho_{DM} \approx 10^{-6} \text{ GeV cm}^{-3}\) is estimated as \(10^{10} \text{ GeV}\). Even if the reheating temperature is much lower than \(10^{10} \text{ GeV}\), there exist many other possibilities to produce \(N_D\) sufficiently, depending on inflationary scenarios. For instance, \(N\) could be non-thermally created directly from the inflaton decay or indirectly via a hidden sector field decay. Or \(N\) could be coupled to the hidden sector fields \(X\) and \(X^c\) with TeV scale masses through \(W \supset NXX^c\). Then \(N, N^c\) could be in a thermal equilibrium state with \(X, \overline{X}\) (and also \(X^c, \overline{X}^c\)) by exchanging their scalar partners \(X^c, \overline{X}\) down to a proper decoupling temperature, which is defined with hidden sector fields. However, we do not specify a possibility in this paper, because we have two dark matter components and so have extremely large flexibility for the portions of \(n_N/n_\chi\), as mentioned above.

As in the co-annihilation DM scenario of refs. [6, 7], the electrophilic coupling of DM, \(N e^cE\)

\[
N e^cE
\]

is essential also in the DM decay scenario to be consistent with the PAMELA’s observations: They did not observe the anti-proton excess from the cosmic ray. Here \(e^c\) indicates the first family of the lepton singlet in the MSSM, and \(E\) is a newly introduced heavy lepton singlet with the same electric charge as \(e^-\). To cancel the anomaly, \(E\) should be accompanied with \(E^c\), whose electric charge is opposite to that of \(E\). They achieve heavy masses (of order the GUT scale) from the Dirac mass term \(M_{EE}E^cE^c\).

Of course, one could think the possibility that the singlet \(N\) couples also to the quark singlets and extra vector-like heavy quarks. In this case, however, the coupling with them should be relatively small such that the hadronic decay rates do not exceed 10% for the consistency with the PAMELA’s observations [10]. In this paper we do not introduce such heavy extra quarks for simplicity of our discussion.

Since the \(N\) is required to discriminate leptons and quarks, the interaction \(N e^cE\) can not be accommodated in the conventional GUT such as SU(5) and SO(10). It is, however, well embedded in the flipped SU(5) \(\equiv \text{SU(5)} \times \text{U(1)}_X\) [7], which is a phenomenologically promising GUT. Indeed, flipped SU(5) is the leptophilic GUT. It means that the leptons, particularly the lepton singlets are special in flipped SU(5). Since the lepton singlet \(e^c\) remains an SU(5) singlet \((= 1_5)\) under SU(5) \(\times \text{U(1)}_X\), the \(N \ (= 1_0)\) can couple to \(e^c\) and \(E\).
(=1_{-5}) without being accompanied with quarks, and $N e^c E$ (= $1_61_51_{-5}$) is invariant under the flipped SU(5) gauge symmetry.

For dimension 6 dominance in the $N$ decay, the dimension 4 and 5 operators from $N h_d h_d$, $N l_i h_u$, $N l_i h_d e^c / M_P$, $N l_i l_j e^c / M_P$, etc. in the superpotential, where $h_u$, $h_d$, and $l_i$ ($i=1,2,3$) indicate the MSSM Higgs and lepton doublets, should be removed from the Lagrangian by introducing a proper symmetry, because they open too fast $N$’s decay channel into $\chi$ and the standard model leptons ($\Gamma_N \sim m_N^3 / M_P^2 \sim 10^{-4}$ sec.$^{-1}$, if the dimension 5 operators are dominant.) The dominant GUT suppressed dimension 6 operator would be generated from renormalizable operators, in which GUT scale heavy fields are involved. The Feynman diagram displaying such induced dimension 6 operators would satisfy

$$\left( \text{Number of heavy fermion propagators} \right) - \left( \text{Number of heavy mass insertions} \right) = 2. \quad (2.6)$$

We introduce a pair of vector-like heavy SU(2) lepton doublets $(L, L^c)$ with their Dirac mass term $M_LL^c$, where $M_L \sim M_G \sim 10^{16}$ GeV, in the superpotential for the dimension 6 process.

In SUSY theories, a diagram replacing some heavy fermions lines by the scalar partners’ lines is always present. The heavy scalars’ mass squareds are the same as the fermions’ upto the SUSY breaking soft mass squareds of $O\left( m_{3/2}^2 \right)$. Since the contributions by the scalar propagators are suppressed by $\sim 1/M_G^2$ at low energies, the diagram by the heavy fermions dominates over the diagram replacing some of them by their scalar partners.

