Cosmic-Ray Positron from Superparticle Dark Matter and the PAMELA Anomaly

(a)Koji Ishiwata, (b)Shigeki Matsumoto and (a)Takeo Moroi

(a)Department of Physics, Tohoku University, Sendai 980-8578, Japan
(b)Department of Physics, University of Toyama, Toyama 930-8555, Japan
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Motivated by the anomalous positron flux recently reported by the PAMELA collaboration, we study the cosmic-ray positron produced by the pair annihilation and the decay of superparticle dark matter. We calculate the cosmic-ray positron flux and discuss implications of the PAMELA data. We show that the positron excess observed by the PAMELA can be explained with some of the dark-matter particle.

Dark matter, which accounts for about 23% of the mass density of the present universe, has been a mystery in the fields of particle physics, astrophysics, and cosmology. Even though there exist various well-motivated candidates for dark matter, like the lightest superparticle (LSP), axion, and the lightest Kaluza-Klein particle in the universal extra-dimension scenario, the nature of dark matter is completely unknown and many possibilities have been discussed to study dark-matter properties. Direct and indirect detection of dark-matter signals as well as with colliders. Among them, measurements of the anti-particle fluxes in the cosmic ray give important information about dark matter; annihilation or decay of some classes of dark matter particle produces energetic anti-particle, which may be observed in the cosmic ray.

Very recently, the PAMELA collaboration has announced the first result of the measurement of the positron flux for the energy range 1.5–100 GeV, which indicates an anomalous excess of the positron flux over the expected background. In particular, the PAMELA results show a significant increase of the positron fraction at the energy range 20 GeV ≲ E ≲ 100 GeV, even though the positron fraction is expected to decrease as energy increases. In addition, in the past measurement of the positron flux by HEAT, similar excess was also pointed out. To understand the anomalous behavior of the positron flux, an unaccounted mechanism is necessary from particle-physics and/or astrophysical point of view.

One important possibility of realizing enhanced cosmic-ray positron flux is the annihilation or the decay of dark matter particle. (Recently, another possibility is also pointed out that the anomalous flux may be due to the positron emission from Pulsars.) In this study, we pursue a possibility that the anomalous cosmic-ray positron is from the pair annihilation or the decay of the dark matter particle. There are various candidates for dark matter. Among those, in this study, we consider one of the most well-motivated candidates for dark matter, i.e., the LSP in models with low-energy supersymmetry (SUSY). Conventionally, in the LSP dark matter scenario, it is assumed that the R-parity is conserved and that the LSP is Bino-like lightest neutralino or the gravitino. Then, the cosmic-ray positron flux is negligibly small. This is because, in such a case, the positron is produced by the pair-annihilation of the LSP, whose cross section is significantly suppressed in the cases of the Bino-like and gravitino dark matter. However, the above assumptions are not necessary in realizing the LSP dark matter scenario; in several well-motivated scenarios, one of the above assumptions is relaxed and an enhanced positron flux may be realized.

In this letter, we consider the implication of the positron-flux observation of the PAMELA experiment to the SUSY model in which the LSP becomes dark matter. We calculate the production rate of the cosmic-ray positrons in several scenarios. Then, we show that, even if we adopt the conventional estimation of the background e± fluxes, the positron excess observed by the PAMELA can be explained in some of the cases.

Let us first summarize our procedure to calculate the positron flux Φe± (as well as the electron flux Φe−). (For detail, see [10].) We solve the diffusion equation to take account of the effects of the propagation of the positron. The energy spectrum of the positron from dark matter f±(E, r) evolves as

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

The function K is expressed as \( K = K_0 E_{\text{GeV}}^2 \), where E_{\text{GeV}} is the energy in units of GeV. In our numerical calculation, we use the following three sets of the model parameters, called MED, M1, and M2 models, which are defined as \( (i, K_0, [\text{kpc}^2/\text{Myr}], L_{\text{kpc}}) = (0.70, 0.0112, 4) \) (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 \( \bar{R} \) 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. In addition, we use \( b = 1.0 \times 10^{-16} \times E_{\text{GeV}}^2 \, \text{GeV/sec} \). For the case where the primary positron is produced by the pair annihilation of dark matter, the source term is given by

\[ Q_{\text{ann}} = \frac{1}{2} B (\sigma v) \frac{\rho_{\text{halo}}^2}{m_{\text{DM}}^2} \frac{dN_{e^\pm}}{dE} \bigg|_{\text{ann}}. \]

