Cosmic-ray Electron and Positron Excesses from Hidden Gaugino Dark Matter

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Abstract

We study a scenario that a hidden gaugino dark matter decays into the standard-model particles (and their supersymmetric partners) through a kinetic mixing with the gaugino of a $U(1)_{B-L}$ broken at a scale close to the grand unification scale. We show that decay of the hidden gaugino can explain excesses in the cosmic-ray electrons and positrons observed by PAMELA and Fermi.
1 Introduction

The cosmic-ray electrons and positrons have attracted much attention since the PAMELA collaboration \cite{1} released the data showing rapid growth in the positron fraction from several tens GeV up to about 100 GeV. Recently, the cosmic-ray electron plus positron flux was measured with the Fermi satellite \cite{2} with significantly improved statistics. The Fermi data shows that the ($e^- + e^+$) spectrum falls as $E^{-3.0}$ over energies between 20 GeV and 1 TeV without prominent spectral features. The H.E.S.S. collaboration also measured the cosmic-ray ($e^- + e^+$) spectrum from 340 GeV up to several TeV \cite{3}, suggesting that the spectrum steepens above 1 TeV. The Fermi and H.E.S.S. results are in agreement with each other where the energy of the two data overlaps. Combining the PAMELA, Fermi and H.E.S.S. results, therefore, it is likely that there is an excess in the electron and positron flux above several tens GeV up to 1 TeV.

We have recently presented a scenario that thermal relic Wino dark matter (DM) of mass about 3 TeV, decaying through an R-parity violating operator $\bar{e}LL$, naturally accounts for the PAMELA and Fermi excesses simultaneously \cite{4}. In the model, the magnitude of the R-parity breaking as well as the Wino mass are closely tied to the gravitino mass, $m_{3/2}$, of $\mathcal{O}(10^3)$ TeV. Interestingly enough, the lifetime of the Wino DM naturally becomes of $\mathcal{O}(10^{26})$ seconds, which is suggested by observation to account for the electron/positron excess. The only drawback of this scenario might be that all supersymmetric (SUSY) particles must have masses heavier than several TeV and therefore beyond the reach of LHC.

In this paper, we consider a hidden gaugino of an unbroken U(1) gauge symmetry as a candidate for DM \cite{5, 6}. Since the longevity of DM originates from its extremely weak interactions with the standard model (SM) particles, the SUSY particles in the SM sector can have masses well below the DM mass, possibly within the reach of LHC. As pointed out in Ref. \cite{3}, the decay of the hidden gaugino proceeds through a kinetic mixing with a U(1)$_{B-L}$ gaugino living in the bulk (see also Ref. \cite{7}). The decay rate suppressed by the U(1)$_{B-L}$ breaking scale provides the desired magnitude of the lifetime. In addition, the hidden gaugino DM will mainly decay into a lepton and slepton pair, if the squarks are substantially heavier than the sleptons. Therefore the decay process can be lepto-philic
in concordance with the absence of the excess in the antiproton fraction. In Ref. [5], we considered a case that the hidden gaugino decays universally into a lepton and slepton pair in the three generations. In this paper, we study more generic decay processes such as that into the third generation as well as three-body decays with a virtual slepton exchange. We will show the decays of the hidden gauginos can explain the anomalous excesses observed by PAMELA and Fermi.

This paper is organized as follows. In Sec. 2 we briefly describe our hidden gaugino DM model. The predicted positron fraction and the electron spectrum will be shown in Sec. 3. The last section is devoted to discussion and conclusions.

2 Model

In this section we will briefly describe the model proposed in Ref. [5]. The reader is referred to the original reference for more details.

Suppose that a hidden U(1) gauge multiplet \((\lambda_H, A_H, D_H)\) is confined on a brane, which is geometrically separated from the brane on which the SUSY SM (SSM) particles reside, in a set up with an extra dimension. We introduce a U(1)\(_{B-L}\) gauge multiplet in the bulk so that those two sectors are in contact only through a kinetic mixing of the U(1)\(_{B-L}\) and hidden U(1) multiplets. The mixing is written as

\[
L_K = \frac{1}{4} \int d^2 \theta (W_H W_H + W_{B-L} W_{B-L} + 2\kappa W_H W_{B-L}) + \text{h.c.,}
\]

