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PAMELA/ATIC anomaly from exotic mediated dark matter decay

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Abstract: We discuss dark matter decay mediated by exotically charged particles ("exotics") in a supersymmetric model with two dark matter (DM) components: one is the (bino-like) lightest supersymmetric particle (LSP) χ, and the other is a newly introduced meta-stable neutral singlet N. N decays to χe^+e^- via a dimension 6 operator induced by a penguin-type one loop diagram with the life time of 10^{26} sec., explaining energetic cosmic $e^{\pm}$ excess observed recently by PAMELA and ATIC/PPB-BETS. The superheavy masses of exotics ($\sim 10^{15-16}$ GeV) are responsible for the longevity of N. The superpartner of N develops the vacuum expectation value (VEV) of order TeV so that the DM N achieves the desired mass of 2 TeV. By the VEV, the $\mathrm{U(1)_R}$ symmetry is broken to the discrete Z_2 symmetry, which is identified with the matter parity in the minimal supersymmetric standard model (MSSM). Since we have the two DM components, even extremely small amount of N [$\mathcal{O}(10^{-10}) \lesssim (n_N/n_\chi)$] could account for the observed positron flux with relatively light exotics' masses [$10^{12}\,\mathrm{GeV} \lesssim M_{\mathrm{exo}} \lesssim 10^{16}\,\mathrm{GeV}$].

Keywords: Cosmology of Theories beyond the SM, Supergravity Models, Supersymmetric Standard Model

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Contents

1 Introduction

The recently reported observations by PAMELA [1, 2] and ATIC/PPB-BETS [3, 4] collaborations on excess of high energy positrons from cosmic ray have attracted more and more attentions. As many literatures pointed out, dark matter (DM) decay [5–7] or annihilation [8] would be deeply involved in the observed positron excess.[1] If it is indeed caused by DM, however, the observation should be accepted as a puzzle, because it is hard to be understood within the framework of the conventional DM scenario, particularly, by the minimal supersymmetric standard model (MSSM). Thus, the observed positron excess might be a hint toward a new physics beyond the standard model (SM).

As noticed in refs. [5], the positron flux needed to explain the observation of ATIC/PPB-BETS (and also PAMELA) can be produced by leptonic decay of DM [6, 7] with 2 TeV mass ($= m_{\rm DM}$) via a dimension 6 operator (four fermion interaction) suppressed by $M_{\rm GUT}^2 \sim (10^{16}\ {\rm GeV})^2$, by which the decay rate is estimated as

$$\Gamma_{\rm DM} \sim \frac{m_{\rm DM}^5}{192\pi^3 M_{\rm GUT}^4} \sim 10^{-26}\,{\rm sec.}^{-1}. \tag{1.1}$$

Hadronic decay channels should not exceed 10% to be consistent with the PAMELA's data [2]. The DM decay scenario avoids the constraint from the γ ray flux [10] by the HESS observations of galactic ridge [11]. However, it is not trivial to see which physics at the $M_{\rm GUT}$ scale can provide such a low energy effective four fermion interaction, allowing DM to decay dominantly into the SM leptons: in most of grand unified theories (GUTs) embedding the SM, the gauge interactions by superheavy gauge boson exchanges can easily provide four fermion interactions suppressed by $M_{\rm GUT}^2$. But they do not prefer only such a leptophilic decay mode of an electrically neutral particle or DM. Hence, one should explore the possibility of a leptophilic *Yukawa* interaction for DM decay.

Recently, supersymmetric (SUSY) models possessing one more dark matter component N apart from the (bino-like) lightest supersymmetric particle (LSP) χ have been suggested as the resolutions of the PAMELA/ATIC anomaly [7, 12, 13]. Particularly in the model of ref. [7], the anomaly is explained by decay of the extra DM component N into $\chi e^+ e^-$

[1] Alternatively, astrophysical sources such as pulsars could explain the positron excess [9].

through a dimension 6 operator. The effective dimension 6 operator for DM decay is obtained from some renormalizable leptophilic Yukawa interactions with the dimensionless coupling of order unity, after a pair of vector-like SU(2) lepton doublets (L, L^c) and lepton singlets (E, E^c) decoupled. The superheavy masses of $L^{(c)}$, $E^{(c)}$ ($\sim 10^{16}$ GeV) are responsible for the longevity of N. Since the gauge group is just that of the SM and the low energy field spectrum is the same as that of the MSSM except the neutral singlet N, the gauge coupling unification in the MSSM is protected in the model. This model is easily embedded in flipped SU(5), which is a leptophilic unified theory [13].

