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Decaying Hidden Gauge Boson and the PAMELA and ATIC/PPB-BETS Anomalies

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Abstract

We show that the PAMELA anomaly in the positron fraction as well as the ATIC/PPB-BETS excesses in the $e^- + e^+$ flux are simultaneously explained in our scenario that a hidden $U(1)_H$ 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, the $B-L$ charge assignment suppresses an antiproton flux in consistent with the PAMELA and BESS experiments, while the hierarchy between the $B - L$ symmetry breaking scale and the weak scale naturally leads to the right lifetime of $O(10^{26})$ seconds.

The nature of dark matter has been a big mystery in modern cosmology. Recently, there appeared several exciting observational data on high-energy cosmic-ray particles, which may be shedding light on this issue.

The PAMELA data [1] shows that the positron fraction starts to deviate from the theoretically expected value for secondary positrons around 10 GeV and continues to rise up to 100 GeV, and no drop-off has been observed so far. The excess in the positron fraction observed by PAMELA strongly indicates that there is an unidentified primary source of the galactic positrons. It is natural to expect that the electron flux may be also modified above 100 GeV, because normally electron-positron pairs are produced by such a primary source, and the PAMELA anomaly suggests a rather hard positron energy spectrum. Interestingly enough, the ATIC balloon experiment collaboration [2] measured the total flux of electrons plus positrons, and has recently released data which shows a clear excess peaked around 600 GeV, in consistent with the PPB-BETS experiment [3]. Since it is difficult to produce such hard spectrum with a sharp drop-off as observed in the ATIC/PPB-BETS data by conventional astrophysical sources like pulsars, the galactic electrons and positrons may be generated though the annihilation and/or decay of dark matter.

We have recently proposed a scenario that a hidden $U(1)_H$ gauge boson constitutes dark matter of the Universe and decays into the standard-model (SM) particles through a kinetic mixing with a $U(1)_{B-L}$ gauge boson [4, 5], and it was shown that our model can explain the PAMELA excess without producing too many antiprotons, in consistent with the PAMELA [6] and BESS [7] experiments.[#1] In this letter we show that our model can naturally explain both the PAMELA and ATIC/PPB-BETS anomalies, for the hidden gauge boson of a mass about 1.2 TeV, while the antiproton flux is still suppressed enough due to the $B-L$ charge assignment. Interestingly, our scenario predicts an excess in the diffuse gamma-ray background peaked around 100 GeV, which will be tested soon by the Fermi (formerly GLAST) [9] satellite in operation.

Let us here briefly review our set-up (see Ref. [5] for more details). 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, which are well separated from each other so that direct interactions between the two sectors are exponentially suppressed.

[#1] See Refs. [8] for other dark matter models that account for the PAMELA excess.

We assume that a $U(1)_{B-L}$ gauge field resides in the bulk. Then the hidden $U(1)_H$ gauge field can have an unsuppressed gauge kinetic mixing with the $U(1)_{B-L}$. We expect that the $U(1)_{B-L}$ gauge symmetry is broken around the grand unification theory (GUT) scale of about 10^{15} GeV, since the seesaw mechanism [10] for neutrino mass generation suggests the right-handed neutrinos of a mass about 10^{15} GeV. 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 with a extremely long lifetime due to the hierarchy between the $B-L$ breaking scale and weak scale.

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 [5],

$$\mathcal{L}_{\rm int} \;=\; -\lambda\, q_i \frac{m^2}{M^2} A_H^\mu\, \bar{\psi}_i \gamma_\mu \psi_i, \tag{1}$$

where λ is a coefficient of the kinetic mixing, q_i denotes the $B-L$ charge of the fermion ψ_i, and m and M are the masses of the hidden gauge boson A_H and the $U(1)_{B-L}$ gauge boson, respectively.

The partial decay width for the SM fermion pair is

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

where we have neglected the fermion mass, and N_i is the color factor (3 for quarks and 1 for leptons). Note that the coefficient $N_i q_i^2$ is 1/3 and 1 for quarks and leptons, respectively, which results in the suppression of the antiproton flux. The lifetime τ is therefore given by

$$\tau \;\simeq\; 1 \times 10^{26}\,{\rm sec} \left(\sum_i N_i q_i^2\right)^{-1} \left(\frac{\lambda}{0.01}\right)^{-2} \left(\frac{m}{1.2\,{\rm TeV}}\right)^{-5} \left(\frac{M}{10^{15}{\rm GeV}}\right)^{4}, \tag{3}$$

where the sum is taken over the SM fermions. 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.

