PAMELA’s cosmic positron from decaying LSP in SO(10) SUSY GUT

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Abstract. We propose two viable scenarios explaining the recent observations on cosmic positron excess. In both scenarios, the present relic density in the Universe is assumed to be still supported by thermally produced WIMP or LSP ($\chi$). One of the scenarios is based on two dark matter (DM) components scenario, and the other is on SO(10) SUSY GUT. In the two DM components scenario, extremely small amount of non-thermally produced meta-stable DM component [$O(10^{-10}) < n_X/n_\chi$] explains the cosmic positron excess. In the SO(10) model, extremely small R-parity violation for LSP decay to $e^\pm$ is naturally achieved with a non-zero VEV of $\tilde{\nu}_c$ and a global symmetry.

1. Introduction
For a long time thermally produced weakly interacting massive particles (WIMPs) have been believed to be the most promising dark matter (DM) candidates. It is because the correct order of the magnitude of the cross section for explaining the present relic density of the Universe is naturally possible with WIMPs. Particularly, the lightest supersymmetric particle (LSP), which is a well-motivated particle coming from the promising particle physics model, i.e. the minimal supersymmetric standard model (MSSM), has attracted much attentions as an excellent example of WIMP. Actually, the Universe relic density by WIMP or LSP DM is the traditional scenario, which has been believed so far.

However, recently some astrophysical experimental groups including PAMELA [3], ATIC [4], and the Fermi-LAT collaborations [5] reported the very challenging observations in cosmic ray: PAMELA observed positron fractions [$e^+/(e^++e^-)$] exceeding the theoretical expectation [6] above 10 GeV upto 100 GeV. On the other hand, the PAMELA’s observations on antiproton/proton flux ratio were quite consistent with the theoretical calculation. The ATIC and Fermi-LAT’s observations exhibit excesses of $(e^++e^-)$ flux in cosmic ray from 100 GeV to 1 TeV. They would result from the positron flux that keeps rising upto 1 TeV.

Apparently the above observational results are very hard to be interpreted in view of the conventional MSSM cold DM scenario: explaining the excess positrons with annihilations of Majorana fermions such as the LSP needs a too huge boost factor. Moreover, ATIC and Fermi-LAT’s observations seem to require a TeV scale DM, if they are caused indeed by DM annihilation or decay. However, TeV scale DM seems to be disfavored by the gamma ray data, if the excess positron flux should be originated from the same physics explaining DM creation in the early Universe, i.e. from DM annihilation [7].

1 This article is based on Refs. [1, 2].
Such astrophysical observations seem to destroy our traditional scenario on DM. In this article, however, it will be pointed out that such observations do not necessarily imply the presence of a new DM theory replacing the traditional one. We will propose two viable scenarios explaining them, in which the present relic density in the Universe is assumed to be still supported by thermally produced WIMP.

2. Two dark matter components scenario

Let us consider DM decay scenario to explain the cosmic positron excess. “Helicity suppression” is not valid in DM decay any longer. Unlike the DM annihilation scenario, DM decay scenario is relatively free from the gamma ray constraint, since the positron flux is just linearly proportional to the number density of DM [8]. In the DM decay scenario, however, there are some serious hurdles to overcome: (1) one is to naturally obtain the extremely small decay rate of the DM, \( \Gamma_{DM} \sim 10^{-26} \text{ sec}^{-1} \), and (2) the other is to naturally explain the relic density of the DM.

