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R-parity violating right-handed neutrino in gravitino dark matter scenario

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Abstract: A decay of the gravitino dark matter is an attractive candidate to explain the current excesses of the PAMELA/ATIC cosmic-ray data. However, R-parity violations are required to be very tiny in low-energy scale. We suggest a R-parity violation in the right-handed neutrino sector. The violation is suppressed by a see-saw mechanism. Although a reheating temperature is constrained from above, the thermal leptogenesis is found to work successfully with a help of the R-parity violating right-handed neutrino.

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Contents

1 Introduction

Observations of comic rays have been greatly developed. After a series of cosmic-ray measurements, PAMELA recently published the first result of the positron fraction, which show an excess compared to the background at energies above 10GeV [1]. Interestingly, the ATIC collaboration also reported an excess of the electron plus position flux in a range of $O(100)$GeV [2]. Although the experimental data and the background estimations still involve ambiguities, the excesses may be a sign of the dark matter (DM). In this letter, we focus on decaying DM scenarios. The DM is not always required to be stable as long as its life time is long enough for the DM to survive until today. Then, its decay products are a possible source of the energetic cosmic rays.

It is non-trivial to realize such a long-lived particle. Actually, operators which induce the decay must be incredibly suppressed. A well-motivated candidate of the DM is known to be the gravitino with a broken R-parity. This is because its decay is doubly suppressed by the Planck scale and R-parity violations [3]. Nonetheless, even with the Planck suppression, we notice that the R-parity violation has to be very tiny and looks unnatural unless some mechanisms are taken into account. As a solution of the fine-tuning, we propose a R-parity violation which is introduced in the right-handed neutrino sector. Then, the violation is suppressed in the low-energy scale by a see-saw mechanism. Actually, since the violation appears in low-energy phenomena though the right-handed neutrino, its effect becomes suppressed by the right-handed neutrino mass scale. We will show that the PAMELA/ATIC excesses are explained for $M_N \sim 10^9$GeV without tuning parameters.

This R-parity violation simultaneously opens a window for the successful thermal leptogenesis [4]. Although the mechanism is an attractive and elegant solution to the mystery of the baryon asymmetry of the universe, it usually requires a relatively high reheating temperature, $T_R \gtrsim 10^9$GeV (see e.g. [5]). Such a high reheating temperature is severely constrained by the big-bang nucleosynthesis (BBN) and the overclosure of the universe. In

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the presence of the R-parity violation, the former constraint is greatly ameliorated. Actually, the next-to-lightest superparticle (NLSP) can quickly decay into the Standard Model (SM) particles rather than the gravitino lightest superparticle (LSP). Thus, the standard BBN becomes unaffected [6].

The overclosure then gives a constraint on the reheating temperature. The gravitinos are generally produced in a hot plasma, and they behave as a dark matter. Thus, the reheating temperature is bounded from above to avoid the overclosure of the universe. The thermal production is also a function of the soft breaking parameters. In particular, it is enhanced in a large soft mass region. According to PAMELA/ATIC, the cosmic-ray excesses imply a mass of the gravitino to be $O(100-1000)$GeV. Thus, superparticles tend to have a large mass. We will see that the leptogenesis temperature is unlikely to be satisfied when the gravitino mass is $m_{3/2} \gtrsim 1$TeV, unless the gluino mass parameter is relatively small at the GUT scale. On the contrary, the R-parity violating right-handed neutrino circumvents the difficulty, because it enhances a CP-asymmetric right-handed neutrino decay [7]. In this letter, we will first study the R-parity violating operator in the right-handed neutrino sector, and then see that the thermal leptogenesis can work even in such a heavy gravitino situation.