Most of phenomenologically promising string models predict a lot of vector-like *superheavy* exotic states ("exotics") carrying fractional electric charges [14]. One might expect that such superheavy exotics also can play the role of (L, L^c) and (E, E^c) in the model of ref. [7], mediating DM decay via the dimension 6 process. Their superheavy masses ($\sim 10^{16}$ GeV) could lead successfully to 10^{26} sec. life time of the DM as desired. Considering the case that superheavy exotics mediate DM decay, however, one should notice a remarkable point: most of all, fractionally charged heavy particles can not decay to the light SM leptons, because of the charge conservation. Thus, if exotics are involved in the process, $N \rightarrow e^+ + e^- + \textit{neutral particles}$, where the initial and final states are the states only with the integral electric charges, they should be co-created and co-annihilated between the initial and final states. It means that DM decay is possible only at loop levels, if exotics dominantly mediate DM decay.

In this paper, we explore the possibility that DM decay is mediated by a one loop diagram. If the mediators are indeed fractionally charged superheavy particles, we should necessarily consider the loop induced process. However, our study is not confined only to the case of fractionally charged heavy field mediation, but covers more general cases of loop induced DM decays.

2 The model

Let us consider the vector-like superheavy superfields (E, E^c), (X, X^c), and (O, O^c). Their quantum numbers are shown in table 1.

If q is a fractional number, $E^{(c)}$, $X^{(c)}$, and $O^{(c)}$ become regarded as exotics. In table 1, we present only the first generation of the charged lepton singlets, e^c. Concerning the R charges of the other MSSM superfields, we assign 1 to the MSSM matter superfields like e^c, and 0 to the two MSSM Higgs doublets. We leave open the possibility that $E^{(c)}$, $X^{(c)}$, and $O^{(c)}$ are charged also under other (visible or hidden gauge) symmetry $\mathcal{G}$. For the case that this model is embedded in flipped SU(5) [$=$ SU(5) $\times\, U(1)_X$], $\mathcal{G}$ can correspond to SU(5).

If the deviation of $(e^+ + e^-)$ observed by ATIC/PPB-BETS from cosmic ray is indeed caused by DM decay, the mass of DM should be around 2 TeV [5]. In order to protect the status of SUSY as the solution of the gauge hierarchy problem, we should assume that the mass of the LSP is of $\mathcal{O}(100)$ GeV or lighter. Apart from the (bino-like) LSP χ, thus, we introduce one more dark matter component with 2 TeV mass, which is the fermionic component of N in table 1, to account for the ATIC/PPB-BETS' data.

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Superfields	e^c	N	E	E^c	X	X^c	O	O^c
$\mathrm{U(1)_Y}$	1	0	q	$-q$	$-q$	q	$q-1$	$-q+1$
$\mathrm{U(1)_R}$	1	2/3	1/3	5/3	1	1	0	2
$(\ \mathcal{G}\ )$	$\mathbf{1}$	$\mathbf{1}$	$(\ \mathcal{R}\ )$	$(\ \mathcal{R}^*\ )$	$(\ \mathcal{R}^*\ )$	$(\ \mathcal{R}\ )$	$(\ \mathcal{R}\ )$	$(\ \mathcal{R}^*\ )$

Table 1. The hypercharges and R charges of the superfields. The hypercharge q can be a fractional number. The vector-like exotic superfields, $E^{(c)}$, $X^{(c)}$, and $O^{(c)}$ are all decoupled from low energy physics due to their heavy masses. The (visible or hidden) symmetry $\mathcal{G}$ is optional.