Let us now estimate the spectra for the positron fraction, $(e^- + e^+)$, gamma-ray and antiproton fluxes based on the decay modes discussed above. The branching ratios are 2/39 and 2/13 for a quark pair and a charged lepton pair, respectively. To estimate the spectra of the gamma, positrons and antiprotons, we use the PYTHIA [11] 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. [4], and so, we show only the final

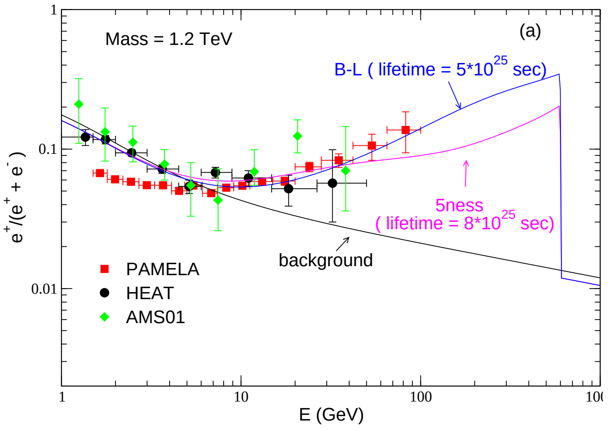

FIG. 1: (a) The predicted positron fraction from A_H decay via the kinetic mixing with $U(1)_{B-L}$ (blue line) and $U(1)_5$ (magenta line), compared with the experimental data [13, 14], including the recent PAMELA results [1]; (b) For $U(1)_{B-L}$ case only, using different sets of parameters in solving

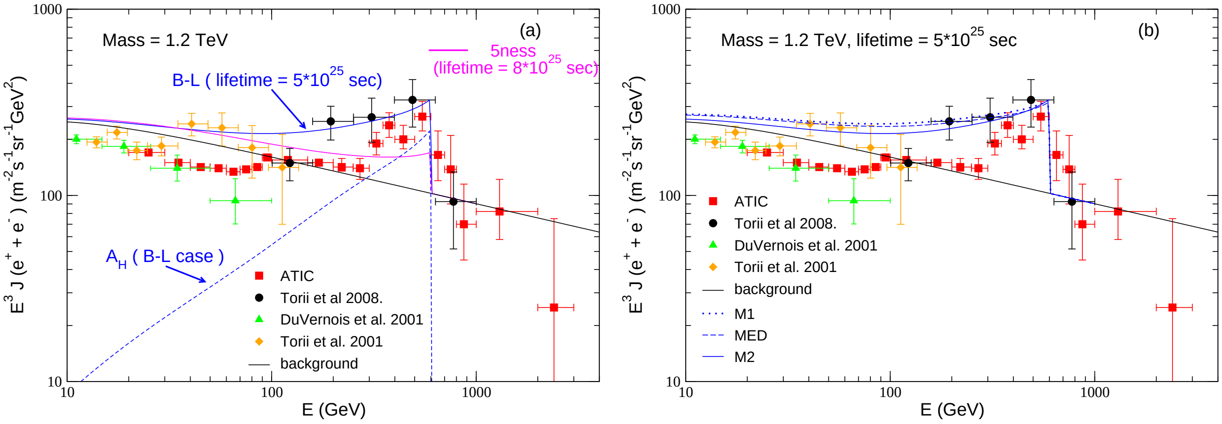

FIG. 2: (a) The predicted $(e^- + e^+)$ spectrum from A_H decay via the kinetic mixing with $U(1)_{B-L}$ (blue line) and $U(1)_5$ (magenta line), compared with the various observational data [15, 16] including the latest ATIC [2] and PPB-BETS [3] results. (b) For $U(1)_{B-L}$ case only, using different sets of parameters in solving diffusion equation.

results in this letter. For readers who are interested in the details of the calculations should be referred to Ref. [12] and references therein.

In our numerical calculations we set $m = 1200\,\text{GeV}$ and the lifetime $\tau = 5 \times 10^{25}$ seconds, and we use the parameter sets that are consistent with the Boron to Carbon ratio (B/C) and produce the maximal (M1), medium (MED) and minimal (M2) positron fluxes [12].

