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High energy positrons from annihilating dark matter

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Results from the PAMELA experiment indicate the presence of an excess of cosmic ray positrons above 10 GeV. In this paper, we consider the possibility that this signal is the result of dark matter annihilations taking place in the halo of the Milky Way. Rather than focusing on a specific particle physics model, we take a phenomenological approach and consider a variety of masses and two-body annihilation modes, including W^+W^-, Z^0Z^0, $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, and e^+e^-. We also consider a range of diffusion parameters consistent with current cosmic ray data. We find that the significant upturn in the positron fraction above 10 GeV can be explained by dark matter annihilation to leptons, although very large annihilation cross sections and/or boost factors arising from inhomogeneities in the local dark matter distribution are required to produce the observed intensity of the signal. We comment on explanations for the large annihilation rate needed to explain the data and additionally on constraints from gamma rays, synchrotron emission, and cosmic ray antiproton measurements.

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Dark matter in the form of a thermal relic is an appealing explanation for the approximately 85% of the matter density of the Universe not composed of baryons. In addition to being a natural extension of the big bang cosmology, the candidates which naturally give the appropriate relic abundance have annihilation cross sections of the order of the electroweak scale, a natural scale for new particles in theoretical frameworks which provide a solution to the hierarchy problem.

If they exist, such thermal relics are expected to be annihilating in the halo today, generating potentially observable fluxes of high energy particles, including gamma rays, electrons, positrons, and antiprotons. To this end, a number of cosmic ray and gamma ray experiments [1–7] have considered the search for dark matter annihilation products to be an important aspect of their science mission. Of particular interest is the satellite-based cosmic ray experiment, PAMELA [8,9]. With its large acceptance ($21.5\ \mathrm{cm}^2\,\mathrm{sr}$) and excellent particle identification, PAMELA is anticipated to measure the spectra of cosmic ray protons, antiprotons, electrons, and positrons up to energies of 700 GeV, 190 GeV, 2 TeV, and 270 GeV, respectively.

Of particular interest for dark matter searches are high energy cosmic ray positrons [10–12] and antiprotons [12–14]. The spectra of such particles are generally expected to be dominated by the products of high energy cosmic ray interactions with the interstellar medium. In contrast, the spectra of protons and electrons are dominated by particles produced in astrophysical accelerators, e.g., supernovae. As a consequence, the ratios $e^+/(e^+ + e^-)$ and $\bar{p}/p$ are, in the absence of primary sources of cosmic ray antimatter, expected to fall at high energies. A signal of an upturn in these ratios would constitute strong evidence for a new primary source, such as dark matter annihilations [15].

Results of the PAMELA experiment [18] show a dramatic upturn in the positron fraction from 10 to 100 GeV (consistent with earlier indications from HEAT [1] and AMS-01 [2]), while showing no excess in the antiproton data [19]. Pulsars provide an astrophysical explanation for these observations [20–26]. These data also invite interpretation within the context of dark matter [27–30]. Such an interpretation, however, is not trivial. In particular, the observed positron spectrum is somewhat harder than the spectral shape expected from dark matter annihilations to hadronic modes. Furthermore, the amplitude of the signal is very large and potentially difficult to reconcile with the expectations of a thermal relic.

To calculate the cosmic ray spectra resulting from dark matter annihilations, we use the publicly available code, GALPROP [31]. For a given choice of the diffusion coefficient, boundary conditions, energy loss rate, and cosmic ray injection spectrum and distribution, this code solves numerically the steady-state diffusion-loss equation:

$$0 = \vec{\nabla} \cdot \left[K(E)\vec{\nabla}\frac{dn}{dE} \right] + \frac{\partial}{\partial E}\left[b(E,\vec{x})\frac{dn}{dE} \right] + Q(E,\vec{x}), \tag{1}$$

where dn/dE is the number density of particles per unit energy, $K(E)$ is the diffusion constant, and $b(E,\vec{x})$ is the energy loss rate. The source term, $Q(E,\vec{x})$, reflects the mass, annihilation cross section, dominant annihilation modes, and distribution of dark matter in the Galaxy. Within GALPROP, a number of additional elements are included, such as momentum space diffusion. The most relevant physical terms at high energies are included in the equation above, however.

