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Production Rate of Quark Pairs, Strangeness Suppression Factor and Ratio of Baryon to Meson in $p\bar{p}$ Collision

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Using the statistical quark model and the experimental data of hadron yields, we investigate the production rate of quark pairs, the strangeness suppression factor and the ratio of baryon to meson in $p\bar{p}$ collisions. The changes of these quantities with the energy $\sqrt{s}$ are obtained.

Key words: $p\bar{p}$ collision, production rate of quark pairs, ratio of baryon to meson.

1. INTRODUCTION

The final state hadrons in $p\bar{p}$ reaction consist of directly produced hadrons (primary hadrons) together with their decay products. Primary hadrons are formed by original quarks in colliding nucleons, and those new quark pairs produced in excited vacuum. But averagely how many new quark paris are produced in $p\bar{p}$ reaction at certain energy? What value is the ratio of the number of strange quarks to that of nonstrange ones, i.e. the strangeness suppression factor λ? These are questions that both theoreticians and experimentalist are interested in.

Assume one original quark q of colliding proton p interacts with its counterpart $\bar{q}$ of antiproton

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$\bar{p}$. Averagely, there are N quark-antiquark pairs produced through vacuum excitation, where the relative weights of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ are 1, 1 and λ respectively. These N pairs of quarks and antiquarks together with the interacting pair $q\bar{q}$ combine into hadrons which contribute to central rapidity region. The spectators qq ($\overline{qq}$) of p ($\bar{p}$) which do not interact draw from the central region a quark (antiquark) to form the leading baryon (antibaryon). The spectator $\overline{qq}$ (qq) may also draw a quark pair qq (antiquark pair $\overline{qq}$) to form two leading mesons. The leading particles can be distinguished due to their large momenta. If the quarks drawn by the leading particles from the central region are deducted, approximately there are N quark-antiquark pairs in the central region. Assume these N quark-antiquark pairs combine into B primary baryons, $\bar{B}=B$ primary antibaryons and M primary mesons. According to the conservation of quark number

$$2N = 2M + 3(B + \bar{B}) = M(2 + 3\alpha), \quad \alpha = \frac{B + \bar{B}}{M}. \tag{1}$$

where α is the ratio of primary baryons and antibaryons to primary mesons. If N and α are known, then M, B and $\bar{B}$ are determined by

$$M = \frac{2N}{2 + 3\alpha}, \quad B = \bar{B} = \frac{N\alpha}{2 + 3\alpha}. \tag{2}$$

Anisovich et al. have derived $\alpha = 1/3$ at the limit $N \to \infty$ and give the multiplicity ratio of final Kaon to pion[1]

$$\frac{K}{\pi} = \frac{12\lambda + 4\lambda^2}{31 + 12\lambda + 3\lambda^2 + f\left(\frac{16}{3} + 4\lambda + \frac{8}{3}\lambda^2\right)}, \tag{3}$$

where

$$f = \frac{4 + 4\lambda + \lambda^2}{5 + 5\lambda + 3\lambda^2 + \lambda^3}. \tag{4}$$

From Eq. (3) and (4), one can derive λ from K/π data. This is one of the main method to determine λ. Ref [2] obtains three λ data 0.29 ± 0.05, 0.30 ± 0.03 and 0.33 ± 0.03 at $\sqrt{s}$ = 200, 546 and 900GeV, respectively. However, it is necessary to emphasize that the number N is not very large in this energy range. Even for $\sqrt{s}$ = 900GeV, we only have $N < \langle n_{ch} \rangle = 35.6$. Hence it is doubtful to choose α to be 1/3. One the other hand, many experiments show the signs of increasing α with the growing energy in the current energy range. In this paper, we regard α as a parameter to be determined and emerge together with N and λ in the expression of final hadron multiplicity $\langle \pi^+ + \pi^- \rangle$, $\langle K^+ + K^- \rangle$ and $\langle p + \bar{p} \rangle$. We will determine α, N and λ by comparing data with theoretical values and study energy behaviors of these parameters. We calculate hadron multiplicities in statistical quark model (SQM). Recently, the "spin suppression" effect in baryon production is proved by experiments. The "spin suppression" effect is that the ratio of spin 3/2 baryons to spin 1/2 ones is about 0.3 instead of their spin counting ratio 2. This effect is not considered in the early SQM. We consider it in our later calculation.

