PAMELA AND ATIC ANOMALIES
IN DECAYING GRAVITINO DARK MATTER SCENARIO

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Motivated by the recent results from the PAMELA and ATIC, we study the cosmic-ray electron and positron produced by the decay of gravitino dark matter. We calculate the cosmic-ray electron and positron fluxes and discuss implications to the PAMELA and ATIC data. In this paper, we will show that the observed anomalous fluxes by the PAMELA and ATIC can be explained in such a scenario. We will also discuss the synchrotron radiation flux from the Galactic center in such a scenario.

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1. Introduction

In astrophysics, the existence of dark matter (DM) is almost conclusive. According to the recent survey of WMAP, it accounts for 23% of the total energy density in the universe. In the standard model of particle physics, however, there does not exist candidate for DM, which is one of the reasons to call for beyond the standard model. Supersymmetry (SUSY) is a promising model which can give an answer to the question: in the framework of SUSY, lightest superparticle (LSP) is a viable candidate for DM.

The fluxes of high energy cosmic rays give information about the properties of DM. In the recent years, accuracy of the measurements of the fluxes have been significantly improved. In particular, anomalous signals are reported by PAMELA and ATIC in the observations of cosmic-ray $e^\pm$. The PAMELA and ATIC results have attracted many attentions because the anomalies may indicate an unconventional nature of DM. In fact, there have been a sizable number of DM models are proposed to explain the anomalies after the announcements of the PAMELA and ATIC results. Among them, especially in decaying DM scenarios, the observed anomalies can be well explained with the appropriate choice of the lifetime of DM.
especially in leptonically decaying scenarios. (For works calculating cosmic-ray $e^\pm$, see $^4,^5$ and references therein.)

In usual supersymmetric scenario, $R$-parity conservation is assumed, which protects LSP from decaying into standard model particles and makes it a viable candidate of DM. If we consider the case that $R$-parity is violated, LSP is no longer stable; however, if $R$-parity violation (RPV) is weak enough, the lifetime of the LSP can be much longer than the present age of the universe and LSP can play the role of DM.$^6$ In addition, when the order of the RPV is properly chosen to give the lifetime of $O(10^{26}$ sec), produced cosmic-ray positron gives excellent agreement with PAMELA data.$^4$

On the other hand, synchrotron radiation from the decay of DM may give constrains directly to scenarios explaining the PAMELA and ATIC anomalies. Since DM decays into energetic $e^\pm$ under the magnetic fields in our galaxy, synchrotron radiation is inevitably induced. Importantly, the WMAP collaboration has observed the radiation in the whole sky, so that the observation gives constraints on the scenarios of the $e^\pm$ production due to the decay of DM in the Galactic halo.

In this paper, we consider gravitino (donated as $\psi_\mu$) LSP in RPV. In the scenario, we calculate cosmic-ray $e^\pm$ and synchrotron radiation flux induced by them, paying particular attentions to PAMELA and ATIC anomalies. We will see that the PAMELA and ATIC anomalies are simultaneously explained if the lifetime of the gravitino DM is $O(10^{26}$ sec) and the mass is $\sim 1-2$ TeV.$^4,^5$ In addition, synchrotron radiation from the Galactic center is comparable with or smaller than the observation.$^7$

2. The Scenario and Model Framework

In this section, we briefly explain the cosmological aspects and the model framework of $\psi_\mu$-DM scenario in RPV. With RPV, the $\psi_\mu$ LSP becomes unstable and energetic positron can be produced by the decay. Even if the $\psi_\mu$ is unstable, it can be DM if the RPV is weak enough so that the lifetime of the gravitino $\tau_{3/2}$ is much longer than the present age of the universe.$^6,^8$ In fact, such a scenario has several advantages. In the $\psi_\mu$-LSP scenario with RPV, the thermal leptogenesis$^9$ becomes possible without conflicting the big-bang nucleosynthesis constraints. In addition, the fluxes of the positron and $\gamma$-ray can be as large as the observed values, and the anomalies in those fluxes observed by the HEAT$^{10}$ and the EGRET$^{11}$ experiments, respectively, can be simultaneously explained in such a scenario if $\tau_{3/2} \sim O(10^{26}$ sec)$^{12,13}$