2 R-parity violation in right-handed neutrino sector

Let us consider the gravitino DM scenario with a decay due to R-parity violations. A spectrum of the cosmic rays from its decay products are determined by the type of the R-parity violating operator, the gravitino mass and its life time. Here, we briefly review a case of the bilinear R-parity violation. The dominant decay channels are $\psi_{3/2} \to W\ell$, $Z\nu$, $\gamma\nu$ and $h\nu$ [8–10] and the decay is parametrized by the sneutrino vacuum expectation values (VEV). With the operator, $W = \mu' LH$, it becomes (c.f. [9])

$$\langle \tilde{\nu} \rangle \simeq -\frac{\mu'^* \mu v \cos\beta}{m_{\tilde{\nu}}^2}, \tag{2.1}$$

where L and H are the left-handed lepton and up-type Higgs, respectively. The parameters are the higgsino mass μ, the Higgs VEV $v \simeq 174$GeV, the Higgs VEV ratio $\tan\beta = \langle H \rangle / \langle \bar{H} \rangle$, and the sneutrino soft mass $V_{\rm soft} = m_{\tilde{\nu}}^2 \tilde{\nu}^* \tilde{\nu}$. Then, the gravitino life time is estimated as

$$\tau_{3/2} \simeq 1 \times 10^{26} \mathrm{sec} \left(\frac{\eta}{10^{-10}} \right)^{-2} \left(\frac{m_{3/2}}{1\mathrm{TeV}} \right)^{-3} \tag{2.2}$$

for $m_{3/2} \gg 100$GeV, where η is defined as $\eta \equiv |\langle \tilde{\nu} \rangle|/v$. According to the current PAMELA/ATIC data, the mass and life time of the gravitino is favored to be

$$m_{3/2} \gtrsim O(100-1000)\mathrm{GeV}, \qquad \tau_{3/2} \sim 10^{26}\mathrm{sec}. \tag{2.3}$$

which leads to the R-parity violation parameter as [1]

$$\eta \sim 10^{-10} \left(\frac{m_{3/2}}{1\mathrm{TeV}} \right)^{-3/2}. \tag{2.4}$$

[1] The other bilinear terms including the soft breaking ones give the similar results.

It is mentioned that this η satisfies with the other cosmological constraints (see e.g. [9] for details).

From the view point of the naturalness, the violation is too tiny and must be fine-tuned. We can also check that the other R-parity violating operators have to be suppressed at the weak scale, too. To realize such a small parameter, we propose a simple framework of the R-parity violation. In this letter, we introduce the R-parity violating operator in the right-handed neutrino sector,

$$W = \lambda N H \bar{H}. \tag{2.5}$$

Adding the right-handed neutrino mass and the Yukawa terms, $W = M_N NN/2 + Y_N NLH$, we obtain the effective R-parity violating operators in low-energy scale after decoupling the heavy right-handed neutrino:

$$W = -\frac{\lambda Y_N (LH)(H\bar{H})}{M_N}. \tag{2.6}$$

It is noticed that the R-parity violating effects appear with $1/M_N$ because they contribute through the right-handed neutrino. Thus, the R-parity violating effects are naturally suppressed by the see-saw mechanism[2].

Taking the Higgs VEVs, (2.6) behaves as a bilinear R-parity violating operator. Actually, combined with the μ term and the sneutrino soft mass, the sneutrino acquires VEV as

$$\langle \tilde{\nu} \rangle \simeq -\frac{\lambda Y_N \mu v^3 \sin^3\beta}{M_N m_{\tilde{\nu}}^2}. \tag{2.7}$$

Then, η is estimated to be

$$\eta \simeq 0.6 \times 10^{-10} \cdot \lambda \left(\frac{M_N}{10^9 \mathrm{GeV}}\right)^{-\frac{1}{2}} \left(\frac{m_{\tilde{\nu}}}{1\mathrm{TeV}}\right)^{-2} \left(\frac{\mu}{1\mathrm{TeV}}\right) \left(\frac{\bar{m}_\nu}{0.1\mathrm{eV}}\right)^{\frac{1}{2}} \sin^2\beta, \tag{2.8}$$

where $\bar{m}_\nu$ is a typical scale of the light neutrino masses defined as $Y_N \equiv \sqrt{M_N \bar{m}_\nu}/v \sin\beta$. Here, we omitted flavor indices. As a result, we find that the gravitino life time $\tau_{3/2} \sim 10^{26}$sec required from PAMELA/ATIC is realized for $\lambda \sim 1$ and $M_N \sim 10^9$GeV. We want to emphasize that there is no fine-tuning in the R-parity violating parameters.