2. THE FORMULA FOR HADRON MULTIPLICITIES

According to SQM, the central region hadrons produced by N pairs of quarks are mesons of 36-plet and baryons of 56-plet. In 36-plet, the ratio of production weight of 1^- meson to that of 0^- one is chosen to be their spin counting ratio 3. In 56-plet, the ratio β of $3/2^+$ baryon to $1/2^+$ baryon is determined by the following formula derived in Ref. [3] instead of their spin counting ratio 2,

$$\beta = \frac{1+\lambda}{3+2\lambda}. \tag{5}$$

for $\lambda = 0.2-0.4$, $\beta = 0.35-0.37$, which agree with data fairly well. The ratio of 36-plet meson to 56-plet baryon is denoted by α. Assume the weight of pion and proton are 1 and γ respectively. In Table 1 the production weights of all mesons and baryons are listed. Denote

$$A = 16 + 16\lambda + 4\lambda^2, \tag{6}$$

$$C = 2 + 4\beta + (4 + 3\beta)\lambda + 2(1+\beta)\lambda^2 + \beta\lambda^3. \tag{7}$$

where A is the total sum of the relative weights of all primary mesons while γC is that of all baryons (all antibaryons). γ is determined by $\alpha = (B+\bar{B})/M = 2\gamma C/A$ and finally we obtain

$$\gamma = \frac{\alpha A}{2C}. \tag{8}$$

The production weights are also listed in Table 1. They are obtained after all decay contributions are taken into account while the decay channels and their branch ratios are taken from Ref. [4]. Considering that the baryon number is conserved during decay process and that the probability of one primary baron decaying into proton equals to that into neutron, the weight of final proton and neutron are γC. The following final hadron multiplicities are derived from their relative weights given in Table 1.

$$\begin{aligned}\langle \pi^+ + \pi^- \rangle = {} & \frac{4N}{(2+3\alpha)A}(10.46 + 6.74\lambda + 1.69\lambda^2) \\ & + \frac{2\alpha N}{(2+3\alpha)C}[3.34\beta + (2.76 + 2.96\beta)\lambda \\ & + (2.28 + 3.62\beta)\lambda^2 + 0.96\beta\lambda^3],\end{aligned} \tag{9}$$

$$\langle K^+ + K^- \rangle = \frac{4N}{(2+3\alpha)A}(4\lambda + 1.47\lambda^2), \tag{10}$$

$$\langle p + \bar{p} \rangle = \frac{\alpha N}{2+3\alpha}, \tag{11}$$

$$\begin{aligned}\langle n_{ch} \rangle = {} & \langle \pi^+ + \pi^- \rangle + \langle K^+ + K^- \rangle + \langle p + \bar{p} \rangle \\ = {} & \frac{4N}{(2+3\alpha)A}(10.46 + 10.74 + 3.16\lambda^2) \\ & + \frac{2\alpha N}{(2+3\alpha)C}\left[\frac{C}{2} + 3.34\beta + (2.76 + 2.96\beta)\lambda \right. \\ & \left. + (2.28 + 3.62\beta)\lambda^2 + 0.96\beta\lambda^3\right].\end{aligned} \tag{12}$$

Table 1

The relative weights of hadrons in central region.

