Understanding the New High Energy Data-sets Measured by BESS, CAPRICE and PAMELA on Antiproton Flux and \( \bar{P}/P \) Ratios.

Goutam Sau\(^1\), P. Guptaroy\(^2\), A. Bhattacharya\(^3\)& S. Bhattacharyya\(^4\)
\(^1\) Beramara RamChandrapur High School, South 24-Pgs, 743609(WB), India.
\(^2\) Department of Physics, Raghunathpur College, Raghunathpur-723133, Purulia, India.
\(^3\) Department of Physics, Jadavpur University, Kolkata- 700032, India.
\(^4\) Physics and Applied Mathematics Unit(PAMU), Indian Statistical Institute, Kolkata - 700108, India.

Abstract

Reliable data from the very recent high-precision measurements on the antiproton fluxes and the antiproton-to-proton ratios by the PAMELA Collaboration at relatively much higher energies are now available. The results with regard to antiproton production phenomena spring no special surprises; rather they are sharply in contrast with and contradiction to the case of positron production at the same energy-range. However, the totality of data on antiproton production from the past experiments to the very recent PAMELA outburst seem to be a very challenging exercise for interpretation in terms of the secondary production mechanisms alone, the galactic propagation model etc against the background of the ‘dark-matter’-related controversy. In the present work we assume the validity of the simple leaky box model, choose a simple particle production model and attempt at providing a comprehensive interpretation of the totality of data on both antiproton flux measurements and the \( \bar{P}/P \) ratio-values for the various experiments ranging from BESS, CAPRICE to the latest PAMELA experiment. With the assumption of no contribution from the exotic sources to the antiproton production process, our model and the method describe the totality of the measured data with a fair degree of success.

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

PACS nos.: 13.85.Tp, 96.50.Sb, 98.70.Sa, 95.35.+d

\(^{*}\) e-mail: sau_goutam@yahoo.com
\(^{†}\) e-mail: gpradeepta@rediffmail.com
\(^{‡}\) e-mail: aparajita_bh@yahoo.co.in
\(^{§}\) e-mail: bsubrata@www.isical.ac.in (Communicating Author).
1 Introduction

In recent times the cosmic ray (CR) antiproton and positron flux measurements have assumed much importance, as they could signal, according to a section of the astroparticle physicists, to the indirect detection of dark matter. In fact, the tremendous surge of interest on the very recent PAMELA experiments centres around this expectation. It is a fact that the PAMELA experiment on antiproton production[1] is, so far, not that controversial as is the case for the positron excess measurements by the same PAMELA group[2]. And in a previous publication we successfully dealt with the positron-excess-problem with some non-standard points of view[3].

In the astroparticle sector the observed particles fall under two categories: primaries and secondaries. The primaries are considered to be those which are accelerated by astrophysical objects of our galaxy and comprise of electrons, protons, other light and heavier nuclei[4]. In the course of its journey in the space these energetic primaries undergo the process of spallation on the Interstellar Medium (ISM) mainly with the components Hydrogen and Helium. Besides, they also suffer energy losses by successive high energy interactions in the Earth’s atmosphere while passing through the earth. After their production from the supernovae remnants, cosmic rays traverse and propagate in the galactic turbulent magnetic field, experience some deflections and finally enter the Earth. Both the spallation process and the interactions of the primaries with the ISM give rise to the various secondaries of which the antimatter particles, e.g., positrons, antiprotons etc. constitute a considerable part. For antiproton production spallation of secondaries too might play some role, though for all practical purposes we will certainly neglect such tertiary mode of production.

The concept of dark matter and its coupling to the Standard Model (SM) sector allows some annihilation or decay chains which could be additional sources of both matter and antimatter in equal measure. But in the general background matter is much more abundant than antimatter. So, it is quite understandable that the primary component due to so-called Dark Matter has relatively better chances to be detected[5] among antimatter cosmic rays. In a way, this accounts for the increased importance of the antimatter studies in the recent times.

In view of the importance of antiproton research in appreciating the role of production and propagation of primary cosmic rays, we have motivated ourselves here to find a compatibility of the various data-sets by using the simple leaky box model (SLBM) for galactic propagation and using a particular secondary antiproton production model as described in some detail in the next.