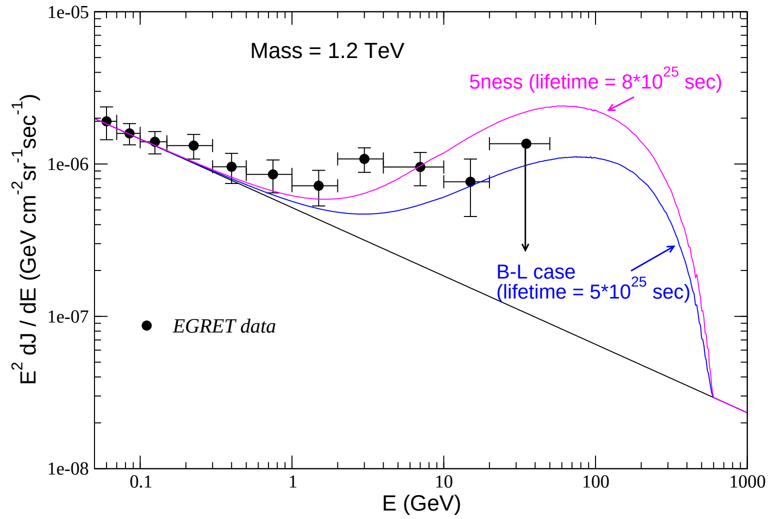

FIG. 3: The predicted flux of the diffuse gamma-ray background from A_H decay via the kinetic mixing with $U(1)_{B-L}$ (blue line) and $U(1)_5$ (magenta line), compared with the EGRET data [17, 18]

In Fig. 1 (a), we show the predicted positron fraction (blue line) together with the recent PAMELA data and other experiments. The prediction of our model fits very well with the PAMELA excess, and increases up to $E = 600$ GeV, a half of the mass of A_H. We also show the $(e^- + e^+)$ spectrum together with the latest ATIC [#2] and PPB-BETS data in Fig. 2 (a) (blue line). The contribution from the dark matter decay is shown as the dotted line in the $B-L$ case, and the characteristic drop-off can be used to infer the mass scale of dark matter. Furthermore, the upcoming PAMELA data in higher energy region ($100 \sim 270$ GeV) will be able to test our prediction. In Figs. 1 (b) and 2 (b), we show the results for different parameters used in solving the diffusion equation. As we can see, the electron and positron spectrum in the M1 and MED cases are softer than that in the M2 case.

The gamma-rays are mainly produced by π^0's generated in the QCD hadronization process and the decay of τ, since quark pairs as well as a tau lepton pair are produced from the decay of A_H. In Fig. 3, we plot the gamma-rays together with the EGRET data [17, 18] (blue line). The excesses in the gamma-ray flux are between a few GeV and 600 GeV.

Finally, we show in Fig. 4 the predicted antiproton-to-proton ratio, $\bar{p}/p$, compared with

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[#2] The ATIC data points were read from Fig. 3 in Ref. [2]. The background line shown in Fig. 2 is slightly different from that adopted in Ref. [2]. Here we have used the same estimate that we adopted to fit the PAMELA data. Note that, even with a slightly lower background (as in Ref. [2]), we can still fit both the PAMELA and ATIC/PPB-BETS excesses by varying the lifetime accordingly.

experimental data [6, 19]. We adopt the MIN diffusion model [12] to calculate the contribution from dark matter. For the lifetime $\tau = 5 \times 10^{25}$ sec, the prediction (solid red line) is consistent with the observational data up to $E \lesssim 40\,\mathrm{GeV}$, and slightly exceeds the PAMELA data point around $E \simeq 60\,\mathrm{GeV}$. This does not necessarily mean that our model is inconsistent with the PAMELA data. First, it should be noted that the predicted antiproton flux sensitively depends on the propagation model, and the one we adopt is based on several simplifications which has enabled us to solve the diffusion equation analytically. Second, the predicted antiproton flux depends on the dark matter profile and model parameters such as mass and lifetime. For example, by increasing the mass of dark matter, the place where our prediction starts deviating from the data will be shifted up to higher energy; we may also simply decrease the decay rate. See the red dashed line shown in the Fig.4, which corresponds to $\tau = 10^{26}$ sec. In this case, the predicted fluxes of electrons and positrons will be slightly reduced as well. We may need to adopt different normalization of the primary electrons to have a better fit to the observed data. However, given relatively large errors of the ATIC/PPB-BETS data, this may not be a severe issue. In any case, the current PAMELA data in the high energy still does not have large enough statistics, and we expect that the behavior of $\bar{p}/p$ in the higher energy will enable us to test or refute the current model in the near future.