The relevant superpotential in our model is composed of the trilinear and bilinear terms: $W = W_{\rm tri} + W_{\rm bi}$, where $W_{\rm tri}$ and $W_{\rm bi}$ are, respectively, given by

$$W_{\rm tri} = NEX + XOe^c + N^3, \tag{2.1}$$

$$W_{\rm bi} = M_E EE^c + M_X XX^c + M_O OO^c. \tag{2.2}$$

We dropped the dimensionless Yukawa coupling constants in eq. (2.1) for simplicity. They are tacitly assumed to be *of order unity*. The dimensionful parameters, M_E, M_X, and M_O in eq. (2.2) are 10^{15}–10^{16} GeV. Thus, the vector-like fields (E, E^c), (X, X^c), and (O, O^c) are superheavy. To avoid couplings with the other charged lepton singlets, μ^c and τ^c, one can introduce a family dependent $\mathrm{U(1)_{PQ}}$ symmetry. It can explain the smallness of the electron mass [7, 13]. The N^3 term in eq. (2.1) is introduced such that the scalar component of N, i.e. $\tilde{N}$ promptly decays into the two fermionic components $2N$. The mass of the fermionic component of N ($\approx 2\,\mathrm{TeV}$) is induced by the vacuum expectation value (VEV) $\langle\tilde{N}\rangle$. On the other hand, the mass squared of the scalar component of N is given by $(|\langle\tilde{N}\rangle|^2 + m_{3/2}^2)$, where $m_{3/2}^2$ comes from the soft scalar mass term of $\tilde{N}$. We will discuss later how the VEV of $\tilde{N}$ could be developed. We just assume that the soft mass of $\tilde{N}$ is heavy enough ($\gtrsim 4\,\mathrm{TeV}$) for the decay $\tilde{N}^* \to 2N$ to be possible. Since we don't want the N^2 term with a too large mass parameter in the superpotential, we employ the $\mathrm{U(1)_R}$ symmetry to forbid it from the bare superpotential.

This model is easily embedded in flipped SU(5) [15]. To account for the PAMELA's important observation, i.e. no excess of anti-proton [2], the lepton singlet e^c should not be accompanied with quarks in eq. (2.1), when the model embedded in a GUT. Since in flipped SU(5) e^c and N remain SU(5) singlets, $\mathbf{1_5}$ and $\mathbf{1_0}$, respectively, flipped SU(5) models can be perfectly consistent with the PAMELA's data [13]. Moreover, flipped SU(5) is phenomenologically attractive: the notorious doublet/triplet splitting problem in GUTs is very easily resolved via the missing partner mechanism [15]. The predicted fermion mass relation in flipped SU(5) is just that between up-type quarks and Dirac neutrinos masses. Since the Majorana neutrino masses are still not constrained, however, the mass relation in flipped SU(5) does not encounter any difficulty in matching the real data on fermion masses.

The presence of the A-term corresponding to N^3, i.e. $(m_{3/2}'\tilde{N}^3 + \text{h.c.})$, and $|\tilde{N}|^4$, (and also the soft mass term $m_{3/2}^2|\tilde{N}|^2$) in the scalar potential permits two vacua, on which $\langle\tilde{N}\rangle = 0$ and $\langle\tilde{N}\rangle \sim \mathcal{O}(m_{3/2})$, respectively. We assume that our universe is at the latter, which can be the absolute minimum of the scalar potential for a proper set of the

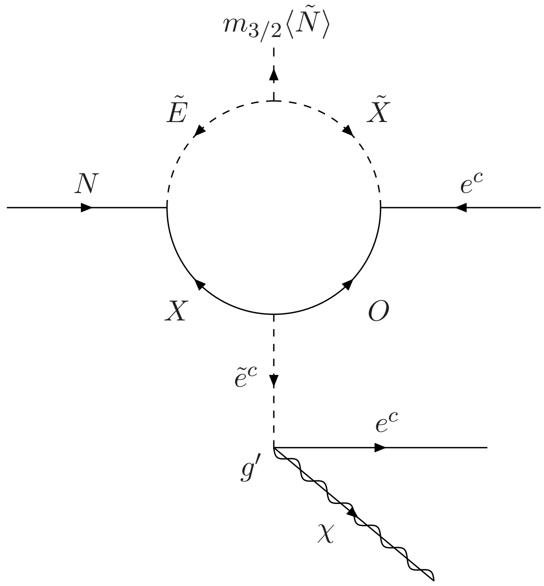

Figure 1. Penguin-type one loop decay diagram of N: it is the dominant diagram of $N \to \chi + e^- + e^+$. The dimensionless Yukawa couplings are of order unity.

parameters. Then, the Majorana mass term of the fermionic component of N, i.e. $m_N N^2$ is generated in the superpotential:

$$\langle\tilde{N}\rangle \ \sim \ m_N \ \sim \ \mathcal{O}(m_{3/2}). \tag{2.3}$$

Since we regard the fermionic component of N as the extra DM component explaining the ATIC/PPB-BETS' observation, we take $m_N = m_{\rm DM} \approx 2\,{\rm TeV}$.