...
Section. The observations made and reported by various groups like, BESS’95\[6\], BESS’97\[6\], BESS’99\[7\], BESS’00\[7\], BESS’02\[8\] etc., CAPRICE’98\[9\] and PAMELA(2008)\[1\] would here be dealt with on the basis of the SLBM\[10\] alone which is nowadays very much a text book matter, for which no further details about it would be presented here.

In the present work we will assort the data on antiproton flux measurements and the $\overline{P}/P$ ratios by BESS[1995 - 2002], CAPRICE[1998] and PAMELA groups and try to understand the totality of data in a comprehensive manner with the clear emphasis laid on the latest PAMELA results.

2 Mechanism for Antiproton Production and the Expression for Invariant Cross Sections

According to the secondary production model the low-$p_T$ (soft) baryon-antibaryon secondaries are produced here through the decays of (virtual) secondary pions of which proton-antiproton pairs comprise nearly one third of the total. Bandyopadhyay and Bhattacharyya\[11\] and Bandyopadhyay et al\[12\] have 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 high energies and by the average antiproton multiplicity

$$E \frac{d^3\sigma}{dp^3}|_{pp\rightarrow πX} \simeq 1.87 \times exp[-7.38 \frac{p_T^2 + m_{π}^2}{1 - x}] exp[-5.08x]$$

(1)

and

$$< n_π > \simeq 1.08 \times 10^{-2} S^{2/5}$$

for $\sqrt{S} \leq 100GeV$ \hspace{1cm} (2)

$$< n_π > \simeq 2 \times 10^{-2} S^{1/4}$$

for $\sqrt{S} > 100GeV$ \hspace{1cm} (3)

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

The points of emphasis about this model are: i) It gives dynamically a unified picture of both low- and large-transverse-momentum phenomena and admits of no compartmentalization between soft and hard production of particles which is an artifact from the dictates of the Standard Model in particle physics. The only difference between them, according to this model, is in kinematics and in one additional feature of constituent rearrangement at high $p_T$. ii) It explains the $\ll$ universality $\gg$ property of high-energy lepton-hadron, hadron-hadron, hadron-nucleus collisions and $e^+e^-$ reactions in a nice dynamical and unambiguous way. iii) It subscribes to the ideas of jettiness of particle
production at high energies in the form of two-sided ≪ sprays ≫ of sequential arrays of hadrons.

iv) It explains the by-now established leading-particle effect (LPE) in high- and very-high-energy collisions in a very satisfactory manner. v) Save and except a single parametrization, wherein there is a degree of uncertainty, there is no hand-inserted parameter in the model. The model proposes a power law multiplicity for high-energy particle production and introduce Feynman scaling violation in an inbuilt manner even for relatively low-transverse-momentum region. For exceedingly low-$p_T$ region a logarithmic nature of multiplicity might work and Feynman scaling might be valid under some stringent conditions and some strict restrictions. Naturally, this region is very limited and only a case for exception. vi) Last but not the least, another potential success of the model lies in its ability to explain the very slow rise of $K/\pi$ ratio emphasized\cite{13, 14} even very recently.

3 Estimation of Antiproton Flux and the $\overline{P}/P$ Ratios

This Section is divided into the following few subsections and the undernoted sub-captions.

3.1 Primary Spectra, Secondary Antiproton Production Model and the Working Formulae

In actual evaluation 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\cite{15}:

$$\frac{d\sigma}{dE} = \frac{\pi}{p_L} \int (E \frac{d^3\sigma}{dp_T^3})_{pp \to \pi X} \frac{d^2p_T}{dp_T^2}.$$ \hspace{2cm} (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

$$\left. \frac{d\sigma}{dE} \right|_{p_T \to 0} \simeq 0.496 \exp[-5.08x]$$ \hspace{2cm} (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\cite{16, 17} have worked out that the antiproton-to-proton ratio is to be given finally by

$$f_{\overline{p}}(E) = \frac{J_{\overline{p}}(E)}{J_p(E)} = \frac{2K\lambda(E)}{m_p} \int_0^{X_s} \frac{d\sigma_p}{dE} X^{\gamma-1} dx$$ \hspace{2cm} (6)
where $J_p$ and $J_{\overline{p}}$ 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 \((gcm^{-2}\text{ as the unit})\), \(m_p\) is the mass of the proton \((g\text{ as the unit})\), \(E_p\) 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 and it is used \(\gamma=1.75\), \(X = E/E_p\) 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

$$J_p(E_p) = J_0 E_p^{-(\gamma+1)}$$  \(\text{(7)}\)

