High Energy Physics and Nuclear Physics

Volume 16, Number 1

The Origin and Universality of "Spin Suppression" in Baryon Production

Xie Qubing

Department of Physics, Shandong University, Jinan, Shandong, China

In high energy reactions the production of spin $(3/2)^+$ baryons is strongly suppressed in comparison with that of $(1/2)^+$ baryons. I show that the observed λ broken $SU_f(3)$ symmetry in multihadron production is consistent with stochastic quark arrangement, and this self-consistency determines the ratios among $SU_f(3)$ singlet, octet and decuplet, including all of their excited states. But for $(1/2)^+$ and $(3/2)^+$ baryon production, as in the case of the popular models, then the strangeness suppression factor $\lambda = \langle N_s\rangle/\langle N_u\rangle$ completely determines the ratio of $(3/2)^+$ to $(1/2)^+$, and $\beta = (1 + \lambda)/(3 + 2\lambda)$. The universality of this relation is emphasized.

1. INTRODUCTION

In high energy reactions, baryon production reflects the meson production. In recent years, scientists, especially those involved in the research on high-energy $e^+e^- \to h$, have discovered a series of rules [1] which are very difficult to explain with the popular models and become very interested [2]. For example, both the directly produced $(3/2)^+$, $(1/2)^+$ baryons and mesons satisfy the broken $SU_f(3)$ and have the same strangeness suppression, but the ratio of 1^- to 0^- mesons satisfies $SU(6)$ symmetry [6], and the ratio of $(3/2)^+$ to $(1/2)^+$ baryons is only about 0.3, far from 2 of $SU(6)$ symmetry, which displays very strong spin suppression. Fig.1 compares the data and the popular models [3]. By now various models explain this suppression with certain mass effects. Webber model attributes kinematical phase space decrease to the mass difference between $(1/2)^+$ and $(3/2)^+$, which could not have led $SU(6)$ breaking so seriously. Fig.1 shows that only Lund model can agree with data approximately, but this is achieved by adjusting four parameters related to the ambiguous masses of point-like diquarks in addition to $\lambda = 0.3$. Still, it cannot agree well with all of those data. Furthermore, baryon-antibaryon flavor correlation has excluded the production of point-like diquark-

Supported by the National Natural Science Foundation of China.
Received on February 19, 1991.

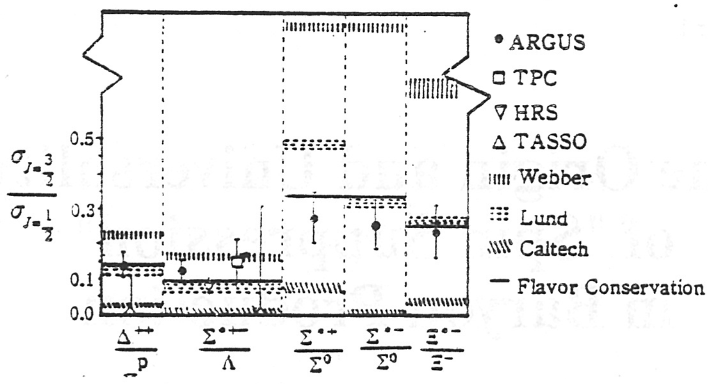

Fig.1

Ratios of cross sections for $(1/2)^+$ and $(3/2)^+$ baryons. Only baryons with the same strangeness content are compared. Data and model predictions (shaded bands) are taken from Ref.[3] and new data are added [1].

antidiquark pairs as a dominant source of baryons [4,5].

In fact, the mass effect of quarks has been expressed by strangeness suppression λ, which means that the directly projected hadrons have the λ broken $SU_f(3)$ symmetry: just because the quark mass m_i is different, the probability for a q$\bar{q}$ pair created in vacuum excitation by QCD

$$p_\nu \propto e^{-k m_\nu^2} \tag{1}$$

is also different [7]. Put constituent quark mass into Eq.(1), we can obtain $p_u = p_d$. p_c, p_b can be ignored completely. The production of strange quark s is suppressed in comparison with u or d, its suppression factor is

$$\lambda = \frac{p_s}{p_u} = \frac{\langle N_s \rangle}{\frac{1}{2}(\langle N_u \rangle + \langle N_d \rangle)} = \frac{\langle N_s \rangle}{\langle N_u \rangle}. \tag{2}$$