\[
\supset -i \left( \tilde{\lambda}_H \tilde{\sigma}^\mu \partial_\mu \lambda_H + \tilde{\lambda}_{B-L} \tilde{\sigma}^\mu \partial_\mu \lambda_{B-L} + \kappa \lambda_H \tilde{\sigma}^\mu \partial_\mu \lambda_{B-L} + \kappa \tilde{\lambda}_{B-L} \tilde{\sigma}^\mu \partial_\mu \lambda_H \right), \tag{1}
\]

where \(\kappa\) is a kinetic mixing parameter of \(O(0.1)\). Using the same notation \(\lambda_H\) for the hidden gaugino in the mass eigenstate, its interaction with the SSM particles can be expressed as [5]

\[
\mathcal{L}_{\text{int}} \simeq -\sqrt{2} g_{B-L} Y_\psi \kappa \left( \frac{m}{M} \right)^2 \lambda_H \phi_{\text{SSM}}^* \psi_{\text{SSM}} + \text{h.c.,} \tag{2}
\]

where \(g_{B-L}\) denotes the U(1)\(_{B-L}\) gauge coupling, \(Y_\psi\) is the (B–L) number of \(\phi\) and \(\psi\), \(m\) represents a soft SUSY breaking Majorana mass of \(\lambda_H\), and \(M(\equiv 4g_{B-L}v_{B-L})\) is the mass of \(\lambda_{B-L}\) arising from the spontaneous breaking of U(1)\(_{B-L}\) at a scale \(v_{B-L}\). If the masses
of $\phi$ and $\psi$ are much smaller than $m$, the lifetime of $\lambda_H$ is estimated to be
\[
\Gamma^{-1}_{\text{DM}}(\lambda_H \rightarrow \psi + \phi) \sim 10^{24} \text{ sec} \ g_{B-L}^{-2} Y_\psi^{-2} \kappa^{-2} \left( \frac{m}{3 \text{ TeV}} \right)^{-5} \left( \frac{M}{10^{16} \text{ GeV}} \right)^4 \frac{1}{C_\psi},
\] (3)
where $C_\psi$ is a color factor of $\psi$, i.e., 3 for quarks and 1 for leptons. On the other hand, if the mass of $\phi$ is larger than $m$, the decay proceeds with a virtual exchange of $\phi$, leading to
\[
\Gamma^{-1}_{\text{DM}}(\lambda_H \rightarrow \psi + \psi^* + \tilde{\chi}) \sim 10^{26} \text{ sec} \ g_{B-L}^{-2} Y_\psi^{-2} \kappa^{-2} \left( \frac{m_\phi}{m} \right)^4 \left( \frac{m}{3 \text{ TeV}} \right)^{-5} \left( \frac{M}{10^{16} \text{ GeV}} \right)^4 \frac{1}{C_\psi},
\] (4)
where we have assumed that the main decay of $\phi$ is into $\psi^*$ and a SM gaugino $\tilde{\chi}$.

It is quite remarkable that the hierarchy between the B–L breaking scale $\sim 10^{16} \text{ GeV}^1$ and the SUSY breaking mass of the hidden gaugino of $\mathcal{O}(1) \text{ TeV}$ naturally leads to the lifetime of $\mathcal{O}(10^{26})$ seconds that is needed to account for the electron/positron excess. Note also that the longevity of the $\lambda_H$ DM arises from the geometrical separation and the hierarchy between $M$ and $m$, not from conservation of some discrete symmetry such as the R parity.

Throughout this paper we assume that the R parity is preserved, and that the lightest supersymmetric particle (LSP) is the lightest neutralino in the SSM which also contributes to the DM density. For the moment we assume that $\lambda_H$ is the dominant component of DM, while the abundance of the neutralino LSP is negligible. Even if this is not the case, the prediction on the cosmic-ray fluxes given in the next section can remain unchanged, since the fraction of $\lambda_H$ in the total DM density can be traded off with the lifetime, as long as the fraction is larger than about $10^{-10}$. We will come back to this issue in Sec. 4.