hadron	relative weights of the directly produced hadrons	relative weights of the final observed hadrons
$\pi^+ \pi^-$	1	$10.46 + 6.74\lambda + 1.69\lambda^2 + \gamma[3.34\beta + (2.76 + 2.96\beta)\lambda + (2.28 + 3.62\beta)\lambda^2 + 0.96\beta\lambda^3]$
π^0	1	$11.10 + 6.51\lambda + 2.55\lambda^2 + \gamma[1.34\beta + (2.46 + 4.10\beta)\lambda + (3.42 + 4.76\beta)\lambda^2 + 1.36\beta\lambda^3]$
$K^+ K^-$	λ	$4\lambda + 1.47\lambda^2$
$K^0 \bar{K}^0$	λ	$4\lambda + 1.03\lambda^2$
η	$\frac{1}{3} + \frac{2}{3}\lambda^2$	$0.76 + 0.93\lambda^2$
η'	$\frac{2}{3} + \frac{1}{3}\lambda^2$	$\frac{2}{3} + \frac{1}{3}\lambda^2$
$\rho^+ \rho^-$	3	$3 + 0.13\lambda^2$
ρ^0	3	$3.20 + 0.23\lambda^2$
ω	3	$3.02 + 0.01\lambda^2$
$K^{*+}K^{*0}\bar{K}^{*0}K^{*-}$	3λ	3λ
ϕ	$3\lambda^2$	$3\lambda^2$
$pn\bar{p}\bar{n}$	γ	$\gamma C/2$
$\Lambda \bar{\Lambda}$	$\gamma\lambda$	$[(2 + 2.76\beta)\lambda + 2(1 + \beta)\lambda^2 + \beta\lambda^3]\gamma$
$\Sigma^+\Sigma^-\bar{\Sigma}^+\bar{\Sigma}^-\Sigma^0\bar{\Sigma}^0$	$\gamma\lambda$	$(1 + 0.12\beta)\lambda\gamma$
$\Delta^{++}\Delta^+\Delta^0\Delta^-$ $\bar{\Delta}^{++}\bar{\Delta}^+\bar{\Delta}^0\bar{\Delta}^-$	$\gamma\beta$	$\gamma\beta$
$\Sigma^{*+}\Sigma^{*0}\Sigma^{*-}$ $\bar{\Sigma}^{*+}\bar{\Sigma}^{*0}\bar{\Sigma}^{*-}$	$\gamma\beta\lambda$	$\gamma\beta\lambda$
$\Xi^{*0}\Xi^{*-}\bar{\Xi}^{*0}\bar{\Xi}^{*-}$	$\gamma\beta\lambda^2$	$\gamma\beta\lambda^2$
$\Omega^-\bar{\Omega}^+$	$\gamma\beta\lambda^3$	$\gamma\beta\lambda^3$

3. THE DETERMINATION OF N, α AND λ

The experimental multiplicity data of long lived particles in pp and $p\bar{p}$ collision at 5 energies are given in Table 2, where the data of pp reaction at $\sqrt{s} = 27.4$GeV are taken from Ref. [5] while others from Ref. [6]. From Eq. (9) and (11), we obtain

$$\frac{\langle \pi^+ + \pi^- \rangle}{\langle p + \bar{p} \rangle} = \frac{4}{\alpha A}[10.46 + 6.74\lambda + 1.69\lambda^2] + \frac{2}{C}[3.34\beta + (2.76 + 2.96\beta)\lambda + (2.28 + 3.62\beta)\lambda^2 + 0.96\beta\lambda^3], \tag{13}$$

Table 2
The yield data of long lived particles and the values of α, N and λ determined.

$\sqrt{s}$ (GeV)	27.4	53	200	546	900
reaction type	pp	$p\bar{p}$	$p\bar{p}$	$p\bar{p}$	$p\bar{p}$
$\langle \pi^+ + \pi^- \rangle$	7.44±0.19	9.20±0.23	17.5±0.9	23.6±1.0	27.7±1.3
$\langle K^+ + K^- \rangle$	0.555±0.027	0.74±0.11	1.56±0.24	2.24±0.16	3.02±1.20
$\langle p + \bar{p} \rangle$	0.126±0.004	0.30±0.05	0.87±0.28	1.45±0.16	1.85±0.46
$\langle n_{ch} \rangle$	8.12±0.19	10.24±0.23	19.93±0.97	27.29±1.03	32.57±1.40
λ	0.21±0.01	$0.23^{+0.07}_{-0.06}$	$0.27^{+0.17}_{-0.14}$	$0.29^{+0.05}_{-0.02}$	$0.33^{+0.25}_{-0.21}$
α	0.041±0.001	$0.08^{+0.02}_{-0.01}$	$0.13^{+0.06}_{-0.03}$	0.16±0.02	$0.17^{+0.06}_{-0.04}$
N	6.4±0.2	8.2±0.2	16.4±1.0	22.8±0.9	$27.3^{+1.5}_{-2.1}$
λ_0	0.25±0.01	$0.26^{+0.08}_{-0.07}$	$0.29^{+0.18}_{-0.15}$	$0.30^{+0.05}_{-0.02}$	$0.34^{+0.26}_{-0.22}$

$$\frac{\langle K^+ + K^- \rangle}{\langle p + \bar{p} \rangle} = \frac{4}{\alpha A}(4\lambda + 1.47\lambda^2). \tag{14}$$

Substitute $<\pi^+ + \pi^->$, $<K^+ + K^->$ and $<p + \bar{p}>$ data into (13) and (14), one can derive N, α and λ from (12). The results are shown in Table 2.