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

$$\frac{f_{\overline{p}}(E)}{K \lambda_e(E)} = \frac{2}{m_p} \int_0^{X_s} 0.496 \exp[-5.08x]x^{\gamma-1}dx$$  \(\text{(8)}\)

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

### 3.2 The Effect of Annihilation Channels : A Damping Effect

At the relatively lower energy sides of ultra high energy interactions, both proton-antiprotons might enter into some annihilation reactions which would suppress the production ratio of $\overline{P}/P$ in the main. In order to accommodate this probability we assume a damping correction term for the $\overline{P}/P$-ratios to be parameterized by \(\sim \phi \exp[-\alpha E_{\overline{p}}]\) where \(\phi\), \(\alpha\) and \(\epsilon\) are the chosen parameters and $E_{\overline{p}}$ is the measured antiproton energy. We assume here that only the ratio-values of $\overline{P}/P$ would suffer this diminutive change as the annihilations involve both the protons and antiprotons, though the individualized production of both protons and antiprotons would be considered to remain unaffected. The used values of $\phi$, $\alpha$ and $\epsilon$ are 0.55, 0.7 and 0.5 respectively.

### 3.3 Choice of the Working Primary Proton Spectra

It is to be observed that the value of $f_{\overline{p}}(E)/K \lambda_e(E)$ is sensitive to the value $\gamma$ and the value of $\gamma$ could be different in different regions of the primary proton energy. But we have left out this issue for the present with the acceptance of a specific value of $\gamma = 1.75$ throughout this entire work. In order to proceed we have found the relationship between the secondary antiproton energy and the primary proton energy to follow the nature depicted by figure 1(a).
In figure 1(b), 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 until then, the median energies of primary protons were about 25-80 GeV. The present energy-region is somewhat higher. But we take the cue from Tan and Ng [15] and proceed in a similar manner to draw the figures shown in figure 1(b) and figure 1(c) as described in the figure-captions in some detail. Very carefully, we have chosen a modestly accurate primary proton spectrum. Modifying Bhadwar et al. [18], we use here

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

(9)

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

Using this spectrum and our invariant cross section formulae, we have calculated the \( f_P(E) / K \lambda_e(E) \) curve as given in figure 1(c).

4 Results

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

\[ R_{P/P}(E_P) = \frac{J_P(E)}{J_{p}(E)} \times \phi \exp[-\alpha E_P^\gamma] \int_0^{X_S} E \frac{d\sigma_p}{dE} X^\gamma dx \times \phi \exp[-\alpha E_P^\gamma] \]  

(11)

The graphical plots drawn in figure 2 and figure 3 with expression (10) describe the nature of relatively low-energy antiproton-data measured by BESS, CAPRICE on antiproton flux. And the plot of model-based \( P/P \) 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).

After delivering the results by graphical plots and the necessary table(s), we would like to make in the following section some crucial observations about some very exciting and interesting recent works [19, 20, 21, 22] which appear to be somewhat concurrent with our views on some aspects of astroparticle physics-divisions. The final chapter of discussions and conclusions drawn from the present work just follows thereafter.
5 Some Contemporary and Novel Studies on PAMELA-Results: The Specific Features and a Few Comments

In the very recent past Blasi[19] proposed an “alternative and even simpler astrophysical explanation”[20] for the anomalous positron excess observed and reported by PAMELA group[2]. Of late, thereafter the same postulates (plus mechanism) of hadronic production of secondaries in aged supernova remnants (SNRs) and acceleration therein have been successfully applied for calculating the $\bar{P}/P$ flux-ratio which has been generically predicted to be of flattened nature in the intermediate energy range under study now, and is expected to rise very weakly in the superhigh energy domain. In fact, the initial experimental observations on this ratio in the TeV-region corroborate this predicted trend of the data. But confirmation of this behaviour is still awaited by both the theorists and experimentalists[23].

The different probable sources for production of antimatter components, like positrons, antiprotons etc are: dark matter annihilation/decay, secondary production and supernova remnants[24]. These three are mutually independent of each other, apparently with no known and perceptible overlapping or intersection. The SNR components are transient sources, in which most of the matter-antimatter particles are accelerated and injected into the interstellar space in a very short time compared to cosmic ray propagation scales. The difference with the two other sources mentioned above is that those are rather inhomogeneous in the nearby region to the solar system. Normally this kind of source is taken as a smooth distribution across the whole galaxy due to the diffusive propagation of cosmic rays. However, when sources are too close - on time and distance - the distribution pattern changes and the approximation is no longer valid.