Just because the probability p_s or number $\langle n_s \rangle$ of s (or $\bar{s}$) is λ times as much as that of u or d ($\bar{u}$ or $\bar{d}$) in newborn quarks and antiquarks, the directly produced baryons or mesons only satisfy the λ broken $SU_f(3)$ symmetry, i.e., each $SU_f(3)$ multiple with the same J^{PC} has the same production rates (or yields), but the production rates of the members of the same multiple which differ by a s (or $\bar{s}$) quark have a λ-fold decrease. This means that quark flavors must be conserved in hadron production process. For simplicity, the terms hadrons, mesons, baryons used in this paper will always denote the directly produced ones unless otherwise indicated, and I also use s, u instead of $\langle N_s \rangle$, $\langle N_u \rangle$ as many references do. In practice, the λ value is measured based on this assumption. Hence the fact that these measured values obtained from various species of meson and baryon are consistent with each other is very good evidence in itself for the λ broken $SU_f(3)$ symmetry and flavor conservation in high energy reaction.

From dynamic consideration, color forces are independent of flavor, and quark flavor must be conserved, so that λ = s/u cannot be changed in various strong interactions, including hadronization. In section 2, we will see that flavor conservation is always satisfied automatically in meson production. For $(3/2)^+$ and $(1/2)^+$ baryons, it can only be satisfied when they are produced with a certain ratio $\beta = (1 + \lambda)/(3 + 2\lambda)$. Section 3 compares the prediction in section 2 with the available data in e^+e^- and h—h reactions, which shows that our results are consistent with the experiments without any adjustable parameters. In the next paper, I will show that the requirements are consistent with stochastic quark combination; in this framework, the ratios among $SU_f(3)$ singlet, octet and decuplet, including all of their excited states, are determined and the "spin suppression" of $(3/2)^+$ to $(1/2)^+$ baryons and $[\Lambda(1520)/\Sigma(1385)] \geq 1$ can be explained.

2. FLAVOR CONSERVATION AND "SPIN SUPPRESSION"

Since quantum chromadynamics (QCD) is independent of quark flavor, the flavor must be conserved in hadronization, i.e., the ratio λ of s to u (or d) quarks before hadronization must be equal to that in produced mesons and baryons after hadronization. Otherwise some flavor would be in excess or not enough, which is neither possible nor permitted.

We all know that each J^P meson multiple either $L = 0$ mesons 0^-, 1^- or $L = 1$ mesons $0^+, 1^+, 2^+$, are $SU_f(3)$ nonet of the same flavor content $u\bar{d}$, $u\bar{s}$, ... $s\bar{s}$. For members of the same multiple, the production rates of mesons containing an s (or $\bar{s}$) quark have a λ-fold decrease compared with that of mesons without strange quarks and then the rate of content $s\bar{s}$ in mesons will be suppressed by λ^2. The number of u and s quark carried in each J^{PC} nonet is always

$$u:\ 2 + \lambda, \tag{3}$$

$$s:\ 2\lambda + \lambda^2. \tag{4}$$

It is easy to see from Eqs. (9) and (10) that the ratio of s to u in each J^{PC} note mesons is

$$\frac{s}{u} = \lambda. \tag{5}$$

This means that there is no restriction arising from flavor conservation in meson production. Of course, the flavor conservation can also be satisfied when all produced hadrons are mesons.

Now that meson production does not change the ratio $\lambda = s/u$, baryon production must satisfy $s/u = \lambda$. Otherwise, s quark would be in excess or not enough, both of which are impossible and forbidden by the flavor conservation. As mentioned in section 1, for all of the excited baryon production, the flavor conservation can always be satisfied. But for the $(1/2)^+$ and $(3/2)^+$ baryon production, let us see whether the flavor conservation is still satisfied and what the requirement of flavor conservation is.

