Source of cosmic ray particles

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Abstract

An analysis of high altitude cosmic ray p, $\overline{\mathrm{p}}$, e^- and e^+ from the AMS Collaboration indicates that the proton-antiproton asymmetry ratio is similar to the cross-section ratio of $\overline{\mathrm{p}}$p annihilation to pp inelastic scattering. Thus the asymmetry is due to annihilations by matter in the interstellar medium. The particles p, $\overline{\mathrm{p}}$ and π^o are produced under energy equipartition by a fireball of mass $\sim$ 9.92 GeV, with π^o leading to e^- and e^+, then all the particles are accelerated by plasma shock waves.

In a satellite experiment at an altitude of 3.5 g/cm^2 for the search of antimatter in the universe, the AMS Collaboration [1-3] has made the most precise measurements of the p, $\overline{\mathrm{p}}$, e^- and e^+ momentum distributions. Their data, as shown in Fig 1, provide precious information to investigate the nature of the source producing these high energy particles.

In view of the complexity of the production mechanism of cosmic ray particles, we assume the process to be stochastic and use the longitudinal phase space of the particle under consideration

$$\zeta = \mathrm{LogP}, \tag{1}$$

to describe the momentum distribution by means of a lognormal distribution of Kolmogorov [4], namely

$$\frac{\mathrm{dn}}{\mathrm{dP}} = \mathrm{N}e^{-(\zeta+\zeta^*)^2/2\mathrm{L}} \quad \mathrm{P} < \mathrm{P}_\times, \tag{2}$$

together with the well-known power law suggested by Fermi [5] and predicted by various models for the acceleration of cosmic rays by shock waves [6-12],

$$\frac{\mathrm{dn}}{\mathrm{dP}} = \frac{\mathrm{A}}{\mathrm{P}^\gamma} \quad \mathrm{P} > \mathrm{P}_\times. \tag{3}$$

The two distributions are joined tangentially at $P_\times$ determined by

$$P_\times = \text{antilog}(2.303\gamma L - \zeta^*). \tag{4}$$

The parameters are: the maximum shift ζ^*, the Gaussian width L and the spectral index γ, N and A being the normalization coefficients.

The least-squares fits are shown by the solid lines in Fig. 1, together with the transition momentum $P_\times$ marked by a small bar on the plot. The estimates of parameters are listed in Table 1, together with the number of particles n and the mean momentum $\overline{P}_<$ for $P < P_\times$. note that for positrons, we have used the same momentum range as in the case of electrons.

Table 1: Parameters of the lognormal distribution Eq. (2) and the power law Eq. (3), the transition momentum Eq.(4) $P_\times$ in GeV/c, the mean momentum for $P < P_\times$ and the number of particles in $(m^2\,sr\,sec)^{-1}$.

	p	$\overline{p}$	e^-	e^+
P range	180	350	37	2.55
ζ^*	0.195 ± 0.026	-0.391 ±0.012	0.142 ±0.006	0.230 ± 0.039
L	0.187 ± 0.006	0.085 ±0.018	0.129 ± 0.002	0.092 ± 0.018
N	430.4 ± 24.1	0.021 ± 0.003	25.65 ± 0.25	5.72 ± 0.57
$P_\times$	9.873	6.943	6.453	
γ	2.762 ± 0.019	2.471 ± 0.153	3.204 ± 0.058	
A	583.3 ± 4.04	1.02 ± 0.22	280.6 ± 29.1	
$\overline{P}_<$	2.784 ± 0.056	3.467 ± 0.0.084	2.073 ± 0.006	1.277 ±0.079
n	1053	0.123	52	6

A comparison with the data indicates that, except for the positrons, the fits are, in general, very satisfactory.

As regards the proton-antiproton asymmetry, we note that the ratio $R = n(\text{p})/n(\overline{\text{p}})$ depends critically on the momentum of the particles under consideration, as shown by the log-plot in Fig. 2. There is a change of curvature at the inflection point estimated around [13]

$$P_o = 6.248 \pm 0.392 \quad \text{GeV/c},$$

corresponding to a threshold of nucleon-antinucleon production by collisions of a cosmic ray proton with quasi-stationary nucleons in the plasmas of interstellar space, the center of mass energy of such collisions being $\sqrt{s} = 3.689 \pm 0.098$ GeV $\sim 4m_p$.

