PHYSICAL REVIEW D **79,** 023512 (2009)

PAMELA data and leptonically decaying dark matter

Peng-fei Yin,[1] Qiang Yuan,[2] Jia Liu,[1] Juan Zhang,[2] Xiao-jun Bi,[2,3,4] Shou-hua Zhu,[1,4] and Xinmin Zhang[5]

[1]*Institute of Theoretical Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, People's Republic of China*

[2]*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

[3]*Center for High Energy Physics, Peking University, Beijing 100871, People's Republic of China*

[4]*Kavli Institute for Theoretical Physics China, Chinese Academy of Science, Beijing 100190, People's Republic of China*

[5]*Theoretical Division, Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918-4, Beijing 100049, People's Republic of China*

(Received 26 November 2008; published 20 January 2009)

Recently PAMELA released their first results on the positron and antiproton ratios. Stimulated by the new data, we studied the cosmic ray propagation models and calculated the secondary positron and antiproton spectra. The low energy positron ratio can be consistent with data in the convection propagation model. Above $\sim$10 GeV PAMELA data shows a clear excess on the positron ratio. However, the secondary antiproton is roughly consistent with the data. The positron excess may be evidence of dark matter annihilation or decay. We compare the positron and antiproton spectra with the data by assuming that dark matter annihilates or decays into different final states. The PAMELA data actually excludes quark pairs being the main final states, and disfavors gauge boson final states. Only in the case of leptonic final states can the positron and antiproton spectra be explained simultaneously. We also compare the decaying and annihilating dark matter scenarios which can account for the PAMELA results and find that the decaying dark matter is preferred. Finally, we consider a decaying neutralino dark matter model in the frame of supersymmetry with R-parity violation. The PAMELA data is well fitted with a neutralino mass of $600 \sim 2000$ GeV and a lifetime of $\sim 10^{26}$ seconds. We also demonstrate that a neutralino with mass around 2 TeV can fit PAMELA and ATIC data simultaneously.

DOI: 10.1103/PhysRevD.79.023512 PACS numbers: 95.35.+d, 13.15.+g, 95.55.Vj, 98.62.Gq

I. INTRODUCTION

The existence of dark matter (DM) has been confirmed by many astronomical observations, but the nature of DM is still an open question. Many kinds of particles in theories beyond the standard model (SM) are proposed as DM candidates [1]. The DM particles are usually stable due to the protection of some discrete symmetry. For example, the lightest supersymmetric particle (LSP) in the supersymmetric (SUSY) model is stable due to the conservation of R-parity, and is a well-motivated candidate for DM [2].

Generally there are three kinds of strategies to detect the DM particles: the "collider search" at large colliders such as the CERN large hadron collider (LHC) or the international linear collider (ILC); the "direct detection" to find the signal of nuclei recoil when DM particles scatter off the detector; the "indirect detection" to search for the products from DM annihilation or decay, such as neutrinos, photons, and antimatter particles. Indirect detection is a challenge due to the difficulty in discriminating the signal from the astrophysical background. Therefore precise measurements with a wide energy range and improved resolution are necessary for DM indirect detection.

PAMELA is a satellite borne experiment designed to measure the cosmic rays (CRs) in a wide energy range with unprecedented accuracy [3]. Recently, the PAMELA Collaboration released the first data about antiprotons and positrons [4,5]. Usually it is thought that antiprotons and positrons are produced when CRs propagate in the Milky Way and collide with the interstellar medium (ISM). The abundance of these secondaries can be calculated with relatively high precision. However, the PAMELA results show an obvious excess in the fraction of $e^+/(e^+ + e^-)$ at energies above $\sim$10 GeV. Interestingly the excess keeps rising up to energy $\sim$100 GeV. On the other hand, the spectrum of antiprotons fits the prediction quite well. These results confirm the previous results by HEAT [6] and AMS [7] within the error bars.

The PAMELA results may provide evidence of DM in the way of indirect detection. However, before resorting to the exotic physics of DM, it is necessary to go through the possible astrophysical sources to account for these results. The model-independent spectral shape analysis shows that there might be most likely a primary source with e^+e^- pairs required to explain the rise of the positron fraction [8]. The nonexcess of the antiproton data [4] also favors a leptonic origin of the positrons. Pulsar is thought to be a good candidate to produce only leptons, and was used to explain the previous HEAT data [9,10]. The recent analysis shows that the PAMELA data can also be fitted considering the contributions from nearby pulsars such as Geminga and B0656 + 14 [11,12]. It should be noted that another interesting conclusion in Ref. [13] shows that the uncertainties

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of the propagation of CRs, the production cross section of secondary particles, and the errors of electron measurements might lead to the underestimation of the positron fraction, and the "excess" is actually not an excess.

As one possibility, the contribution from DM annihilation or decay is also widely discussed. The scenarios about DM annihilation include (i) annihilation to SM particle pairs, like gauge boson, quark, and lepton pairs [14–17]; (ii) virtual internal bremsstrahlung process to $e^+e^-\gamma$ [18]; (iii) annihilation to new mediating particle pairs which would decay to e^+e^- [19–21], etc. However, in the DM annihilation scenario, an unnatural large "boost factor" is necessary to reproduce the PAMELA positron data. Another problem is that the nonexcess of the $\bar{p}/p$ data will set constraints on the properties of annihilating DM [17], which makes the model building difficult.

Considering the difficulties of explaining the large positron excess by annihilating DM, we propose to solve the problem using decaying DM in the present work. If there exists some tiny symmetry violation, the DM particles can decay very slowly to SM particles. The decaying DM models are studied extensively in the literature to explain the observational data [22–29] or set constraints on the decay properties of DM [30–34].

For the self-consistency of this work, we first study the process of cosmic ray propagation carefully, and give realistic propagation models to produce the background contributions to positrons and antiprotons from CR interaction with ISM. The DM induced positrons and antiprotons are calculated in the same propagation models. We find that the PAMELA data can be well fitted for a leptonically decaying DM (LDDM) model. The results for different decay final states are discussed in detail. And a possible model in the SUSY frame with R-parity violation is proposed.

The paper is organized as follows. In Sec. II, we discuss the propagation of CRs and give the updated positron and antiproton background estimations. In Sec. III, we present a model-independent approach to recover the PAMELA data and discuss why we need the decaying DM whose decay products are mainly leptons. In Sec. IV, we give an example of this LDDM model and discuss another possibility. Finally, we give the summary and discussion in Sec. V.

