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Production cross-section of antiprotons in p-p collisions

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Abstract: The production cross-section for antiprotons ($\bar{p}$) in p-p collisions is presented for the study of cosmic-ray antiproton (CR-$\bar{p}$) propagation in the Galaxy. We propose a semi-empirical production cross-section of $\bar{p}$, with only three free parameters, the average multiplicity, $N_{\bar{p}}$, the average transverse momentum, $\langle p_T \rangle$, and the deformation parameter, τ, which characterises the deformation from the isotropic angular distribution of $\bar{p}$ in the center of mass system (CMS).

Introduction

In Paper I [1], we proposed an approach to the production cross-section for γ's in p-p collisions, avoiding debate over the merits of the model, and putting the theoretical basis aside. Namely, as was emphasized in Paper I, for the study of the γ-ray astronomy from the practical point of view, we have neither interest in secondary products other than γ's nor in the type of intermediate neutral mesons decaying into γ's, via either π^0, η, or η'. It is more important for us, regardless of the theoretical basis, to first find the form of production cross-section *reproducing* (*or interpolating*) the *experimental data* now available in the energy range of our interest, 1 GeV–1 PeV in p-p collisions.

In the present paper, in the line with Paper I, we propose a semi-empirical formula for the production cross-section of $\bar{p}$ in p-p collisions, foucssing upon the average transverse momentum, $\langle p_T \rangle$, the multiplicity, $N_{\bar{p}}$, and the parameter, τ, related to the angular distribution. We compare the present formula with the various kinds of experimental data over the wide energy range, 10–1000 GeV, covering a large portion of the energy region of our interest, and find that it reproduces very well the accelerator data nowdays available. Energy dependences of the parameters appearing in the formula are summarized in the last subsection. We also compare it with the numerical results performed by Stephens & Golden [2], and Tan & Ng [3].

Antiproton production cross-section

Basic distribution function in CMS

Let us assume the invariant cross-section of $\bar{p}$'s produced by p-p collision in the CMS, slightly modifying the form given in Paper I,

$$\frac{1}{\sigma_{pp}} E^*_{\bar{p}} \frac{d^3\sigma}{d^3\boldsymbol{p}^*_{\bar{p}}} = \frac{N_{\bar{p}}\Theta_c}{4\pi p_c^2}\left(1-\frac{p^*_{\bar{p}}}{p_c}\right)^{\chi_c} \mathrm{e}^{-Z_c(\boldsymbol{p}^*_{\bar{p}})}, \quad (1)$$

$$\text{with} \quad Z_c(\boldsymbol{p}^*_{\bar{p}}) = \frac{p^*_{\bar{p}}}{T_0} + \frac{p_T}{p_0} + \varDelta_c \frac{p_T^2}{M_{\bar{p}}^2}, \quad (2)$$

where σ_{pp} is the inelastic cross-section in p-p collisions, $N_{\bar{p}}$ is the average multiplicity of $\bar{p}$, Θ_c is a normalization constant discussed later. p_c is the maximum momentum of $\bar{p}$ in the CMS, given by

$$p_c = M_{\bar{p}}\beta_c\sqrt{\Gamma_c^2 - 4}, \quad (3)$$

where $M_{\bar{p}}$ (= 938 MeV/c^2) is the mass of $\bar{p}$, and β_c is the velocity of the CMS against the LS in units of the velocity of light c, and Γ_c (≥ 2) is the Lorentz factor corresponding to β_c. Two additional parameters, χ_c and $\varDelta_c$, not appearing in the case of the production cross-section for γ-rays, come from the suppression of the production for the high energy $\bar{p}$ coming from the Baryon number conservation. In the present paper we assume the following forms,

$$\chi_c = 1 + \varDelta_c(9.89\xi_c)^4 \exp[-10.5\xi_c], \quad (4)$$

$$\Delta_c = 1 - \exp[-(5.54\xi_c)^{3.5}], \tag{5}$$

with $$\xi_c = \frac{M_{\bar{p}}}{p_c} = \frac{1}{\beta_c\sqrt{\Gamma_c^2 - 4}}, \tag{6}$$

which are determined so that the experimental data are well reproduced, but the forms of (4) and (5) are not critical, and other choices may be possible, as we don't go into the detail about the theoretical basis.

