R-violating Decay of Wino Dark Matter and electron/positron Excesses in the PAMELA/Fermi Experiments

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\textbf{Abstract}

We show that R-parity violating decay of Wino dark matter of mass $\sim 3$ TeV can naturally account for the flux and spectral shape of the cosmic-ray electrons and positrons observed by the PAMELA and Fermi satellites. To provide a theoretical basis for the scenario, we also present a model that trilinear R-parity breaking appears with a coefficient suppressed by powers of the gravitino mass, which naturally leads to the Wino lifetime of $O(10^{26})$ sec.
1 Introduction

The lightest supersymmetry (SUSY) particle called as LSP in the SUSY standard model (SSM) is known as a good candidate of dark matter (DM) in the Universe if its mass is $O(100)\text{GeV} - O(1)\text{TeV}$. The stability of the LSP can be guaranteed by assuming an exact R parity. However, the R parity may not necessarily be an exact symmetry. In fact, the LSP can be still DM as long as R-parity breaking terms are sufficiently small and the lifetime of the LSP is much longer than the present age of the Universe. If this is the case, the decay of DM may give rise to some excesses in cosmic rays.

Much attention was recently attracted to the anomalies in cosmic-ray electron/positron fluxes observed by PAMELA [1] and ATIC [2], and decaying LSP scenarios were extensively discussed in this context [3, 4, 5]. Most of the proposals assume bilinear R-parity breaking terms such as $LH_u$, since they are the lowest dimensional R-parity breaking operators which most likely dominate R-parity breaking effects at low energies. However, the bilinear R-parity breaking terms induce DM decays into quarks and hence produce too many antiprotons in cosmic rays. Therefore, it is much safer to consider the next lowest dimensional operators such as $\bar{e} LL$ [5, 7, 8, 9]. However, it seems very unnatural to consider the second lowest dimensional operators, suppressing the lowest dimensional bilinear operators. In addition, even if the trilinear term dominates over the bilinear one, the magnitude of the R-parity breaking should be extremely small, especially in the case of neutralino LSP. No rigorous explanation for the smallness was known, and the size of the R-parity violation was treated as a free parameter.

Very recently, the Fermi collaboration has released data on the electron/positron fluxes from 20 GeV up to 1 TeV [10]; the spectrum falls as $E^{-3.0}$ without prominent spectral features, and it is in agreement with the H.E.S.S. data at $E \sim 1\text{TeV}$ [11, 12]. The index of the observed electron/positron spectrum is close to the high end of theoretically expected value. Moreover, if we combine the Fermi data for $E \lesssim 1\text{TeV}$ and the H.E.S.S. data for $E \gtrsim 1\text{TeV}$, it looks that the spectrum becomes softer at energies above 1 TeV. From this observation, we regard the relatively hard (and almost featureless) electron/positron

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1 See also Ref. [6] for other decaying DM models.

2 The Fermi result is not consistent with the excess around $E \simeq 600\text{GeV}$ reported by ATIC. In this letter we adopt the Fermi result and do not consider the ATIC data.
spectrum below 1 TeV reported by Fermi as an excess with respect to the background. If the electron/positron spectrum observed by Fermi (as well as the positron fraction observed by PAMELA) is to be explained by the DM decay, the mass of DM must be about a few TeV. The suggested mass scale is intriguingly close to the mass of a Wino LSP required for the thermal relic to explain the observed DM abundance.

In this letter we present a model that trilinear R-parity breaking appears with a coefficient suppressed by powers of the gravitino mass. Interestingly, the size of the R-parity breaking is naturally small, and moreover, it leads to the required size of the R-parity breaking suggested by observation, in the case of the Wino LSP of a mass $\sim 3$ TeV. Based on this model, we show that the Fermi as well as PAMELA data can be simultaneously explained by the Wino LSP decaying through the trilinear term $\bar{\epsilon}LL$.

## 2 A model of R-parity breaking

It is known that the superpotential possesses a constant term $C_0$ to cancel the positive energy density induced by SUSY breaking. The constant term is equal to the gravitino mass, $C_0 = m_3/2$, in the Planck unit in which the Planck mass $M_P \simeq 2.4 \times 10^{18}$ GeV is set to be unity. The constant term breaks the continuous $U(1)_R$ symmetry down to a discrete $Z_2$ symmetry, which is nothing but the R parity. A crucial observation is that, if the R symmetry at high-energies is not the continuous $U(1)_R$ but a discrete $Z_{2k+1}$ ($k = \text{integer}$), the constant term $C_0$ results in the R-parity breaking. In this letter we take $k = 2$, since, as we will see later, it leads to the required magnitude of the R-parity breaking operators to account for the anomalous excess in cosmic-ray electrons and positrons.