We have adopted three sets of diffusion parameters which we have found to provide good fits to B/C and sub-Fe/Fe cosmic ray data above 5 GeV, and Be^{10}/Be^{9} data above 1 GeV (for a review, see Ref. [32,33]). These parameter sets provide a good sampling of the diffusion-loss parameter space. Throughout this paper, we will refer to the following as Models A, B, and C:

$$\text{A: } K(E) = 5.3 \times 10^{28}\ \text{cm}^2/\text{s} \quad (E/4\ \text{GeV})^{0.43}, \quad L = 4\ \text{kpc};$$

$$\text{B: } K(E) = 1.4 \times 10^{28}\ \text{cm}^2/\text{s} \quad (E/4\ \text{GeV})^{0.43}, \quad L = 1\ \text{kpc};$$

$$\text{C: } K(E) = 7.3 \times 10^{28}\ \text{cm}^2/\text{s} \quad (E/4\ \text{GeV})^{0.43}, \quad L = 6\ \text{kpc};$$

where L is the distance above and below the Galactic plane at which charged particles freely escape the Galactic magnetic field. For the electron/positron energy loss rate, we adopt the GALPROP defaults which include losses due to inverse compton scattering and synchrotron, with a local magnetic field of 5 μG. For the source term, we adopt an Narvarro-Frenk-White (NFW) halo profile [34] with a local density of $0.35\ \text{GeV/cm}^3$.

The injection spectra for the dark matter component of electrons and positrons are generated using PYTHIA version 6.409 [35]. The primary electrons and protons are described by a power law with a break. For the electrons, the values of the indices are $(-1.60, -1.60, -2.15)$ below and $(-2.54, -2.49, -2.54)$ above the break energy of 4.0 GeV for Model (A, B, C) before propagation. The primary proton injection spectrum has indices -1.98 below and -2.25 above the break energy of 9.0 GeV for all three models. The resulting propagated spectra fit the local measurements for electrons [36–39] and protons [40–42] above 4 GeV and 1 GeV, respectively.

In Fig. 1, we plot the positron fraction as a function of energy for various dark matter masses, annihilation modes, and diffusion parameters. In each case, we have normalized the dark matter annihilation rate to provide the best possible fit to the PAMELA data above 10 GeV [18] (below which the effects of charge dependent solar modulation can be significant). The normalization of the annihilation rate is proportional to the annihilation cross section, the square of the local dark matter density ρ_0^2, and a quantity known as the boost factor, which parameterizes the combined effects of the enhancement of the annihilation cross section over the value assumed and the enhancement of $\langle\rho_0^2\rangle$ due to clumps and other inhomogeneities in the local dark matter distribution relative to a smooth NFW profile [43]. In each frame of Fig. 1, we adopt a default value for the dark matter annihilation cross section ($\sigma v = 3 \times 10^{-26}\ \text{cm}^3/\text{s}$) and the local density ($0.35\ \text{GeV/cm}^3$), and vary the boost factor to obtain the required normalization.

We find that dark matter annihilations to leptons, in particular, to e^+e^- and $\mu^+\mu^-$, naturally provide a good fit to the spectral shape observed by PAMELA. Annihilations to gauge bosons or quarks, however, produce too soft a spectrum. This can be ameliorated somewhat if the diffusion boundary is small enough to limit the contribution from more distant annihilations. See, for example, diffusion model B. Moreover, subsequent to the initial draft of this paper, it was shown in [46] that if the dominant contribution to the local e^+e^- flux is due to DM annihilations in a *nearby clump* of dark matter, then annihilations to nonleptonic states can generate the positron fraction observed by PAMELA while evading constraints from antiprotons, gamma rays, and synchrotron observations. In Table I, we give a qualitative measure of the quality of the fit to the PAMELA spectrum (the χ^2 per degree of freedom for the data points above 10 GeV) for each case, along with the boost factor required to normalize each case to the PAMELA spectrum assuming a local dark matter density of $0.35\ \text{GeV/cm}^3$.