As the momentum distribution follows Eqs. (2) and (3), consequently the behavior of the log-plot of R may be described by a quadratic fit in terms of $\zeta = \text{Log P}$, the power law being cancelled out in the ratio,

$$\log R = C - \frac{\text{sgn}(\zeta - \zeta_o)}{2.303}\frac{(\zeta - \zeta_o)^2}{2L} \tag{5}$$

we get

$$\zeta_o = 0.909 \pm 0.014, \quad \mathrm{L} = 0.156 \pm 0.002, \quad \mathrm{C} = 3.530 \pm 0.027.$$

The fit is shown by a dotted line in Fig.2. Note that L agrees with what expected from those for p and $\bar{\mathrm{p}}$ in Table I. Indeed,the property of Gaussian distributions requires:

$$\frac{1}{\mathrm{L}} = \frac{1}{\mathrm{L}_p} - \frac{1}{\mathrm{L}_p},$$

yielding $\mathrm{L} = 0.156 \pm 0.050$ in agreement with the fit value. Never-the-less, the position of the inflection point according to ζ_o, namely $8.109 \pm 0.014 >> \mathrm{P}_o$, is not right, because of the asymmetry of the plot.

We therefore have to refit the the plot in two parts corresponding to $\mathrm{P} < \mathrm{P}_o$ and $\mathrm{P} > \mathrm{P}_o$, as shown by the solid lines in Fig. 2. The parameters are listed in Table 2.

Table 2: Parameters of quadratic fits with Eq. (5) for the two branches separated by the inflection point at P_o

	$\mathrm{P} < \mathrm{P}_0$	$\mathrm{P} > \mathrm{P}_0$
ζ_o	0.814 ± 0.075	0.588 ± 0.151
L'	0.147 ± 0.019	0.258 ± 0.042
C	3.624 ± 0.053	3.684 ± 0.104
χ^2	1.66/0.16	3.01/19

Note that the normalization coefficients are practically equal, whereas the parameters ζ_o and L' are quite different.

Clearly, this ratio of asymmetry between cosmic ray protons and antiprotons is due to the difference between their interactions with cosmic matter. It is therefore imperative to compare its behavior with the cross-section ratio of $\bar{\mathrm{p}}\mathrm{p}$ annihilations and pp inelastic collisions of accelerator data.

The values of $\sigma(\bar{\mathrm{p}}\mathrm{p})_{ann}/\sigma(\mathrm{p})_{ine}$ thus obtained using low energy annihilation data from the LEAR and the Serpukov experiments [14-18] and pp inelastic cross-sections from the Review of Particle Physics [19] are shown by full circles in the same log-plot in Fig. 2. The solid line represents a fit according to Eq. (5), here, $\zeta = \mathrm{Log}\ (\mathrm{P}_{beam})$, the parameters are

$$\zeta_o' = 3.220 \pm 0.830, \quad \mathrm{L}' = 0.534 \pm 0.111, \quad \mathrm{C}' = -3.559 \pm 1.336.$$

It is interesting to note that the magnitude of the normalization coefficients C′ here found as well as those in Table 2 are comparable to the coefficient C for the ratio $\mathrm{R}(\mathrm{p}/\bar{\mathrm{p}})$ of cosmic rays mentioned above, the minus sign being conventional, because use has been made of $\bar{\mathrm{p}}/\mathrm{p}$ instead of $\mathrm{p}/\bar{\mathrm{p}}$ such as in the case of cosmic rays.

The similarity of the two log-plots in Fig 2, ratios of cosmic ray proton to antiproton on the hand, and cross-section ratios of $\bar{\mathrm{p}}\mathrm{p}$ annihilation to pp inelastic scattering on the other hand, is very striking, to the point that the characteristic parameters ζ_o' and L$'$ of the cross-section ratios may be scaled from those of R(p/$\overline{\rm p}$) cosmic rays for P < P_o in Table 2 to be specified by a subscript < , as unrevealed by their scaling property, namely

$$\frac{\zeta_o'}{(\zeta_o)_<} = 3.780 \pm 1.016, \quad \frac{\mathrm{L}'}{(\mathrm{L})_<} = 3.373 \pm 0.240,$$

so that the plot of cross-section ratio may be superposed into that of proton-antiproton asymmetry ratio of cosmic rays by sliding either one plot along the coordinates axes of the other.

