On the Special Significance of the Latest PAMELA Results in Astroparticle Physics

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Abstract

In continuation of their earlier measurements, the PAMELA group reported data on antiproton flux and $\frac{\mathcal{P}}{P}$ ratios in 2010 at much higher energies. In past we had dealt with these specific aspects of PAMELA data in great detail and each time we captured the contemporary data-trends quite successfully with the help of a multiple production model of secondary antiprotons with some non-standard ilk and with some other absolutely standard assumptions and approximations. In this work we aim at presenting a comprehensive and valid description of all the available data on antiproton flux and the nature of $\frac{\mathcal{P}}{P}$ ratios at the highest energies reported so far by the PAMELA experiment in 2010. The main physical implication of all this would, in the end, be highlighted.

Keywords: Cosmic ray interactions. Composition, energy spectra and interactions. Cosmic rays (including sources, origin, acceleration, and interactions). Dark Matter (stellar, interstellar, galactic, and cosmological).

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In the cosmic ray physics and astroparticle domain the most familiar and important antiparticles are the positrons and antiprotons. The energy dependent behaviours of $e^+/e^−$ and $\overline{P}/P$ are experimentally found to be sharply in contrast. While for the former (positron-to-electron ratio) the antiparticle-to-particle ratio experimentally shows a slowly rising trend with increasing energy, the behaviour for the latter is seem to be quite different. And the controversy persists over the question whether $\overline{P}/P$ ratios remain nearly constant with increasing antiproton energy or there is a gradual fall-off of the ratio with a not-very-sharp slope. Besides, it is well known that cosmic ray antiproton energy spectrum provides valuable information on the origin and propagation of cosmic rays. It also throws light on the feasibility of the ‘exotic’ sources of primary antiprotons, such as annihilations of dark matter particles and the evaporation of the primordial black holes.

Our work here would be grounded on the following physical considerations which are being listed at the outset. (i) We would counter the hypothesis of the exotic sources of antiprotons, nor we would assume any contribution from the supersymmetric particles-decays. (ii) We accept the simple leaky box model for propagation of cosmic rays. (iii) We will assume here the primary proton spectra represented by Bhadwar et al[1] to remain valid. (iv) We concentrate only on the secondary antiprotons which arise of the multiparticle production phenomena at high/superhigh energies. (v) We induct a multiple production model which is certainly not of the typically ‘standard’ variety. In fact, herein an element of exoticity would come into the whole of the physics scenario. (vi) As the present study pertains to much higher energies, the probability of occurrence of contributions from annihilation channels would be considered to be totally switched off in our mathematical calculations, for which the damping term[2] that was introduced in one of our previous works on the same topic would be eliminated here altogether.

According to the model the low-$p_T$ (soft) baryon-antibaryons are produced through the decays of (virtual) secondary pions in a sequential chain of which proton-antiproton pairs comprise nearly one third of the total. Bhattacharyya[3] had worked out the details of the necessary field-theoretic calculations based on Feynman diagrams and obtained the following formulae for inclusive cross-sections at low-$p_T$ valid for moderately high to very high energies and the expression for average antiproton multiplicity

$$E^3 d^3 \sigma_{\overline{p}p \to \pi X} \simeq 1.87 \times exp[-7.38 \frac{p_T^2 + m_{\overline{p}}^2}{1-x}] exp[-5.08x]$$  \hspace{1cm} (1)

and

$$< n_{\overline{p}} > \simeq 1.08 \times 10^{-2} s^{2/5} \hspace{1cm} \text{for} \sqrt{s} \leq 100 GeV$$ \hspace{1cm} (2)

$$< n_{\overline{p}} > \simeq 2 \times 10^{-2} s^{1/4} \hspace{1cm} \text{for} \sqrt{s} > 100 GeV$$ \hspace{1cm} (3)

where $m_{\overline{p}}$ is the mass of the antiproton and $n_{\overline{p}}$ is the measured antiproton multiplicity. With (2) we get at $\sqrt{s}=53 GeV$, $< n_{\overline{p}} > \simeq 0.2$ for both the formulae.

