High-energy cosmic-ray positrons from hidden-gauge-boson dark matter

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ABSTRACT

We provide a scenario in which a hidden $U(1)$ gauge boson constitutes dark matter of the Universe and decays into the standard-model particles through a kinetic mixing with an $U(1)_{B-L}$ gauge boson. Interestingly, our model can naturally account for the steep rise in the positron fraction recently reported by PAMELA. Moreover, we find that due to the charge assignment of $U(1)_{B-L}$, only a small amount of antiprotons are produced in the decay, which is also consistent with the PAMELA and other observational data.

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1. Introduction

The presence of the dark matter has been firmly established by numerous observations, although we have not yet understood what dark matter is made of. It is promising that the PAMELA [1] and Fermi (formerly GLAST) [2] satellites in operation may reveal the nature of dark matter, helping us to pin down the dark matter particle.

Recently much attention has been attracted to a scenario that the dark matter decays into the standard-model (SM) particles [3–11], since the energetic particles produced in the decay may account for the excesses in the positron fraction reported by PAMELA [12] or HEAT [13] and in the diffuse extra galactic gamma-ray background observed by EGRET [14,15]. The PAMELA also released data on the antiproton flux [16], suggesting that most of the observed antiprotons are the secondaries produced by interactions between the primary cosmic rays and the interstellar medium. The suppression in the antiproton flux from the dark matter decay is particularly important because some decaying dark matter scenarios predict too large antiproton flux at the solar system [6].

We have recently proposed a scenario that a hidden $U(1)$ gauge boson may decay into the SM particles through its kinetic mixing with the $U(1)_Y$ in the SM gauge group [8]. In order to explain the longevity of the hidden gauge boson, the kinetic mixing needs to be suppressed down to an extremely small value, and direct couplings between the hidden and SM sectors must be negligibly small [17]. In order to achieve those features we introduced messenger fields having a large mass close to the grand unifica-

tion theory (GUT) scale, and assumed that the hidden sector is sequestered from the SM sector.

In this Letter we present a model in which such a small coupling between the hidden $U(1)$ gauge boson and the SM particles are naturally realized in the extra dimension framework. The essential idea is to separate the hidden sector from the SM sector in an extra dimension so that the two sectors can communicate with each other only through the interactions with another $U(1)_m$ gauge field in the bulk, which is assumed to be broken at a high-energy scale. The branching ratios simply reflect the charges of the SM particles under the $U(1)_m$ gauge group. Interestingly, our model can account for the steep rise in the positron fraction reported by PAMELA as well as the gamma-ray excess observed by EGRET. Moreover, the antiproton flux can be suppressed enough to be consistent with the PAMELA observations, if $U(1)_m$ is identified with $U(1)_{B-L}$.

2. Set-up

We introduce an extra dimension with two branes at the boundaries. Suppose that the hidden gauge sector is on one brane and the SM particles are on the other brane well separated from each other. In such a set-up, dangerous direct interactions between the two sectors are exponentially suppressed, and the hidden gauge boson becomes quasi-stable.[1] It is worth noting that its stability is guaranteed by the geometric separation in the extra di-

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[1] The interactions are suppressed by e^{-M_*L}, where M_* is the five-dimensional Planck scale and L denotes the size of the extra dimension. For $M_*L \sim 10^2$, the direct couplings are so small that the hidden gauge boson will become practically stable in a cosmological time scale. Then M_* is roughly equal to $M_P/10 \simeq 10^{17}$ GeV which is larger than the GUT scale ($\sim 10^{15}$ GeV), and so, our analysis in the text is valid.

mension, not by a discrete symmetry such as a R-parity. If there is a $U(1)_{B-L}$ gauge field in the bulk, the hidden $U(1)_H$ gauge field can have an unsuppressed gauge kinetic mixing with the $U(1)_{B-L}$. After integrating out the heavy $U(1)_{B-L}$ gauge boson, the effective couplings between the hidden $U(1)_H$ gauge boson A_H and the SM particles are induced, which enables A_H to decay into the SM particles. The longevity of the hidden gauge boson is realized by the hierarchy between $B-L$ symmetry breaking scale and the weak scale. As we will see below, taking the $B-L$ breaking scale around the GUT scale[2] and the mass of the hidden gauge boson of $\mathcal{O}(100)$ GeV naturally leads to the lifetime of $\mathcal{O}(10^{26})$ second that is needed to account for the positron excess.