Here, let us consider the bi-linear RPV interactions. Using the bases
where the mixing terms between the up-type Higgs and the lepton doublets are eliminated from the superpotential, the relevant RPV interactions are given by

\[ \mathcal{L}_{\text{RPV}} = B_i \bar{L}_i H_u + m_{\tilde{L}_i}^2 \bar{\tilde{L}}_i H_d^* + \text{h.c.}, \]  

(1)

where \( \tilde{L}_i \) is left-handed slepton doublet in \( i \)-th generation, while \( H_u \) and \( H_d \) are up- and down-type Higgs boson doublets, respectively. Then, the \( \psi_\mu \) decays as \( \psi_\mu \rightarrow l_\pm^{i} W^{\mp}, \nu_i Z, \nu_i h, \) and \( \nu_i \gamma \), where \( l_\pm^{i} \) and \( \nu_i \) are the charged lepton and the neutrino in \( i \)-th generation, respectively. Taking account of all the relevant Feynman diagrams, we calculate the branching ratios of these processes.

12 When the gravitino mass \( m_{3/2} \) is larger than \( m_W \), the dominant decay mode is \( \psi_\mu \rightarrow l_\pm^{i} W^{\mp} \). In such a case, we see \( \tau_{3/2} \approx 6 \times 10^{25} \text{ sec} \times (\kappa_i/10^{-10})^{-2}(m_{3/2}/1 \text{ TeV})^{-3} \), where \( \kappa_i = (B_i \sin \beta + m_{\tilde{L}_i}^2 \cos \beta)/m_{\tilde{\nu}} \) is the ratio of the vacuum expectation value of the sneutrino field to that of the Higgs boson, with \( \tan \beta = \langle H_u^0 \rangle/\langle H_d^0 \rangle \), and \( m_{\tilde{\nu}} \) being the sneutrino mass. Thus, \( \tau_{3/2} \) is a free parameter and can be much longer than the present age of the universe if the RPV parameters \( B_i \) and \( m_{\tilde{L}_i}^2 \) are small enough.

3. Electron and Positron Fluxes

Let us first summarize our procedure to calculate the \( e^{\pm} \) fluxes \( \Phi_{e^{\pm}} \). (For detail, see 4,5,12) We solve the diffusion equation to take account of the effects of the propagation of \( e^{\pm} \). The energy spectrum of the \( e^{\pm} \) from DM \( f_{e^{\pm}}(E, \vec{r}) \) evolves as

\[ \frac{\partial f_{e^{\pm}}}{\partial t} = K(E) \nabla^2 f_{e^{\pm}} + \frac{\partial}{\partial E} [b(E) f_{e^{\pm}}] + Q. \]  

(2)