In actual evaluation of the cosmic antiproton production observables the model dependence comes into picture for getting values of $d\sigma/dE$ which is related with the inclusive cross-section in the following way[4] :

$$\frac{d\sigma}{dE} = \frac{\pi}{p_L} \int (E^3 d^3 \sigma_{\overline{p}p \to \pi X} \ dp_T^2 d\pi_T^2)$$  \hspace{1cm} (4)

Here we take $p_L \simeq E$ as the transverse momenta of the produced secondary antiprotons is assumed to be small.
Inserting expressions (1), (2) and (3), our model-derived formula for inclusive cross-section valid at moderately high energies in eqn.(4) and integrating over $p_T$ with normal approximations we get

$$\frac{d\sigma}{dE}_{p\to p} \simeq 0.496 \exp[-5.08x]$$

(5)

where we have used the low-transverse-momentum upper limit up to $p_T=1$ GeV/c. It must also be recalled that $p_L \simeq E$. Bhattacharyya and Pal[5, 6] have worked out that the antiproton-to-proton ratio is to be given finally by

$$f_p(E) = \frac{J_p(E)}{J_p(E)} = \frac{2K\lambda_e(E)}{m_p} \int_0^{X_s} E d\sigma_p dE X^{-1} x \gamma^{-1} dx$$

(6)

where $J_p$ and $J_p$ are the differential fluxes of the primary protons and the secondary antiprotons ($m^{-2}sr^{-2}s^{-1}GeV^{-1}$) respectively. $K$ is the correction coefficient taking into consideration the composition of the primary cosmic rays and the interstellar gas, $\lambda_e(E)$ is the average path length of antiprotons against escape (gcm$^{-2}$ as the unit), $m_p$ is the mass of the proton (g as the unit), $E_p$ is the total energy of the primary proton, $E_s$ is the integral lower limit relevant to the production threshold of antiprotons, $\gamma$ is the integral energy spectrum exponential of the primary protons and is the sole quantity taken from cosmic-ray information. For actual calculations we use here : $\gamma=1.75$, $X = E/E_p$ and $X_s = E_s/E_p$ (we took $X_s \simeq -(m_p c^2/E)+[(m_p c^2/E)^2+1]^{1/2}$).

Usually, $J_p$ is expressed as

$$J_p(E_p) = J_0 E_p^{-(\gamma+1)}$$

(7)

Now using eqn.(5), eqn.(7) in eqn.(6) we get

$$\frac{f_p(E)}{K\lambda_e(E)} = \frac{2}{m_p} \int_0^{X_s} 0.496 \exp[-5.08x] x \gamma^{-1} dx$$

(8)

Here, we have always used $K = 1.26$, $\lambda_e = 5$ gcm$^{-2}$ and $m_p \simeq 1$GeV.

In figure 1, the median energy of primary protons is shown as a function of the secondary antiproton energy. It was found earlier that for antiproton energies of 3-9 GeV, which were relevant to the experimental work performed up until then, the median energies of primary protons were about 25-80 GeV. The present energy-region is much higher. But we take the cue from Tan and Ng[4] and proceed in a similar manner to draw the figure shown in figure 1 as described in the figure-caption in some detail. Very carefully, we have chosen a modestly accurate primary proton spectrum. Modifying Bhadwar et al[1], we use here

$$J_P(E_P) = 2 \times 10^5 E_P^{-2.75}$$

(9)

where $J_P(E_P)$ is in protons $m^{-2}sr^{-2}s^{-1}GeV^{-1}$.

The final results have here been actually worked out on the basis of the following two deduced expressions :

$$f'_P(E_P) = f_P(E)J_P(E_P)$$

(10)

and

$$R_P(E_P) = \frac{J_P(E)}{J_p(E)} = \frac{2K\lambda_e(E)}{m_p} \int_0^{X_s} E d\sigma_p dE X^{-1} x \gamma^{-1} dx$$

(11)

The graphical plots presented in figure 2 and figure 3 are done with the help of eqn.(8). The expression (10) describes the nature of data measured by PAMELA group and others on antiproton
production flux. And the plot of model-based $\mathcal{P}/P$ ratio-values based on expression (11) are displayed in figure 4 and figure 5 against the data-background. The used values of the parameters are shown in the adjoining table (Table 1).

Very recently, there has been a new twist in the situation vis-a-vis the $\mathcal{P}/P$ ratio behaviour with the availability of the results on the same observable ($\mathcal{P}/P$ ratios) measured by ARGO-YBJ collaboration[7]. The measured values depict the $\mathcal{P}/P$ values at some higher ranges of values than what could be expected of just an extrapolation of the PAMELA-data-trends.