The first hurdle could be somehow resolved by introducing an extra symmetry, an extra DM component with a TeV scale mass, and grand unified theory (GUT) scale superheavy particles, which mediate DM decay into the standard model (SM) charged leptons (and the LSP) [2]. It is because the required decay rate of \( 10^{-26} \text{ sec}^{-1} \) can be achieved, if the dominant operator for decay to \( e^+ e^- \) is dimension 6 suppressed by \( M_{GUT}^2 \), i.e. a four fermion interaction:

\[
\Gamma_{DM} \sim \frac{m_{DM}^5}{196\pi^3 M_{GUT}^4} \sim 10^{-26} \text{ sec}^{-1} ,
\]

where \( m_{DM} \sim \text{a few TeV} \). The fact that the GUT scale particles are involved in the DM decay might be an important hint supporting GUT [9]. However, since the interaction between the new DM and the SM charged lepton are made extremely weak by introducing superheavy particles mediating the DM decay, it is hard to thermally produce the new DM, and so non-thermal production of DM with a carefully tuned reheating temperature should be necessarily assumed for the required relic density. One way to avoid it is to consider a SUSY model with two DM components (\( \chi, X \)), where \( \chi \) is just the ordinary WIMP such as the LSP and \( X \) indicates a new DM component [2, 9]:

\( \chi \) : main component of DM explaining the relic density, thermally produced, absolutely stable.

\( X \) : (extremely) small number density, non-thermally produced, meta-stable, decay to \( e^+ e^- \) explaining PAMELA/Fermi-LAT.

In this class of models, a (global) symmetry should be introduced to forbid all unwanted dimension 4 and 5 operators contributing to DM decay. The required number density of \( X \) (\( \equiv n_X \)) turns out to be just \( O(10^{-10}) < n_X/n_\chi \). It is possible only if the suppression of the dimension 6 operator is smaller than \( M_{GUT}, 10^{12} \text{ GeV} < M_\ast < 10^{16} \text{ GeV} \) [2], since the positron flux in the case of DM decay is proportional to \( n_X \cdot \Gamma_X \). The low energy field spectrum in this class of models [2] is the same as that of the MSSM except for the neutral singlet extra DM component. Moreover, the models of [2] can be embedded in the flipped SU(5) GUT.

3. LSP DM scenario: SO(10) SUSY GUT model

In the second scenario, we suppose again that just the conventional bino-like LSP is the main component of the DM. Since the “bino” is a WIMP, thermally produced binos could explain well the relic density of the Universe. Without introducing a new DM component and interaction, we will attempt to explain the PAMELA’s observation within the framework of the already existing particle physics model, SO(10) SUSY GUT.
3.1. SU(5) vs. SU(2)R scales

In terms of the SM’s quantum numbers, the SO(10) generator (= 45_G) is split into the generators of the SM gauge group plus \{(1, 1)_{-1}, (1, 1)_1\}, \{(1, 1)_0\}, \{(3, 2)_{-5/6}, (3, 2)_5/6\}, and \{(3, 2)_{1/6}, (3, 2)_{-1/6}\}. We will simply write them as

\[ \{E, E^c\}, \ N, \ \{Q', Q'^c\}, \ \{Q, Q^c; U, U^c\}, \ (2) \]

respectively. The SM gauge group’s generators and \{E, E^c\}, \ N compose the generators of SU(3)_c × SU(2)_L × SU(2)_R × U(1)_{B-L} (≡ LR), where \{E, E^c\} and a linear combination of the SM hypercharge generator and \ N (≡ N_R) correspond to the SU(2)_R generators. The other combination orthogonal to it is the U(1)_{B-L} generator (≡ N_{BL}). Note that \{E, E^c\} and \ N don’t carry color charges.

By the VEV of the adjoint Higgs \[ \langle H \rangle \equiv \left\{ 16_H \right\} \] (3.2. LSP decay in SO(10)

To achieve the needed extremely small decay rate of the bino-like LSP \( \chi \), we need extremely small R-parity violation naturally. \( \chi \) can never decay, if (1) R-parity is absolutely preserved and (2) \( \chi \) is really the LSP. We mildly relax these two conditions such that \( \chi \) can decay by assuming

(1) a non-zero VEV of the superpartner of one family of RH neutrino, \( \tilde{\nu}_i^c \)

(i.e. R-parity violation), or

(2) a mass of \( \tilde{\nu}_i^c \) lighter than the \( \chi \)’s mass, \( m_\chi \) (i.e. \( \tilde{\nu}_i^c \) LSP).