However, that the secondary to primary ratios should rise with energy, if secondaries are accelerated in the same spatial region as the primaries, have been noted quite some time ago in the context of cosmic ray acceleration in the interstellar medium. This model is conservative since it invokes only processes that are expected to occur in candidate cosmic ray sources, in particular supernova remnants. Our way to distinguish it from the other models is to compute the expected antiproton-to-proton ratio, which is experimentally observed so far to be consistent with the standard background[21, 22]. This finding is, in fact, in agreement with the model by Blasi[19], more particularly by Blasi and Serpico[20]. It is to be noted that Blasi’s acceleration mechanism applies to a certain stage of the (old) SNR evolution with some other provisos and conditionalities related
to magnetic field damping, time-dependence or time-independence etc. However, till date, the model is found to be consistent with the measurements.

The commonness in the approaches by us, Blasi [or Blasi and Serpico] and Ahlers et al lie in the facts that (i) all of these models are not based on the assumed/hypothetical existence of the dark matter or, for that matter, decay/annihilation of dark matter etc.; and (ii) there is no concern or consideration about the existence of the pulsars and the role of the emissions from the pulsars. In our mechanism, we confined ourselves only to the ‘secondary’ proton-antiprotons. Blasi, Blasi and Serpico opted singularly for the third source, the SNRs, which we did not, at all, reckon with. So these two approaches might be viewed as parallel to each other. In future, it is quite probable that a combination of these two contributions would be an indispensable necessity to have a perfectly valid explanation for the measured data at ultrahigh energies. In order to confirm/discard any model whatsoever under consideration here, one needs to have very reliable high-statistics data simultaneously on the individual fluxes of both the protons, antiprotons and the ratio-values of the antiprotons-to-protons as well.

6 Concluding Remarks

The entire data-sets measured by three distinctly separate groups at somewhat different energy-ranges of the proton primaries have here been described in an integrated manner and in a modestly satisfactory way. In our calculations we have not taken into consideration any exotic source of antiprotons. So, no specific support to the concept of ‘dark matter’ could be rendered by our calculations and method; rather in a tacit manner the idea is virtually disfavored. This is in contrast with the contentions of Buchmüller et al [25]. Even the probable emissions from the pulsars find no place in our approach. With regard to all these exoticities, we obviously share the ideas of both Blasi [19] and Blasi and Serpico [20].

We have based our calculations here on the Simple Leaky Box Model (SLBM). Even our previous work on positron results [3] by PAMELA group [2] was also done with the same propagation model, viz, SLBM. So the emphasis laid on the Nested Leaky Box Model (NLBM) by Cowsik and Burch [26, 27] on understanding the PAMELA-data related to the detection of positron excess is not substantiated by our works. Besides, the fair agreement between calculations and measurements provides a support to the secondary antiproton production model and the choice of the nature of
primary proton spectrum put into use here. But, in our approach there are a few chosen parameters which cannot be clearly accounted for right now from the physical considerations. This definitely constitutes some strong limitations to our claims on the successes in interpreting the data-trends and/or data-character(s).

**Acknowledgement**

The authors express their thankful gratitude to the honourable referee for making an insightful comment and a constructive suggestion for improvement on an earlier draft of the manuscript.
References

[1] O. Adriani et al : Phys. Rev. Lett. 102 (2009) 051101 [astro-ph/0810.4994 v2 25 February 2009].

[2] O. Adriani et al : Nature 458 (2009) 607-609.

[3] Goutam Sau, S.K.Biswas and S.Bhattacharyya : Hadronic Journal 31 (2008) 529.

[4] T. Delahaye, P. Brun, F. Donato, N. Fornengo, J. Lavalle, R. Lineros, R. Tailliet and P. Salati : Proceedings for XLVemes rencontres de Moriond, Electroweak Interactions and Unified Theories session; LAPTH-Conf-1321/09 [hep-ph/0905.2144 v2 20 May 2009].

[5] Arnon Dar : Summary talk at the 44th Rencontre De Moriond on High Energy Phenomena In The Universe which was held in La Thuile, Italy during February 1-8, 2009 [astro-ph.HE/0906.0973 v1 04 June 2009].

