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Klein Dark Matter

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PAMELA and Fermi LAT signals from long-lived Kaluza-Klein dark matter

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We propose a simple extension of the minimal universal extra dimension model by introducing a small curvature. The model is formulated as a small anti-de Sitter curvature limit of the five-dimensional standard model (SM) in the Randall-Sundrum background geometry. While the lightest Kaluza-Klein (KK) particle can be thermal relic dark matter as usual in the universal extra dimension model, the KK parity is explicitly broken in the presence of the small curvature and the KK dark matter decays into the SM fermions with a long lifetime. Couplings of the KK dark matter with SM fermion pairs in the five-dimensional bulk are controlled by fermion bulk masses. By tuning bulk masses of quarks, we can suppress KK dark matter decay into quarks. With a suitable choice of bulk masses for leptons, KK dark matter decay into leptons can account for the cosmic-ray electron/positron excesses reported by the recent PAMELA and Fermi LAT satellite experiments.

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Although the existence of (cold) dark matter has been established, its identity remains a mystery in particle physics and cosmology. Pair annihilations or decays of the dark matter particles in the halo associated with our Galaxy can produce cosmic rays which could be detected by ongoing and future planned experiments. If observed, properties of the dark matter particle can be indirectly identified.

Recently, the PAMELA satellite experiment [1] has reported a significant cosmic-ray positron fraction without a corresponding increase of the cosmic-ray antiproton fraction. This result seems to be consistent with the previous results of the HEAT [2] and AMS-01 [3] experiments. In addition, the ATIC [4] and PPB-BETS [5] have reported an excess of the total positron plus electron flux at energies around 100–800 GeV. Very recently, the Fermi LAT Collaboration has released high quality data on the sum of electrons and positrons from 20 GeV to 1 TeV [6]. Although the Fermi LAT data do not confirm the peak claimed by ATIC/PPB-BETS, they still seem to indicate an excess compared to the expected background.

While these excesses could be reasonably explained by some astrophysical source nearby [7], interpretation in terms of annihilations or decays of dark matter particles are particularly interesting in the particle physics point of view. Since the PAMELA data were released, this interpretation of the excesses of the cosmic-ray fluxes has been intensively investigated. One remarkable point is that the PAMELA data show no excess for the cosmic-ray antiproton fraction, which implies a leptophilic nature of the dark matter particle. Several dark matter models possessing this nature have been proposed [8] and it has been shown that dark matter pair annihilation or dark matter decay dominantly into leptons can account for the excesses of the cosmic-ray fluxes. After the very recent Fermi LAT data, it has been argued [9] (see, also, [10]) that models where

the dark matter particle only pair annihilates into charged leptons can give a satisfactory fit to both the PAMELA and Fermi LAT data for the dark matter masses between 400 GeV and 2 TeV with a suitable annihilation cross section $\langle\sigma v\rangle = 10^{-24}\text{--}10^{-23}\text{ cm}^3/\text{s}$. For the scenario of a long-lived dark matter particle decaying only into charged leptons, this cross section is translated to the lifetime of the dark matter particle through the relation $\rho^2\langle\sigma v\rangle/(2M^2) \leftrightarrow \rho/(M\tau)$ with a local dark matter density $\rho \sim 0.3\text{ GeV}/\text{cm}^3$, and we find the dark matter particle with a mass in the range of 800 GeV–4 TeV and a lifetime $\tau \sim 10^{27}\text{ sec}$ can fit the data.

Here we note that both scenarios of the dark matter pair annihilation and the long-lived dark matter have some phenomenological issues. In the scenario of the dark matter pair annihilation, the pair annihilation cross section consistent with the dark matter observed relic abundance is too small to fit the cosmic-ray excesses, so that the “boost” factor as big as 100–1000 is necessary to enhance the annihilation cross section of dark matter in the halo. This boost factor could either have an astrophysical origin (large inhomogeneity of dark matter distribution) or have a particle physics origin such as the Sommerfeld enhancement [11] and Breit-Wigner enhancement [12]. However, according to the result of recent N -body simulations [13], the probability of forming such a large inhomogeneity may be quite small. On the other hand, in order to accommodate the particle physics mechanism for enhancing the cross section, we need to elaborate models for dark matter. In the scenario of a long-lived dark matter (gravitino as the lightest superpartner in supersymmetric models with R -parity violation is a typical example), the dark matter superweakly couples with the standard model (SM) particles and cannot be in thermal equilibrium. Thus, the relic density of the dark matter highly depends on the history

of the early Universe such as reheating temperature after inflation. In this paper, we propose a model for dark matter which can account for the cosmic-ray electron/positron excesses without these issues.