II. PROPAGATION OF GALACTIC COSMIC RAYS

In this section, we will study the cosmic ray propagation model carefully so that we can predict the positron and antiproton spectra to compare with the PAMELA data. The charged particles propagate diffusively in the Galaxy due to the scattering with a random magnetic field [35]. The interactions with ISM and the interstellar radiation field (ISRF) will lead to energy losses of CRs. For heavy nuclei and unstable nuclei there are fragmentation processes by collisions with ISM and radiactive decays, respectively. In addition, the overall convection driven by the galactic wind and reacceleration due to the interstellar shock will also affect the distribution function of CRs. The propagation equation can be written as [36]

$$\frac{\partial \psi}{\partial t} = Q(\mathbf{x}, p) + \nabla \cdot (D_{xx}\nabla\psi - \mathbf{V_c}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \times \frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V_c}\psi)\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}, \tag{1}$$

where ψ is the density of cosmic ray particles per unit momentum interval; $Q(\mathbf{x}, p)$ is the source term; D_{xx} is the spatial diffusion coefficient; $\mathbf{V_c}$ is the convection velocity; D_{pp} is the diffusion coefficient in momentum space used to describe the reacceleration process; $\dot{p} \equiv dp/dt$ is the momentum loss rate; τ_f and τ_r are time scales for fragmentation and radioactive decay, respectively. We describe a bit more about the relevant terms in Eq. (1) in the following paragraphs.

For primary particles such as the protons and some heavy nuclei, the source function is the product of two parts: the spatial distribution $f(\mathbf{x})$ and energy spectrum $q(p)$. $f(\mathbf{x})$ can follow the distribution of possible sources of CRs, such as the supernova remnants (SNR) [37]. The injection spectrum $q(p) \propto p^{-\gamma}$ is usually assumed to be a power law or broken power law function with respect to momentum p. For secondary particles the source function is given according to the distributions of primary CRs and ISM

$$Q(\mathbf{x}, p) = \beta c \psi_p(\mathbf{x}, p)[\sigma_{\rm H}(p)n_{\rm H}(\mathbf{x}) + \sigma_{\rm He}(p)n_{\rm He}(\mathbf{x})], \tag{2}$$

where $\psi_p(\mathbf{x}, p)$ is the density of primary CRs; βc is the velocity of injection CRs; $\sigma_{\rm H}$ and $\sigma_{\rm He}$ are the cross sections for the secondary particles from the progenitors of H and He targets; $n_{\rm H}$ and $n_{\rm He}$ are the interstellar hydrogen and helium number densities, respectively.

The spatial diffusion is regarded as isotropic and described using a rigidity dependent function

$$D_{xx} = \beta D_0\left(\frac{\rho}{\rho_0}\right)^\delta. \tag{3}$$

The reacceleration is described by the diffusion in momentum space. The momentum diffusion coefficient D_{pp} relates with the spatial diffusion coefficient D_{xx} as [38]

$$D_{pp}D_{xx} = \frac{4p^2 v_A^2}{3\delta(4-\delta^2)(4-\delta)w}, \tag{4}$$

where v_A is the Alfvén speed, and w is the ratio of magnetohydrodynamic wave energy density to the magnetic field energy density, which characterizes the level of turbulence. w can be taken as 1 and the reacceleration is determined by the Alfvén speed v_A [38].

TABLE I. The propagation parameters in the DC and DR models.

	D_0 (10^{28} cm^2 s^{-1})	Diffusion index[a] δ_1/δ_2	v_A (km s^{-1})	dV_c/dz (km s^{-1} kpc^{-1})	e^- injection[b] γ_1/γ_2	Nuclei injection[c] γ_1/γ_2
DC	2.5	0/0.55	$\cdots$	6	1.50/2.54	2.45/2.25
DR	5.5	0.34/0.34	32	$\cdots$	1.50/2.54	1.94/2.42

[a]Below/above the break rigidity $\rho_0 = 4$ GV.
[b]Below/above 4 GeV.
[c]The break energy is 25 GeV for the DC model, and 15 GeV for the DR model.

The convection velocity, which corresponds to the galactic wind, is assumed to be cylindrically symmetric and increase linearly with the height z from the galactic plane [36]. It means a constant adiabatic energy loss of CRs. $V_c(z = 0) = 0$ is adopted to avoid the discontinuity across the galactic plane.

Finally the energy losses and fragmentations can be calculated according to the interactions between CRs and ISM or ISRF. For some simplified cases the propagation equation (1) can be solved analytically using the Green's function method [39–41]. However, generally it is not easy to find the analytical solution. A numerical method, known as the GALPROP model, has been developed by Strong and Moskalenko to solve this equation [36,42]. In GALPROP, the realistic astrophysical inputs such as the ISM and ISRF are adopted to calculate the fragmentations

