High-energy cosmic antiparticle excess vs. isotropic gamma-ray background problem in decaying dark matter Universe

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Abstract. We are going to show that any conventional decaying dark matter model, providing an explanation of cosmic antiparticle excess observed by PAMELA and AMS-02, inevitably faces the contradiction with isotropic diffuse gamma-ray background, measured by FERMI/LAT.

1. Introduction

Charged cosmic particles seems to be one of the most essential source of information about our Galaxy, it’s structure and composition. In spite of the evident role, which charged cosmic rays play in astrophysics, they also provide a unique tool to search for new physics. An indeed sensitive “probe” to reveal the presence of some exotic objects inside our Galaxy (like dark matter particles, microscopic black holes, Q-balls and etc.) is the abundance of high-energy charged antiparticles (HECA), since their production rate in ordinary astrophysical phenomena rapidly falls to zero with the growth of energy.

The unceasing experimental attempts of studying the antiparticle cosmic rays component had lead to the discovery of high-energy positron excess in PAMELA experiment [1]. The same apparatus has in addition observed the hints of high-energy antiproton excess [2]. Recently AMS-02 experiment (which has also detected the increase of positron fraction [3] and measured it more accurately) confirmed the PAMELA’s guess on antiprotons [4]. Thus we have an unexplained surplus over secondaries in both antiproton and positron spectrum, which insinuates the existence of unknown primary sources of energetic antiparticles.

Though a few articles (see for instance [5, 6]) claim that there’s no excess at all, but only secondaries, arising due to the uncertainties in cosmic ray propagation model (especially in antiprotons), theoretical endeavours in understanding the nature of HECA source can be mainly divided in two groups. Authors belonging to the first group (e.g. [7, 8]) state that well-known astrophysical objects like old supernova remnants and pulsars are responsible for the aforementioned effects. The second ones (e.g. [9–11]) turn to a new and undiscovered essence (mostly dark matter) to explain the experimental results.
In this work we are going to consider a lax, though demonstrative, proof that any reasonable dark matter model (with conventional isotropical distribution of unstable or annihilating component) producing enough charged antiparticles to explain PAMELA and AMS-02 results is strictly constrained by FERMI/LAT data on diffuse isotropic gamma-ray background [12].

2. Cosmic rays from dark matter decays

Let us consider a common phenomenological dark matter model, where a fraction of dark matter $\xi$ consist of metastable particles $X$ with mass $M_X$ and lifetime $\tau$ (in fact an independent parameter of our model defining the fluxes of HECA is $\xi/\tau$, so one can easily increase the amount of metastable dark matter by increasing it’s lifetime or vice versa), decaying to various SM particles (for our purposes it is enough to introduce only $e^- e^+$, $\mu^- \mu^+$, $\tau^- \tau^+$ and $u\bar{u}$ channels since any other rational decay mode like $b\bar{b}$, $ZZ$ or $W^- W^+$, providing charged antiparticles couldn’t significantly improve the result) with different branching ratios. Our aim is to fit the data on charged cosmic particles (especially antiparticles), taking into account the effects of their propagation in the Galaxy (diffusion, re-acceleration, energy losses and etc.). To calculate the propagation of charged particles (including “background” fluxes, such as primary electrons and protons of common astrophysical origin and secondary positrons, electrons and antiprotons from spallation of cosmic rays on interstellar media) and gamma rays brought by these charged particles, traveling through magnetic halo of the Galaxy (inversed compton scattering (ICS) photons and bremsstrahlung), we used GALPROP [13]. In our analysis we assumed that the dark matter density profile is Navarro-Frenk-White (NFW):

$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{(r/r_s) \left[ 1 + (r/r_s)^2 \right]}$$

(1)

with scale radius $r_s = 24$ kpc and the factor $\rho_0$ was chosen to reproduce the local dark matter density $\rho_\odot = 0.39$ GeV/cm$^3$ at $R_\odot = 8.5$ kpc [14]. The chosen values of propagation parameters corresponds to MED model [15]. The primary (injection) spectra of cosmic rays was simulated using Pythia 8.1 [16].

Besides charged particles and antiparticles decaying dark matter component also produce gamma rays (and neutrinos which, however, have nothing to do with the aim of our analysis) and thus contribute to the isotropic diffuse gamma-ray background. This contribution includes prompt radiation (i.e. final-state radiation and gamma rays from meson decays in case of $\tau$-lepton and hadronic modes), coming to us directly from the point where a dark matter decay took place, and radiation induced by “roaming” charged particles, born in these decays (the last component of gamma rays, as we’ve mentioned, was calculated using GALPROP). The prompt radiation in its turn can be classified by its origin as Galactic and extragalactic radiation.