Let us take the R charges for all quark and lepton chiral multiplets to be 1 and those for the Higgs chiral multiplets $H_u$ and $H_d$ to be 0. (See Table 1.) Then, the following lepton-number violating trilinear term is allowed by the $Z_{5R}$ symmetry:

$$W = \kappa_{ijk}(C_0)^2 \bar{\epsilon}_i L_j L_k,$$

(1)

where $\kappa_{ijk}$ is a numerical coefficient, $i, j, k = 1, 2, 3$ denote the generation, and summation over the SU(2) gauge indices is understood. The coupling $\kappa_{ijk}$ must be antisymmetric under the exchange of the last two indices ($j \leftrightarrow k$) due to the SU(2) gauge invariance.
Note that the R charge of $C_0(= m_{3/2})$ is 2. We may presume that the coefficient $\kappa_{ijk}$ takes a larger value for the third (and second) generation. Therefore, in the following we focus on $\kappa_{i23}$ with $i = 1, 2, 3$, which is assumed to be unsuppressed with the other terms of different combination of flavors being suppressed.

We assume that a Wino LSP accounts for the DM in the Universe. In order to explain the observed DM abundance, the Wino mass must be in the range between $2.7 - 3$ TeV [13]. The Wino LSP is naturally realized in the anomaly-mediated SUSY breaking [14]. Then, using the relation between the Wino mass and the gravitino mass in the anomaly mediation, we find that the gravitino mass should be about $10^3$ TeV. In the presence of the R-parity breaking (1), the Wino LSP is no longer stable, and decays into neutrinos and charged leptons through the exchange of a virtual slepton. One of the decay diagrams is shown in Fig. 1. The decay rate of the Wino LSP through the interaction (1) with $(j, k) = (2, 3)$ is given by [15]

$$\Gamma(\tilde{W}^0 \rightarrow \tau^\pm \nu_\tau e_i^\mp, \nu_\tau \mu^\pm e_i^\mp) \sim \left(10^{27}\text{sec}\right)^{-1} |\kappa_{i23}|^2 \left(\frac{m_{3/2}}{10^3 \text{ TeV}}\right)^4 \left(\frac{m_{\tilde{W}_0}}{3 \text{ TeV}}\right)^5 \left(\frac{m_{\tilde{\ell}}}{5 \text{ TeV}}\right)^{-4},$$

where $m_{\tilde{W}_0}$ denotes the Wino mass, and we have assumed the common slepton mass, $m_{\tilde{\ell}}$, for simplicity. As we will see in the next section, the lifetime (2) is close to what is needed to explain the cosmic-ray observation.

Several comments are in order. First, there could be other trilinear terms including quark multiplets, but they may have only negligible effects on the decay processes if squarks are substantially heavier than sleptons. Second, the bilinear term is also allowed.
Table 1: The assignment of R-charge and $Z_3$. 

|   | $Q$ | $\bar{u}$ | $L$ | $\bar{\epsilon}$ | $H_u$ | $H_d$ | $N$ | $M$ | $C_0$ |
|---|-----|-------|-----|-------------|------|------|-----|-----|-------|
| R | 1   | 1     | 1   | 1           | 0    | 0    | 1   | 0   | 2     |
| $Z_3$ | 1 | 1     | 1   | 1           | 1    | 1    | 1   | 0   | 0     |

by the $Z_{5R}$ symmetry and takes the following form:

$$W = (C_0)^3 L H_u.$$  

(3)

Since the bilinear term is suppressed by an additional factor $C_0$ compared to the trilinear term, the latter becomes much more effective than what is naively expected based on the dimensional grounds. It is not trivial, though, if the trilinear term dominates over the bilinear term as the decay processes of the LSP. We will come back to this issue in Sec. 4, and for the moment, we simply assume that the bilinear term does not have sizable effects on the decay.

3 Cosmic-ray signal from LSP decay

Let us discuss the cosmic ray signals from the LSP decay. Its decay pattern depends on R-breaking structure and the SSM mass spectrum. For a demonstration, we consider the case that the $\bar{\epsilon}_i L_2 L_3$ ($i = 1, 2, 3$) term dominates the R-breaking and assume that $\text{BF}(\text{DM} \rightarrow \tau^\pm \nu_\mu e^\mp_i) = \text{BF}(\text{DM} \rightarrow \nu_\tau \mu^\pm e^\mp_i) = 0.5$. We have used the constant matrix element in the three-body phase space, for simplicity. The electron and positron energy spectrum is estimated with the program PYTHIA [16]. For the propagation of the cosmic ray in the Galaxy, we adopt the same set-up in Ref. [17], based on Refs. [18, 19]. As for the electron and positron background, we have used the estimation given in Refs. [20, 21], with a normalization factor $k_{bg} = 0.68$. In Fig. 2 we show the positron fraction and the electron and positron total flux. We set that $m_{\text{DM}} = 3$ TeV and the lifetime is $9 \times 10^{25}$ sec. As can be seen from Fig. 2 the cosmic-ray signal in the present model can nicely fit the PAMELA data for $i = 1, 2, 3$. On the other hand, the prediction in case of $i = 1$ fails to explain the Fermi data due to the presence of hard electrons produced by the LSP decay, leading to the bump at 1 TeV. The prediction in case of $i = 2$ gives a very good fit.
Figure 2: Cosmic ray signals in the present model. (a): positron fraction with experimental data [1, 22, 23]. (b): positron and electron fluxes with experimental data [10, 11, 12, 2, 24]. The yellow zone shows a systematic error and the dashed line shows the background flux. I, II and III represent the cases that $\bar{e}_1L_2L_3$, $\bar{e}_2L_2L_3$ and $\bar{e}_3L_2L_3$ dominate the R-breaking, respectively.