The non-vanishing VEV $\langle\tilde{N}\rangle$ breaks $\mathrm{U}(1)_\mathrm{R}$ to the discrete Z_2 symmetry, because the unit R charge is 1/3 in this model. Since the superfields carrying $\mathrm{R} = 1/3, 1, 5/3$ $(0, 2/3, 2)$ become odd (even) under Z_2, the remaining Z_2 symmetry is exactly identified with the R (or matter) parity. In fact, the $\mathrm{U}(1)_\mathrm{R}$ breaking source is the SUSY breaking source $\langle F\rangle \sim m_{3/2}M_P \sim (10^{10}\,\mathrm{GeV})^2$, which is the VEV of the F-component of a hidden sector superfield, and generates the SUSY breaking soft terms in the visible sector. Since the R parity of N is even, N can not be the Majorana neutrino participating in the seesaw mechanism. Since the coupling of N to the MSSM Higgs doublets is possible, at best, only at the high order superpotential, $(\langle\tilde{N}\rangle^2/M_P^2)Nh_uh_d$, it can not also be the extra singlet appearing in the "next-to-minimal supersymmetric standard model (NMSSM)" [16].

With the terms in the superpotential eq. (2.1), the DM N can decays to χe^+e^- via a dimension 6 operator induced by a one loop diagram, if $m_{\rm DM} \lesssim m_{\tilde{e}^c}$:

$$N \longrightarrow \chi + e^- + e^+. \tag{2.4}$$

See the dominant Feynman diagram in figure 1, which looks similar to "Penguin diagram" appearing in the K and B meson decays. As seen in figure 1, the effective dimensionless coupling of $\tilde{e}^{c*}Ne^c$ in the Lagrangian is induced by the loop. It is estimated as

$$\frac{m_{3/2}\langle\tilde{N}\rangle}{48\pi^2 M_*^2}\times\mathcal{O}(y^4)\times\mathcal{N}, \tag{2.5}$$

where we set $M_{\tilde{E}}^2 = M_X^2 = M_{\tilde{X}}^2 = M_O^2 \equiv M_*^2$. $\mathcal{O}(y^4)$ denotes the contributions of the dimensionless Yukawa coupling constants, which are assumed to be of order unity at the GUT scale. Since the superheavy fields are involved in the relevant Yukawa terms in eq. (2.1), the couplings of the terms "NEX," and "XOe^c" do not much evolve with energy after the superheavy fields decoupled. [The order of magnitudes of the N^3 coupling at the GUT and lower energies are the same because of the small beta function coefficient.] Thus, the low energy effective coupling, i.e. eq. (2.5), which is obtained by integrating out the superheavy particles, is extremely small [$< \mathcal{O}(m_{3/2}^2/M_*^2)$]. If E, X, and O are in large dimensional representations under the other (visible or hidden) non-abelian (gauge) groups $\mathcal{G}$, the dimension "$\mathcal{N}$" can be crucial in eq. (2.5). The decay rate of $N \to \chi + e^- + e^+$ is estimated as

$$\Gamma_N \approx \frac{m_{\rm DM}^5}{192\pi^3}\times\left[\frac{g' m_{3/2}\langle\tilde{N}\rangle}{96\pi^2 M_*^2 m_{\tilde{e}^c}^2}\right]^2\times\mathcal{O}(y^8)\times\mathcal{N}^2, \tag{2.6}$$