[6] S. Orito et al : Phys. Rev. Lett. 84 (2000) 1078-1081 [astro-ph/9906426 v1 26 June 1999].

[7] Y. Asaoka et al : Phys. Rev. Lett. 88 (2002) 051101 [astro-ph/0109007 v2 25 January 2002].

[8] S. Haino et al : 29th International Cosmic Ray Conference, Pune 3 (2005) 13-16.

[9] M. Boezio et al : The Astrophysical Journal 561 (2001) 787.

[10] R. Cowsik and B. Burch : astro-ph.CO/0908.3494 v1 24 August 2009.

[11] P. Bandyopadhyay and S. Bhattacharyya : Nuovo Cimento A, 43 (1978) 323.

[12] P. Bandyopadhyay, R. K. Roy Chowdhury, S. Bhattacharyya and D. P. Bhattacharyya : Nuovo Cimento A, 50 (1979) 133.

[13] T. T. Chou, C. N. Yang and E. Yen : Phys. Rev. Lett. 54 (1985) 510.

[14] Bonn-Brussels-Cambridge-CERN-Stockholm-UA5 Collaboration (G. J. Alner et al) : Nucl. Phys. B, 258 (1985) 505.

[15] L. C. Tan and L. K. Ng : J. Phys. G, 7 (1981) 123.

[16] S. Bhattacharyya and P. Pal : IL Nuovo Cimento C, 9 (1986) 961.

[17] S. Bhattacharyya and D. Roy : Mod. Phys. Letts. A, 13 (1998) 2173.

[18] G. D. Bhadwar, S. A. Stephens and R. L. Golden : Phys. Rev. D, 15 (1977) 820.

[19] P. Blasi : Phys. Rev. Lett. 103 (2009) 051104 [astro-ph.HE/0903.2794 v1 16 March 2009].

[20] P. Blasi and P. D. Serpico : Phys. Rev. Lett. 103 (2009) 081103 [astro-ph.HE/0904.0871 v2 30 September 2009].

[21] M. Ahlers, P. Mertsch and S. Sarkar : astro-ph.HE/0909.4060 v1 22 September 2009.

[22] P. Mertsch and S. Sarkar : Phys. Rev. Lett. 103 (2009) 081104 [astro-ph.HE/0905.3152 v3 30 July 2009].
[23] http://ams.cern.ch/

[24] Roberto Lineros : Proceedings for conference "Topics in Astroparticle and Underground Physics" (TAUP2009) Rome, July 1-5, 2009 [astro-ph.GA/0910.2671 v1 14 October 2009].

[25] W. Buchmüller, A. Ibarra, T. Shindou, F. Takayama and D. Tran : Journal of Cosmology and Astroparticle Physics, 021 (2009) 0909 [hep-ph/0906.1187 v3 31 August 2009].

[26] R. Cowsik and B. Burch : astro-ph.CO/0905.2136 v2 11 June 2009.

[27] R. Cowsik and B. Burch : To appear in Proceedings of the 31st ICRC [astro-ph.CO/0906.2365 v1 12 June 2009].
Figure 1: (a) Plot of the relationship between the variation of antiproton energy (E) and primary proton energy ($E_P$), (b) 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, (c) The calculated antiproton to proton flux ratio (in terms of $K/\lambda_0(E)$) against the antiproton energy E.
Figure 2: Antiproton fluxes at the top of the atmosphere as measured by BESS’95[2(a)], BESS’97[2(b)], BESS(’97+’95)[2(c)] and Caprice’98[2(d)]. The solid lines represent the calculations based on our theoretical model (10). The experimental data are collected from Ref.[6,9]
Figure 3: BESS'99[3(a)], BESS'00[3(b)], BESS'02[3(c)] and together of BESS, CAPRICE[3(d)] Antiproton fluxes at the top of the atmosphere. The solid curves shows the calculations of our theoretical model (10). The experimental data are collected from Ref.[7 8 9].
Figure 4: Plot of $\overline{\nu}/\nu$ ratios measured by BESS (‘95+’97)[4(a)], CAPRICE’98[4(b)], BESS’99[4(c)] and BESS’00[4(d)]. The solid curves represent our calculations based on our model based approach (11). The experimental data are collected from Ref.[6, 9, 7].
Figure 5: Plot of $\overline{P}/P$ ratios 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.[1].