to the Fermi data. Considering uncertainties in the background estimation as well as the SSM mass spectrum, however, the case of $i = 3$ may be able to give an equally good fit.

4 Discussion and conclusions

Let us discuss several issues in the model presented in Sec. 2 and possible solutions. First of all, the bilinear term like (3) could induce additional decay processes into lepton and Higgs, which may result in too many antiprotons. Note that the effective mixing angle induced by the bilinear term is given by the ratio of $C_{\theta}^3$ to the Higgs mass or slepton mass. Therefore, if $m_{3/2}$ is the same orders of magnitude of the Higgs mass or the slepton mass, the bilinear term will be as important as the trilinear term.

To make the matter worse, the bilinear term will be enhanced in the presence of right-handed neutrinos $N$. This is because, if we assign the R-charge 1 to $N$ as in Table 1, the
following interactions are allowed by the $Z_{5R}$ symmetry.

$$W = C_0^3 N + \frac{1}{2} MNN + y_\nu N L H_u,$$

(4)

where $M$ denotes the Majorana right-handed neutrino mass, $y_\nu$ is the neutrino Yukawa coupling, and we have suppressed the flavor indices. Since the first term is generically present, the right-handed neutrino will develop a non-vanishing expectation value of $O(C_0^3/M)$. Then, the neutrino Yukawa coupling induces the bilinear term $y \langle N \rangle L H_u \sim (C_0^3/M) L H_u$, which is enhanced by $1/M$ compared to (3). Thus, the presence of the right-handed neutrino of mass lighter than the Planck mass leads to the enhancement of the bilinear term.

Those problems can be easily solved by introducing a $Z_3$ symmetry, under which the SSM particles and $M$ are charged by an unit charge. (See Table 1.) Namely, the $Z_3$ symmetry is broken by $M \ll 1$. Then the bilinear term (3) is suppressed by $M$, while the first term in (4) by $M^2$. Therefore, the trilinear term (1) will be the dominant source of the LSP decay.

In this letter we have presented the R-parity breaking model in which the trilinear term becomes important and appears with a coefficient proportional to powers of the gravitino mass. We have also shown that the Wino LSP decaying through the lepton-number violating trilinear term (1) can account for the PAMELA and Fermi data.

There are several non-trivial coincidence in our scenario. First of all, the change in the power index of the electron/positron spectrum suggests the DM of mass a few TeV. This is intriguingly close to the mass of the thermal relic Wino DM. Assuming the anomaly mediation, the gravitino mass is determined to be about $10^3$ TeV. In our model on the R-parity violation, the lifetime of the Wino LSP is determined by some combination of the Wino mass and the gravitino mass. Substituting the above values for the Wino and gravitino masses, we have obtained the lifetime which is surprisingly close to what is needed to account for the cosmic-ray anomalies. Further study of the prediction of other cosmic rays such as gamma-rays, antiprotons and neutrinos\textsuperscript{3}, as well as future observational data, will enable us to tell whether those are just coincidence or

\textsuperscript{3} Our model is consistent with the current observational bound on the neutrino production from decaying DM \textsuperscript{25}.  

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Figure 3: Predicted signals of diffuse gamma-ray flux shown together with the EGRET data [27, 28].

may reflect from the characteristics of DM and the underlying physics beyond the SM.

We can see from Fig. 2 that the fit to the Fermi data becomes better if the decay products include the charged leptons in the second and third generations, namely, muons and taus. In particular, if the decay product is dominated by the muon (as in the case II of Fig. 2), the fit looks pretty good. It is actually possible to give a equally nice fit to the Fermi data, if we properly combine the contributions from the first and third generations. This is indeed the case if we consider unsuppressed $\kappa_{313}$. Such flavor dependence may be probed by studying the diffuse gamma-ray in detail. For reference we show in Fig. 3 the predicted diffuse gamma-ray signals for the cases I, II and III. Including more taus in the final states generically lead to larger signal in the diffuse gamma-ray. We may be able to untangle the flavor dependence by making use of the different predictions.

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4 See Ref. [26] for a model in which the muons are mainly produced by the DM decay.
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