The function \( K \) is expressed as \( K = K_0 E_{\text{GeV}}^8 \), where \( E_{\text{GeV}} \) is the energy in units of GeV, while \( b = 1.0 \times 10^{-16} \times E_{\text{GeV}}^2 \text{ GeV/sec} \). In our numerical calculation, we use the following three sets of the model parameters, called MED, M1, and M2 models, which are defined as \( \langle \delta, K_0, L, R \rangle = (0.70, 0.0112, 4) \) (MED), \( (0.46, 0.0765, 15) \) (M1), and \( (0.55, 0.00595, 1) \) (M2), with \( R = 20 \text{ kpc} \) for all models. Here, \( L \) and \( R \) are the half-height and the radius of the diffusion zone, respectively. The MED model is the best-fit to the boron-to-carbon ratio analysis, while the maximal and minimal positron fractions for \( E \gtrsim 10 \text{ GeV} \) are expected to be estimated with M1 and M2 models, respectively. We found that the MED and M1 models give similar positron fraction, so only the results with the MED and M2 models are
shown in the following. The source term is given as,
\[
Q_{\text{dec}} = \frac{1}{\tau_{\text{DM}}} \frac{\rho_{\text{DM}}(\vec{x})}{m_{\text{DM}}} \left[ \frac{dN_{e^\pm}}{dE} \right]_{\text{dec}},
\]
where \(\tau_{\text{DM}}\) is the lifetime of DM. In the above expressions, \(dN_{e^\pm}/dE\) is the energy distributions of the \(e^\pm\) from single decay processes, respectively, and are calculated by using PYTHIA package\(^{16}\) for each DM candidate. In addition, \(\rho_{\text{DM}}\) is the DM mass density for which we adopt the Navarro-Frank-White (NFW) mass density profile:\(^{17}\)
\[
\rho_{\text{NFW}}(\vec{x}) = \rho_\odot \frac{r_\odot^3}{r_c^2/(r_c + r_\odot)^2/r(r_c + r)^2},
\]
where \(\rho_\odot \simeq 0.30 \text{ GeV/cm}^3\) is the local halo density around the solar system, \(r_c \simeq 20 \text{ kpc}\) is the core radius of the DM profile, \(r_\odot \simeq 8.5 \text{ kpc}\) is the distance between the Galactic center and the solar system, and \(r\) is the distance from the Galactic center.

Once \(f_{e^\pm}\) are given by solving the above equation, the fluxes can be obtained as
\[
[\Phi_{e^\pm}(E)]_{\text{DM}} = \frac{4\pi}{c^2} f_{e^\pm}(E,\vec{x}_\odot),
\]
where \(\vec{x}_\odot\) is the location of the solar system, and \(c\) is the speed of light. In order to calculate the total fluxes of \(e^\pm\), we also have to estimate the background fluxes. In our study, we adopt the following fluxes for cosmic-ray \(e^\pm\) produced by collisions between primary protons and interstellar medium in our galaxy:\(^{14,18}\)
\[
[\Phi_{e^-}]_{\text{BG}} = 0.16E_{\text{GeV}}^{-1.1}/(1 + 11E_{\text{GeV}}^{0.9} + 3.2E_{\text{GeV}}^{2.15}) + 0.70E_{\text{GeV}}^{0.7}/(1 + 110E_{\text{GeV}}^{1.3} + 600E_{\text{GeV}}^{2.9} + 580E_{\text{GeV}}^{4.2}) \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sec}^{-1} \text{ str}^{-1} \text{ for the electron, and}
\]
\[
[\Phi_{e^+}]_{\text{BG}} = 4.5E_{\text{GeV}}^{0.7}/(1 + 650E_{\text{GeV}}^{2.3} + 1500E_{\text{GeV}}^{4.2}) \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sec}^{-1} \text{ str}^{-1} \text{ for the positron.}
\]

4. Synchrotron Radiation: formalism and the observation

In this section, we first show the formalism for calculation of synchrotron radiation flux. (The detail is in.\(^7\)) Then, we address the implication of the present observation of synchrotron radiation from the Galactic center region.

Synchrotron radiation energy density per unit time and unit frequency is expressed as
\[
L_{\nu}(\vec{x}) = \int dE \mathcal{P}(\nu, E) f_{e^\pm}(E, \vec{x}).
\]
Here, \(\mathcal{P}(\nu, E)\) is synchrotron radiation energy per unit time and unit frequency from single \(e^\pm\) with energy \(E\). Adopting the Galactic magnetic flux density of \(B \sim 3 \mu\text{G}\), we can see that the synchrotron radiation in the observed frequency band of the WMAP (i.e, 22 – 93 GHz) is from the \(e^\pm\) with the energy of \(E \sim 10 – 100 \text{ GeV}\). For the \(e^\pm\) in such an energy range,
$f_{e^\pm}$ can be well approximated by

$$f_{e^\pm}^{(local)}(E, \vec{x}) = \frac{1}{\tau_{DM}} \frac{\rho_{DM}(\vec{x}) Y_{e^\pm}(>E)}{b(E, \vec{x})},$$