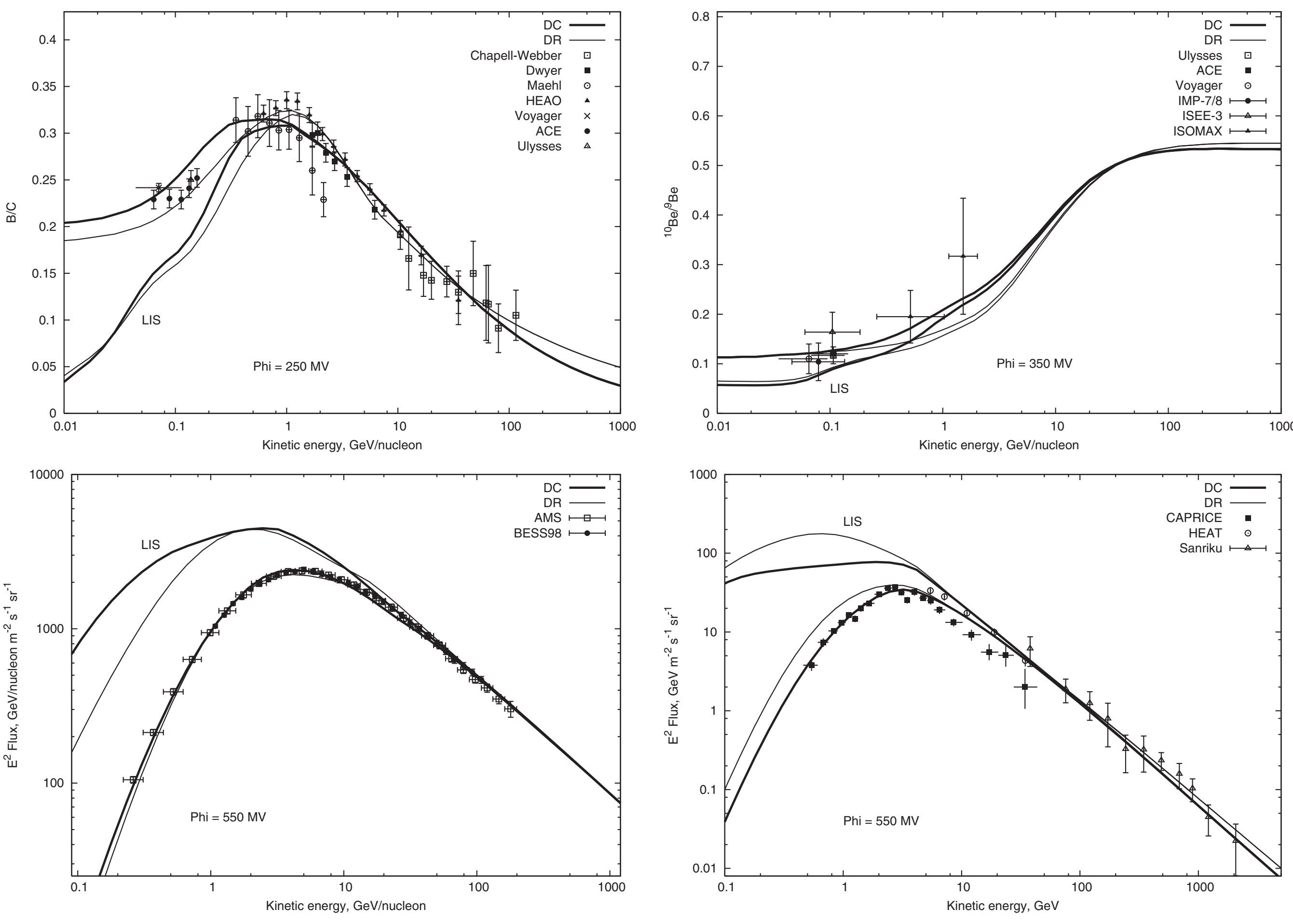

FIG. 1. Propagated B/C, ^{10}Be/^{9}Be, protons and electrons spectra in the DC and DR models of GALPROP. In each panel of the figure, the thick solid lines represent the results of the DC model, while the thin solid lines show results of the DR model. For each model the LIS spectrum together with the solar modulated one are plotted. In order to match the low energy data, different modulation potentials are adopted as labeled in the figure. The references of the data are B/C: Chapell-Webber [76], Dwyer [77], Maehl [78], HEAO [79], Voyager [80], ACE [81], Ulysses [82]; ^{10}Be/^{9}Be: Ulysses [83], ACE [84], Voyager [80], IMP-7/8 [85], ISEE-3 [85], ISOMAX [86]; protons: BESS98 [87], AMS98 [88]; electrons: CAPRICE [89], HEAT [90], Sanriku [91].

and energy losses of CRs. The parameters are tuned to reproduce the observational CR spectra at Earth. It is shown that the GALPROP model can give relatively good descriptions of all kinds of CRs, including the secondaries such as e^+, $\bar{p}$, and diffuse γ rays [36,42–45].

In this work, we employ GALPROP models to calculate the propagation of CRs. Two GALPROP models are adopted. One is the diffusion + convection (DC) scenario and the other is the diffusion + reacceleration (DR) model. It has been shown that the DR model is easier to reproduce the energy dependence of the observed boron-to-carbon ratio (B/C) data [36]. However, the reacceleration will produce more low energy CRs and overestimate the low energy spectra of electrons, positrons, protons, and helium [46]. In addition, the DR model seems to underproduce the antiprotons [43,47]. In the DC model, the results of e^-, e^+, p, and $\bar{p}$ are in better agreement with the data, but the "peak" around 1 GeV of the B/C data is not well generated in the model[36]. Here, we quote these two models in the sense that the differences between these models are regarded as the uncertainties of the propagation model of CRs. The propagation parameters are listed in Table I. Other parameters which are not included in the table are the height of the propagation halo $z_h = 4$ kpc, and the spatial distribution of primary CRs $f(\mathbf{x}) \propto (\frac{\mathbf{R}}{\mathbf{R}_\odot})^\alpha \times \exp(-\frac{\beta(\mathbf{R}-\mathbf{R}_\odot)}{\mathbf{R}_\odot}) \exp(-\frac{|z|}{\mathbf{z_s}})$ with $\alpha = 0.5$, $\beta = 1.0$, $R_\odot = 8.5$ kpc, and $z_s = 0.2$ kpc[48].

In Fig. 1, we show the observed and calculated CR spectra of B/C, ^{10}Be/^{9}Be, protons and electrons for both the DC and DR models. For the solar modulation of the local interstellar (LIS) spectrum we adopt the force field approximation [49]. It is shown that these two models can both give satisfactory descriptions of the data. We can also note that the DR model indeed produces more low energy electrons, and a larger solar modulation potential is needed to suppress the low energy spectra.

Figure 2 gives the results of the positron fraction and $\bar{p}/p$ ratio for the DC and DR models, respectively. We can see from this figure that the DR model gives too many positrons at low energies. The solar modulation does not change the results significantly since it affects positrons and electrons simultaneously. The charge-dependent solar modulation effect might be helpful in softening the discrepancy between the calculation and data. The result of the DC model shows a better agreement with the low energy data. We will not focus on the low energy behavior of the positron fraction since it might be mainly due to the solar effect. For energies higher than several GeV, the results of the two models are similar, and both seem to underestimate the positron fraction compared with the HEAT [6] and PAMELA data [5]. As for $\bar{p}/p$, the DC model is consistent with the measurements, including the recent PAMELA data [4]. The DR model shows an underproduction of antiprotons. This means that if the DC model is correct, the excess of positrons and nonexcess of antiprotons will set strong constraints on the properties of the source of positrons, e.g., [17]. On the other hand, the DR model will leave looser constraints.

III. MOTIVATION FOR A LEPTONICALLY DECAYING DM MODEL

In this section, we will adopt a model-independent approach to constrain the DM annihilation or decay products from the PAMELA data. We find the PAMELA data actually excludes the annihilation or decay products being quark pairs, strongly disfavors the gauge bosons, and favors dominant leptonic final states.