Introducing two parameters,

$$\tau = T_0/p_0, \quad \omega_c = p_c/T_0, \tag{7}$$

Eq. (2) is rewritten

$$Z_c(\xi, \xi_T) = \omega_c(\xi + \tau\xi_T) + \Delta_c \xi_T^2/\xi_c^2, \tag{8}$$

with $$\xi = \frac{p_{\bar{p}}^*}{p_c}, \quad \xi_T = \frac{p_T}{p_c} = \xi \sin\theta^*, \tag{9}$$

which appears often in the following discussions. In the low energy limit (where $\xi \approx 0$, and $\tau \approx 0$), one finds that the angular distribution of $\bar{p}$ becomes isotropic in the CMS. On the other hand, it is deformed into the "cigar-type" (or flat-type) distribution at higher energies, i.e., with larger τ, which is a well-known character of multiple meson production. We refer to τ as the deformation parameter (see also Paper I).

Eq. (1) must be normalized to the average multiplicity of $\bar{p}$, $N_{\bar{p}}$, leading to

$$\Theta_c = 1/\Xi_{2,1}(\tau, \omega_c), \tag{10}$$

where

$$\Xi_{\ell,m}(\tau, \omega_c) = \int_0^1 (1-\xi)^{\chi_c} \frac{\xi^\ell d\xi}{\sqrt{\xi^2 + \xi_c^2}} \times \int_0^1 \mathrm{e}^{-Z_c(\xi,\, \xi t)} \frac{t^m dt}{\sqrt{1 - t^2}}. \tag{11}$$

Energy distribution in laboratory system

For practical purposes, we need the energy distribution in the LS after integrating over the emission angle θ of $\bar{p}$ in the LS, given by

$$\frac{d\sigma}{dE_{\bar{p}}} = 2\pi p_{\bar{p}} \int_{\min}^{\max} E_{\bar{p}} \frac{d^3\sigma}{d^3\boldsymbol{p}_{\bar{p}}} d(\cos\theta), \tag{12}$$

where $E_{\bar{p}}$ is the *total* energy of $\bar{p}$ in the LS, and the minimum value for $\cos\theta$ relates to both $E_{\bar{p}}$ and p_c.

Now, introducing a scaling variable, X, related to the energy $E_{\bar{p}}$ of $\bar{p}$,

$$X \equiv \frac{E_{\bar{p}}}{2p_c\beta_c\Gamma_c} = \frac{E_{\bar{p}}/\sqrt{s}}{\beta_c^2\sqrt{\Gamma_c^2 - 4}}, \tag{13}$$

where $\sqrt{s}$ is the total energy in the CMS, which corresponds to the fractional energy of $\bar{p}$, $E_{\bar{p}}/E_p$, (E_p: total energy of the incident proton) in the high energy limit, we obtain the energy distribution of $\bar{p}$ in the LS

$$\frac{1}{\sigma_{pp}}\frac{d\sigma}{dX} = N_{\bar{p}}(E_p)\,\Theta_c(E_p) \times \int_{\xi_m}^1 (1-\xi)^{\chi_c} \mathrm{e}^{-Z_c(\xi,\, \xi_T)} \frac{\xi d\xi}{\sqrt{\xi^2 + \xi_c^2}}, \tag{14}$$

where

$$\xi_m(X) = 2(\Gamma_c^2 - 1)\Big|1 - \beta_{\bar{p}}(X)/\beta_c\Big| X, \tag{15}$$

$$\xi_T(\xi, X) = \sqrt{\xi^2 - [2X - \sqrt{\xi^2 + \xi_c^2}/\beta_c]^2}, \tag{16}$$

and $\beta_{\bar{p}}$ is the velocity of $\bar{p}$ in units of the velocity of light c, depending on X in the low energy region. For the high energy region ($\Gamma_c \gg 1$, and $E_{\bar{p}} \gg M_{\bar{p}}$), we have

$$\frac{\xi_m}{X} \approx \left|\frac{s}{4E_{\bar{p}}^2} - 1\right| \left[1 + \frac{1}{4\Gamma_c^2}\left(\frac{3s}{4E_{\bar{p}}^2} - 1\right)\right], \tag{17}$$

leading to

$$\xi_m(X) \approx X \approx E_{\bar{p}}/E_p, \quad \text{for } E_{\bar{p}} \gg \sqrt{s}/2. \tag{18}$$

One should remember that the familiar Feynman scaling variable, $x = 2p_L^*/\sqrt{s}$ (p_L^*: longitudinal momentum of $\bar{p}$ in the CMS), is also given by the fractional form, $E_{\bar{p}}/E_p$, in the high energy limit.

Comparison with the experimental data

Procedure for parameter determination

Before comparing our numerical results with the experimental data, we discuss the parameter setting in our model, and the procedure for parameter determination in advance.