There have been many models proposed which can naturally provide a dark matter particle and among them, we consider the minimal universal extra dimension (UED) model [14,15] in this paper. In this model, the 1st Kaluza-Klein (KK) mode of the SM $U(1)_Y$ gauge boson is the lightest KK particle (LKP) and the candidate for the dark matter thanks to the conservation of KK parity [16]. Thermal relic abundance of the KK dark matter was first investigated in Ref. [17]. Through more elaborate analysis by taking into account all possible processes such as coannihilations with other KK particles and higher KK particles resonances [18], the allowed region of the KK dark matter mass has been found to be in the range of 600 GeV–1.3 TeV [19]. A KK dark matter mass ≥ 800 GeV may be favorable; otherwise the KK graviton can be the LKP. The region ≥ 1.3 TeV is excluded, since in this case, the 1st KK mode of the charged Higgs boson becomes the LKP [19].

We extend the minimal UED model by introducing a small curvature. In fact, we define the model as the limit of a very small anti-de Sitter (AdS) curvature of the five-dimensional SM [20–22] in the Randall-Sundrum (RS) warped background geometry [23]. In the presence of the curvature, the KK parity is explicitly broken and hence the KK dark matter particle is no longer stable and, in fact, decays into SM fermion pairs. We tune an extremely small curvature so as to make the dark matter particle long-lived with lifetime $\tau \sim 10^{27}$ sec. Such a small curvature has no effect on the relic abundance of the dark matter, while the dark matter decay can produce the cosmic rays. The branching ratio of the dark matter decay depends on the mass parameters of bulk fermions and hence is controllable. It is even possible to completely eliminate a specific decay mode by tuning bulk fermion masses. By suitably fixing free parameters in our model, we can provide a set of parameters chosen to give a satisfactory fit to both the PAMELA and Fermi LAT data in Ref. [9], while satisfying the correct thermal relic abundance of the KK dark matter with mass 800 GeV–1.3 TeV.

Let us now formulate our model. We consider the 5D SM model in the RS warped background geometry, in which the fifth dimension is compactified on the orbifold S^1/Z_2 with radius r_c . The 5D metric is given by [23]

$$ds^2 = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \quad (1)$$

where $\sigma(y) = k|y|$ for $-\pi r_c \leq y \leq \pi r_c$ with the AdS curvature k .

The action for a bulk fermion in the RS background geometry is given by [20–22]

$$S_f = \int d^4x \int dy e^{-4\sigma} \left[V_n^M \left(\frac{i}{2} \bar{\Psi} \gamma^n \mathcal{D}_M \Psi + \text{H.c.} \right) - \text{sgn}(y)(ck) \bar{\Psi} \Psi \right], \quad (2)$$

where $n, M = 0, 1, \dots, 4$, $\mathcal{D}_M = \partial_M - ig_5 A_M$ is the 5D covariant derivative with a 5D gauge field A_M , $V_\mu^M = e^\sigma \delta_\mu^M$, $V_4^4 = 1$, and $\gamma^n = (\gamma^\mu, i\gamma_5)$. The bulk fermion mass term is defined as ck with a dimensionless constant c . We expand the bulk fermion by the KK modes as

$$\Psi(x, y) = \sum_{n=0}^{\infty} \psi_L^{(n)}(x) e^{2\sigma(y)} f_L^{(n)}(y) + \sum_{n=0}^{\infty} \psi_R^{(n)}(x) e^{2\sigma(y)} f_R^{(n)}(y). \quad (3)$$

Because of the requirement of the Z_2 symmetry of the action, $f_L^{(n)}(y)$ and $f_R^{(n)}(y)$ must have opposite Z_2 parity. In this paper, we treat all the SM fermions as left-handed and choose $f_L^{(n)}(y)$ to be Z_2 -even, so that zero-mode left-handed fermions are identified as the SM fermions. Solving the equation of motion for KK modes with suitable boundary conditions at the orbifold fixed points corresponding to the Z_2 -parity assignment, we have zero-mode wave functions such as

$$f_L^{(0)}(y) = N_c^0 e^{c\sigma(y)}, \quad f_R^{(0)}(y) = 0 \quad (4)$$

with a normalization factor

$$N_c^0 = \sqrt{\frac{k(1+2c)}{2(e^{k\pi r_c(1+2c)} - 1)}}. \quad (5)$$

Next, we consider a 5D gauge field $\mathcal{B}_M(x, y)$ and expand its wave function as