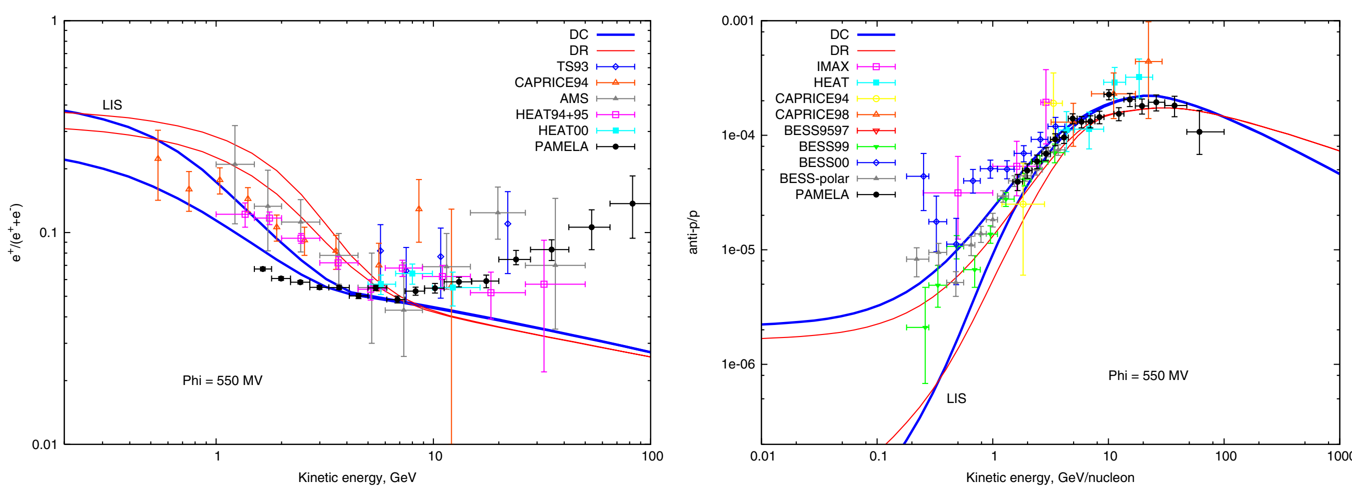

FIG. 2 (color online). Left: the calculated positron fraction compared with observations; right: $\bar{p}/p$ ratio. References of the observational data are positron fraction: TS93 [92], CAPRICE94 [89], AMS [7], HEAT94 + 95 [6], HEAT00 [93], PAMELA [5]; $\bar{p}/p$: IMAX [94], HEAT [95], CAPRICE94 [96], CAPRICE98 [97], BESS95 + 97 [98], BESS99 [99], BESS00 [99], BESS-polar [100], PAMELA [4].

In principle, there should be no difference in treating annihilation or decay. However, there is a subtle difference for the two scenarios. We know that the annihilation or decay depends on the DM density in different ways. Further, since what we observed on Earth is the integrated positron or antiproton flux from the nearby region, we may get slightly different spectra after propagation for the annihilation or decay scenarios even though the source spectra are the same. In this section, we only study the case of decay to show the result. The main conclusion will be unchanged for annihilation. In addition, we show why decaying DM is superior to annihilating DM.

The source term in Eq. (1) is given by

$$Q \sim \frac{1}{\tau_{\rm DM}} \frac{\rho(r)}{m_{\rm DM}} \frac{dN}{dE}\bigg|_{\rm decay}, \tag{5}$$

where $\rho(r)$ is the DM density distribution in the Galaxy; $\tau_{\rm DM}$ is the lifetime of DM; dN/dE is the original positrons spectrum from each DM decay. The DM mass $m_{\rm DM}$ is supposed to be a free parameter while its life $\tau_{\rm DM}$ will be fixed by the positron fraction. In this work, we take the Navarro-Frenk-White [50]profile for DM distribution with the local DM density $\rho_\odot = 0.3\ {\rm GeV/cm^3}$.

We assume a two-body final state with an energy of 100 and 300 GeV for either quark, lepton, or gauge boson pairs (1 TeV is also discussed in this case). The spectra of positron and antiproton are simulated by PYTHIA [51] and then propagated by adopting the DC and DR propagation models as introduced in the last section. The lifetime of DM is taken to give the correct positron flux.

In Fig. 3, we show the positron and antiproton fraction when the decay products are gauge boson pairs. We find that the positron spectrum from gauge boson decay is usually softer than the PAMELA data given even taking the gauge boson energy at 1000 GeV. Especially, we find the gauge boson channel is problematic for the antiproton spectrum. They give an antiproton fraction several times larger than the data in the two transportation models. Therefore DM decaying to gauge bosons are strongly disfavored by the antiproton data. This conclusion is similar to Ref. [17,52]; the authors suggest using extremely high energy gauge bosons of about 10 TeV to interpret both positron and antiproton spectra. In that case, only the soft tail of positron and antiproton spectra from high energy gauge bosons are adopted. Since the endpoint of the antiproton soft tail has energy larger than 100 GeV it has no conflict with the present PAMELA data that cut off at ~100 GeV. It predicts a very high antiproton flux above ~100 GeV. The model requires very heavy DM (~ 10 TeV). It should be mentioned that the PPB-BETS [53] and ATIC [54] experiments seem to have a significant excess in electron spectrum above several hundred GeV and also a cutoff around 800 GeV. The heavy DM with mass of 10 TeV seems not to account for this electron/positron excess [17].

In Fig. 4, we show the positron and antiproton fraction when DM decay to quark pairs. Positrons are produced