This most remarkable scaling property implies that the proton-antiproton asymmetry in cosmic rays is merely due to annihilations of antiprotons by cosmic matter.

We now proceed to investigate the source of these cosmic ray protons and antiprotons. For this purpose, let us consider their rest-frame, denoted by an asterisk to distinct it from the lab system of measurements, and denote by $\gamma = 1/\sqrt{1-\beta^2}$ the Lorentz factor of transformation. Then, under the assumption that they are produced as a pair of particle-antiparticle, with the same energy E_p^* and the opposite momentum P_p^* in the rest-frame, their average momentum listed in Table 1 may be written as

$$\overline{\mathrm{P}}_p = \gamma(-\mathrm{P}_p^* + \beta \mathrm{E}_p^*), \quad \overline{\mathrm{P}}_p = \gamma(\mathrm{P}_p^* + \beta \mathrm{E}_p^*). \tag{6}$$

or by addition and division of these equations

$$\frac{\beta}{\sqrt{1-\beta^2}}\,\mathrm{E}_p^* = \frac{\overline{\mathrm{P}}_p + \overline{\mathrm{P}}_{\overline{p}}}{2}, \quad \beta\,\frac{\mathrm{E}_p^*}{\mathrm{P}_p^*} = \frac{\overline{\mathrm{P}}_p + \overline{\mathrm{P}}_{\overline{p}}}{\overline{\mathrm{P}}_p - \overline{\mathrm{P}}_{\overline{p}}}. \tag{7}$$

We now use the values of mean momentum in Table 1 to estimate

$$\beta = 0.957 \pm 0.002, \quad \mathrm{E}_p^* = 0.942 \pm 0.002 \text{ GeV}.$$

Note that the kinetic energy of this proton-antiproton pair is very low, $\sim 4 \pm 2$ MeV. They are produced almost at rest.

Next, we turn to the electrons and the positrons. as they arise from decays of $\pi^o \to \gamma + \gamma$ followed by $\gamma \to e^+ + e^-$ or $\pi^\pm \to \mu^\pm \to e^\pm + \nu$ with $\mu^\pm \to e^\pm + \nu + \overline{\nu}$. We find for the mean energy of the γ's in the AMS Experiments [2] $\overline{\mathrm{E}}_\gamma = \overline{\mathrm{P}}_{e-} + \overline{\mathrm{P}}_{e+} = 3.350 \pm 0.080$ GeV. Therefore the mean energy of pions in the pair production of protons and antiprotons is

$$\overline{\mathrm{E}}_\pi = 2\,\overline{\mathrm{E}}_\gamma = 6.701 \pm 0.080 \text{ GeV}.$$

which, neglecting the pion mass, leads to an energy in the rest-frame of the proton and the antiproton

$$\overline{\mathrm{E}}_\pi^* = \sqrt{\frac{1-\beta}{1+\beta}}\,\overline{\mathrm{E}}_\pi = 0.993 \pm 0.024 \text{ GeV}.$$

It is interesting to notice that the mean energy of the pions is the same as those of the proton and the antiproton, namely

$$\overline{\mathrm{E}}_p^* = \overline{\mathrm{E}}_{\overline{p}}^* = \overline{\mathrm{E}}_\pi^* = 0.959 \pm 0.024 \text{ GeV}.$$

We therefore have the strong feeling that the fundamental principle of energy equipartition in the particle production process holds in the production of cosmic ray protons, antiprotons, electrons and positrons. The energy of the fireballs observed in the AMS experiments [1-3] is estimated to be

$$E_{FB} = \gamma\,(\overline{E}_p^* + \overline{E}_{\bar{p}}^* + E_\pi^*) = 9.917 \pm 0.034 \ \text{GeV}.$$

To sum up, the asymmetry between the protons and the antiprotons of the AMS experiments [1 - 3] is due to annihilations of antiprotons by the matter in the interstellar medium. They are produced in pair, together with a π^o under energy equipartition. Then the particles in the final state p, $\overline{\text{p}}$, e^- and e^+ are accelerated by shock waves of cosmic plasma.