Gamma-ray flux from decays in the Galactic halo can be calculated as

$$F_{\gamma}^G(E) = \frac{\xi}{4\pi M_X \tau \Delta \Omega} \sum_i \text{Br}_i \frac{dN_i}{dE} \int_{\Delta \Omega} d\Omega \int_{\text{line-of-sight}} ds \rho_{\text{DM}}[r(s, b, l)],$$

(2)

where $\Delta \Omega$ is the observable angular region of the sky (in our analysis it corresponds to the range of Galactic coordinates $20^\circ \leq b \leq 90^\circ$ and $0^\circ \leq l < 360^\circ$, where FERMI/LAT measures IGRB), $\rho_{\text{DM}}$ is the dark matter density distribution (NFW) as a function of galactocentric radius (which can be expressed as $r(s, b, l) = \sqrt{8.5^2 + s^2 - 2 \cdot 8.5 s \cos(b) \cos(l)}$), $\text{Br}_i$ denotes the branching ratio of i-th decay channel and $dN_i/dE$ is the energy spectrum of primary photons, emitted in that channel.

The extragalactic contribution to IGRB from dark matter decays can be estimated as
\[ F_{\gamma}(E) = \frac{c \xi \Omega_{\text{DM}} \rho_{\text{crit}}}{4 \pi M_X \tau} \int_{0}^{\min\{E_{\text{max}}/E, 1100\}} \frac{dz}{H_0 \sqrt{\Omega_{m} + \Omega_{m}} (1 + z)^3} \sum_i \frac{dN_i}{dE} [(1 + z)E], \]  

where \( c \) is the speed of light, \( \rho_{\text{crit}} = 4.9 \text{ keV/cm}^3 \) is the critical density of the Universe, \( E_{\text{max}} = M_X/2 \) denotes the maximal energy of the photon (and \( z = 1100 \) corresponds to the beginning of recombination epoch), \( \Omega_{m} = 0.315, \Omega_{\text{DM}} = 0.265 \) and \( \Omega_{\Lambda} = 0.685 \) denotes matter, dark matter and dark energy cosmological densities respectively, \( H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is the modern Hubble expansion rate.

3. The problem of gamma-ray overabundance

![Figure 1](image_url)

**Figure 1.** Predicted fraction of positrons in cosmic rays. The values of model parameters corresponds to those listed in the top left part of the plot. We compare our results to data in the energy range above 20 GeV, where the effects of solar modulation are insignificant.

As it was noted in [17], any conventional decaying (or annihilating) dark matter model pretending to explain experimental data on both high-energy cosmic antiproton and positron abundance inevitably suffers from diffuse gamma rays “pollution”. Here we are going to show a special case, where this problem arise, though it appears to be a global issue (see section 4 for details). Suppose the metastable fraction of dark matter \( (\xi \sim 10^{-6}) \) has a mass \( M_X \sim 1800 \text{ GeV} \) and lifetime \( \tau \sim 10^{20} \text{ s} \). The exact values of its lifetime and branching ratios were found to adequately reproduce the observed fluxes of HECA. In figures 1-3 we present the predicted positron fraction, antiproton flux and diffuse gamma-ray flux respectively, compared to the corresponding experimental data.
Figure 2. Predicted antiproton flux from dark matter decays, compared to the PAMELA data. The yellow strip corresponds to the flux of secondary and tertiary antiprotons, scattered due to the uncertainties of propagation parameters.

So, as one can clearly see, an attempt to explain the excess of high-energy positrons and antiprotons clashes with IGRB observation (note that in our analysis we do not try to reproduce the IGRB spectrum, but our intention is just not to exceed it). Though we haven’t provided a mathematically accurate fit of the data yet, in this case it is quite obvious that a “fine tuning” of the model parameters won’t relieve the considering problem.

4. Conclusion
In this work we have demonstrated, how gamma rays accompanying dark matter decays to charged particles complicates the satisfactory explanation of positron and antiproton anomaly in cosmic rays. Despite the fact that we’ve considered only some special case a number of reasons let us suppose that this problem covers any reasonable dark matter model, assuming isotropical distribution of particles and a set of propagation parameters, consistent with B/C ratio. First of all, variation of mass parameter can not change the situation substantially, because lower values of mass (≲ 1 TeV) harden the explanation of high-energy positrons and antiprotons, while greater values of mass (> 1800 GeV) are strictly constrained by IGRB data. Since positron flux is almost insensitive to the choice of propagation model (MIN, MED or MAX) and since the drastic contribution into the gamma-ray spectrum comes mostly from leptonic modes variation of propagation parameters do not help either. The difference between annihilations and decays (as well as the difference between various dark matter distribution profiles) also doesn’t affect the gamma-ray spectrum, if the model provides a statistically acceptable fit of (at least) positron data. All these features though should be taken into account while doing the global statistical
Figure 3. Predicted diffuse gamma-ray flux from dark matter decays, compared to the FERMI/LAT data. The contributions from leptonic (blue dot-dashed) and hadronic (red dashed) channels are shown separately. The flux is averaged over the solid angle corresponding to the range of Galactic coordinates $20^\circ \leq b \leq 90^\circ$ and $0^\circ \leq l < 360^\circ$, in which FERMI/LAT measures IGRB. The uncertainties of IGRB are related to the arbitrary choice of foreground model.

analysis, which will be the next step of our research. Also we propose a possible solution to the discussed problem, requiring a reconsideration of conventional isotropic distribution of decaying dark matter [18].

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