The large annihilation rate necessary to fit the PAMELA data can be explained by the Sommerfeld enhancement [47–49] or by capture into WIMPonium [50–52]. Both require a new force in the dark sector mediated by a $\sim$GeV scale force carrier [47]. If dark matter annihilates into the new light particle, then antiproton production is kinematically forbidden [44,66]. In this case, the constraints from the PAMELA antiproton measurements, which restrict the boost factor to 40 for a 1 TeV WIMP annihilating through W's [67] (for a local DM density of $0.30\ \text{GeV/cm}^3$) and therefore are a problem for DM models with large branching ratios to quarks or gauge bosons, are not an issue. Additionally, π^0's are generally not copiously produced in these annihilations, so prompt photons are limited to those from final state radiation [68–77], which are suppressed compared to electronic production.

Such a large annihilation rate could also be generated by a nonthermally produced dark matter candidate with a large annihilation cross section, such as a wino in an anomaly mediated supersymmetric scenario [78,79], but this scenario is tightly constrained by EGRET's measurements of the diffuse gamma ray spectrum [80], by cosmic ray antiproton measurements [67], and to a lesser extent synchrotron measurements [78,81]. For example, although nonthermal $\sim$150 GeV winolike neutralinos could produce the measured flux of positrons, they would also exceed the diffuse gamma ray constraint by at least a factor of 2 (see the discussion in Ref. [80].) A nonthermal dark matter candidate which annihilates largely to leptons, however, could evade such constraints.

Moreover, these constraints can be reduced somewhat if the local dark matter annihilation rate is boosted by inhomogeneities in the surrounding few kiloparsecs without