Let us first consider the kinetic mixing between the hidden $U(1)_H$ and the $U(1)_{B-L}$ gauge symmetries. The relevant effective interactions in the four dimensions are written as

$$\mathcal{L}_{(4D)} = -\frac{1}{4}F^{(H)}_{\mu\nu}F^{(H)\mu\nu} - \frac{1}{4}F^{(B)}_{\mu\nu}F^{(B)\mu\nu} + \frac{\lambda}{2}F^{(H)}_{\mu\nu}F^{(B)\mu\nu}$$
$$+ \frac{1}{2}m^2 A_{H\mu}A_H^\mu + \frac{1}{2}M^2 A_{B\mu}A_B^\mu, \quad (1)$$

where λ denotes a coefficient of the kinetic mixing of order unity, and $F^{(H)}$ and $F^{(B)}$ are the field strengths of the $U(1)_H$ and $U(1)_{B-L}$ gauge bosons, A_H and A_B, respectively. We assume that both gauge symmetries are spontaneously broken, and therefore A_H and A_B acquire masses m and M, respectively. We also assume that the kinetic mixing is unsuppressed as $\lambda = \mathcal{O}(0.1)$, and we take $m = \mathcal{O}(100)$ GeV and $M = \mathcal{O}(10^{15})$ GeV throughout this Letter. We can make the kinetic terms canonical and diagonalize the mass matrix by appropriate transformations. The relations between (A_H, A_B) and the mass eigenstates (A'_H, A'_B) are

$$A_H \simeq A'_H + \lambda\left(1 + \frac{m^2}{M^2}\right)A'_B, \quad (2)$$

$$A_B \simeq A'_B - \lambda\frac{m^2}{M^2}A'_H, \quad (3)$$

where we have approximated $m^2 \ll M^2$ and $\lambda \lesssim 0.1$ for simplicity.

The low-energy effective interactions between the hidden gauge boson A'_H and the SM fermion ψ_i can be extracted from the $U(1)_{B-L}$ gauge interactions by using the relation (3),

$$\mathcal{L}_{int} = q_i A_B^\mu \bar{\psi}_i \gamma_\mu \psi_i \supset -\lambda q_i \frac{m^2}{M^2}A'^\mu_H \bar{\psi}_i \gamma_\mu \psi_i, \quad (4)$$

where q_i denotes the $B-L$ charge of the fermion ψ_i. The partial decay width for the SM fermion pair is

$$\Gamma(A_H \to \psi_i\bar{\psi}_i) \simeq \lambda^2 \frac{N_i q_i^2}{12\pi}\left(\frac{m}{M}\right)^4 m, \quad (5)$$

where we have neglected the fermion mass, and N_i is the color factor (3 for quarks and 1 for leptons). Thus the lifetime τ is given by

$$\tau \simeq \frac{2.5 \times 10^{27}\text{ s}}{\lambda^2 \sum_i N_i q_i^2}\left(\frac{m}{100\text{ GeV}}\right)^{-5}\left(\frac{M}{10^{15}\text{ GeV}}\right)^4, \quad (6)$$

where the sum is taken over those SM fermions of masses lighter than $m/2$.

We show the coefficient $N_i q_i^2$ for the quarks and the leptons in Table 1. It should be noted that the branching ratios are not sensitive to the mass of A_H and they simply reflect the $B-L$ charge assignment, which makes our analysis very predictive.

Table 1
The coefficients appearing in the partial decay rates for quarks and leptons.

	quark	lepton
$N_i(B-L)^2$	$\frac{1}{3}$	1

3. Cosmic-ray spectra

In this section we show the predicted spectra for the positron fraction, gamma-ray and antiproton fluxes based on the decay modes shown in the previous section. More precisely, the branching ratios are 2/39 (2/37), 2/13 (6/37) and 1/13 (3/37) for a quark pair, a charged lepton pair and a light neutrino pair, respectively, if the top quark decay channel is (not) allowed kinematically. To estimate the spectra of gamma, positron and antiproton, we use the PYTHIA [19] Monte Carlo program. After cosmic-ray particles are produced during the decay of A_H, the following calculations are straightforward and identical to those adopted in Ref. [8], and so, we show only the final results in this Letter. For readers who are interested in the details of the calculations should be referred to Ref. [6] and references therein.