Finally, an analysis has been made for the proton and the antiproton spectrum of the BESS Collaboration [20]. Their balloon experiment was at an altitude of 3.8 gr/cm^2, but at different space and time from the AMS experiment. No electron nor positron data are available. None-the-less, we have found for the' average momentum $\overline{P}_p = 2.075 \pm 0.013$ and $\overline{P}_{\overline{p}} = 3.129 \pm 0.008$ GeV/c for the protons and the antiprotons, respectively; less than those of the AMS experiment as listed in Table 1. But here, the velocity of the rest frame of p and $\overline{p}$ is $\beta = 0.933$ and their energy $E_p^* = 0.953 \pm 0.008 GeV$, comparable to that of the AMS experiment as mentioned above. This suggests that the energy of the fireball may be the same $\simeq 10\,m_p$ for both the AMS and the BESS experiments and that energy equipartition holds for the production of cosmic ray particles. It would be interesting to further investigate this important property of energy equipartition of the fireball of cosmic rays, when future high statistics data covering a wide range of momentum will be available.

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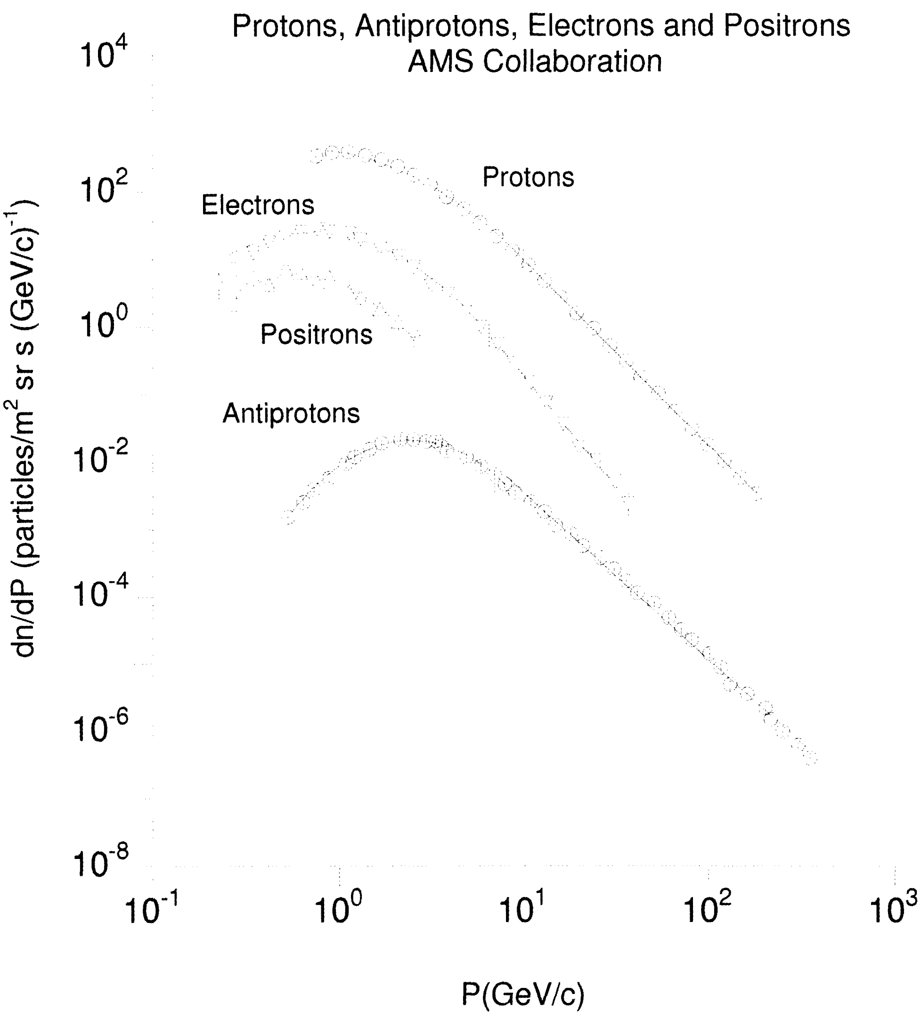