For completeness we consider a case that the $U(1)$ gauge symmetry in the bulk is $U(1)_5$, so-called "fiveness", instead of $U(1)_{B-L}$. The $U(1)_5$ is anomaly free and the charge is proportional to $4Y - 5(B-L)$, where Y is the hypercharge. We show the predicted spectra in the case of the $U(1)_5$ as the magenta lines in Figs. 1, 2, 3 and 4. Note that the hadronic decay branching ratio, which is a measure for the antiproton flux, becomes larger, with respect to that in the $U(1)_{B-L}$ case.

In this letter, we have shown that both the PAMELA excess in the positron fraction and the ATIC/PPB-BETS anomaly in the electron plus positron flux are simultaneously explained in our model that the hidden-gauge-boson dark matter decays into the SM particles via the kinetic mixing with the $U(1)_{B-L}$ gauge field in the bulk. Interestingly, our model can naturally avoid the constraint on the antiproton flux by PAMELA and BESS experiments due to the smallness of quark's quantum number under the $U(1)_{B-L}$. Moreover, our model predicts an excess in the diffuse gamma-ray background between a few GeV and 600 GeV, which will be tested by the Fermi satellite in operation. Finally we would like to emphasize

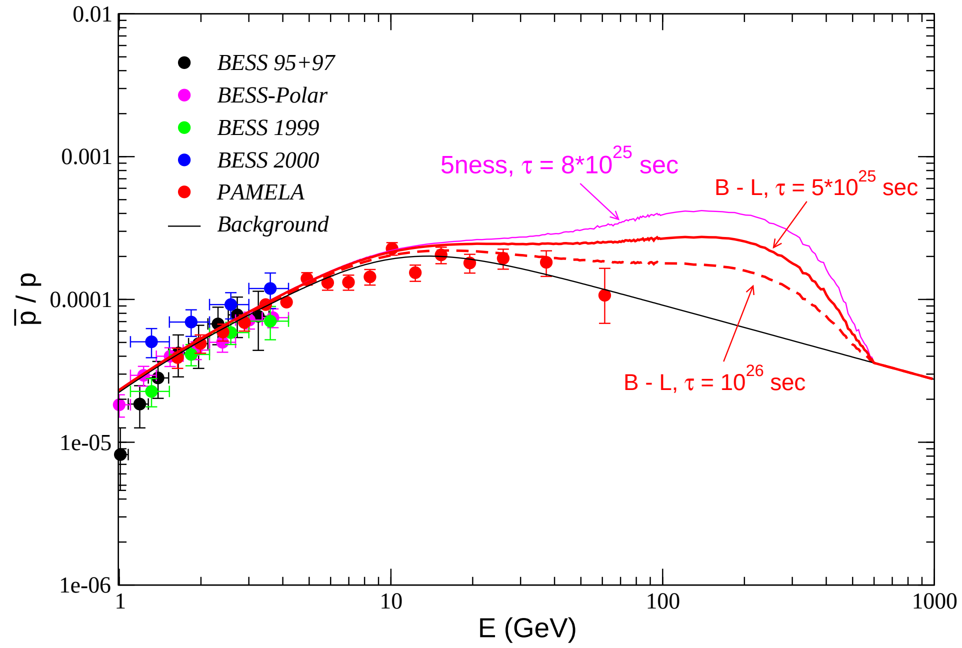

FIG. 4: The predicted $\bar{p}/p$ ratio and the BESS and PAMELA data. The red solid (dahsed) lines corresponds to $\tau = 5 \times 10^{25}$ sec (10^{26} sec) for the $B-L$ case, while the purple line represents the fiveness.

that the needed lifetime of $\mathcal{O}(10^{26})$ seconds 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.

Note added: Recently the Fermi LAT collaboration has released the data on the electron plus positron flux [20] , and the ATIC excess was not confirmed. Our model may also fit the Fermi data for a different choice of the mass and lifetime, but detailed analysis is beyond the scope of this letter. We are also aware that the preliminary result of diffuse gamma-ray from Fermi LAT collaboration has been presented in several conferences [21]. However, we need to wait for the official release of the data in order to compare it with the prediction of our model.

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