The gravitino decay is almost the same as that by the bilinear R-parity violation. In fact, it is dominantly induced by the sneutrino VEV (2.7), while the other decaying channels from (2.6) are subdominant. Although $W = -\lambda^2 (H\bar{H})^2/2M_N$ is also derived from (2.5), the resultant decay operators are negligible for the cosmic ray spectra.

According to the current cosmic-ray data, the positron spectrum has a steep rise in high-energy region. This behavior prefers the gravitino DM decaying direct into the

[2] It is assumed that the renormalizable R-parity violating operators at the weak scale such as LH are forbidden. This can be realized by symmetries or geometrical configurations. For example, let us introduce two chiral superfields, Φ and X, which are singlet under the SM gauge symmetries, and postulate two global Z_2 symmetries with charges $(L, E, N, Q, D, U, H_d, H_u, \Phi, X) = (-,-,-,-,-,-,+,+,+,-)$ and $(L, E, N, Q, D, U, H_d, H_u, \Phi, X) = (+,-,+,+,-,+,-,+,-,-)$. Then, the renormalizable R-parity violating operators at the weak scale are suppressed, while we obtain the superpotential, $W = \Phi H_d H_u + N\Phi X + M\Phi\Phi$, and the scalar potential for X. Since X is odd under the R-parity and can have a Mexican-hat potential, its VEV gives (2.5) after decoupling Φ.

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positron or anti-muon [11, 12]. The decay product is determined by flavour structure of the sneutrino VEV. Denoting the flavour indexes explicitly in (2.7), $\langle\tilde{\nu}_j\rangle$ is proportional to $\lambda_i (Y_N)_{ij}/M_{Ni}$ with respect to the flavor structure, where i is the index of the heavy neutrino and j for the light one. Thus, it is not surprising to expect the positron and anti-muon to be produced in the decay. Consequently, the R-parity violating operator (2.5) can naturally explain the current PAMELA/ATIC excesses with $m_{3/2} = O(100-1000)$GeV.[3]

Let us comment on radiative corrections with the R-parity violation (2.5). They induce a linear term of the right-handed neutrino in the Kähler potential. This then leads to the right-handed sneutrino VEV in the framework of the supergravity. Although this can give a similar contribution to the effective R-parity violating operators (2.6), the results in this letter do not change qualitatively. Thus, we will neglect it hereafter.

We may also have the R-parity violating operators in the right-handed neutrino sector other than (2.5) such as the superpotential terms, N and N^3. However, their couplings are required to be suppressed since they can induce large R-parity violations through the right-handed sneutrino VEV. In fact, if we introduce the linear term, $W = M'^2 N$, the right-handed sneutrino acquires a VEV, $\langle\tilde{N}\rangle = M'^2/M_N$, at the potential minimum. This leads to too large bilinear R-parity violation through the right-handed neutrino Yukawa term. Actually, we obtain $M' \lesssim 10^4$GeV for $M_N = 10^9$GeV from the cosmic ray constraint. Thus, the result is very small compared to the fundamental scales, e.g. the right-handed neutrino one, and we need additional mechanism to realize the parameter. On the other hand, when the trilinear term, $W = \xi N^3$, exists, a radiative correction induces a linear term of N in the Kähler potential, $K = O(0.1)\xi M_N^* N + h.c.$, assuming the Planck scale to be the cutoff. Then, the supergravity scalar potential of the right-handed sneutrino has the potential minimum at $\langle\tilde{N}\rangle = O(0.1)\xi m_{3/2}$. This exceeds the phenomenological constraint given above, and K must be suppressed at least by $(2-3)$ orders of magnitude. Thus, we consider that the operators are forbidden by (discrete) symmetries for simplicity.

In the above, we focused on the SUSY invariant operators for the R-parity violations. Apart from them, we may have the violations in the SUSY breaking term. It can be noticed that the analysis is similar to the above, and the result is almost the same.