If the couplings between $E^c$ and the MSSM lepton doublets $l_i$ such as $l_i h_d E^c$ (and also $l_i l_j E^c$) were present in the superpotential, $N l_i h_d E^c / M_E$ (and $N l_i l_j e^c / M_E$) could be induced after integrating out $E$ and $E^c$ from $l_i h_d E^c$ ($l_i l_j E^c$) and $N e^c E$. Therefore, $l_i h_d E^c$ and $l_i l_j E^c$ also should be disallowed from the superpotential by a symmetry. Even though they were generated when the symmetry, which forbids them, is broken, they are still safe only if their coefficients are suppressed by $O(m_{3/2}/M_G)$.

On the other hand, we require the presence of

$$Lh_d E^c \quad \text{and} \quad m_{3/2} l_1 L^c$$

in the superpotential in order to make it possible for $N$ (and also $N^c$) to decay into $\chi e^- + e^+$ via the dimension 6 operator. Here $l_1$ stands for the first generation of the lepton doublet in the MSSM, and $m_{3/2}$ indicates a TeV scale mass parameter. See the Feynman diagram in figure 1 for the process

$$N \quad (N^c) \longrightarrow \chi + e^- + e^+. \quad (2.8)$$

It is the dominant diagram of $N$ and $N^c$ decay, if $m_N \lesssim m_{e^c}$. Its decay rate is estimated as

$$\Gamma_N \approx \frac{m_N^5}{192\pi^3} \times \left[ \frac{g' (h_d) m_{3/2}}{2m_{e^c}^2 M_E M_L} \right]^2 \times O(y^4), \quad (2.9)$$

where $\Gamma_N \sim 10^{-26}$ sec.$^{-1}$ for $m_N \sim 2$ TeV [$\gtrsim 10 \times O(m_\chi)$], $M_E \sim M_L \sim 10^{16}$ GeV, and the contributions by the dimensionless Yukawas $O\left( y^4 \right) \sim 1$.

If the selectron $e^c$ is relatively light, $m_N \gtrsim m_{e^c}$, however, the decay channel $N \rightarrow e^+ + \tilde{e}^c$ is kinematically allowed, and $\tilde{e}^c$ can be an on-shell particle in figure 1. Then, the decay rate
becomes enhanced by $O(100)$:

$$
\Gamma_N \approx \frac{(m_N^2 - m_{\tilde{e}}^2)^2}{16\pi m_N^3} \left[ g' \langle h_d \rangle m_{3/2}^2 \right] \times O(y^4).
$$

For $\Gamma_N$ giving $10^{-26}$ sec$^{-1}$, however, $M_E \sim M_L \sim 10^{16}$ GeV is not much affected.

The $N$ (and also $N^c$) could decay also into the hadrons through the Higgs of figure 1. However, such decay modes are much more suppressed than 10%. It is because they are 5-body decay channels with much suppressed phase factors, and the quarks’ (except the top quark) Yukawa couplings at the vertices, from which quark branches start, are so small.

$L, L^c$ and $h_d$ are embedded, respectively, in $5_{-3}, 5_3$ and $5_{-2}$ in flipped SU(5), which are accompanied with quark singlets. Since $Ne^cE (= 1_0 1_5 1_{-5})$ is still electrophilic and the doublets/triplets in $5_2, 5_{-2}$ are split by the missing partner mechanism [17], however, the decay channels to hadrons are suppressed also in the flipped SU(5) model.$^1$

3 The model

The relevant superpotential is composed of $W = W_{N\text{decay}} + W_{\text{mass}}$, where $W_{N\text{decay}}$ and $W_{\text{mass}}$ are, respectively, given by

$$
W_{N\text{decay}} = Ne^cE + Lh_dE^c + N^3 + m_{3/2}l_1L^c,
$$

$$
W_{\text{mass}} = M_LL^c + M_EEE^c + m_NNN^c,
$$

where we drop the dimensionless Yukawa coupling constants for simplicity. All the dimensionless Yukawa couplings in the above expressions are tacitly assumed to be of order unity.