In our numerical calculations we set $m = 300$ GeV and the lifetime $\tau = 1.2 \times 10^{26}$ s, and we use the so-called M2 diffusion model that are consistent with the boron to carbon ratio (B/C) and produce the minimal positron flux [6,20]. In Fig. 1 (blue line), we show the predicted positron fraction together with the recent PAMELA data and other experiments. The prediction of our model fits very well with the excess reported by PAMELA. The positron fraction steeply increases from $E \sim 10$ GeV and drops off sharply at $E = m/2 = 150$ GeV, which is mainly caused by the contribution of e^+ directly produced by the A_H decay. Such a drop-off can be checked by the upcoming PAMELA data in the higher energy region. For the MED and M1 diffusion models [20], the positron fraction becomes slightly softer in the low energy (around several tens GeV), while the difference is negligible in the high end around the peak. We mention here that, with these new data of positron from PAMELA [12], the background estimation may be different from what we adopted here [21,22]. However, since the signal of positron from decay of A_H is negligible in the low energy and is important in the high energy region, i.e. $E \gtrsim 10$ GeV, we expect that our model will still be able to explain the excess even with such a new background estimation that fits the low energy data better.

The gamma-rays are mainly produced by the π^0 generated in the QCD hadronization process, since quark pairs are produced from the decay of A_H. In Fig. 2 (blue line), we plot the gamma-rays together with the EGRET data. The gamma-ray flux peak at $E \sim 20$ GeV, and ends at $E = m/2$, which reflects the mass of decaying dark matter. With no surprise, we see that the excess observed by EGRET may also be explained by the decay of A_H.

Finally we show in Fig. 3 our predicted contribution to the antiproton flux (blue line). In Fig. 3, we have not included the prediction on the secondary antiproton flux, which should explain the BESS data [23]. Importantly, the predicted contribution to the antiproton flux from the A_H decay is smaller than the observed one by more than one order of magnitude, if the MIN propagation model [24] is adopted, as shown in Fig. 3 (a). The suppression in the antiproton flux is particularly crucial, because the recent data from PAMELA are consistent with the previous BESS result, which suggested that the secondary production dominates the observed antiproton flux. Furthermore, too many antiprotons tend to be generated as a by-product when we require the dark matter annihilation/decay to account for the positron excess [6,25]. Of course, the predicted antiproton flux still has a large uncertainty mainly due to our poor understanding of the cosmic-ray propagation inside our galaxy. As we can see in Fig. 3 (b), for different
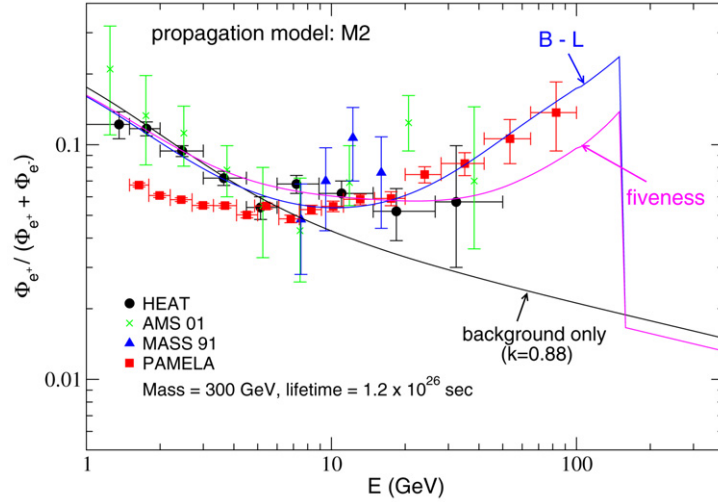
Fig. 1. The predicted positron fraction from A_H decay via the kinetic mixing with $U(1)_{B-L}$ (blue line) and $U(1)_5$ (magenta line) using the M2 propagation model, compared with the experimental data, including the recent PAMELA results. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)
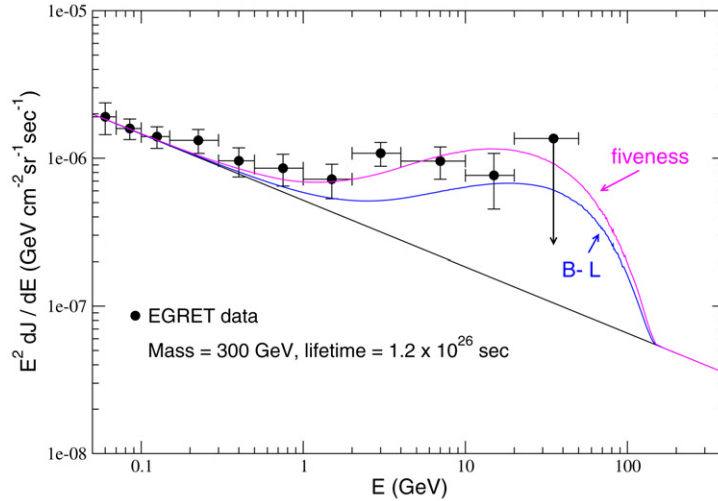