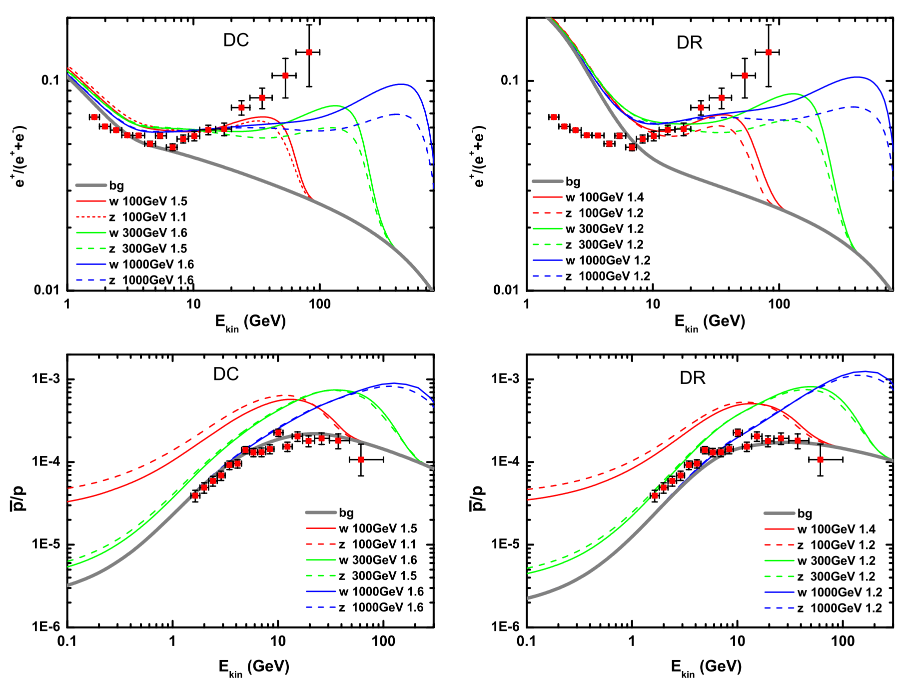

FIG. 3 (color online). The positron and antiproton fraction, $\frac{\Phi_{\bar e}}{\Phi_{\bar e}+\Phi_e}$ and $\frac{\Phi_{\bar p}}{\Phi_p}$, as a function of energy from DM decaying to gauge boson pairs. The black lines are background for the positron and antiproton. The data points are from the preliminary PAMELA results [4]. The numbers 100, 300, and 1000 GeV refer to the energy of gauge bosons, while the numbers 3.6 and so on refer to the lifetime of DM in units of 10^{26} s. In the title, DC and DR are the two propagation models discussed in Sec. II.

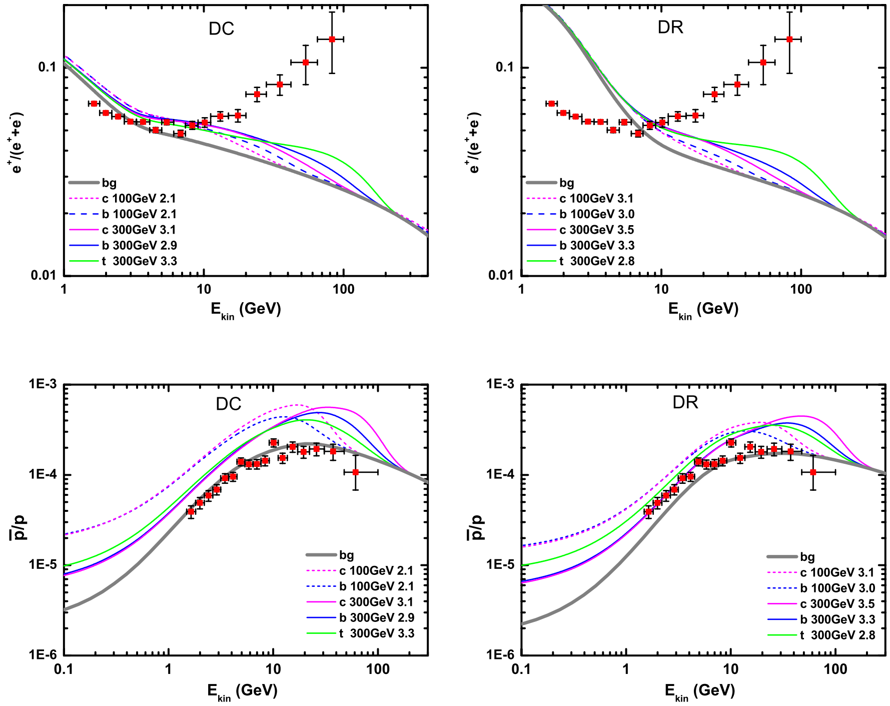

FIG. 4 (color online). Positron and antiproton fraction as a function of energy from DM decaying to quark pairs. The labels are the same as those in Fig. 3.

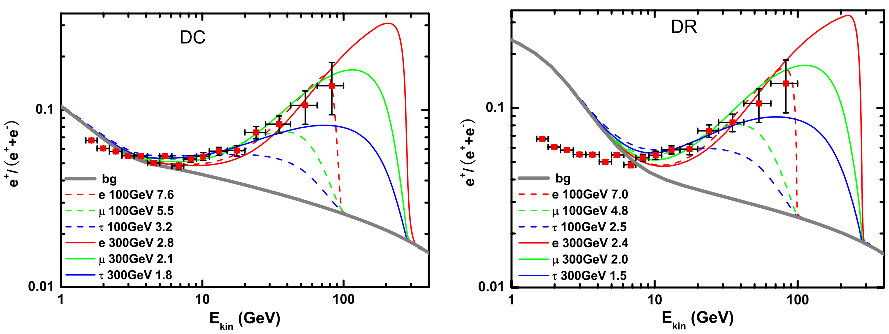

FIG. 5 (color online). Positron and antiproton fraction as a function of energy from DM decaying to lepton pairs. The labels are the same as those in Fig. 3.

after hadronization of quarks via the decay of charged pions. However, we find these positrons are too soft and cannot account for the excess of positrons above $\sim$10 GeV. Furthermore, quark hadronization produces unwanted antiprotons as expected which are several times larger than the experimental data.

In Fig. 5, we show the case of leptonic final states. The positron spectrum easily fits the PAMELA data in this case for e and μ final states. However, for τ final states we may need the τ energy larger than $\sim$300 GeV to account for the hard positron spectrum. Certainly there is negligible influence on the antiproton spectrum in the pure leptonic decay.

In Table. II, we give a summary on these three channels to fit the PAMELA data. The gauge boson final states with energy around hundreds of GeV to $\sim$TeV have problems with antiprotons.[1] However, if the energy is extremely high ($\sim$ 10 TeV), the positron and antiproton data can be satsified due to the energy cutoff of the PAMELA data. The quark final states have a problem in both the positron and antiproton spectra, that is, they give too soft of a positron spectrum and too large of an antiproton flux. The lepton final states with a hundred GeV can give a hard positron spectrum and easily fit the PAMELA data very well. At the same time they are free from upsetting the antiproton spectrum.

[1]The conclusion is drawn in the conventional propagation model. It is possible to moderate or overcome the problem in some special propagation models.

TABLE II. The summary of three kinds of decay products to account for the PAMELA data.