3 Upper bound on reheating temperature

In the decaying gravitino DM scenario, the cosmological constraint comes from the over-closure of the universe. Actually, the gravitino is thermally produced in the hot plasma. At the leading order, the relic abundance is evaluated as

$$\Omega_{3/2}h^2 \simeq \sum_{i=1}^{3} \omega_i g_i^2(T_R) \ln \frac{k_i}{g_i(T_R)} \left(1 + \frac{M_i^2(T_R)}{3m_{3/2}^2}\right) \left(\frac{m_{3/2}}{100\text{GeV}}\right) \left(\frac{T_R}{10^{10}\text{GeV}}\right), \tag{3.1}$$

where the definition of the parameters are found in [13]. In the numerical analysis, we include the electroweak contributions, which can be sizable especially when the gluino

[3] The Higgs and Weak bosons also generate the anti-protons. Although the estimation of its flux contains a large uncertainty, the result is consistent with the current data [10–12].

mass parameter is rather small compared to the Bino and Wino ones at the GUT (namely T_R) scale. It should be mentioned that the gravitino production rate includes an $O(1)$ uncertainty from unknown higher order contributions and nonperturbative effects [14]. In addition, resummation of thermal masses potentially increases the rate by about a factor of two[4] [15]. Since the massive gravitino behaves as a cold dark matter, its abundance is constrained from the measurements. According to the WMAP 5-year data, the abundance is required to satisfy [17],

$$\Omega_{3/2}h^2 \;\leq\; \Omega_{\rm DM}h^2 \;\simeq\; 0.1223, \tag{3.2}$$

at the 2σ level. Thus, once we provide the gaugino and gravitino masses, an upper bound on the reheating temperature is obtained.

It is interesting to study the overclosure bound in terms of the superparticle masses at the weak scale, which are expected to be measured by LHC. From (3.1) we notice that the gravitino production is evaluated with the parameters at the reheating temperature scale. Then, they are correlated with those at the weak scale by solving the renormalization group equations. Let us mention that the 1-loop result includes large uncertainties especially in the colored sector: 2-loop contributions can give an $O(10)\%$ correction, and the renormalization scale at the 1-loop level potentially contains additional $O(10)\%$ uncertainty, which is reduced by taking the higher order corrections into account. Noting that (3.1) includes the gluino mass squared, the thermal gravitino abundance can change drastically. Actually, $\Omega_{3/2}h^2$ is found to be almost as twice as the previous 1-loop analyses for $M_i(T_R) \gg m_{3/2}$ with the gluino mass fixed at the weak scale [14] (see also the discussion in [18]). In the following numerical analysis, we evolve the renormalization group running at the 2-loop accuracy and include the 1-loop threshold corrections by means of `SOFTSUSY` 2.0.18 [19].

In figure 1, we plot the maximal reheating temperature allowed by the overclosure bound with varying the gluino mass M_3 compared to the gaugino mass $M_{1/2}$ at the GUT scale. Here, the Bino and Wino masses are set to be equal $M_1 = M_2 \equiv M_{1/2}$ and realize the NLSP mass $m_{\rm NLSP}$ on each solid lines. Since the universal soft scalar mass m_0 except for the Higgs ones is chosen to be $m_0 = M_{1/2}$, the Bino-like neutralino is the NLSP, while the Higgs mass squared are assumed to be $m_{\bar{H}}^2 = m_0^2$ and $m_H^2 = -m_0^2$ for the electroweak symmetry breaking to give arise especially in a large m_0 region. The scalar trilinear couplings, a_0, and $\tan\beta$ are $a_0 = 0$ and $\tan\beta = 30$, though they are irrelevant for the maximal reheating temperature.

The gravitino mass is relevant for the upper bound on the reheating temperature. We assumed that it is equal to the NLSP mass. In fact, this setup maximizes T_R for $M_3/M_{1/2} > 0.5$. Namely, if we reduce the gravitino mass for the fixed NLSP mass, the allowed maximal temperature decreases. Thus, figure 1 gives the upper bound on the reheating temperature. On the other hand, a properly smaller gravitino mass allows a larger temperature in a lighter gluino region. However, it can be checked that the difference of T_R is less than 10% from figure 1 even for $M_3/M_{1/2} = 0.2$. It is commented that the gluino can become the NLSP for $M_3/M_{1/2} < 0.2$.