(5)

where $Y_{e^\pm}(>E) \equiv \int_{E}^{\infty} dE' [dN_{e^\pm}/dE']_{\text{dec}}$. Thus, we use $f_{e^\pm}^{(local)}$ in the calculation of synchrotron radiation flux. Here, we note in this formula that we take into account the effects of both synchrotron radiation and inverse Compton scattering for energy loss rate as $b(E, \vec{x}) = P_{\text{synch}} + P_{\text{IC}}$. This is because, in the Galactic center region, the inverse Compton scattering in the infrared $\gamma$-ray from stars becomes the dominant energy-loss process, thus it can not be neglected.

In order to calculate the observed radiation energy flux, we integrate $L_{\nu}(\vec{x})$ along the line of sight (l.o.s.), whose direction is parametrized by the parameters $\theta$ and $\phi$, where $\theta$ is the angle between the direction to the Galactic center and that of the line of sight, and $\phi$ is the rotating angle around the direction to the Galactic center. (The Galactic plane corresponds to $\phi = 0$ and $\pi$.) Then, the synchrotron radiation flux is given by

$$J_{\nu}(\theta, \phi) = \frac{1}{4\pi} \int_{\text{l.o.s.}} d\vec{I} L_{\nu}(\vec{I}).$$

(6)

Notice that, adopting the approximation of the constant magnetic flux in the Galaxy, the line of sight and energy integrals factorize.

Radiation flux from Galactic center region has been observed by the WMAP for frequency bands of 22, 33, 41, 61, and 93 GHz.\textsuperscript{19,20} Since then, intensive analysis has been performed to understand the origins of the radiation flux. (For recent studies, see.\textsuperscript{19–21}) Most of the radiation flux is expected to be from astrophysical origins, such as thermal dust, spinning dust, ionized gas, and synchrotron radiation, which have been studied by the use of other survey data.\textsuperscript{22} With the three-year data, the WMAP collaboration claimed that the flux intensity can be explained by the known astrophysical origins.\textsuperscript{23} On the contrary, Refs.\textsuperscript{19,21} also studied the WMAP three-year data, and claimed that there exists a remnant flux from unknown origin which might be non-astrophysical; the remnant flux is called the “WMAP Haze”. However, no clear indication of the WMAP Haze from unknown source was reported by the WMAP collaboration after five-year data.\textsuperscript{20}

The existence of the WMAP Haze seems still controversial, and the detailed studies of the WMAP Haze using the data is beyond the scope of our study. Here, we adopt the flux of the WMAP Haze suggested in\textsuperscript{21} (i.e. $O(1 \text{ kJy/str})$) as a reference value.
5. Numerical results

First, we show the numerical results of the positron fraction. For simplicity, assuming a hierarchy among the RPV coupling constants, we consider the case where the $\psi_\mu$ decays selectively into the lepton in one of three generations (plus $W^\pm$, $Z$, or $h$). In Fig. 1, we show the positron fraction for the case that the $\psi_\mu$ decays only into first- (second-) generation lepton. Here, we use MED (M2) model for first- (second-) generation case and take $m_{3/2} = 300$ GeV, 600 GeV, and 1.2 TeV (from left to right), with \( \tau_{3/2} = 2.0 \times 10^{26} \text{ sec} \), \( 1.1 \times 10^{26} \text{ sec} \), and \( 8.6 \times 10^{25} \text{ sec} \) (9.3 \( \times 10^{25} \text{ sec} \), 5.8 \( \times 10^{25} \text{ sec} \), and \( 5.0 \times 10^{25} \text{ sec} \)) in (a) ((b)), respectively. Dot-dashed line is the fraction calculated only by the background fluxes.