Some comments are in order for reported data by ARGO-YBJ (AY) Collaboration, especially because of the fact that their measurements put the $\mathcal{P}/P$ ratios apparently to much higher values. The word ‘apparent’ used here is firstly to draw attention to the large error bars indicated by this AY Collaboration through the downward-oriented arrow marks. The energy values are much higher for AY Collaboration - so are the ranges of uncertainties in measurement. But in the literature related to the studies at TeV energy region the terms, like, primary and secondary, seem to have been messed up. The definition of ‘primary’ used by Preghenella[8] is at variance with what the connotation of the word is in Cosmic Ray Physics. Still, there is a striking commonness between the tendencies of the measured data to measure and report the $\mathcal{P}/P$ ratios quite at high values. This is somewhat possible in purely nuclear collisions and also in nucleus-dominated cosmic interactions[9] at very high energies. Still, such high values of $\mathcal{P}/P$ ratios seem unlikely, for which further scrutiny by the experiments is surely warranted.

And this newest piece of observation or evidence pushes the controversy on $\mathcal{P}/P$ nature to a different pitch. The predicted rising nature of $\mathcal{P}/P$ ratio with $\mathcal{P}$ energy is a new addition. Thus the possibilities that arise are threefold : (i) nearly constant (or steady) nature of $\mathcal{P}/P$ ratio (ii) decreasing value of the ratio and (iii) the rising ratio of $\mathcal{P}/P$.

There is another not-very-clear and questionable aspect in ARGO-YBJ experiment. The measurement or the Monte Carlo Simulations were apparently made for matter + antiproton production. Firstly, no specific comment on what ‘matter’ represents here is given by the Collaboration. Secondly, the protonic content was taken to be nearly 72% on the average on an absolutely arbitrary basis. The particular model which obtains the $\mathcal{P}/P$ values at such high orders is also based on the assumption of emission of primary antiproton production by antistars. This is simply too speculative; the other models which depict similar high $\mathcal{P}/P$ values referred to by ARGO-YBJ Collaborations are also based on some wild assumptions; and so they are under the spell of strong doubts. Thus, on an overall and general basis, we are not in favour of attaching too much importance to ARGO-YBJ results at this point of time.

It is to be noted that PAMELA results, especially those reported in 2010, cover substantially quite a high energy band. We are of the opinion that it would probably be more justified to use the nature of the primary proton spectrum suggested by JACEE Collaboration[10, 11]. This would surely be given a fair trial in one of our future works.

The implication of this work will now be spelt out. Contributions arising out of the exotic sources, like, (i) dark matter particles, dark matter annihilations etc., (ii) supernova remnants and (iii) emission from the pulsars are being ruled out in our approach to this work. Besides, matter-antimatter components expected to be emanated from any extragalactic sources are also entirely excluded in our calculations. We also assume that the solar modulation phenomenon affects both proton and antiproton in an identical manner. So, it does not have any effect, at least on $\mathcal{P}/P$ ratios. Finally, the emphasis rests mainly and only on the choice of a heretic multiple production model. So, the focus of the problem is being transferred here from the domain of Astroparticle Physics to the sphere of Particle Physics. In essence, this represents virtually a case of ‘Paradigm
Shift' in the area of contemporary Astroparticle Physics.

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Table 1: Chosen values of the parameters

| $\lambda_e (gcm^{-2})$ | $m_p (GeV)$ | $\gamma$ | $K$ |
|------------------------|-------------|----------|-----|
| 1.26                   | $\simeq 1.00$ | 1.75     | 5.00 |

Figure 1: Relation between primary proton energy ($E_P$) and the total antiproton energies ($E$); the plot has been done with $E_P/E$ as Y-axis and $E$-valus as X-axis.

Figure 2: The antiproton energy spectrum at the top of the payload as measured by the PAMELA group and others. The solid curves shows the calculations of our theoretical model (10). The experimental data are collected from Ref.[12]-[16].
Figure 3: The antiproton energy spectrum at the top of the payload as measured by the PAMELA group. The solid curves shows the calculations of our theoretical model (10). The experimental data are collected from Ref.[12]

Figure 4: The antiproton-to-proton flux ratio at the top of the payload as measured by PAMELA group and others. The solid curves represent our calculations based on our model based approach (11). The experimental data are collected from Ref.[7], [12]-[17]
Figure 5: The antiproton-to-proton flux ratio at the top of the payload as measured by PAMELA group and the solid curves represent our calculations based on our model based approach (11). The experimental data are collected from Ref.[12].