Here, \( B \) is the so-called boost factor, \( (\sigma v) \) is the averaged pair annihilation cross section, and \( m_{\text{DM}} \) is the mass of...
dark matter particle. In addition, $\rho_{\text{halo}}$ is the dark matter mass density for which we adopt the isothermal profile \[ \rho(r) = \rho_\odot (r_{\text{core}}^2 + r^2_{\text{kpc}})^{-3/2}, \] where $\rho_\odot \simeq 0.43$ GeV/cm$^3$ is the local halo density, $r_{\text{core}} \simeq 2.8$ kpc is the core radius, $r_\odot \simeq 8.5$ kpc is the distance between the galactic center and the solar system, and $r_{\text{kpc}}$ is the distance from the galactic center in units of kpc. If the positron is from the decay of dark matter, \[ Q_{\text{dec}} = \frac{1}{\tau_{\text{DM}}} \frac{\rho_{\text{halo}}(r)}{m_{\text{DM}}} \left[ \frac{dN_{e^+}}{dE} \right]_{\text{dec}}, \] where $\tau_{\text{DM}}$ is the lifetime of dark matter. In the above expressions, $[dN_{e^+}/dE]_{\text{ann}}$ and $[dN_{e^+}/dE]_{\text{dec}}$ are the energy distributions of the positron from single pair annihilation and decay processes, respectively, and are calculated by using PYTHIA package \[ [12] \] for each dark matter candidate.

Now, we discuss the positron flux for several models of superparticle dark matter. We first consider the case where the LSP is Wino-like neutralino, which we denote $W^0$. (Implications of the Wino dark matter scenario to the PAMELA results were first discussed in \[ [9] \].) The thermal relic density of the Wino is much smaller than the present mass density of dark matter if $m_{W^0} \lesssim 1$ TeV (with $m_{W^0}$ being the Wino mass). However, its mass density can be consistent with the present dark matter density if the Wino is non-thermally produced in the early universe \[ [13] \] (or if $m_{W^0} \simeq 2.5 - 3$ TeV \[ [14] \], which we do not consider in this letter). In addition, the Wino becomes the LSP in some of the well-motivated scenarios of SUSY breaking, like the anomaly-mediation model \[ [13] \]. If $W^0$ is dark matter, it mainly annihilates into $W^+W^-$ pair when $m_{W^0} \lesssim 1$ TeV. Then, the subsequent decays of $W^\pm$ produce energetic positrons, which become the source of the cosmic-ray positron.

We calculate the positron flux from such an annihilation process. In Fig. 1 we plot the positron fraction using the MED and M2 propagation models. (Results with the M1 model are similar to those with the MED model, and hence are not shown.) In the figure, the Wino mass is taken to be 200 GeV, and 1 TeV, for which $\langle \sigma v \rangle = 1.9 \times 10^{-24}$, and $8.5 \times 10^{-26}$ cm$^3$/sec, respectively. In calculating the positron fraction, we adopt the following background fluxes \[ [4] \]: $[\Phi_{-e}BG = 0.16 E_{\text{GeV}}^{-1.1} (1 + 11E_{\text{GeV}}^{+1.1} - 0.7E_{\text{GeV}}^{-0.9}) + 0.7E_{\text{GeV}}^{-1.2} (1 + 110E_{\text{GeV}}^{+1.5} - 600E_{\text{GeV}}^{+2.9} + 580E_{\text{GeV}}^{+1.2})$ GeV$^{-1}$ cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ for the electron, and $[\Phi_{e^+}BG = 4.5E_{\text{GeV}}^{1.7} (1 + 650E_{\text{GeV}}^{2.3} + 1500E_{\text{GeV}}^{1.2})$ GeV$^{-1}$ cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ for the positron. As one can see, when the Wino-like LSP is dark matter, an enhancement of the positron flux is possible. However, irrespective of the boost factor, such a scenario fails to realize the increasing behavior of the positron fraction at $20 \text{ GeV} \lesssim E \lesssim 100$ GeV with the MED propagation model. This is mainly because the positrons from hadrons produced by the hadronic decays of $W^\pm$ significantly contribute to the flux much below the threshold. On the contrary, with the M2 model which tends to suppress low-energy positrons relative to high energy ones, the shape of the positron fraction becomes consistent with the PAMELA data at high energy region (i.e., $E \gtrsim 20$ GeV) for $m_{W^0} \sim 200$ GeV and $B \sim 3$. However, in such a case, the agreement between the theoretical positron fraction and the PAMELA data is poor at $E \lesssim 20$ GeV with the present choice of background. In addition, in the Wino dark matter case, the anti-proton flux tends to be too large \[ [6] \], which may exclude the possibility of explaining the PAMELA positron excess in the Wino dark matter scenario.