$$\mathcal{B}_\mu(x, y) = \sum_{n=0}^{\infty} B_\mu^{(n)}(x) f_B^{(n)}(y) \quad (6)$$

with the gauge choice $\mathcal{B}_4 = 0$. The Z_2 parity of the wave functions is chosen to be even. Solving the equation of motion for the KK modes with suitable boundary conditions [20], the wave functions for zero mode and the 1st KK mode are found to be

$$f_B^{(0)}(y) = \sqrt{\frac{1}{2\pi r_c}},$$

$$f_B^{(1)}(y) = N_B^1 e^{\sigma(y)} \left[J_1\left(\frac{m_1}{k} e^{\sigma(y)}\right) - \frac{J_0\left(\frac{m_1}{k}\right)}{Y_0\left(\frac{m_1}{k}\right)} Y_1\left(\frac{m_1}{k} e^{\sigma(y)}\right) \right], \quad (7)$$

where J_q and Y_q denote Bessel functions of order q , the normalization factor N_B^1 is given by

$$1/N_B^1 = \sqrt{\int_{-\pi r_c}^{\pi r_c} dy e^{2\sigma(y)} \left[J_1\left(\frac{m_1}{k} e^{\sigma(y)}\right) - \frac{J_0\left(\frac{m_1}{k}\right)}{Y_0\left(\frac{m_1}{k}\right)} Y_1\left(\frac{m_1}{k} e^{\sigma(y)}\right) \right]^2}, \quad (8)$$

and the 1st KK mode mass is obtained as $m_1 = z_1 k$ with z_1 being the first positive solution of

$$J_0(z_1 e^{\pi k r_c}) Y_0(z_1) - J_0(z_1) Y_0(z_1 e^{\pi k r_c}) = 0. \quad (9)$$

Now we identify the bulk gauge field as the SM $U(1)_Y$ gauge field and the $U(1)_Y$ gauge coupling in 4D is defined as

$$g_Y = g_5 \int_{-\pi r_c}^{\pi r_c} dy e^{\sigma(y)} f_B^{(0)}(y) f_L^{(0)}(y) f_L^{(0)}(y) = \frac{g_5}{\sqrt{2\pi r_c}} \quad (10)$$

with the 5D gauge coupling g_5 , which is independent of the bulk fermion mass term c . In the same way, the effective gauge coupling among the 1st KK gauge boson and a pair of SM fermions is given by

$$g_Y^{(1)}(c) = g_5 \int_{-\pi r_c}^{\pi r_c} dy e^{\sigma(y)} f_B^{(1)}(y) f_L^{(0)}(y) f_L^{(0)}(y), \quad (11)$$

which depends on the bulk mass parameter c .

We now consider our model which is a simple extension of the minimal UED model with a small curvature, and we take $1/r_c \sim 1$ TeV for a typical KK particle mass scale in the minimal UED model and $\sigma_\pi = \pi k r_c \ll 1$ to obtain almost flat extra dimensions. In this case, $z_1 \gg 1$ in Eq. (9). Using the asymptotic expansion of Bessel functions,

$$J_\nu(z) \sim \sqrt{\frac{2}{\pi z}} \cos\left(z - \frac{2\nu + 1}{4} \pi\right), \quad (12)$$

$$Y_\nu(z) \sim \sqrt{\frac{2}{\pi z}} \sin\left(z - \frac{2\nu + 1}{4} \pi\right)$$

for $z \gg 1$ and $e^{\pi k r_c} \sim 1 + \sigma_\pi$, Eq. (9) is reduced into $\sin(z_1 \sigma_\pi) = 0$ and the 1st KK mode mass is approximately given as $m_1 \simeq 1/r_c$, which is consistent with the 1st KK particle mass at the tree level in the UED model.

Let us evaluate the effective coupling among the 1st KK mode of the SM $U(1)_Y$ gauge boson (KK dark matter) and a pair of SM fermions with the bulk mass ck . At the leading order of the small parameter σ_π , we find

$$\begin{aligned} g_Y^{(1)}(c) &= g_5 \int_{-\pi r_c}^{\pi r_c} dy e^{\sigma(y)} f_B^{(1)}(y) f_L^{(0)}(y) f_L^{(0)}(y) \\ &\simeq g_Y \sigma_\pi \frac{1 + 2c}{e^{(1+2c)\sigma_\pi} - 1} \frac{\int_0^1 dt e^{((3/2)+2c)\sigma_\pi t} \cos(\pi t)}{\int_0^1 dt e^{\sigma_\pi t} \cos^2(\pi t)} \\ &\simeq g_Y \left[-\frac{\sqrt{2}}{\pi^2} (3 + 4c) \right] \sigma_\pi. \end{aligned} \quad (13)$$

The effective coupling is controlled by the bulk mass parameter c and becomes zero in the flat space-time limit

(UED limit) $\sigma_\pi \rightarrow 0$, as expected. Note that we can obtain a vanishing coupling (in the leading order of σ_π) for $c = -3/4$.