$^1$In flipped SU(5), $10_1$ and $10_{-1}$ contain $\{d^c, q, u^c\}$ and $\{u^c, l\}$, respectively, where $d^c$ ($u^c$) denotes the quark singlet of $Q_{u,m} = 1/3$ ($-2/3$), and $q$ ($l$) is the quark (lepton) doublet. Note that the SU(2) singlets are interchanged by each other, compared to the Georgi-Glashow’s SU(5). Particularly, while the Majorana neutrino $\nu_e$ is included in the tensor multiplet, the charged lepton singlet $e^c$ is the SU(5) singlet. The MSSM Higgs doublets $h_u$ and $h_d$ are embedded in $5_2$ ($\equiv 5_h$) and $5_{-2}$ ($\equiv 5_u$), respectively, in flipped SU(5). The flipped SU(5) gauge group is broken to the standard model gauge group by the Higgs fields of the tensor representations $10_H, \bar{10}_H$. In flipped SU(5), the doublets/triplets included in $5_h, 5_u$ are simply split just through $10_H 10_H 5_h$ and $\bar{10}_H 10_H 5_u$. 

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Figure 1. Dominant diagram of $N$ (and $N^c$) decay: The dimensionless Yukawa couplings are of order unity. The mass parameters $M_E$ and $M_L$ are of order the GUT scale.
| Superfields | $N$ | $N^c$ | $E$ | $E^c$ | $L$ | $L^c$ | $\Sigma$ | $e^c$ | $l_1$ | $h_u$ | $h_d$ |
|-------------|-----|-------|-----|-------|-----|-------|--------|-------|-------|-------|-------|
| SU(2)$_Y$  | 10  | 10    | 1-1 | 11    | 2-1/2| 21/2  | 10     | 11    | 2-1/2 | 21/2  | 2-1/2 |
| $R$         | 2/3 | -4    | 1/3 | 5/3   | 1/3 | 5/3   | 0      | 1     | -5/3  | 0     | 0     |
| $PQ$        | 0   | 2     | 1   | -1    | 0   | 0     | 1      | 1     | 1     | 0     | 1     |
| $Z_2^m$     | +   | +     | -   | -     | -   | -     | +      | -     | -     | +     | +     |

**Table 1.** The quantum numbers of the superfields. The superfields written with the capital letters are the newly introduced fields, which are absent in the MSSM. Except $N$, $N^c$ and the MSSM Higgs fields, the vector-like superfields are all decoupled from low energy physics due to their heavy masses.

Not introducing $N$ couplings to quarks, we can avoid anti-proton excess. We assume that the masses of $L$, $L^c$, and $E$, $E^c$, i.e. $M_L$ and $M_E$ are of order $M_G$ ($\sim 10^{16}$ GeV). On the other hand, the masses of the DM $N$, $N^c$ should be constrained to be about $2$ TeV in order to explain the observations of ATIC/PPB-BETS. In fact, the mixing term $l_1L^c$ and the mass terms of $N$, $N^c$ and also $h_u$, $h_d$, all of which are proportional to $m_{3/2}$, can not be present in the bare superpotential due to the $U(1)_R$ symmetry, which will be presented later. However, via the Giudice-Masiero mechanism [18], the Kähler potential

$$
\int d^2\theta d^2\bar{\theta} \left[ \frac{\Sigma^\dagger}{M_P} (\lambda_1L^c + \lambda'h_uh_d) + \text{h.c.} \right] \tag{3.3}
$$

can induce such supersymmetric mixing term seen in eq. (3.1), and also the MSSM “μ term”, if SUSY is broken by a nonvanishing VEV of the $F$ component of the singlet superfield $\Sigma$. We assume that $\langle F_{\Sigma} \rangle \sim m_{3/2}M_P$, where $m_{3/2} \sim 10^6$ GeV. We will explain later how the Dirac mass term of $N$ and $N^c$ in eq. (3.2) ($m_N \sim 2$ TeV) is naturally generated. Concerning the gaugino mass terms, the gauge kinetic functions are involved in their mass generations in supergravity. We assume that the LSP is the (bino-like) neutralino with the mass of $\mathcal{O}(100)$ GeV. It is stable and also a component of the DM together with $N_D$.

The cubic term of $N$ in eq. (3.1) is introduced such that the superpartner of $N$, i.e. $\tilde{N}$ promptly decays to $2\tilde{N}$. We just assume that the soft mass of $\tilde{N}$ is heavy enough ($\gtrsim 4$ TeV) for this decay process to open. Were it not for $N^3$ in the superpotential, $\tilde{N}$ could remain meta-stable together with $N$. Actually it is not a serious problem. But we prefer smaller number of species of DM. By the SUSY breaking B-term corresponding to the third term in eq. (3.2), $\tilde{N}^c$ can be converted to $\tilde{N}$, and so $\tilde{N}^c$ also can decay to $2N$ through the $N^3$ term.