By introducing a global symmetry, one can forbid the (renormalizable) Yukawa couplings between \( \tilde{\nu}_i^c \) and the MSSM fields. Then, \( \tilde{\nu}_i^c \) can interact with the MSSM fields only through the superheavy gauge fields and gauginos of SO(10), since the (s)RH neutrino \( \nu_i^c \) (\( \tilde{\nu}_i^c \)) is a neutral singlet under the SM gauge symmetry but it is charged under SO(10). It is embedded e.g. in \( 16 \) of SO(10). Consequently, decay of \( \chi \) is possible but extremely suppressed. For instance, refer to the diagram of Figure 1-(a). We will discuss how this diagram can be dominant for the \( \chi \) decay.

3.3. The conditions for leptonic decay of \( \chi \)

Let us consider the interactions of the superheavy gauginos. In Table 1, we list all the gauge interactions between the superheavy gauginos of SO(10) and two MSSM fields. They are, of course, the renormalizable operators. As seen in Table 1, \( \tilde{\nu}_i^c \) or \( \nu_i^c \) couples to the superheavy SO(10) gauginos, \{\( \tilde{E}, E^c \), \( \tilde{N}, Q, Q^c \), and \( \tilde{U}, U^c \)\}.

According to PAMELA data [3], the branching ratio of the hadronic DM decay modes should not exceed 10%. To make the leptonic interactions, i.e. \( \tilde{\nu}_i^c \nu_i^c \tilde{E}^c \), \( \tilde{\nu}_i^c e_i^c \tilde{N} \), and \( \tilde{\nu}_i^c \nu_i^c \tilde{N} \), dominate over the other interactions in Table 1, we assume that

2 Alternatively, one can employ the large representations, \( 126_H, 126_H, \) and \( 210_H \), instead of \( 16_H, 16_H, \) and \( 45_H, 126_H, \) and \( 126_H \) break SO(10) to SU(5), while \( 210_H \) breaks SO(10) to SU(4) × SU(2)_L × SU(2)_R. In our discussion throughout this article, \( 16_H, 16_H, \) and \( 45_H \) can be replaced by \( 126_H, 126_H, \) and \( 210_H \), respectively.

3 In this article we don’t discuss the cases in which \( \chi \) decays through the mediation of the superheavy gauge bosons. However, it turns out that the decay channels of \( \chi \) through the mediation of the superheavy gauge fields are relatively suppressed, compared to the mediation of the superheavy gauginos discussed here [1].
The triplets Higgs contained in the DM mass should be around 300 – 400 GeV [11].

PAMELA and Fermi-LAT’s data in a suitable parameter range [12]. However, this does not imply that DM in pulsars (and/or with the sub-dominant extra TeV scale DM component [2]). In fact, pulsars can explain both the electrically charged superheavy LR gauginos and the MSSM lepton singlets (b).

Figure 1. Dominant diagram of the bino decay (a) and the gauge interaction between electrically charged superheavy LR gauginos and the MSSM lepton singlets (b).

Table 1. Gauge interactions between two MSSM fields and a heavy gaugino in the SO(10) GUT