[4] Apart from the thermal production, we also have nonthermal contributions to the gravitino abundance, particularly from inflaton decay [16]. Since they are model dependent, we neglect them for simplicity.

We find that the maximal reheating temperature can be as large as $O(10^8)$GeV in a large parameter region, while $T_R \geq 10^9$GeV is realized for a smaller NLSP mass, e.g. $m_{\rm NLSP} \lesssim 600$GeV for the universal gaugino mass $M_3 = M_{1/2}$. This is because the thermal gravitino abundance (3.1) increases as the soft mass scale is larger. From figure 1, we see that $T_R > 10^9$GeV leads to $m_{\rm NLSP} < 1.5$TeV for $M_3/M_{1/2} > 0.2$ (see [25] for a hierarchical gaugino mass case). According to PAMELA, the gravitino mass is indicated as $m_{3/2} \gtrsim O(100)$GeV, i.e. $m_{\rm NLSP} \gtrsim O(100)$GeV. Then, it is easy to obtain the leptogenesis temperature in a wide class of models (see [18], in which discussions of superparticle mass spectrum are also explored).

In contrast, the ATIC result implies a larger gravitino mass, $m_{3/2} \gtrsim 1$TeV. Then, the gluino mass is required to be suppressed. For instance, when the gravitino mass is 1TeV, $T_R > 10^9$GeV needs $M_3 \lesssim 0.7 M_{1/2}$ at the GUT scale, and $M_3 \lesssim 0.3 M_{1/2}$ for $m_{3/2} = 1.5$TeV. Thus, the SUSY breaking models become specified to realize the leptogenesis temperature. A lighter gluino mass parameter is favored at the GUT scale, and thus a mass spectrum of the superparticles tends to degenerate at the weak scale especially when the gravitino mass is heavier.[5] On the other hand, the universal gaugino mass models look inconsistent with the thermal leptogenesis in the light of the ATIC result, though the usual gauge- and many gravity-mediation models have this feature. Thus, we will revisit the thermal leptogenesis in the next section in the presence of the R-parity violation.

Before proceeding to the next section, let us comment on the other parameter dependence. In the analysis, we take $m_0 = M_{1/2}$ at the GUT scale. For tiny m_0, the stau can be the NLSP. Then, the upper constraint in figure 1 becomes severer for fixed $m_{\rm NLSP}$, since the gaugino masses increase. Thus, the model parameters discussed above are limited more severely.

4 Thermal leptogenesis revisited

We now revisit the thermal leptogenesis in the presence of the R-parity violating operator (2.5). In the above, we found that a gluino mass is bounded from above to realize the leptogenesis temperature $T_R \gtrsim 10^9$GeV in a large gravitino mass region. In particular, the universal gaugino mass models are inconsistent with the temperature if we take the ATIC result. On the other hand, we have introduced the R-parity violating operator in the right-handed neutrino sector. We will see that a CP asymmetry of the decay of the right-handed neutrino is enhanced by the violation [7], and thus the leptogenesis mechanism works successfully.

In the thermal leptogenesis, the baryon density relative to the photon density becomes (cf. [20])

$$\frac{n_B}{n_\gamma} \simeq -1.04 \times 10^{-2} \epsilon_1 \kappa, \tag{4.1}$$

[5] This mass spectrum looks like that of the mirage mediation [26]. However, it is usually obtained by enhancing the anomaly mediation, namely with a large gravitino mass, e.g. $m_{3/2} \gtrsim 100$TeV. Thus, the gravitino is not the LSP.