where $\Gamma_N \sim 10^{-26}\,\text{sec.}^{-1}$ for $m_{\rm DM}\sim 2\,\text{TeV}$ [$\gtrsim 10\times\mathcal{O}(m_\chi)$], $M_*\sim 10^{15}\,\text{GeV}$, $\mathcal{O}(y^8)\sim 1$, and $\mathcal{N} = 1$. Note that if the dimensionless Yukawa couplings in eq. (2.1) are about 3, M_* can be slightly heavier upto $10^{16}\,\text{GeV}$, yielding the same decay rate. The other non-abelian (global or gauge) symmetry $\mathcal{G}$, under which E, X, and O are charged, would be useful in raising M_* higher. For instance, if $\mathcal{G}$ = flipped SU(5) in the visible sector and the superheavy fields are of the SU(5) tensor representation, $\mathcal{R} = \mathbf{10}$ [or if $\mathcal{G}$ = SO(10) in the hidden sector and the superheavy fields are of the SO(10) vector representations, $\mathcal{R} = \mathcal{R}^* = \mathbf{10}$], then the circulating fields on the loop are 10 times more (i.e. $\mathcal{N} = 10$) and so the decay rate is 100 times enhanced, compared to the case of the singlets.

If the selectron $\tilde{e}^c$ is relatively light, $m_{\rm DM} \gtrsim m_{\tilde{e}^c}$, then $\tilde{e}^c$ can be an on-shell particle in figure 1, and so the two body decay channel, $N \to e^- + \tilde{e}^c$ opens. Thus, the decay rate becomes enhanced by $\mathcal{O}(100)$:

$$\Gamma_N \approx \frac{(m_{\rm DM}^2 - m_{\tilde{e}^c}^2)^2}{16\pi\ m_{\rm DM}^3}\left[\frac{m_{3/2}\langle\tilde{N}\rangle}{48\pi^2 M_*^2}\right]^2\times\mathcal{O}(y^8)\times\mathcal{N}^2. \tag{2.7}$$

For Γ_N giving $10^{-26}\,\text{sec}^{-1}$, thus, $M_*\sim 10^{15-16}\,\text{GeV}$ is not much affected.

Note that in this model, (anti-) neutrinos and charged leptons heavier than the electron are not produced at all from the DM decay. [The muons eventually decay to the electrons and (anti-) neutrinos by the weak interaction.] Hence, this model is completely free from the constraints on neutrino flux [17].

In this model, we have the two DM components, N and the (bino-like) LSP χ. As noted in ref. [7], even extremely small amount of N [$\mathcal{O}(10^{-10}) \lesssim (n_N/n_\chi)$] can produce the positron flux needed to account for PAMEL/ATIC data, only if the decay rate is enhanced by taking relatively light masses of the exotic mediators [$10^{12}\,\text{GeV} \lesssim M_* \lesssim$

10^{16} GeV]. Since the other DM component, χ can still support the needed DM density $\rho_{\rm DM} \approx 10^{-6}\,{\rm GeVcm}^{-3}$, thus, we have extremely large flexibility for the portion of n_N/n_χ.

We have already a TeV scale mass of N. Thus, N can play the role of the well-known weakly interacting massive particle (WIMP) such as the neutralino in the MSSM, e.g. if an interaction with some other hidden sector fields H and H^c, $W \supset y_h N H H^c$ is introduced. Here y_h is a Yukawa coupling constant of order unity and the masses of the scalar partners of H and H^c are assumed to be of order the electroweak scale. [Then the annihilation cross section of N would be in the needed range for explanation of dark matter ($\langle\sigma|v|\rangle \sim 10^{-27}\,{\rm cm}^3{\rm s}^{-1}$).] N could be in a thermal equilibrium state with H, H^c by exchanging their scalar partners down to a proper decoupling temperature defined with hidden sector fields. Departure of N from the interactions could leave the relic energy density of order $10^{-6}\,{\rm GeVcm}^{-3}$. Alternatively, N could be non-thermally produced by decay of hidden sector fields. However, we do not specify a possibility, because we have extremely large flexibility of n_N/n_χ.

3 Conclusions

Along the line of ref. [7], we proposed another SUSY model with two DM components (N,χ). A DM could decay to the SM particles only at loop levels, when the exotics are the mediator of the decay process. In this model, the extra DM component N decays to χe^+e^- through a dimension 6 operator induced by a penguin-type one loop diagram. Its extremely long life time 10^{26} sec. required for explaining the observed positron excess is caused by the superheavy masses of exotic states mediating the DM decay. Even with extremely small amount of N, the positron excess could be explained. This model is easily embedded in flipped SU(5), in which e^c and N remain SU(5) singlets.

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