- The LR (or B – L) breaking scale should be lower than the SU(5) breaking scale, i.e. \( \langle 16_H \rangle \ll \langle 45_H \rangle \). Then \( M_Q, M_U \), \( M_U^4 \) become much heavier than \( M_E \) and \( M_N \), and so most of hadronic decay modes of \( \chi \) can be easily suppressed except those by \( E^c \), \( \tilde{E} \), and \( \tilde{N} \) in Table 1.
- The slepton \( \tilde{\nu}^c_1 \), which composes an SU(2) \( _R \) doublet together with \( \nu^c_1 \), needs to be lighter than the squarks. Then the decay channels of \( \chi \) by \( d_i^c u_i^c E^c \), \( u_i^c d_i^c \tilde{E} \), and \( u_i^c \nu_i^c \tilde{N} \), \( d_i^c \tilde{d}_i \tilde{N} \) become suppressed. We also require that \( \chi \) and \( \tilde{\nu}^c_1 \) are much lighter than the charged MSSM Higgs. So the leptonic interactions, \( \tilde{\nu}^c_1 \nu^c_1 \tilde{E}^c \), \( \tilde{\nu}^c_1 \nu^c_1 \tilde{E}^c \), and \( \tilde{\nu}^c_1 \nu^c_1 \tilde{N} \), \( \tilde{\nu}^c_1 \nu^c_1 \tilde{N} \) can dominate over the others.
- At least one RH neutrino, i.e. the SU(2) \( _L \) singlet neutrino \( \nu^c_1 \) (and its superpartner \( \tilde{\nu}^c_1 \)) must be lighter than \( \chi \) so that \( \chi \) decays to charged leptons. It is because \( \nu^c_1 \) is always accompanied by \( \tilde{\nu}^c_1 \) in the effective operators leading to the leptonic decay of \( \chi \), composed of \( \tilde{e}_1^c \nu^c_1 \tilde{E}^c \), \( \tilde{\nu}^c_1 \nu^c_1 \tilde{E}^c \), and \( \tilde{\nu}^c_1 \nu^c_1 \tilde{N} \), \( \tilde{\nu}^c_1 \nu^c_1 \tilde{N} \). If all the sneutrino masses are heavier than \( \chi \), \( \tilde{\nu}^c_1 \) must develop a VEV for decay of \( \chi \). Once \( \nu^c_1 \) is light enough, \( \tilde{\nu}^c_1 \) can achieve a VEV much easily.

To be consistent with PAMELA’s observations on high energy galactic positron excess [3], the DM mass should be around 300 – 400 GeV [11]. Thus, we simply take the following values:

\[ \nu^c_1, \tilde{\nu}^c_1 \tilde{E}^c, d_i^c u_i^c E^c, u_i^c d_i^c \tilde{E}^c, h_u^u h_d^d E^c, h_u^d h_d^u E^c \]

\[ \tilde{\nu}^c_1 \nu^c_1 \tilde{E}^c, \tilde{\nu}^c_1 \nu^c_1 \tilde{E}^c, h_u^u h_d^d \tilde{E}^c, h_u^d h_d^u \tilde{E}^c \]

\[ \tilde{\nu}^c_1 \nu^c_1 \tilde{N}^c, \tilde{\nu}^c_1 \nu^c_1 \tilde{N}^c, h_u^u h_d^d \tilde{N}^c, h_u^d h_d^u \tilde{N}^c \]

\[ \tilde{\nu}^c_1 \nu^c_1 q_i^c Q^c, \tilde{\nu}^c_1 \nu^c_1 l_i^c Q^c, \tilde{\nu}^c_1 \nu^c_1 l_i^c Q^c, \tilde{\nu}^c_1 \nu^c_1 l_i^c Q^c, \]

\[ \tilde{\nu}^c_1 \nu^c_1 \tilde{q}_i^c U^c, \tilde{\nu}^c_1 \nu^c_1 \tilde{l}_i^c U^c, \tilde{\nu}^c_1 \nu^c_1 \tilde{c}_i^c U^c, \tilde{\nu}^c_1 \nu^c_1 \tilde{c}_i^c U^c, \]

4 The triplets Higgs contained in \( 10_h \) can achieve the mass proportional to \( \langle 45_H \rangle \) via \( 10_h, 45_h, 10_h \) [10].

5 The \( (e^+ + e^-) \) excess observed by Fermi-LAT could be explained by astrophysical sources such as nearby pulsars (and/or with the sub-dominant extra TeV scale DM component [2]). In fact, pulsars can explain both the PAMELA and Fermi-LAT’s data in a suitable parameter range [12]. However, this does not imply that DM in
Let us consider the following terms in the superpotential:

1. $\langle \mathbf{16}_H \rangle \ll \langle \mathbf{45}_H \rangle$. (If $m_\chi < m_{\tilde{\psi}^c}$, then $\langle \tilde{\psi}_i^c \rangle \neq 0$.) We will assume $\langle \mathbf{16}_H \rangle \sim 10^{14}$ GeV.