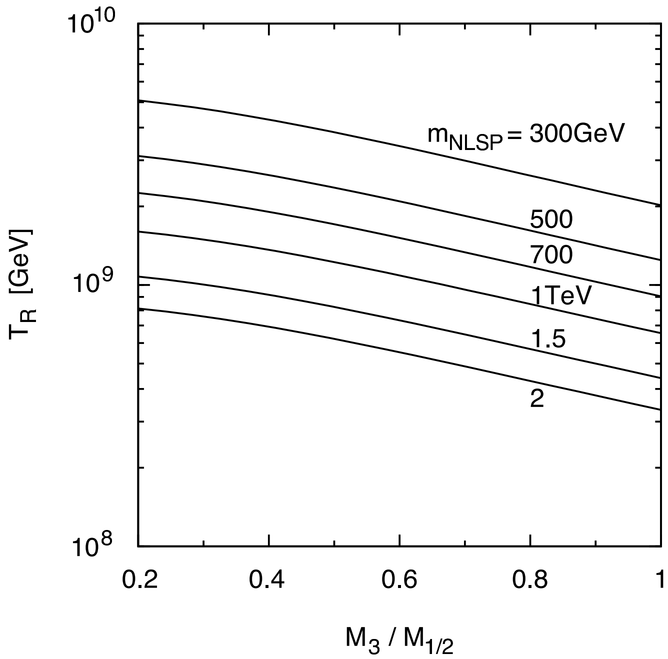

Figure 1. The maximal reheating temperatures allowed by the overclosure bound are drawn for fixed NLSP masses. The gravitino mass is set to be equal to the NLSP mass. Note that these masses are the physical one, while M_3 is given at the GUT scale, and the soft scalar masses are chosen to be $m_0 = M_{1/2}$ with $M_{1/2} \equiv M_1 = M_2$ at the GUT scale. Then, the Bino-like neutralino is the NLSP for $M_3 \gtrsim 0.2 M_{1/2}$. See the text for the other irrelevant parameters.

which is compared to the observation [17],

$$\frac{n_B}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}. \tag{4.2}$$

Here and hereafter, we assume the hierarchical right-handed neutrinos and ignore the flavour effects which does not affect the lower bound on the reheating temperature. The efficiency factor κ represents effects of washout and scattering processes, which is obtained by solving the Boltzmann equations. For the case of zero initial abundance of the right-handed neutrinos, its maximal value is known to be $\kappa \simeq 0.2$ [5, 21].

The CP asymmetry ϵ_1 in the decay of the lightest right-handed neutrino, $N_1 \to LH$, is determined by the structure of the neutrino sector. With $\kappa \lesssim 0.2$ the observed baryon asymmetry requires

$$|\epsilon_1| \gtrsim 3 \times 10^{-7}. \tag{4.3}$$

In the R-parity preserved models, it is known that the $|\epsilon_1|$ has an upper bound as [22–24]

$$|\epsilon_1| \equiv \left| \frac{\Gamma(N_1 \to L + H) - \Gamma(N_1 \to L^c + H^c)}{\Gamma(N_1 \to L + H) + \Gamma(N_1 \to L^c + H^c)} \right| \lesssim \frac{3 M_{N1}}{8\pi \langle H \rangle^2} \frac{\Delta m^2_{\rm atm}}{m_1 + m_3} \tag{4.4}$$

due to the see-saw relation. Here m_i ($m_1 < m_2 < m_3$) are the mass eigenvalues of the light neutrinos, and M_{N1} is the mass of the lightest right-handed neutrino N_1. Using the atmospheric neutrino mass squared difference $\Delta m^2_{\rm atm} \simeq (2.5 \pm 0.2) \times 10^{-3}{\rm eV}^2$, the lower bound on the right-handed neutrino mass becomes

$$M_{N1} \gtrsim 1.4 \times 10^9 \ {\rm GeV} \cdot \sin^2\beta \tag{4.5}$$

with the 3σ values of n_B/n_γ and $\Delta m^2_{\rm atm}$. Consequently, the corresponding lower bound on the reheating temperature is obtained as $T_R \gtrsim 1 \times 10^9$ GeV.