In our model, all bulk mass terms for SM chiral fermions are free parameters and depending on the bulk masses, we can consider a variety of decay modes of the KK dark matter. For example, the leptophilic nature of the dark matter decay can be obtained by fixing c 's for bulk quarks to be around $-3/4$. The flavor dependence of the KK dark matter decay mode corresponds to the fermion bulk masses.

The partial decay width of the dark matter particle into left-handed fermion pairs is given by

$$\Gamma(B_\mu^{(1)} \rightarrow \psi_L^i \bar{\psi}_L^i) = N_i Y_i^2 g_Y^{(1)}(c_i)^2 \frac{m_1}{24\pi}, \quad (14)$$

where we have neglected the fermion mass, i denotes flavor, Y_i is the corresponding hypercharge, and N_i denotes the number of degrees of freedom of final state fermions, for example, $N_i = 3$ for SU(2) singlet quarks. The lifetime of the KK dark matter particle is

$$\begin{aligned} \tau &\simeq 2 \times 10^{28} \text{ sec} \times \left(\frac{10^{-26}}{\sigma_\pi}\right)^2 \left(\frac{1 \text{ TeV}}{m_1}\right) \\ &\times \left[\sum_i N_i Y_i^2 \left(1 + \frac{4}{3} c_i\right)^2 \right]^{-1}. \end{aligned} \quad (15)$$

In order to give $\tau \sim 10^{27}$ sec suitable for explanation of the PAMELA and Fermi LAT data, we need to tune the AdS curvature to be an extremely small value:

$$k \sim 10^{-15} \text{ eV} \times \left(\frac{m_1}{1 \text{ TeV}}\right). \quad (16)$$

We may think of this fine-tuning problem as a cosmological constant problem, because the AdS curvature in the RS model originates from the (negative) bulk cosmological constant.

So far we have only considered the decay modes of the KK dark matter particle to the SM fermion pairs. In precise, the KK dark matter is a mixture of 1st KK modes of the $U(1)_Y$ and charge neutral SU(2) gauge bosons after the electroweak symmetry breaking. Thus, the KK dark matter particle can decay into W -boson pairs through the KK component of the charged neutral SU(2) gauge boson. However, this decay amplitude is suppressed by a small mixing angle $(m_Z/m_1)^2 \sim 0.01$ with Z -boson mass m_Z and $m_1 \sim 1$ TeV, and is negligible compared to the decay amplitude to SM fermion pairs.

In summary, we have proposed a simple extension of the minimal UED model to account for the cosmic-ray electron/positron excesses reported by the recent PAMELA

and Fermi LAT satellite experiments. We have formulated our model as the 5D SM in the RS background geometry with a small AdS curvature. Since the curvature we have introduced is extremely small, the LKP is thermal relic dark matter as usual in the minimal UED model and the correct thermal relic abundance is realized with a suitable mass range $600 \text{ GeV} \lesssim m_1 \lesssim 1.3 \text{ TeV}$. However, the KK parity is explicitly broken in the presence of the AdS curvature and the KK dark matter is no longer stable. We have investigated the decay modes of the KK dark matter particle into SM fermion pairs and found that the partial decay widths are controlled by the bulk fermion masses which are all free parameters of the model. The special choice of the bulk mass term $c = -3/4$ can even eliminate the coupling between the KK dark matter and fermions in the leading order of the small AdS curvature. Therefore, the leptophilic nature of the KK dark matter, which is

implied by the PAMELA data for the cosmic-ray antiproton fraction, can be achieved by fixing bulk masses for quarks around $-3/4$. The model can provide a suitable parameter set, for example, $m_1 = 800 \text{ GeV} - 1.3 \text{ TeV}$ and $\tau \sim 10^{27} \text{ sec}$, which gives not only the correct thermal relic abundance of the KK dark matter but also a satisfactory fit to both the PAMELA and Fermi LAT data through the leptophilic decay of the KK dark matter. In our model, the flavor structure of primary cosmic rays from the KK dark matter decays corresponds to the bulk fermion mass terms. Precise measurements for a variety of cosmic-ray fluxes in future experiments may fix some of SM fermion bulk masses [24].

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