	Gauge boson	Quarks	Leptons
Positron	$\surd$	$\times$	$\surd$
Anti-proton	$\times$	$\times$	$\surd$

Finally, we will try to compare the two scenarios of annihilating and decaying DM. We find, if the positron excess at PAMELA is indeed of DM origin, the decaying DM is superior to annihilating DM. First, annihilating DM has to resort to a large "boost factor" at the order of $\sim 10^2$ to $\sim 10^4$ to account for the large positron flux. However, detailed analysis of the boost factor from the clumpiness of DM structures based on N-body simulation gives that the most probable boost factor should be less than 10–20 [55]. The same conclusion is also found through the direct computation of the antimatter fluxes from N-body simulation [56]. A nearby subhalo or the DM spike around the intermediate mass black hole might be able to provide large boost factors; however, these scenarios are found to be of little probability [57] or suffer large uncertainties [58]. Some authors use Sommerfeld enhancement to increase the annihilation cross section [14,17,19,20,59,60] and some people adopt nonthermal DM such as wino [61].[2] This method is usually constrained by the data of gamma rays [63,64] and need further study. Second, annihilating DM usually produce more quarks or gauge bosons than leptonic final states. For example, the neutralino is easier to annihilate into quarks or gauge bosons than leptons. The Kaluza-Klein DM in some universal extra dimension models may be an exception in that it can annihilate largely to leptons. However, we should mention that Kaluza-Klein DM may still have a problem with the PAMELA antiproton data because in its annihilation final states quarks and gauge bosons are comparable to leptons. From Figs. 3–5 we can roughly estimate that they may still produce too many antiprotons.

In the next section, we will consider a scenario of LDDM. Our example is given in the minimal supersymmetric standard model (MSSM) with the trilinear R-parity violation term which only breaks lepton number conservation. The neutralino, being the lightest SUSY particle, forms dark matter and is produced thermally in the early Universe in the same way as the stable neutralino. To account for the PAMELA positron excess we find it has the lifetime of about $\sim 10^{26}$ seconds, which is much larger than the life of the Universe.

[2]It is interesting to mention that DM may be more than one component. For example, one component is metastable in the early Universe and the other component is stable in that it can annihilate into leptons today which can also avoid the large boost factor [62].

IV. NEUTRALINO WITH R-PARITY VIOLATION AS AN EXAMPLE OF LDDM

In this section, we turn to discuss the specific decaying DM model in the supersymmetry scenario. In the SUSY model, the discrete symmetry of R-parity can be invoked to avoid dangerous baryon-number violation terms which drive unexpected proton decay. Defined as $R = (-1)^{2S+3B+L}$, the R-parity of a SM particle is even while its superpartner is odd. Then, the LSP particle is stable, since the neutralino LSP can have the correct relic density via thermal production which makes it a suitable DM candidate.

Although R-parity symmetry is well motivated for SUSY phenomenology, there is no reason for this symmetry to be exact. One can introduce some R-parity violation terms in the Lagrangian which make the LSP decay into SM particles. The general gauge invariant superpotential of the minimal supersymmetric standard model can be written as

$$W = W_{\rm MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \mu'_i L_i H_u, \tag{6}$$

where $L_i(Q_i)$ and $\bar{E}_i(\bar{U}_i, \bar{D}_i)$ respectively represent the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields, and i, j, k are generation indices (we neglect these indices below). The LH term in this superpotential mixes the lepton and Higgs fields. Because Higgs and lepton have the same gauge quantum numbers, one can rotate away the bilinear term by redefining these fields. The $LL\bar{E}$, $LQ\bar{D}$ terms violate the lepton number, and the $U\bar{D}\bar{D}$ term violates the baryon number [65]. Then, a total of 45 couplings, including $9\lambda_{ijk}$, $27\lambda'_{ijk}$, and $9\lambda''_{ijk}$, are invoked in theory. There might also exist many soft SUSY breaking terms which induce R-parity symmetry breaking. These terms add more additional free parameters, and we do not discuss them here.

The R-parity violation terms must be tiny to satisfy stringent experiment constraints, especially the constraints from proton decay. The tiny R-parity violation may be due to some fundamental theories at a high energy scale. For example, in SU(5) grand unified theories (GUT) the gauge invariant terms as $f_{ijk}\bar{5}^i\bar{5}^j 10^k$, where $\bar{5}$, 10 denote matter field representations contain leptons and quarks, could induce R-parity violation explicitly. f_{ijk} is suppressed and gives tiny R-parity violation couplings [66–68]. To construct a realizable theory taking account for all the experimental constraints, more symmetries and high order operators are always required.

In general, we should consider all R-parity violation terms in Eq. (6). However, they might not appear in theory at the same time. In some theories, only the baryon-number violation term $\bar{U}\bar{D}\bar{D}$ is included [69], while some other theories can only predict the lepton-number violation $LQ\bar{D}$ term [67,68]. In a class of discrete gauge symmetric models, the baryon-number violation term should be absent since it may induce rapid proton decay [70]. In this work, we only consider the lepton-number violation term $LL\bar{E}$ in order to account for the PAMELA positron excess. We assume all the components of λ^{ijk} are equal and neglect the annihilation of neutralinos in the following discussion for simplicity.

To specify the SUSY parameters we choose some benchmark points as denoted in Table III, where LSP is a neutralino with different masses. Point A is SPS 6 in the mSUGRA-like scenario with nonunified gaugino masses; points B, C, D are from the Higgs funnel region in the mSUGRA; point E is from the focus point region in the mSUGRA; and point F denotes a thermal wino in the AMSB scenario. All these points satisfy the correct relic density and other laboratory constraints. We utilize PYTHIA to produce the positron energy spectrum from neutralino decay.

In the limit of heavy and degenerate sleptons, the neutralino with a gaugino component has the lifetime [32]

$$\tau_{\text{gaugino}} \sim 10^{26}\ \text{s} \cdot \left(\frac{\lambda}{10^{-25}}\right)^{-2} \left(\frac{m_\chi}{1000\ \text{GeV}}\right)^{-1} \left(\frac{m_{\tilde{f}}}{m_\chi}\right)^{4}, \quad (7)$$

where λ is the coefficient for $LL\bar{E}$ term and $m_{\tilde{f}}$ is the sfermion mass. The neutralino with a higgsino component has the lifetime

$$\tau_{\text{higgsino}} \sim 10^{26}\ \text{s} \cdot \left(\frac{\tan\beta}{10}\right)^{-2} \left(\frac{\lambda}{10^{-23}}\right)^{-2} \left(\frac{m_\chi}{1000\ \text{GeV}}\right)^{-1} \times \left(\frac{m_{\tilde{f}}}{m_\chi}\right)^{4}. \quad (8)$$