For a quantitative discussion, we calculate the $\chi^2$ variable using the PAMELA data \[ [2] \], neglecting effects of systematic errors in the theoretical calculation. Since the positron fraction in the low-energy region is sensitive to the background fluxes, we only use the data points with $E \gtrsim 15$ GeV (5 data points) in the calculation of $\chi^2$. (The detailed procedure to calculate $\chi^2$ is the same as those given in \[ [2] \].) With the M2 propagation model, the $\chi^2$ variable can become smaller than 11.0, which corresponds to the 95% C.L. bound, in the parameter region from $m_{W^0} = 130$ GeV (with $B \simeq 1$) to

![FIG. 1: Positron fraction for the Wino dark matter case with MED (top figure) and M2 (bottom figure) propagation models. We take $m_{W^0} = 200$ GeV (left) and 1 TeV (right), and the boost factor is taken to be $B = 1$, 3, and 10 (from bottom to top for each figure). The dotted-dashed line is the positron fraction calculated only with the background fluxes. The PAMELA data are also plotted.](image-url)
Gravitino dark matter
Lepton: electron
Propagation: MED

Gravitino dark matter
Lepton: electron
Propagation: M2

Gravitino dark matter
Lepton: muon
Propagation: MED

Gravitino dark matter
Lepton: muon
Propagation: M2

FIG. 2: Positron fractions for the gravitino dark matter case. Gravitino is assumed to decay only into the first generation lepton (plus gauge or Higgs boson). We take $m_{3/2} = 250$ GeV, 500 GeV, and 1 TeV (from left to right), and the MED (top figure) and M2 (bottom figure) propagation models are used. For the case with the MED propagation model, we take $\tau_{3/2} = 8.5 \times 10^{26}$ sec $\times (m_{3/2}/100$ GeV)$^{-1}$, while for the case with the M2 model, we take $\tau_{3/2} = 1.8 \times 10^{26}$ sec, $9.0 \times 10^{25}$ sec, and $6.3 \times 10^{25}$ sec for $m_{3/2} = 250$ GeV, 500 GeV, and 1 TeV, respectively.

$\tilde{m}_W = 310$ GeV (with $B \approx 10$). In addition, with MED and M1 models of propagation, the positron fraction observed by the PAMELA is hardly realized with Wino dark matter scenario with the conventional estimation of the background.

Next, we discuss the case where the gravitino (denoted as $\tilde{\psi}_\mu$) is the LSP and hence is dark matter. The pair annihilation cross section is negligibly small in such a case. However, with $R$-parity violation (RPV), the gravitino LSP becomes unstable and energetic positron can be produced by the decay. Even if the gravitino is unstable, it can be dark matter 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 [16, 17]. In fact, such a scenario has several advantages. In the gravitino LSP scenario with RPV, the thermal leptogenesis [18] 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 [19] and the EGRET [19] experiments, respectively, can be simultaneously explained in such a scenario if $\tau_{3/2} \approx O(10^{26}$ sec) [19, 20].

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

$$\mathcal{L}_{\text{RPV}} = B_i \tilde{L}_i H_u + m^2_{L_i H_d} \tilde{L}_i H_d^* + \text{h.c.},$$  \hspace{1cm} (4)$$

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 gravitino decays as $\psi_\mu \rightarrow l_i^\pm W^\mp$, $\nu_i Z$, $\nu_i h$, and $\nu_i \gamma$, where $l_i^\pm$ 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 branch-
massing ratios of these processes \[9\]. When the gravitino mass \(m_{3/2}\) is larger than \(m_W\), the dominant decay mode is \(\psi \rightarrow l^\pm W^\mp\). In addition, in such a case, \(\tau_{3/2} \approx 6 \times 10^{25} \text{ sec} \times (\kappa_i/10^{-10})^{-2}(m_{3/2}/1 \text{ TeV})^{-3}\), where \(\kappa_i = (B_i \sin \beta + m_{L_i} \cos \beta)/m_{\tilde{\nu}_i}\) 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 \(m_{\tilde{\nu}_i}\) being the sneutrino mass. Thus, the lifetime of the gravitino is a free parameter and can be much longer than the present age of the universe if the RPV parameters \(B_i\) and \(m_{L_i} m_{\tilde{\nu}_i}\) are small enough.

We calculate the positron flux from the decay of the gravitino dark matter. For simplicity, assuming a hierarchy among the RPV coupling constants, we consider the case where the gravitino decays selectively into the lepton in one of three generations (plus \(W^\pm, Z, \text{ or } h\)).