The global symmetry observed in this model is $U(1)_R \times U(1)_{PQ} \times Z_2^m$, where $Z_2^m$ denotes the matter parity (or $R$ parity). The quantum numbers of the superfields under the symmetry are displayed in table 1. It is straightforward to assign the quantum numbers also to all other MSSM chiral superfields, which are not presented in table 1, so as to admit all the needed $R$ parity preserving Yukawa terms in the superpotential.

In fact, the last terms of eqs. (3.1) and (3.2) violate the $U(1)_R$ and $U(1)_{PQ}$ symmetries. They and soft SUSY breaking A- and B-terms corresponding to the superpotential of eqs. (3.1) and (3.2) in the scalar potential break the $R$ symmetry to $Z_6$. That is to say, SUSY breaking effects result in $U(1)_R$ breaking into $Z_6$. Since $\Sigma$ carries the unit charge of $U(1)_{PQ}$ symmetry, it is also broken at the intermediate scale ($\sim \sqrt{m_{3/2}M_P} \sim 10^{10}$ GeV). A proper linear combination of the symmetries could still remain unbroken, but we will see that it is also broken by VEVs of other fields.
Among the unwanted terms in the superpotential, which were discussed in section 2, $N l_1 h_d e^c$ and $l_1 h_d E^c$ are induced from the bare Kähler potential: $K \supset \Sigma^\dagger (N h_d e^c/M_P^3 + l h_d E^c/M_P^2) + \text{h.c.}$, because they are consistent with the charge assignments in table 1. But their suppression factors $m_{3/2}/M_P^2$ and $m_{3/2}/M_P$ are small enough. However, $N l_1 h_d e^c$ and $l_1 h_d E^c$ suppressed, respectively, by $m_{3/2}/M_P^2$ and $m_{3/2}/M_P$ rather than $m_{3/2}/M_P^2$ and $m_{3/2}/M_P$ can be generated. They are exactly what are shown from figure 1.

Indeed, the diagram in figure 1 is reminiscent of that explaining the seesaw mechanism of the neutrino. Integrating out the superheavy fermions $E^c$, $E^c$, and $L$, $L^c$ yields the effective Lagrangian relevant for $N \to e^c + \bar{e}^c$: The equations of motion, $\partial \mathcal{L}/\partial E = \partial \mathcal{L}/\partial E^c = \partial \mathcal{L}/\partial (\bar{E}^c) = 0$, where $E^c(\bar{E}^c)$ are the fermionic components of the corresponding superfields, give $E^c = -\bar{e}^c N/M_E$, $E = -(h_d)L/M_E$, $L^c = -(h_d)E^c/M_L$, and $L = -m_{3/2}l_1/M_L$, respectively. By inserting them back into the original Lagrangian, one can get the effective Lagrangian, and also the effective Kähler potential:

$$\mathcal{L}_{\text{eff.}} = \frac{m_{3/2}}{M_E M_L} h_d \bar{e}^c l_1 N \subset \int d^2 \theta d^2 \bar{\theta} \left[ \frac{\Sigma^\dagger}{M_P M_E M_L} h_d e^c l_1 N + \text{h.c.} \right]. \quad (3.4)$$

Thus, $N$ (and $N^c$) can decay to $e^+ \bar{e}^c$ with the suppressed amplitude $\sim m_{3/2} \langle h_d \rangle M_G^2$. By the gauge interaction $L \supset \sqrt{2} g^\prime \bar{e}^c e^c \chi + \text{h.c.}$, $\bar{e}^c$ eventually decays to $e^- \chi$ as shown in figure 1.

The charge assignments in table 1 forbid the Yukawa coupling for the electron mass, $l_1 h_d e^c$ from the bare superpotential. After $U(1)_R$ and $U(1)_{\text{PQ}}$ broken, however, one can expect the electron mass term is generated. Let us consider the following superpotential:

$$W_{\text{elec}} = S l_1 L^c + L^c h_d e^c + M_L L' L'^c + \frac{1}{M_P} S^2 S^2 + \frac{1}{M_P} S^2 N N^c, \quad (3.5)$$

where the quantum numbers of $S$, $\overline{S}$, and $L'$, $L'^c$ are presented in table 2. The scalar potential derived from the last term of $W_{\text{elec}}$, the A-term corresponding to it, and soft mass terms of $S$, $\overline{S}$ could allow the minimum, where nonzero VEVs of $S$ and $\overline{S}$ are developed (but $\langle N \rangle = (N^c) = 0$), breaking the $U(1)_R$ and $U(1)_{\text{PQ}}$ symmetries completely:

$$\langle S \rangle \sim \langle \overline{S} \rangle \sim \sqrt{m_{3/2}/M_P} \sim 10^{10} \text{ GeV}. \quad (3.6)$$