In Table IV, we give the lifetime and value of λ for the different benchmark points to account for the PAMELA positron excess. We can see these neutralinos generally have a lifetime around 10^{26} s to account for the PAMELA data. It is much longer than the life of the Universe which makes these neutralinos valid dark matter. In order to acquire such a long lifetime neutralino, the value of R-parity violation parameter λ must be very tiny $[O(10^{-25}) \sim O(10^{-23})]$. This tiny λ can be compatible with all the experiment constraints very easily. For example, the proton decay ($p \to lX$) experiments gave stringent constraints for baron number violation couplings as $|\lambda'_{lmk}\lambda''^{*}_{11k}| < 10^{-25}(m_{\tilde{d}_{kR}}/100\ \text{GeV})^2$; the lepton decay ($\mu \to e\gamma$) gave constraints for lepton-number violation couplings as $|\lambda'_{121}\lambda^{*}_{121}| < 5.7\times 10^{-5}$, $|\lambda'_{131}\lambda^{*}_{131}| < 0.57\times 10^{-4}$, etc. [73] (more experiment constraints can be found in Ref. [74] and references therein). However, the tiny λ also means we can not test the scenario directly at LHC or ILC.

TABLE IV. Lifetime τ in units of 10^{26} s and R-parity violation parameter λ in units of 10^{-25} for different benchmark points. "DC" and "DR" refer to the two propagation models we adopted.

DC	$\tau(10^{26}$ s)	$\lambda(10^{-25})$	DR	$\tau(10^{26}$ s)	$\lambda(10^{-25})$
A	4.5	3.2	A	3.9	3.4
B	2.6	14.8	B	2.3	15.7
C	1.7	16.1	C	1.5	17.1
D	1.2	59.5	D	1.1	62.1
E	1.0	253.2	E	0.9	266.9
F	0.6	159.7	F	0.6	159.7
G	0.5	156.7	G	0.5	156.7

In Fig. 6, we show the positron fraction including the contribution from neutralino decay for different benchmark points. From Fig. 6, we can see the positrons are most probably distributed lower than $\frac{1}{3}m_{\tilde{\chi}^0}$. This is due to the three-body decay and the roughly equal decay fraction of $\nu_i l_j^- l_k^+$. The positron spectrum given here with three-body decay is generally softer than two-body final states with monochromatic lepton. We notice that the neutralino heavier than 300 GeV to about 2 TeV can fit the PAMELA data well. If one takes into account the results from PPB-BETS and ATIC experiments, it seems to suggest heavy neutralinos up to ~TeV if they are due to DM decay (Fig. 7). Another feature of this scenario is the neutrino flux from neutralino decay, but we find it is too small to be

TABLE III. The seven benchmark points with different neutralino masses and in different scenarios. "MC" means the main component of neutralino. The other parameters we adopted are sgn(μ) = +1, $m_t = 172.6$ GeV, $A_0 = 0$. The SPS6 point has non-universal mass parameter $M_1/1.6 = M_2 = M_3$ at GUT scale. Suspect [71] and MicrOmega [72] are used in our calculation.

	SUSY	MC	Mass (GeV)	m_0 (GeV)	$m_{1/2}$ (GeV)	Ωh^2	$\tan\beta$
A	SPS6	bino	190	150	300	1.04×10^{-1}	10
	SUSY	MC	Mass (GeV)	m_0 (GeV)	$m_{1/2}$ (GeV)	Ωh^2	$\tan\beta$
B	mSUGRA	bino	341	900	800	9.62×10^{-2}	50
C	mSUGRA	bino	614	1750	1400	9.97×10^{-2}	50
D	mSUGRA	bino	899	5000	2000	1.02×10^{-1}	50
E	mSUGRA	higgsino	1126	9100	3500	1.01×10^{-1}	50
	SUSY	MC	Mass (GeV)	m_0 (GeV)	$m_{3/2}$ (GeV)	Ωh^2	$\tan\beta$
F	AMSB	wino	2040	18 000	640 000	9.15×10^{-2}	10
G	AMSB	wino	2319	20 000	730 000	1.17×10^{-1}	10

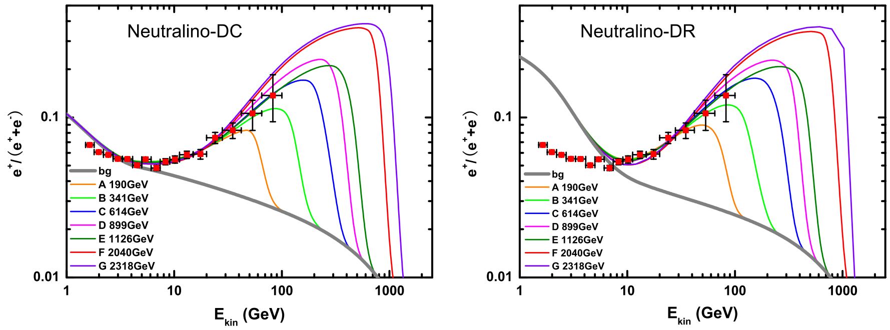

FIG. 6 (color online). Positron and antiproton fraction as a function of energy for different benchmark points. The neutralino mass of each model is given, while the lifetime of the neutralino in each model is given in Table IV. The neutralino mass in each line is increasing from left to right.

detected by neutrino telescopes such as Super-kamiokande, IceCube, etc. And it is also well within the atmospheric neutrino bound from Super-kamiokande (similar analyses for neutrino flux from decaying DM can be found in Refs. [27,34]).

Finally, we will give some comments on other scenarios of decaying dark matter in the SUSY model (discussions of some non-SUSY models for PAMELA results can be found in Refs. [28,75]). In some SUSY scenarios, the LSP may be the neutral particles as gravitino or sneutrino. They can also be the candidates of DM. However, in the bilinear R-parity violation scenario, the gravitino would mainly decay into gauge boson plus lepton [25,26] which is not favored by antiproton data from PAMELA. If the R-parity violation term is $LL\bar{E}$ as we discussed above, the spectrum of decay products is similar. But the decay of the gravitino is suppressed by the Planck scale and the R-parity violation parameter can be as large as $\lambda_{ijk} > 10^{-14}$, which may lead to unstable next lightest supersymmetry particle decay quickly to avoid destroying the success of big bang nucleosynthesis [22,33] and be observable at colliders [22].