2. squarks, charged Higgs, higgsinos and other typical soft masses are of $\mathcal{O}(1)$ TeV.

3. $m_{\nu^c_j} < m_\chi \sim 300 - 400$ GeV $< m_{\tilde{\chi}^0_i} \ll \mathcal{O}(1)$ TeV.

Consequently, SO(10) is broken first to LR, which would be the effective gauge symmetry valid below the GUT scale. As seen from Table 1, the gauge interactions by the LR gauginos (and also gauge fields) preserve the baryon numbers. Even if the masses of the LR gauginos and gauge fields are relatively light, their gauge interactions don’t give rise to proton decay.

### 3.4. Seesaw mechanism

Although one RH neutrino is light enough, the seesaw mechanism for obtaining the three extremely light physical neutrinos still may work. Let us consider the following superpotential:

$$W_\nu = y_{ij}^{(\nu)} l_i h_u \nu^c_j (j \neq 1) + \frac{1}{2} M_{ij} \nu^c_i \nu^c_j (i, j \neq 1),$$

where the Majorana mass term of $\nu^c_i$ could be generated from the non-renormalizable superpotential $\langle \mathbf{16}_H \rangle \langle \mathbf{\overline{16}}_H \rangle \mathbf{16}_i \mathbf{16}_j / M_P (i, j \neq 1)$. Thus, $M_{ij} (\gg \langle h_u \rangle)$ could be determined, if the LR breaking scale by $\langle \mathbf{16}_H \rangle$ is known. In this superpotential, we note that one RH neutrino $\nu^c_1$ does not couple to the MSSM lepton doublets and Higgs. For instance, by assigning an exotic U(1) R-charge to $\nu_1$, one can forbid its Yukawa couplings to the MSSM superfields. Thus, $\nu^c_1$ would be decoupled from the other MSSM fields, were it not for the heavy gauge fields and gauginos of the SO(10) SUSY GUT.

Taking into account only Eq. (3), one neutrino remains massless. The two heavy Majorana mass terms of $\nu^c_2$ and $\nu^c_3$ are sufficient for the other two neutrinos to achieve extremely small physical masses through the constrained seesaw mechanism [13]:

$$m_\nu = m_\nu^T = \begin{pmatrix} v_{12} & v_{13} \\ v_{22} & v_{23} \\ v_{32} & v_{33} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & M_{22}^{-1} & M_{23}^{-1} \\ 0 & M_{32}^{-1} & M_{33}^{-1} \end{pmatrix} \begin{pmatrix} v_{12} & v_{22} & v_{32} \\ v_{13} & v_{23} & v_{33} \end{pmatrix},$$

where $v_{ij} \equiv y_{ij}^{(\nu)} \langle h_u \rangle$, and $M_{ij}^{-1}$ denotes the inverse matrix of $M_{ij}$. One of the eigenvalues of $m_\nu$ is zero and the other two are of order $v^2/M$. Through the diagonalization of the mass matrix in Eq. (4), the three left-handed neutrinos from the lepton doublet $l_1$, $l_2$, and $l_3$ can be maximally mixed, whereas the mixing of the RH neutrinos is only between $\nu^c_2$ and $\nu^c_3$. A complex phase in $y_{ij}^{(\nu)}$ could make the leptogenesis possible [13].

### 3.5. LSP decay rate and the seesaw scale

Let us consider the following terms in the superpotential:

$$W \supset \frac{1}{M_P} \langle \mathbf{16}_H \rangle \mathbf{16}_1 \Sigma^2 + \kappa \Sigma^3,$$

where $M_P = 2.4 \times 10^{18}$ GeV and $\kappa$ is a dimensionless coupling constant. $\Sigma$ is an SO(10) singlet. We assign e.g. the U(1) R-charge of 2/3 to $\mathbf{16}_1$ and $\Sigma$, and 0 to $\mathbf{16}_H$. This charge assignment addition to pulsars can not be the source of the galactic positrons. In fact, we don’t know yet a complete pulsar model, in which all the free parameters would be fixed by the fundamental physical constants.