There are three parameters in Eq. (1), $N_{\bar{p}}$, T_0, and p_0, and we have to find their energy dependence by comparing the formula with the data. We don't

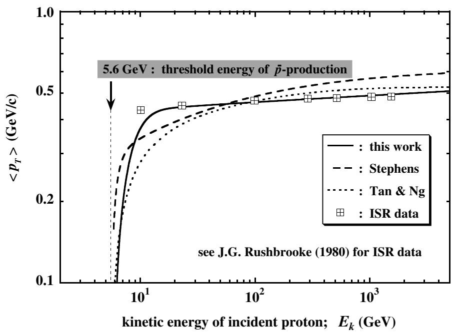

Figure 1: Average transverse momentum of $\bar{p}$

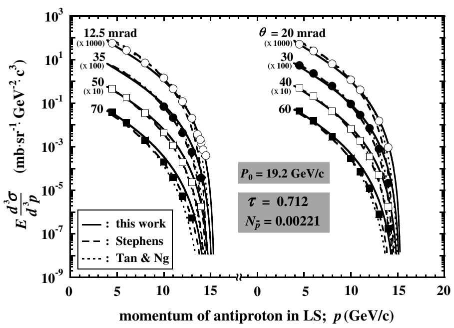

Figure 2: Cross section against momentum.

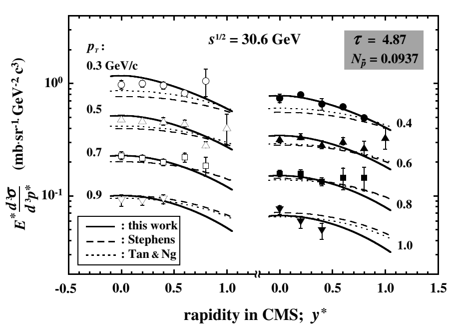

Figure 3: Cross section against rapidity.

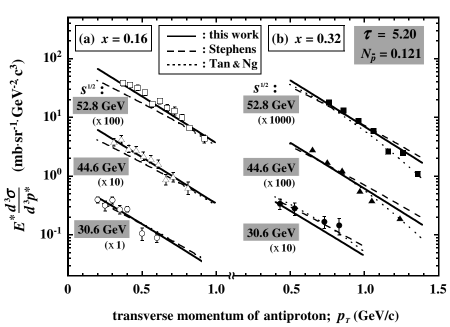

Figure 4: Cross section against p_T.

consider here the two additional parameters, χ_c and $\varDelta_c$, as they are not important in the high energy region. Here, we concentrate our attention upon three parameters, $(N_{\bar{p}},\ \tau,\ \langle p_T\rangle)$, in place of $(N_{\bar{p}},\ T_0,\ p_0)$. This is because the average multiplicity, $N_{\bar{p}}$, and the average transverse momentum, $\langle p_T\rangle$, of $\bar{p}$ are rather reliably determined from experimental data, in particular the latter is quite stable at approximately 500 MeV/c, almost independent of the interaction energy, except near the threshold in the kinetic energy, $E_{\rm th}$ = 5.6 GeV.

Now, from Eq. (1), the average transverse momentum $\langle p_T\rangle$ is given by the use of $\varXi_{\ell,m}(\tau,\omega_c)$ (see Eq. (11)),

$$\langle p_T\rangle/p_c = \varXi_{3,2}(\tau,\omega_c)/\varXi_{2,1}(\tau,\omega_c). \qquad (19)$$

So, first let us examine the data on the average transverse momentum of $\bar{p}$ [4], $\langle p_T\rangle$, against the kinetic energy of the incident proton in the range 10–2000 GeV in Fig. 1. The empirical curve is given by

$$\langle p_T\rangle(E_k) = p_{T,0}\Big[1-\exp(-a_T\hat{E}_k)\Big]\hat{E}_k^{b_T}, \quad (20)$$

$$\text{with} \quad \hat{E}_k = K_E E_k, \quad K_E = 1 - E_{\rm th}/E_k, \quad (21)$$

where $p_{T,0}$ = 416 MeV/c, a_T = 0.450, b_T = 0.0238, and E_k is the kinetic energy of the incident proton in GeV.

In Fig. 1, we draw also two curves expected from the parameterizations of Stephens & Golden (*broken curves*) [2], and Tan & Ng (*dotted curves*) [3]. Unfortunately, we can not confirm how the average transverse momentum of $\bar{p}$, $\langle p_T\rangle$, drops around $E_k \approx E_{\rm th}$, as no data are available near the threshold energy, while it must be kinematically null for $E_k \to E_{\rm th}$.