The determined λ factor in this way is larger than actual value λ_0 of vacuum excited quarks. Denote the numbers of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$, by N_u, N_d and N_s respectively. The relative ratio is $1:1:\lambda_0$. λ is related to λ_0 by

$$\lambda = \frac{N_s}{\frac{1}{2}(2N_u + 1)} = \frac{N_s}{N_u + \frac{1}{2}} = \frac{\lambda_0}{1 + \frac{1}{2N_u}}. \tag{15}$$

Use $N \approx 2N_u + N_s = N_u(2+\lambda_0)$, we obtain

$$\lambda_0 = \frac{(N+1)\lambda}{N - 0.5\lambda}. \tag{16}$$

The values of λ_0 derived in this way are also listed in Table 2.

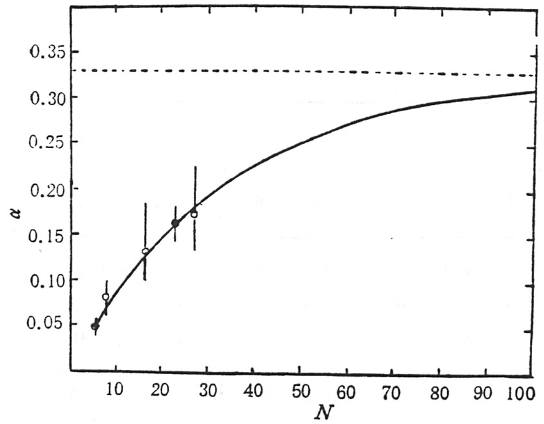

Fig. 1
The variation of alpha as function of N. The dash line is the result given by Anisovich, while the solid curve is that of this paper.

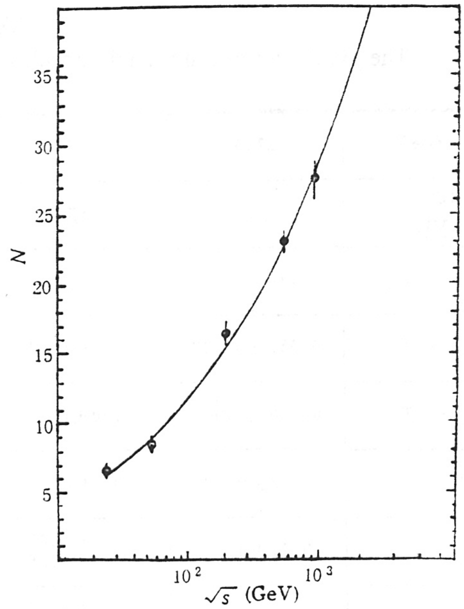

Fig. 2
The variation of N with energy.

4. DISCUSSION

4.1 The strangeness suppression factor λ_0 in various reaction at many energies are studied in detail by Ref. [7]. The conclusion has been drawn that λ_0 is an universal constant and $\lambda_0 = 0.29 \pm 0.02$. According to the flux tube model aimed to explain the excitation of quark pari from vacuum, λ_0 ought to be constant. The theoretical values of λ_0 in the energy range $\sqrt{s} = 53$–900GeV determined in this paper coincide with the data within error.

4.2 We obtain that α grows with energy and that it is much lower than 1/3 which derived by Anisovich at the limit of $N \to \infty$. So 1/3 is inappropriate for α in the current energy range. If $N \to \infty$ is true, we obtain the following parametrization form for α as function of N

$$\alpha = \frac{1}{3}(1 - e^{-0.028N}). \tag{17}$$

The α-N curve of (17) and α data are shown in Fig.1.