Fig. 2. The predicted gamma-ray flux of A_H decay via the kinetic mixing with $U(1)_{B-L}$ (blue line) and $U(1)_5$ (magenta line), compared with the EGRET data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

propagation models (MED and MAX), the antiproton flux from decaying A_H can be enhanced by about two orders of magnitude. However, our scenario can still be consistent with the observed antiproton flux.[3]

4. Discussion and conclusions

So far we have focused on the case that the $U(1)_m$ gauge symmetry in the bulk is identified with the $U(1)_{B-L}$ symmetry, but it is also possible to consider another anomaly-free charge assignments given by a linear combination of the $B - L$ and the hypercharge Y. However, as we can check easily, the hadronic decay branching ratio, which is a measure for the antiproton flux, becomes smaller as the contribution of the hypercharge is suppressed. In this respect, our choice of the $U(1)_{B-L}$ is well moti-

vated by observation, since the antiproton flux is naturally suppressed enough to be consistent with the PAMELA data. For comparison, let us consider a $U(1)_5$, so-called "fiveness", instead of $U(1)_{B-L}$. The charge Q_5 of the $U(1)_5$ is given by the following linear combination of the charges under $U(1)_{B-L}$ and $U(1)_Y$ [26]:

$$\frac{2\sqrt{10}}{5} Q_5 = \frac{4}{5} Y - (B - L). \tag{7}$$

We have similarly estimated the spectra for the positron fraction, gamma-rays, and antiprotons when the $U(1)_m$ in the bulk is identified with $U(1)_5$. In order to compare with the $U(1)_{B-L}$ case, we take the same parameter sets, i.e. $m = 300$ GeV and $\tau = 1.2 \times 10^{26}$ s. The decay branching ratios of A_H decay are roughly 4.5%, 18.3%, 6.5%, 4.8% and 2.3% for up-, down-type quark, charged lepton, neutrino and W-boson pairs, respectively. We show the results of cosmic rays as the magenta lines in Figs. 1, 2 and 3. The distribution of positron fraction in fiveness case seems flatter compared to the $B - L$ case and the inclination of the turnup is softer. This is due to the fact that positrons generated from the decay of hadrons (mainly from π^+) become more important and the branching ratio of e^+e^- mode decreases simultaneously. The five-

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[3] We notice that, the estimated background secondary antiproton flux drops quickly as the energy increases, and that the signal for the MED diffusion model seems to exceed the PAMELA data on the antiproton to proton ratio in the high energy region. However, our scenario is consistent with the PAMELA data in the high end if the MIN propagation model is adopted.
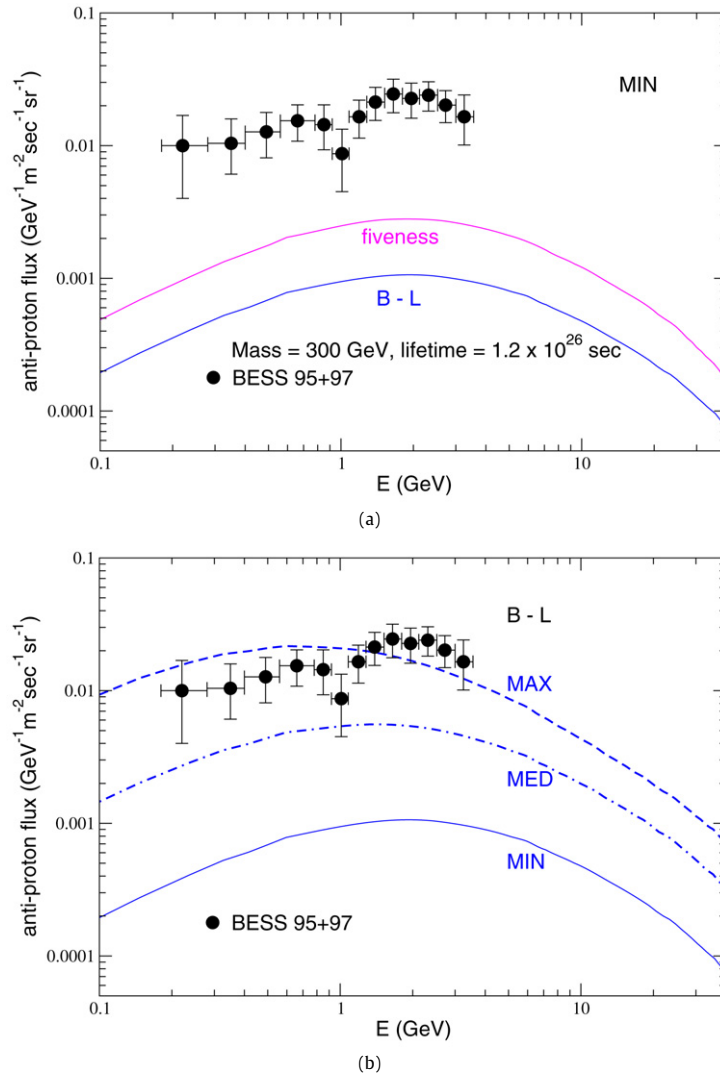
Fig. 3. (a) Antiproton flux from the A_H decay via the kinetic mixing with $U(1)_{B-L}$ (blue line) and $U(1)_5$ (magenta line), compared with the BESS data. (b) Predicted antiproton fluxes from the A_H in the $U(1)_{B-L}$ case, using different propagation models. Note that the secondary antiproton contributions are not included. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