In the following discussions, we regard $N_{\bar{p}}$ and τ as free parameters to be determined from the comparison with the experimental data, and the third one, ω_c, is bound to the average transverse momentum $\langle p_T\rangle$ for a fixed τ, i.e., it is given by a numerical solution, equating Eq. (19) with Eq. (20),

$$\frac{p_{T,0}}{p_c}\Big[1-\exp(-a_T\hat{E}_k)\Big]\hat{E}_k^{b_T} = \frac{\varXi_{3,2}(\tau,\omega_c)}{\varXi_{2,1}(\tau,\omega_c)}. \quad (22)$$

Curve-fitting to the experimental data

First, we present the invariant cross-sections for several fixed emission angles against the momentum of $\bar{p}$ in the LS in Fig. 2 for the incident proton with $P_0 = 19.2\,\mathrm{GeV/c}$ [5], where the best fit curves (*solid ones*) using the least squares method are also plotted.

Second, in Fig. 3 we show the invariant cross-sections for several fixed transverse momenta against the rapidity of $\bar{p}$, $y^* = \frac{1}{2}\ln[(E^*_{\bar{p}} + p^*_L)/(E^*_{\bar{p}} + p^*_L)]$, in the CMS in ISR region [6], $\sqrt{s} = 30.6\,\mathrm{GeV}$, corresponding to the LS *total* energy of the incident proton with $E_p = 500\,\mathrm{GeV}$.

Third, in Fig. 4 we show further the invariant cross-sections for several energies of the incident proton against the transverse momentum of $\bar{p}$ with two sets, $x = 016,\ 0.32$ [7], where x denotes the Feynman variable. In these figures, we draw also the curves expected from Stephens (*broken curves*) [2], and Tan & Ng (*dotted curves*) [3].

Energy dependence of parameters

In the last section we obtained two parameters, $N_{\bar{p}}$, and τ, by fitting our formula to the data for various energies. First let us demonstrate the average multiplicity of $\bar{p}$ $N_{\bar{p}}$, against the kinetic energy of the incident proton, E_k, in Fig. 5, where we plot also the average multiplicity *directly measured* by ISR (*square-cross*) [8] and UA5 (*open square*) [9]. One finds that the average multiplicity obtained from Figs. 2-4 (see [10] for more detail) is in good agreement with the direct data. We plot an empirical curve in the figure, given by

$$N_{\bar{p}} = N_{\bar{p},0}\, K_E^{5.15}\left[1 - \exp(-a_N \hat{E}_k^{1/2})\right]\hat{E}_k^{1/4}, \quad (23)$$

where $N_{\bar{p},0} = 0.0233$, $a_N = 0.0880$.

Second, in Fig. 6, we demonstrate the deformation parameter τ against the available energy for the $\bar{p}$-production in the CMS, $\sqrt{s} - 4M_p$ ($4M_p$: threshold of the CMS energy), where the straight line plotted is given by

$$\tau = \tau_0\left[\sqrt{s} - 4M_p\right]^{a_\tau}, \quad (24)$$

where $\tau_0 = 0.363$, $a_\tau = 0.823$.

There are no spaces to discuss the present results, and the full paper of the present results will be published in the near future [10], together with the application for the experimental data on CR-$\bar{p}$'s.

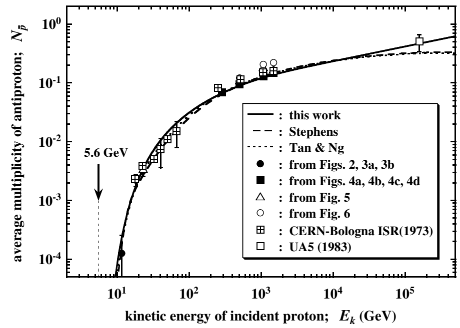

Figure 5: Energy dependence of $N_{\bar{p}}$ (see [10]).

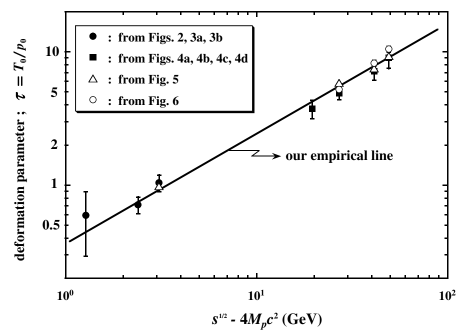

Figure 6: Energy dependence of τ (see also [10]).

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