Figure 1: Momentum distributions of cosmic ray $\mathrm{p}, \overline{\mathrm{p}}, e^-$ and e^+ of the AMS Collaboration [1 - 3]. The curves are fits with the lognormal distribution Eq. (2) and the power law Eq. (3) joined together at $\mathrm{P}_\times$ marked by a small vertical bar. The parameters are listed in Table 1.

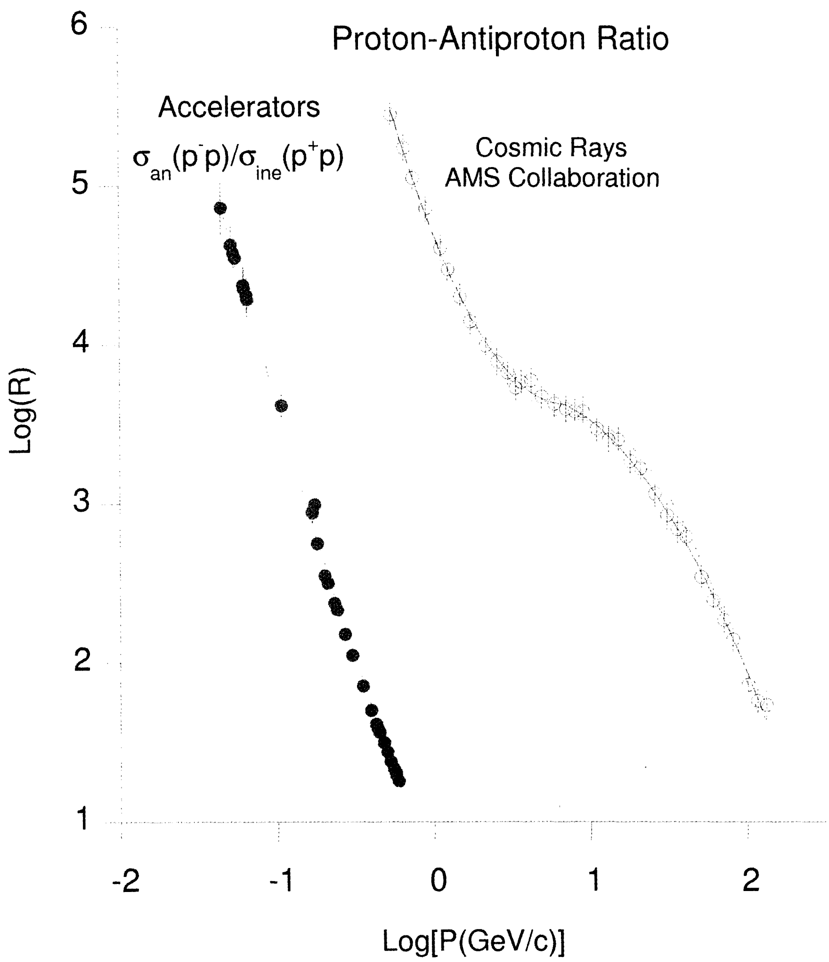

Figure 2: The log-plot of the asymmetry ratio of cosmic ray protons and antiprotons according to the data of the AMS Collaboration [1 - 3]. The inflection point at $P_\times$ is marked by a vertical bar on the horizontal axis. The curves represent quadratic fits with Eq.(5) deduced from the lognormal distribution Eq. (2). The parameters are listed in Table 2. Also shown in full circles, the cross-section ratios of $p\overline{p}$ annihilation and inelastic scattering of the accelerator data. The solid line, a least-squares fit with Eq. (5), is parallel to that of the asymmetry ratio of cosmic ray protons to antiprotons, indicating annihilations of cosmic ray antiprotons by matter in the interstellar medium.