Another possible candidate of DM in SUSY is the sneutrino. The left-handed sneutrino has been ruled out by DM direct detection, therefore the right-handed sneutrino receives more concerns. If we neglect all the soft breaking terms, the interactions for the right-handed neutrino superfield N are induced only from Yukawa term $y_{ij}L_iH_uN_j$. After introducing only bilinear R-parity violation terms $\mu_i' L_i H_u$, the right-handed sneutrino will decay into lepton pairs with a large fraction, due to mixing between Higgs and left-handed lepton superfields. However, it should be mentioned that mixing between the right-handed sneutrino and the Higgs boson cannot be avoided in general. These mixing terms have to be suppressed in order not to conflict with PAMELA antiproton data. The kinematical conditions can be used to suppress the right-handed sneutrino decay to two Higgs or one Higgs plus one lepton. To suppress the LSP direct decay to quarks which is induced by the mixing of right-handed sneutrino and Higgs, an extra relation $\sum_i y_{ij}\mu_i' \sim 0$ is needed for the j-th generation right-handed sneutrino which is the LSP. In Ref. [29], the authors proposed a similar idea. They assume the LSP is the third generation right-handed sneutrino and only $\mu_1' \neq 0$, then the small yukawa coupling y_{13} makes this right-handed sneutrino a good candidate of LDDM. The difference between the leptonically decaying neutralino and the right-handed sneutrino might be represented in the original positron spectrum. The former one is softer than the latter because the former one has a three-body decay while the latter one has a two-body decay. It means that the PAMELA implication on DM mass is different for these two scenarios.

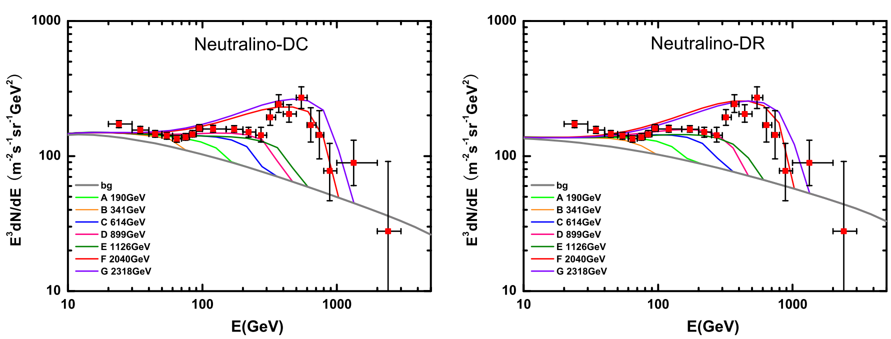

FIG. 7 (color online). Positron and antiproton total flux as a function of energy for different benchmark points to fit ATIC-2 data from Ref. [54]. The labels are the same as those in Fig. 6.

With the synergy of PAMELA and collider experiments, it is possible to distinguish whether the DM is the neutralino, gravitino, or right-handed sneutrino.

V. SUMMARY AND DISCUSSION

The recently released PAMELA data shows interesting features: the positron shows an obvious excess above $\sim$10 GeV while the antiproton flux is consistent with the expectation from the conventional cosmic ray model. The result implies that there should exist some kind of primary positron sources in addition to the secondaries from CRs interactions with the ISM.

Before a discussion of possible exotic sources of positrons it is extremely important to explore the background carefully. In this work, we first recalculate the background contributions of positron and antiprotons from CRs using GALPROP. Considering the CR data of unstable secondaries, such as $^{10}\mathrm{Be}/^{9}\mathrm{Be}$, it is possible to reduce the uncertainties in predicting the positron and antiproton flux from the propagation parameters [13]. Two typical propagation models, diffusion + convection and diffusion+ reacceleration, are adopted as benchmarks of the CR propagation models. In both of the models, propagation parameters are adjusted so that most of the CR spectra, such as B/C, $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ and so on, are consistent with the observation. The DC model is found to be consistent with the $\bar{p}/p$ and the low energy $e^+/(e^+ + e^-)$ data of PAMELA without introducing a charge-dependent solar modulation model, while the DR model shows a bit of underestimation of the $\bar{p}/p$ data and produces more low energy positrons. In both models the positron fraction at high energies shows obvious excess.

We then consider the DM origin of the primary positrons. We compared the positron and antiproton spectra with PAMELA data by assuming that the annihilation or decay products are mainly gauge bosons, quarks and leptons, respectively. We find that the PAMELA data exclude quarks being dominant final states, disfavor gauge bosons, and favor the leptonic final states. Comparing annihilating DM and decaying DM scenarios, we prefer decaying DM because annihilating DM usually requires very large boost factors. Moreover, annihilating DM usually produce more gauge bosons and quarks than leptons.

A concrete example of such a LDDM model is considered in MSSM with a tiny $LL\bar{E}$ R-parity violation term. We choose the neutralino as the LSP and the DM particle. We show that a neutralino with mass $600 \sim 2000$ GeV and lifetime of $\sim 10^{26}$ seconds can fit the PAMELA data very well. We also demonstrate that a neutralino with mass around 2 TeV can fit PAMELA and ATIC data simultaneously. Another LDDM model is right-handed sneutrino being DM with a bilinear R-parity violation term. With the interplay of PAMELA and LHC it is possible to distinguish the DM between the neutralino and the right-handed sneutrino.

Finally, we will discuss the implications of the LDDM models. LDDM can have many interesting phenomena in experiments other than PAMELA, such as gamma ray observation. In general, it can have two-body decay and three-body decay channels as $\mathrm{DM} \to l^+ l^-$ and $\mathrm{DM} \to l^+ l^- X$, where the leptons in the final states are required from PAMELA data. Particle X can be photons γ, neutrino ν, in general. If the LDDM has the decay channel $\mathrm{DM} \to l^+ l^- \gamma$, the spectrum of gamma ray can reveal the property of LDDM and the mechanics behind it.

For our neutralino LDDM model the neutrino observation will provide a way to test the model since the decay produces a hard neutrino spectrum. Another possible way to test the model is to look for the synchrotron emission of the hard electrons and positrons by DM decay. Further studies on this issue are on going.

ACKNOWLEDGMENTS

P. F. Y. and J. L. thank H. Murayama for useful discussion at Jiuhua, Beijing. X. J. B. thanks J. Chang for helpful discussions. This work was supported in part by the Natural Sciences Foundation of China (Grants No. 10775001, No. 10635030, No. 10575111, and No. 10773011), by the trans-century fund of Chinese Ministry of Education, and by the Chinese Academy of Sciences under Grant No. KJCX3-SYW-N2.

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