Fig. 1. Positron fractions for the case that $\psi_\mu$ dominantly decays to (a) the first-generation lepton in MED model and (b) the second-generation lepton in M2 model. Here, we take $m_{3/2} = 300$ GeV, 600 GeV, and 1.2 TeV (from left to right), with $\tau_{3/2} = 2.0 \times 10^{26} \text{ sec}$, $1.1 \times 10^{26} \text{ sec}$, and $8.6 \times 10^{25} \text{ sec}$ ($9.3 \times 10^{25} \text{ sec}$, $5.8 \times 10^{25} \text{ sec}$, and $5.0 \times 10^{25} \text{ sec}$) in (a) ((b)), respectively. Dot-dashed line is the fraction calculated only by the background fluxes.
the low energy region is sensitive to the background fluxes, we only use the data points with \(E \geq 15\) GeV. From the figure, we see that the positron fraction well agrees with the PAMELA data for \(m_{3/2} \gtrsim 100\) GeV irrespective of the gravitino mass if \(\tau_{3/2}\) is properly chosen. (Simultaneously, the energetic \(\gamma\)-ray flux is also enhanced, which can be an explanation of the \(\gamma\)-ray excess observed by the EGRET\textsuperscript{11})

Next, we move on to the total flux: \(\Phi_{\mu} + \Phi_{\mu}^\tau\). The numerical results are shown in Fig. 2. Here, we use the best-fit lifetime with the PAMELA data for each \(m_{3/2}\), namely the same value in (a) and (b) of Fig. 1, respectively. From the figure, we see that the observed anomalous structure is well reproduced in the both cases. Especially, the result is a good agreement with the observation when \(m_{3/2} = 1.2\) TeV (2 TeV) for the case that the final
Fig. 3. Synchrotron radiation fluxes at $\nu = 22$ GHz as functions of gravitino mass for angle $\theta = 5^\circ$, 10$^\circ$, 15$^\circ$, and 20$^\circ$. The final-state lepton in the $\psi_\mu$ decay is in the first generation. Here, we take $\tau_{3/2} = 5 \times 10^{26}$ sec, and show the cases of $B = 1, 3, 10 \mu$G (from the bottom to the top) for each figure.

state lepton is the first- (second-) generation. We also note that, in the total flux, the numerical results does not change drastically by the choice of the background. This is because the signal from the gravitino is larger than (or at least comparable to) the background.

Finally, let us discuss the synchrotron radiation flux. The numerical results are shown in Fig.3. In this figure, we consider the case that the $\psi_\mu$ mainly decays to first generation lepton and plot for $\nu = 22$ GHz as the function of $m_{3/2}$, taking $\tau_{3/2} = 5 \times 10^{26}$ sec. The angle is set as $\phi = \frac{\pi}{2}$, and $\theta = 5^\circ$, 10$^\circ$, 15$^\circ$, and 20$^\circ$, and we take $B = 1, 3, 10 \mu$G. For the $\psi_\mu$-DM case, it can be seen that the synchrotron radiation flux is of the order of $\sim 1$ kJy/str or smaller. As we mentioned, since the the existence of the exotic radiation flux of this size is controversial, it is difficult to confirm or exclude the present scenario without better understandings of the sources of Galactic foreground emission.

6. Conclusions

In this paper, we have studied the cosmic-ray fluxes from the $\psi_\mu$-DM decay in RPV, motivated by the recent observations by PAMELA and ATIC.
Assuming that the $\psi_\mu$ is the dominant component of DM, we calculate the cosmic-ray $e^\pm$, and found that the both anomalies can be well explained when $\tau_{3/2} \sim O(10^{26} \text{ sec})$. In particular, we saw that the ATIC anomaly indicates $m_{3/2} \sim 1 - 2 \text{ TeV}$ in this scenario. We also calculate the synchrotron radiation induced by the cosmic-ray $e^\pm$ from the Galactic center region with the lifetime to explain PAMELA and ATIC anomalies. Then, we obtained the result that the synchrotron radiation flux is $O(1 \text{ kJy/str})$ or smaller, which does not exclude our scenario by the observation of the Galactic foreground emission.

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