4.3 Using the next-to-leading log approximation, Webber gave the expression of the average multiplicity of charged particle $\langle n_{ch} \rangle$ in e^+e^- annihilation as follows

$$\langle n_{ch} \rangle = a\alpha_s^{0.4915} \exp(2.265/\sqrt{\alpha_s}), \tag{18}$$

Table 3
The theoretical multiplicities of final hadrons (with data in the brackets).

$\sqrt{s}$ (GeV)	N	α	$\langle\pi^+ + \pi^-\rangle$	$\langle K^+ + K^-\rangle$	$\langle p + \bar{p}\rangle$	$\langle n_{ch}\rangle$
900	27.86 $\left(27.3^{+1.5}_{-2.1}\right)$	0.178 $\left(0.17^{+0.06}_{-0.04}\right)$	28.27 (27.7±1.3)	2.77 (3.02±1.2)	1.96 (1.85±0.46)	33.01 (32.57±1.40)
1800	35.98	0.212	35.59	3.44	2.89	41.92
10^4	65.41	0.280	61.67	5.80	6.45	73.92

where the coupling constant of strong interaction is calculated by [8]

$$\alpha_s = \frac{12\pi}{23\ln(90.7s)} - \frac{4176\pi\ln\ln(90.7s)}{12167\ln^2(90.7s)}. \tag{19}$$

The parameter a in (18) cannot be calculated by QCD. Choose a = 0.059 to fit $<n_{ch}>$ from 10 to 93GeV in e^+e^- annihilation [9]. Because the number of quark pairs is proportional to $<n_{ch}>$ in e^+e^- annihilation, (18) and (19) can be regarded as the formula for calculating N. Considering that the mechanism of quark pair production in $p\bar{p}$ (pp) collision is similar to that in e^+e^- annihilation because the new quark pairs are all produced through vacuum excitation induced by a pair of primary quarks in both processes. The difference between them lies in that in e^+e^- annihilation, the total center of mass energy of the primary quarks is used to produce new quarks while only a part of it, i.e. $\sqrt{s_{eff}} = k\sqrt{s}$ ($k<1$), is used in $p\bar{p}$ (pp) collision. We choose k = 1/3, a = 0.05, then we derive from (18) and (19) the formula of N

$$N = 0.05\alpha_s^{0.4915}\exp(2.265/\sqrt{\alpha_s}), \tag{20}$$

$$\alpha_s = \frac{12\pi}{23\ln(10.08s)} - \frac{4176\pi\ln\ln(10.08s)}{12167\ln^2(10.08s)}. \tag{21}$$

Eq. (20) is illustrated by the solid curve in Fig.2. As one can see in the figure that all of the theoretical values of N coincide with data within errors.

4.4 Assume λ_0 is constant and choose it to be 0.3. Note that the primary quarks are nonstrange ones, the superficial strangeness suppression factor λ in central region is obtained to be

$$\lambda = \frac{N\lambda_0}{N+1+0.5\lambda_0} = \frac{0.3N}{N+1.15}. \tag{22}$$

β, α and N are determined from (5), (17), (20) and (21). The yields of various final particles in $p\bar{p}$ reaction are calculated from (9)-(12). For $\sqrt{s}$ ≥ 900GeV, $\lambda \approx 0.3$, A = 21.16, β = 0.36, C = 5.2185, we obtain

$$\sqrt{s} \geqslant 900\text{GeV}, \quad \lambda \approx 0.3, \quad A = 21.16, \quad \beta = 0.36, \quad C = 5.2185, \tag{23}$$

$$\langle \pi^+ + \pi^- \rangle = \frac{N}{2 + 3\alpha}(2.388 + 1.034\alpha),$$

$$\langle K^+ + K^- \rangle = \frac{0.2518N}{2 + 3\alpha}, \tag{24}$$

$$\langle p + \bar{p} \rangle = \frac{\alpha N}{2 + 3\alpha}, \tag{25}$$

$$\langle n_{ch} \rangle = \frac{N}{2 + 3\alpha}(2.640 + 2.034\alpha). \tag{26}$$

Note that the leading particles are excluded in calculation. In $p\bar{p}$ collision, there are no 18O0GeV and 10^4GeV data so far. The test of our theory by the future experiments are expected.

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