ness model predicts a larger excess in the gamma-ray flux, since more π^0s are produced. Finally, we can see from Fig. 3 that the antiproton flux is enhanced for the $U(1)_5$ compared to the case of $U(1)_{B-L}$ due to a larger total branching ratio of quark pairs. Note that, in order to explain the PAMELA positron fraction data in the high energy region, we need to adopt a shorter lifetime for fiveness model compared to the case of $B-L$. Accordingly, the gamma-ray and antiproton fluxes increase, which may result in a tension with observed data and make the fiveness model being slightly disfavored. In our previous work [8] we considered a scenario that the hidden $U(1)_H$ gauge boson mixes with the $U(1)_Y$. The predicted spectra in this case are somewhat between the $B-L$ and fiveness cases.

Let us comment on the production of the hidden gauge boson in the early Universe. Although the couplings of A_H to the SM particles are extremely suppressed, we can generate a right abundance of A_H from thermal scatterings as follows. For the reheating temperature about 10^{15} GeV, the $B-L$ gauge bosons will be in thermal equilibrium, and the A_H can be produced through a non-renormalizable coupling such as

$$\mathcal{L} \simeq \frac{\kappa}{M_*^4} F^{(H)2} F^{(B)2}, \tag{8}$$

where M_* denotes the five-dimensional Planck scale (see footnote 1) and κ is a numerical coefficient of order unity. The presence of such non-renormalizable operator on the hidden brane is natural since it is allowed by the gauge symmetries. The abundance of A_H produced via the operator is roughly estimated by

$$\Omega_{A_H} h^2 = \mathcal{O}(0.1) \left(\frac{\kappa}{0.03} \right)^2 \left(\frac{m}{300 \text{ GeV}} \right) \left(\frac{T_R}{10^{15} \text{ GeV}} \right)^3 \left(\frac{M_*}{M_P/10} \right)^{-4}, \tag{9}$$

where T_R is the reheating temperature. Note that the required reheating temperature is smaller than the cut-off scale M_*. Also non-thermal production of A_H by e.g. the inflaton decay [27–29] should work as well.

In this Letter, we propose a scenario that a hidden gauge boson constitutes the dark matter of the Universe and decays into the SM particles via the kinetic mixing with the $U(1)_{B-L}$ gauge field in the bulk. Interestingly, our model can account for the steep rise in the positron fraction reported by PAMELA as well as the gamma-ray excess seen by EGRET, while avoiding the constraint on the antiproton flux by PAMELA and other experiments, if the M2 propagation model is adopted, due to the smallness of quark's quantum number under the gauged $U(1)_{B-L}$. Moreover, the very small decay rate of the hidden A_H gauge boson dark matter is realized

naturally by the hierarchy between weak scale and the large $B - L$ breaking scale which is about the GUT scale as suggested by the neutrino masses.

Acknowledgements

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