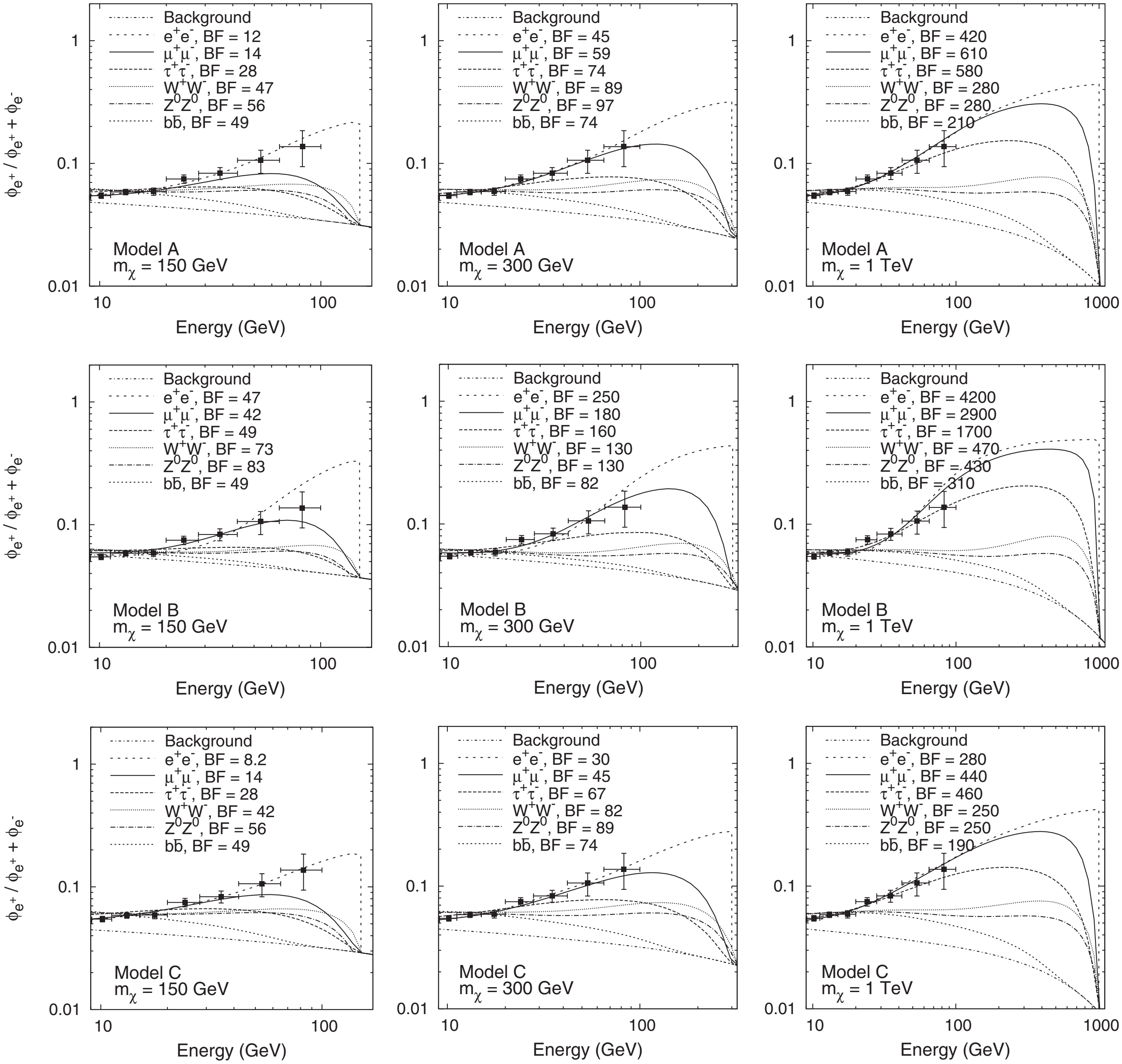

FIG. 1. The positron fraction as a function of energy for various dark matter masses, annihilation modes, and diffusion parameters, compared to the background from secondary production alone (bottom line). In each frame, the annihilation rate was chosen to produce the best fit to the PAMELA data above 10 GeV. The required boost factor was calculated using our default values for the annihilation cross section ($\sigma v = 3 \times 10^{-26}$ cm^3/s) and the local dark matter density (0.35 GeV/cm^3).

comparable boosting of the annihilation rate throughout the remainder of the Galaxy. [82–86] have shown that the distribution of substructure is antibiased with respect to the smooth halo. Therefore, we expect that the local enhancement in the annihilation rate due to substructure is larger than that at the center of the Galaxy. This effect may reasonably lead to a relative reduction of the boost in the Galactic center by up to an order of magnitude. Although somewhat unlikely, it is possible that the Solar System happens to be near a large dark matter subhalo, leading to a large positron flux without the overproduction of gamma rays or antiprotons throughout the halo [87]. Recent results from the Via Lactea II simulation found that although the overall annihilation rate throughout the halo is boosted by only a small value (~ 1.4) on average, there is a small ($\sim 1\%$) chance that the local annihilation rate is enhanced by more than a factor of 10 as a result of a large nearby subhalo [88]. Recent results from the

TABLE I. The quality of the spectral fit (χ^2 per degree of freedom) and the boost factors required for various dark matter masses (in GeV), annihilation modes, and diffusion parameters to produce the PAMELA positron excess. The column BF contains the boost factors required, assuming a local dark matter density of $\rho = 0.35$.