The upper bound on $|\epsilon_1|$ (4.4) can be relaxed by the R-parity violating operator (2.5). The operator contributes to the CP asymmetric decay, $N_1 \to LH$, via the diagrams exchanging H and $\bar{H}$ (and N) in the loop. In addition, a decay, $N_1 \to H\bar{H}$, gives arise with the R-parity violating operator of N_1. Consequently, we obtain [7]

$$\begin{aligned} \epsilon_1^{\rm (RPV)} &= -\frac{1}{8\pi} \frac{1}{(Y_N Y_N^\dagger)_{11} + |\lambda_1|^2} \\ &\quad \times \sum_{i \neq 1} {\rm Im} \left[(Y_N Y_N^\dagger)_{i1} (\lambda_i \lambda_1^*) f\left(\frac{M_{Ni}^2}{M_{N1}^2}\right) + \frac{2 (Y_N Y_N^\dagger)_{i1} (\lambda_i^* \lambda_1)}{M_{Ni}^2 / M_{N1}^2 - 1} \right] \end{aligned} \tag{4.6}$$

where the loop function is $f(x) = -\sqrt{x} \ln(1 + 1/x) - 2\sqrt{x}/(x-1)$. We notice that the result depends on λ_1 and λ_i $(i \neq 1)$. In order to avoid a strong washout by a (inverse) decay, λ_1 is favored to satisfy $|\lambda_1|^2 \lesssim (Y_N Y_N^\dagger)_{11}$, while λ_i is allowed to be $O(1)$. Then, the R-parity violating processes can dominate the CP asymmetry of the right-handed neutrino decay. Actually, it is estimated as

$$\begin{aligned} \epsilon_1^{\rm (RPV)} &\simeq 2 \times 10^{-4} \cdot {\rm Im}[c_1^* \lambda_i] \\ &\quad \times \left(\frac{M_{N1}}{10^8 {\rm GeV}}\right)^{\frac{1}{2}} \left(\frac{M_{Ni}/M_{N1}}{10}\right)^{-\frac{1}{2}} \left(\frac{\tilde{m}_1}{10^{-3}{\rm eV}}\right)^{-\frac{1}{2}} \left(\frac{\bar{m}'_\nu}{0.1{\rm eV}}\right) \frac{1}{\sin^2\beta}, \end{aligned} \tag{4.7}$$

for $M_{Ni}/M_{N1} \gg 1$. Here, the parameters are defined as $(Y_N Y_N^\dagger)_{i1} = \bar{m}'_\nu \sqrt{M_{N1} M_{Ni}}/v^2 \sin^2\beta$, $\tilde{m}_1 = [(Y_N Y_N^\dagger)_{11} + |\lambda_1|^2] v^2 / M_{N1}$ and $c_1 = \lambda_1 v / \sqrt{M_{N1} \tilde{m}_1}$. We can see that the result exceeds the upper bound (4.4) for $\lambda_i \sim 1$ and $|\lambda_1|^2 \lesssim (Y_N Y_N^\dagger)_{11}$, i.e. $c_1 \sim 1$.

In the last section, we found that $T_R = O(10^8)$GeV is obtained even in a heavy NLSP mass region from figure 1. On the other hand, we saw in this section that the CP asymmetry of the right-handed neutrino can be drastically enhanced by the R-parity violating operator (2.5), and the condition (4.3) is easily satisfied, e.g. for $M_1 = 10^8$GeV. Since N_1 is expected to be produced sufficiently in the thermal bath once T_R exceeds M_{N1}, the thermal leptogenesis consequently works in a wide class of models with explaining the cosmic-ray anomalies from PAMELA/ATIC. To be explicit, let us give an example: $\lambda_{i\neq 1} \sim 1$ with the lightest right-handed neutrino mass $M_{N1} = O(10^8)$GeV and $M_{Ni}/M_{N1} = O(10)$.

It is worthwhile to clarify the parameter dependence of the phenomena. The cosmic-ray spectra are sensitive to larger λ_2 and corresponding M_{N2} but insensitive to M_{N1} as long as $\lambda_1 \ll \lambda_2$, while the lightest right-handed neutrino determines the thermal leptogenesis, i.e. the baryon asymmetry depends on M_{N1}. From (4.7) it is possible to lower M_{N1} as well as the reheating temperature required by the thermal leptogenesis, though too small M_{N1} needs tiny λ_1 to avoid a strong washout.