Alternatively, one could assume $m_\chi \approx 3.5$ TeV and the model is slightly modified such that $\chi$ decays dominantly to $\mu^+$, $\nu_2^c$ rather than to $e^+$, $\nu_1^c$, which is straightforward, the Fermi-LAT’s data as well as the PAMELA’s can be also explained [11]. In this case, however, the soft SUSY breaking scale should be higher than 3.5 TeV.
forbids the renormalizable Yukawa couplings between $\nu_1^c$ and other MSSM fields carrying integer R-charges.

The scale of $\langle \overline{T H} \rangle$ (eq. $\langle \overline{T H} \rangle = M_E/\sqrt{2}g_{10}$) can be determined such that it is consistent with PAMELA data. The soft mass term of $\nu_1^c$ and the A-term of $\kappa \Sigma^3$ in the scalar potential permit a VEV $\langle \Sigma \rangle \sim m_{3/2}/\kappa$. Then, the scalar potential generates a linear term of $\nu_1^c$ coming from the A-term corresponding to the first term of Eq. (5), $V \supset m_{3/2}/(\kappa^2 M_P)\langle \nu_1^c \rangle$. The linear term and the soft mass term of $\nu_1^c$ in the scalar potential can induce a non-zero VEV of $\nu_1^c$:

$$\langle \nu_1^c \rangle \sim \frac{m_{3/2}}{\kappa^2} \times \frac{M_E}{M_P}.$$  \hspace{1cm} (6)

Thus, the decay rate of $\chi$ in Figure 1-(a) can be estimated:

$$\Gamma_\chi = \alpha_{10}^2 \alpha_Y m_\chi^5 \frac{96 M_E^2}{\kappa^2 m_\chi^2} \left( \frac{m_{3/2}/(\kappa^2 M_P)}{m_\nu^2} \right)^2 \sim \frac{\alpha_{10}^2 \alpha_Y m_\chi^5}{96 M_E^2 M_P^2} \left( \frac{m_{3/2}/(\kappa m_\nu)}{m_\nu^2} \right)^4 \sim 10^{-26} \text{sec}^{-1},$$

where $\alpha_{10}$ (eq. $g_{10}^2/4\pi$) and $\alpha_Y$ (eq. $g_Y^2/4\pi = (3/5) \times g_1^2/4\pi$, where $g_1$ is the SO(10) normalized gauge coupling of $g_Y$) are approximately 1/24 and 1/100, respectively. Here, we ignore the RG correction to $\alpha_{10}$. $300 - 400$ GeV fermionic DM decaying to $e^\pm$ and a light neutral particle can fit the PAMELA data [11]. For $m_\chi \approx 300 - 400$ GeV, $(m_{3/2}/(\kappa m_\nu^2)) \sim 10$, $M_E$ or $\langle \overline{T H} \rangle$ is estimated to be of order $10^{14}$ GeV. This is consistent with the assumption $\langle \overline{T H} \rangle \ll \langle \overline{45_H} \rangle \sim 10^{16}$ GeV. Therefore, the masses of the other two heavy RH neutrinos, which do not contribute to the process of Figure 1-(a), are around $10^{10}$ GeV or smaller in this case: $W \supset y_{ij}(\langle \overline{T H} \rangle/\langle \overline{45_H} \rangle)M_P 16, 16, (i, j \neq 1) \supset y_{ij}(10^{10} \text{GeV}) \times \nu_{i}^c \nu_{j}^c (i, j \neq 1)$.

4. Conclusion

In this article, we pointed out that the traditional DM scenario based on thermally produced WIMP do not necessarily conflict with the cosmic positron excess observed by PAMELA and Fermi-LAT. We have proposed two viable scenarios based on two DM components and SO(10) SUSY GUT. Particularly in the SO(10) model, extremely small R-parity violation for LSP decay could be naturally achieved with a non-zero VEV of $\nu_1^c$ and a global symmetry.

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