Namely, SUSY breaking triggers the $\text{PQ}$ symmetry breaking at the same energy scale. However the $Z_2^\mu$ symmetry is still unbroken, which plays exactly the role of the matter parity (or $R$ parity) in the MSSM. The $Z_2^\mu$ parity conservation still prevents the dangerous term $l_i l_j E^c$ as well as $l_i l_j e^c$ from being induced. Even with the nonzero $\langle S \rangle$ and $\langle \overline{S} \rangle$, the other unwanted terms also don’t appear at low dimensions.
Once $S$ develops a VEV, the desired mass term of DM $N$ and $N^c$ can be achieved via the last term of eq. (3.5):

$$m_N = \frac{\langle S^2 \rangle}{M_P} \sim 2 \text{ TeV}. \quad (3.7)$$

The electron mass term $(\langle S/M_{L'} \rangle l_1 h de^c)$ also can be generated as seen in figure 2. It dominates over the nonrenormalizable term in the bare superpotential, $(\langle S/M_P \rangle l_1 h de^c)$. Thus, the correct order of magnitude of the electron mass can be achieved if $M_{L'} \sim 10^{16} \text{ GeV}$:

$$m_e = \frac{\langle S \rangle \langle h_d \rangle}{M_{L'}} \sim 10^{-6} \langle h_d \rangle. \quad (3.8)$$

Expanding $S$ in terms of the axion field $a$ [19, 20], $S = (F_a N_{DW} + \rho) \text{e}^{i a/(F_a N_{DW})}$, where $F_a (= \langle S \rangle/N_{DW} \sim 10^{10} \text{ GeV}/N_{DW})$ is the axion decay constant and $N_{DW}$ indicates the domain wall number, $(S/M_{L'}) l_1 h de^c$ yields the axion-electron coupling:

$$\frac{m_e}{F_a N_{DW}} = \pi i \gamma_5 e a. \quad (3.9)$$

In fact, if there is an energy loss mechanism by a very weakly interacting light particle like the axion, it can affect the resulting luminosity function of the white dwarf. Thus, provided that the axion is dominantly involved in the cooling mechanism of white dwarfs, the luminosity function of the white dwarf can be used to estimate the axion decay constant $F_a$: If the axions lighter than 1 eV are produced inside white dwarfs, the axion’s coupling to the electron is estimated as $0.7 \times 10^{-13}$ for the best fit of $\chi^2$ [7, 21], i.e.

$$\left| \frac{m_e \Gamma(e)}{F_a N_{DW}} \right| \approx 0.7 \times 10^{-13}, \quad (3.10)$$

where $\Gamma(e)$ denotes the PQ charge of $e$. Thus, eq. (3.10) means $F_a N_{DW} \approx 0.72 \times 10^{10} \text{ GeV}$ for $\Gamma(e) = \pm 1$, which can be coincident with eq. (3.6).

4 Discussion

The weak scale SUSY is important, because it provides the resolution of the gauge hierarchy problem and a way to connect the standard model at low energies and the string theory at high energies. If the low energy SUSY should be accepted as a basic language describing our nature, the DM in the universe should be understood within this framework. However, the recently reported observations on excess of energetic positrons from cosmic ray might be quite embarrassing, because it is seemingly hard to understand in terms of the conventional MSSM.
In this paper, we present a SUSY model with one more dark matter component with a TeV scale mass apart from the LSP. The observed anomaly could be naturally explained by the extra DM’s decay through a dimension 6 operator, which is induced by the renormalizable operators. The life time of DM (∼10^{26} \text{sec.}) needed to explain the observed positron flux is caused by the heavy masses (∼10^{16} \text{GeV}) of the mediators involved in the decay process. Since this model permits the possibility that the field spectrum below the GUT scale can coincide with that of the MSSM except for \(N_D\), the gauge coupling unification in the MSSM could be still maintained. Therefore, we could rescue the string models realizing the MSSM with sin^2\(\theta_W = 3/8\) [22], because a lot of neutral singlets are easily found in string models.

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