One may be worried that such a large R-parity violation enhances washout effects. The (inverse) decay and $\Delta L = 1$ processes indeed receive additional contributions from the R-parity violating operator. Considering that they are controlled by the washout mass parameter, $\tilde{m}_1 = (Y_N Y_N^\dagger)_{11} v^2/M_{N1}$, we notice that the extra effects just redefine $\tilde{m}_1$ as the new one given in the previous paragraph. On the other hand, the R-parity violation can enhance the $\Delta L = 2$ washout. Actually, we obtain $LH \to HH$ (H means H or $\bar{H}$) by exchanging a heavier right-handed neutrino in the diagram. Since the diagram is almost the same as the R-parity preserved one except for a coupling and corresponding field, the additional contribution is roughly estimated as

$$\gamma_{\rm RPV} \sim \gamma^{(sub)}_{\Delta L=2} \times \frac{|\lambda_i|^2 |(Y_N)_{i1}|^2}{|(Y_N)_{11}|^4} \frac{M_{N1}^2}{M_{Ni}^2}, \tag{4.8}$$

where $\gamma^{(sub)}_{\Delta L=2}$ represents the $\Delta L = 2$ washout term with a subtraction of the resonance [21]. Thus, $\gamma_{\rm RPV}$ becomes larger than $\gamma^{(sub)}_{\Delta L=2}$ for $M_{N1} \ll 10^{13}$GeV. Since $\gamma^{(sub)}_{\Delta L=2}$ is negligibly small for this M_{N1}, we can numerically check that the washout is dominated by the (inverse) decay and $\Delta L = 1$ scattering even for $\lambda_i = O(1)$ (see e.g. [21] for the numerical estimations of the washout terms in the R-parity preserved case). Although $\gamma^{(sub)}_{\Delta L=2}$ increase as M_{N1} grows, $\gamma_{\rm RPV}$ decreases at the same time. Thus, the R-parity violating contribution does not change the result.

5 Conclusions

The gravitino DM scenario is an attractive candidate to explain the PAMELA/ATIC excesses. However, the R-parity violations are required to be very tiny in the low-energy scale. In this letter, we proposed the R-parity violation of the right-handed neutrino to solve the fine-tuning. Actually, the violating effect is naturally suppressed in the low-energy scale due to the see-saw mechanism. We found that the life time required by PAMELA/ATIC, $\tau_{3/2} = O(10^{26})$sec, is realized by an order one coupling, $\lambda \sim 1$, of the operator $W = \lambda N H \bar{H}$ when the right-handed neutrino scale is $O(10^9)$GeV.

The R-parity violation is also favored by the thermal leptogenesis. In the presence of the R-parity violation, the reheating temperature is bounded from above by the overclosure bound. We found that $T_R \gtrsim 10^9$GeV is widely accessible for $m_{3/2} < 600$GeV. However the gluino is restricted to be small to satisfy $T_R \gtrsim 10^9$GeV for the gravitino mass heavier than 1TeV which is implied by ATIC. On the contrary, the R-parity violation of the right-handed neutrino ameliorates this inconsistency. Namely, the leptogenesis was shown to work even for $T_R \lesssim 10^9$GeV. Thus, the gravitino LSP with the R-parity violation in the right-handed neutrino sector is an attractive scenario of the cosmology.

The cosmic-ray spectra of the anti-matter and photon also depends on the R-parity violation. In this letter, the flavor structure is determined by the neutrino Yukawa coupling and λ^i. By obtaining more cosmic-ray data in future such as FGST and AMS-02 and refining the astrophysical knowledge, we may distinguish the R-parity violating operators. Furthermore, since the R-parity violating operator can be embedded in a high-scale models such as SU(5) GUT and heterotic string models, by combining with the future collider data, we might be able to access physics in high-energy scale.

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