3 Electron and positron excesses from the decaying hidden-gaugino DM

As we have seen in the last section, $\lambda_H$ has a very long lifetime and decays into the SSM particles through a small mixing with the $\lambda_{B-L}$. The decay of $\lambda_H$ causes the SUSY

\footnote{The seesaw mechanism for neutrino mass generation suggests the Majorana mass of the (heaviest) right-handed neutrino at about the GUT scale. Such a large Majorana mass can be naturally provided if the U(1)$_{B-L}$ symmetry is spontaneously broken at a scale around 10$^{16}$ GeV.}
cascade decays, emitting high energy SM particles. If the squarks are heavier than $\lambda_H$, the hadronic decay can be suppressed, which results in a small amount of antiprotons and photons $^{10}$. We assume that it is the case.

We fix in the present analysis the masses of the $\lambda_H$ and the neutralino LSP to be 3 TeV and 200 GeV, respectively. In general, SUSY cascade decays are very complicated. To simplify the analysis, we focus on the following three extreme cases.

**Case I** [Universal decay into a lepton and slepton pair]: The $\lambda_H$ decays into the three lepton and slepton pairs at the same rate, and the sleptons subsequently decay into LSP + charged lepton. We set that the lifetime of $\lambda_H$ is $9 \times 10^{25}$ sec., and $m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = m_{\tilde{\tau}_1} = 2.5$ TeV and the other sfermion particles are heavier than $\lambda_H$.

**Case II** [Decay into a tau and stau pair]: The $\lambda_H$ decays into a tau and stau pair, and the stau decays into LSP + tau. The lifetime of $\lambda_H$ is $6 \times 10^{25}$ sec., and $m_{\tilde{\tau}_1} = 2.5$ TeV and the other sfermion particles are heavier than $\lambda_H$.

**Case III** [Three-body decay into the lepton, anti-lepton and neutralino]: The $\lambda_H$ decays into the $e^+ + e^- + \text{LSP}$, $\mu^+ + \mu^- + \text{LSP}$, $\tau^+ + \tau^- + \text{LSP}$ at the same rate. The lifetime of $\lambda_H$ is $1.1 \times 10^{26}$ sec. All sfermion particles are heavier than $\lambda_H$. As for the matrix element of the DM decay, we approximate that the sleptons are much heavier than $\lambda_h$, i.e., $m_{\tilde{\ell}} \gg m$.

The electron and positron energy spectrum is estimated with the program PYTHIA $^{11}$. For the propagation of the cosmic ray in the Galaxy, we adopt the same set-up in Ref. $^5$ based on Refs. $^{12}$ $^{13}$, namely the MED diffusion model $^{14}$ and the NFW dark matter profile $^{15}$. As for the electron and positron background, we have used the estimation given in Refs. $^{16}$ $^{17}$, with a normalization factor $k_{bg} = 0.68$. In Figs. $^1$ and $^2$ we show the positron fraction, the electron plus positron total flux and the diffuse gamma ray flux.

We can see from Fig. $^1$ the above three cases nicely explain the PAMELA result, while the case III seems to give a slightly better fit to the Fermi and H.E.S.S. data with respect to the other two cases. Note however that the fit to the data has an ambiguity due to the relatively large uncertainties in the background estimation, as well as possible

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$^2$ If the LSP is the Wino, the slepton may also decay into neutrino and charged Wino with a large branching fraction.
astrophysical contributions \[24, 25, 26, 27, 28\]. As to the diffuse gamma-ray flux shown in Fig. 2, the $\tau$ decay in the case II tends to give more contribution. In all the three cases we might be able to see some signatures from the $\lambda_H$ decay in the diffuse gamma-rays in the future observation with the Fermi satellite.

4 Discussion and conclusions

So far we have assumed that the hidden gaugino $\lambda_H$ is the main DM component. However, as long as the R parity is conserved, the neutralino LSP in the SSM also contributes to the DM density. To avoid the overproduction of the neutralino LSP, we assume either neutralino-stau coannihilation or the Wino-like LSP. In the former case the stau mass must be close to the neutralino mass of $\mathcal{O}(100)$ GeV, and the cosmic-ray spectra for such a mass spectrum were studied in Ref. \[5\]. In the latter case, the thermal relic abundance of the Wino LSP of mass $\mathcal{O}(100)$ GeV is smaller than the observed DM density \(^3\) and we easily avoid the overproduction of the LSP.