When the gravitino decays only into first generation lepton, the dominant decay mode is \(\psi \rightarrow e^\pm W^\mp\) and a large amount of positrons with the energy of \((m_{3/2}^2 - m_W^2)/2m_{3/2}\) are produced by the decay. Such monochromatic positron results in the significant increase of the positron fraction at 20 GeV \(\lesssim E \lesssim 100\) GeV. Then, contrary to the Wino dark matter case, a dramatic enhancement of the high energy positron fraction is possible with any of the propagation model. In such a case, the PAMELA anomaly is well explained with the MED model; we found that, with the M2 model, the high energy positron fraction is too much enhanced to be consistent with the PAMELA data. We found that the \(\chi^2\) variable may become smaller than the 95 \% C.L. bound (i.e., 11.0) with the MED model; if \(\tau_{3/2}\) is properly chosen, the positron fraction well agrees with the PAMELA data for \(m_{3/2} \gtrsim 100\) GeV irrespective of the gravitino mass. (Simultaneously, the energetic \(\gamma\)-ray flux is also enhanced, which can be an explanation of the \(\gamma\)-ray excess observed by the EGRET \[19\].) With the MED model, we found that the PAMELA data suggests \(\tau_{3/2} \approx 8.5 \times 10^{26} \text{ sec} \times (m_{3/2}/100 \text{ GeV})^{-1}\). In Fig. 2, the positron fraction is shown with this choice of the lifetime. We can see a good agreement between the theoretical and observational positron fractions. Once the statistics will be increased, the PAMELA may see the end-point at \(E \approx (m_{3/2}^2 - m_W^2)/2m_{3/2}\). One can also see that the positron fraction at \(E \approx 10\) GeV has a notable dependence on the gravitino mass; with a better understanding of the background fluxes, it may be used to derive a more stringent constraint on the gravitino mass.

When the gravitino decays into second or third generation lepton, the positron from the decay of the primary lepton (i.e., \(\mu^\pm\) or \(\tau^\pm\)) is less energetic than the positron directly produced by the process \(\psi \rightarrow e^\pm W^\mp\). Then, the energetic positron flux becomes suppressed. Even in such a case, it is still possible to have an enhanced high energy positron flux. For example, for the case where the gravitino decays only into the second generation lepton, we find the 95 \% C.L. allowed region for any of the propagation model. For the M2 model, which gives a better fit to the data than MED and M1, the best-fit value of \(\tau_{3/2}\) is \(1.6 \times 10^{26}\) sec, \(1.0 \times 10^{26}\) sec, and \(7.9 \times 10^{25}\) sec for \(m_{3/2} = 250\) GeV, 500 GeV, and 1 TeV, respectively. In Fig. 3, we show the positron fraction for these cases. With the MED propagation model, the agreement between the theoretical prediction and the PAMELA data becomes slightly worse.

In the scenario with \(\psi \rightarrow l^\pm W^\mp\), cosmic-ray antiproton is also produced. However, we have checked that the resultant anti-proton flux becomes comparable or smaller than the observed values, taking account of the uncertainties in the propagation model of anti-proton. In particular, the best-fit lifetime to explain the PAMELA anomaly is about 5 times longer than that used in the calculation of \[20\], and we obtain the anti-proton flux smaller than that presented in \[20\]. The detailed analysis is given in \[21\].

So far, we have concentrated on two important candidates for SUSY dark matter. Even in other cases, however, the positron flux may be also enhanced. For example, with the RPV interaction given in Eq. (4), the PAMELA anomaly may be explained for the Bino dark matter case. In such a scenario, the Bino dominantly decays as \(B \rightarrow e^\pm W^\mp\) and the monochromatic positron produced by the decay becomes the origin of the energetic cosmic-ray positron.

Our study indicates that the PAMELA anomaly may be well explained if (almost) monochromatic positrons are emitted from the decay or the pair annihilation of dark matter. Thus, we finally consider the case where the dark matter is unstable and dominantly decays into \(e^+e^-\) pair. This is the case if the left- or right-handed sneutrino is the LSP and hence is dark matter, and also if the \(\tilde{L}_i\tilde{L}_1\tilde{E}_1\) type RPV superpotential exists. (The left- and right-handed sneutrinos are viable candidates for dark matter; see \[22, 23\].) With the \(\chi^2\) analysis, we found that the positron fraction becomes consistent

![FIG. 4: Positron fractions for the case where dark matter decays only into \(e^+e^-\) pair. We take \(m_{DM} = 250\) GeV, 500 GeV, and 1 TeV (from left to right), and \(\tau_{DM} = 2.2 \times 10^{27}\) sec \times \((m_{DM}/100 \text{ GeV})^{-1}\). The MED propagation model is used.](image)
with the PAMELA data when \( \tau_{DM} \simeq 2.2 \times 10^{27} \text{ sec} \times (m_{DM}/100 \text{ GeV})^{-1} \) for \( m_{DM} \gtrsim 100 \text{ GeV} \) in the MED model. In Fig. 4, we show the positron fraction for \( m_{DM} = 250 \text{ GeV}, 500 \text{ GeV}, \) and 1 TeV, using the above \( \tau_{DM} \). As one can see, in such a case, an excellent agreement between the theoretical prediction and the PAMELA data is obtained.

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