		Model A		Model B		Model C	
Mass	Mode	χ^2/df	BF	χ^2/df	BF	χ^2/df	BF
150	e^+e^-	0.303	12	1.462	47	0.239	8.2
150	$\mu^+\mu^-$	1.203	14	0.840	42	0.821	14
150	$\tau^+\tau^-$	3.109	28	3.515	49	3.352	28
150	W^+W^-	3.518	47	4.496	73	3.437	42
150	ZZ	4.311	56	4.999	83	4.267	56
150	$b\bar{b}$	7.641	49	6.524	49	8.330	49
300	e^+e^-	0.260	45	1.307	250	0.228	30
300	$\mu^+\mu^-$	0.235	59	0.625	180	0.299	45
300	$\tau^+\tau^-$	1.472	74	2.023	160	1.428	67
300	W^+W^-	3.851	89	4.856	130	3.652	82
300	ZZ	4.730	97	5.348	130	4.630	89
300	$b\bar{b}$	6.439	74	5.989	82	6.851	74
1000	e^+e^-	0.277	420	1.480	4200	0.467	280
1000	$\mu^+\mu^-$	0.280	610	0.987	2900	0.285	440
1000	$\tau^+\tau^-$	0.338	580	0.771	1700	0.308	460
1000	W^+W^-	3.186	280	4.078	470	3.014	250
1000	ZZ	3.714	280	4.421	430	3.613	250
1000	$b\bar{b}$	4.248	210	4.647	310	4.304	190

Aquarius Project are more pessimistic, however [89]. Alternatively, dark matter annihilating in a density spike surrounding a nearby black hole ($M \sim 10^2$–$10^6 M_\odot$) could strongly boost the local annihilation rate [90]. It is also interesting to note that the spectrum of positrons from a nearby subhalo or intermediate mass black hole would appear harder than if the positrons were produced from throughout a larger volume, perhaps enabling a better fit to the PAMELA data for annihilations to $b\bar{b}$ and other non-leptonic channels [87].

In summary, the PAMELA excess of high energy positrons, confirming earlier excesses from HEAT and AMS-01, raises the exciting possibility that we are seeing evidence of dark matter annihilations. In this paper, we have considered a range of dark matter annihilation channels and masses and find several scenarios which provide a good fit to the data. In particular, dark matter annihilations to leptons (especially e^+e^- and $\mu^+\mu^-$) quite easily fit the observed spectrum. Annihilations to heavy quarks or gauge bosons, in contrast, provide a poor fit to the data. This can be improved if most of the annihilations occur locally (such as is expected if the Solar System resides near a large subhalo or if the Galactic magnetic field confines charged particles only to a region within 1–2 kpc of the Galactic plane). In almost every case we have considered, very large annihilation rates are required to produce the observed signal. In particular, 150 GeV (1 TeV) dark matter particles require annihilation rates boosted by a factor of approximately ~8 to 80 (~ 200 to a few thousand) relative to the rate expected for a typical thermal cross section ($\sigma v \approx 3 \times 10^{-26}$ cm^3/s) and a smooth halo with a local density of 0.35 GeV/cm^3. The large annihilation rate can be explained by the Sommerfeld enhancement, by the existence of dark matter bound states, or by a nonthermally produced dark matter candidate. Additionally, large boost factors could arise from inhomogeneities in the local dark matter distribution, such as the presence of a large nearby subhalo or a density spike surrounding a nearby intermediate mass black hole.

The results of this paper disfavor dark matter candidates which annihilate largely to quarks or gauge bosons, including neutralinos (for a possible exception, see Ref. [27]), and prefer those which annihilate largely to leptons, including Kaluza-Klein dark matter in models with a universal extra dimension [91,92] or "exciting" dark matter (XDM) [44,66] as a source of the PAMELA signal. We acknowledge, however, that dramatic departures from the diffusion models or dark matter distribution used here might make it possible to evade these conclusions. As PAMELA data become available at higher energies, it will become increasingly possible to discriminate between various dark matter models. Data from Fermi [80] will also be very useful in constraining the possibility of annihilations to nonleptonic channels.

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