Let us discuss the production mechanism of the hidden gaugino, $\lambda_H$, in the early universe. Since the $\lambda_H$ has only extremely suppressed interactions with the SSM particles, very high reheating temperatures would be needed to generate a right amount of $\lambda_H$ from thermal particle scatterings. This will be in conflict with the big bang nucleosynthesis (BBN) constraint on the gravitino abundance \[31\]. As pointed out in Ref. \[5\], one possible way to produce $\lambda_H$ is to make use of the gravitino decay. In fact, the gravitino must be heavier than $\lambda_H$, since otherwise the $\lambda_H$ would promptly decay into the massless hidden gauge boson and the gravitino. Therefore, the gravitino produced at the reheating will decay into the hidden gaugino and gauge boson as well as the SSM particles.

Let us estimate the $\lambda_H$ abundance from the gravitino decay. To be concrete we consider two cases: $m_{3/2} = 10$ TeV and 100 TeV, since the BBN constraint on the gravitino abundance depends on the gravitino mass. In the former case, the gravitino abundance

\(^3\) The Wino-like neutralino LSP can be realized in anomaly mediation \[29\], which is feasible with more than two extra dimensions. In this scheme, hidden matter multiplets charged under the hidden U(1) gauge symmetry must be introduced so that the hidden gaugino acquires a SUSY breaking mass.

\(^4\) Another possibility is non-thermal production from the inflaton decay. However, as shown in Ref. \[30\], an equal or even greater amount of the gravitino will be also generated in a similar process, and the situation will not be improved much.
can be as large as $Y_{3/2} \sim 10^{-13}$ without spoiling the BBN result \[31\]. The corresponding reheating temperature is about $10^9$ GeV, assuming the thermal gravitino production. The expected branching ratio of producing $\lambda_H$ is $\mathcal{O}(1)\%$, and the $\lambda_H$ abundance will be $\Omega_{\lambda H^2} \sim 10^{-3}$. Note that the abundance of the neutralino LSP produced through the gravitino decay does not have enough abundance to explain the total DM density, and therefore the dominant contribution must come from the thermal relic neutralino. This may be realized in the neutralino-stau coannihilation region. On the other hand, in the case of $m_{3/2} = 100$ TeV, the gravitino abundance can be as large as $Y_{3/2} \sim 10^{-12}$ for a reheating temperature $T_R \sim 10^{10}$ GeV. The resultant $\lambda_H$ abundance will be $\Omega_{\lambda H^2} \sim 10^{-2}$. Interestingly, the neutralino abundance from the gravitino decay is just a right amount to explain the observed DM density $\Omega_{\lambda h^2} \sim 0.1$.\[5\] Thus, even if the $\lambda_H$ may not be the dominant component of DM, its fraction can be naturally in the range of $1-10\%$ depending on the gravitino mass and the reheating temperature. The predictions on the cosmic-ray spectra remain unchanged if we make the lifetime shorter correspondingly by adopting a slightly smaller value of the $B-L$ breaking scale $v_{B-L}$.

In this paper we have studied representative decay processes in a scenario that a hidden $U(1)$ gaugino DM decays mainly through a mixing with a $U(1)_{B-L}$, producing energetic leptons. We have shown that those energetic leptons from the DM decay can account for the PAMELA and Fermi excesses in the cosmic-ray electrons/positrons. The predicted excess in the diffuse gamma-ray flux around several hundred GeV can be tested by the Fermi satellite, and will provide us with information on the decay processes. One of the merits of the current scenario is that the gaugino in the SSM can be within the reach of LHC, since at least one of the SSM neutralino lighter than the hidden gaugino DM is necessary for the DM to decay.

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\[5\] The non-thermally produced neutralino will not annihilate efficiently even in the case of the Wino LSP, unless the gravitino mass is extremely large.
for Young Scientists.

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Figure 1: Cosmic ray signals in the present model. (a): positron fraction with experimental data [1, 18, 19]. (b): \((e^- + e^+)\) flux with experimental data [2, 3, 20, 21]. The yellow zone shows a systematic error and the dashed line shows the background flux. III’ is the same as the Case III except for DM’s lifetime and branching fraction. In this case, we set \(\tau_{\text{DM}} = 9 \times 10^{25}\) sec and the branching fraction of decay into \(e, \mu\) and \(\tau\) as 1:1:3, taking the mass ratio of stau to smuon (selectron) as \(\simeq (1/3)^{1/4}\).
Figure 2: Predicted signals of diffuse gamma ray shown together with the EGRET data [22, 23].