By the same method as mesons, according to the λ broken $SU_f(3)$ symmetry, the ratios of cross sections for members of the octet should be p(uud) (= n(udd)): Σ^+(uus) (= Σ^0(uds) = Σ^-(dds) = Λ(uds)): Ξ^0(uss) (= Ξ^-(dss)) = 1: λ: λ^2 and the numbers of u and s quark contained in a octet are

$$u:\ 3 + 4\lambda + \lambda^2, \tag{6}$$

$$s:\ 4\lambda + 4\lambda^2. \tag{7}$$

and their ratio is always

$$\frac{s}{u} = \lambda\left(\frac{4 + 4\lambda}{3 + 4\lambda + \lambda^2}\right) = \frac{4\lambda}{3 + \lambda}. \tag{8}$$

In other words, as long as $\lambda < 1$ (i.e., $m_s > m_u$), whatever the λ value is, for all of produced $(1/2)^+$ baryons, we always have

$$\frac{4}{3 + \lambda} > 1, \tag{9}$$

i.e.,

$$\frac{s}{u} > \lambda. \tag{10}$$

which cannot satisfy the flavor conservation alone.

Following the same method for the decuplet, the ratios of cross sections for its members are $\Delta^{++}(uuu)$ $(= \Delta^{+}(uud) = \Delta^{0}(udd) = \Delta^{-}(ddd))$: $\Sigma^{*+}(uus)$ $(= \Sigma^{*0}(uds) = \Sigma^{*-}(dds))$: $\Xi^{*0}(uss)$ $(= \Xi^{*-}(dss))$: $\Omega^{-}(sss) = 1: \lambda: \lambda^2: \lambda^3$, then we obtain

$$u: \; 6 + 3\lambda + \lambda^2, \tag{11}$$

$$s: \; 3\lambda + 4\lambda^2 + 3\lambda^3, \tag{12}$$

their ratio is

$$\frac{s}{u} = \lambda\left(\frac{3 + 4\lambda + 3\lambda^2}{6 + 3\lambda + \lambda^2}\right) < \lambda. \tag{13}$$

Eqs. (8) and (13) mean that neither $(1/2)^+$ nor $(3/2)^+$ baryons satisfies flavor conservation alone. The only possible way to achieve conservation is that $(3/2)^+$ baryons be produced in a certain ratio $\beta = (3/2)^+/(1/2)^+$ and β satisfies the requirement of flavor conservation,

$$\frac{s}{u} = \lambda\left[\frac{(4 + 4\lambda) + (3 + 4\lambda + 3\lambda^2)\beta}{(3 + 4\lambda + \lambda^2) + (6 + 3\lambda + \lambda^2)\beta}\right] = \lambda, \tag{14}$$

i.e.,

$$\beta = \frac{1 + \lambda}{3 + 2\lambda}. \tag{15}$$

Because of the flavor conservation or $s/u = \lambda$ being unchangeable in strong interactions, $(1/2)^+$ and $(3/2)^+$ baryons can only be produced in the definite ratio of Eq.(15), but not in $\beta = 2$ of $SU(6)$ or any other ratios. Because $\lambda < 1$, β determined by Eq. (15) is also smaller than 1. Therefore, baryons are different from mesons and have no $SU(6)$ symmetry. And β is completely determined by strangeness suppression factor λ via Eq. (15), which is independent of reaction type and energy.

From the following discussion, we can clearly see the universality of relation (15). We know the ratio of mesons to baryons and their yields may vary with reaction type and energy in high energy reactions. To predict these changes correctly is always a crucial test for various phenomenological models. But as long as hadron production has the λ broken $SU_f(3)$ symmetry, the flavor ratio of quarks is independent of their yields, and depends on the ratio of produced mesons to baryons at most. Let α be the ratio of baryons to mesons, and β still be that of $(3/2)^+$ to $(1/2)^+$. Then we can obtain the ratio of s to u quark number in all hadrons (including all mesons and baryons) via Eqs. (3), (4), (6), (7), (11) and (12):

$$\frac{s}{u} = \lambda\left[\frac{\alpha(2 + \lambda) + (4 + 4\lambda) + (3 + 4\lambda + 3\lambda^2)\beta}{\alpha(2 + \lambda) + (3 + 4\lambda + \lambda^2) + (6 + 3\lambda + \lambda^2)\beta}\right].$$

But since flavor conservation requires the square brackets to be one, all those terms containing α will disappear. Hence we are back to Eq. (15). Obviously, relation (15) is independent of not only the yields of mesons and baryons, but also of their ratio α. It comes completely from the flavor conservation and the $SU_f(3)$ structural characteristics of the octet and decuplet themselves, and has nothing to do with reaction type and energy.

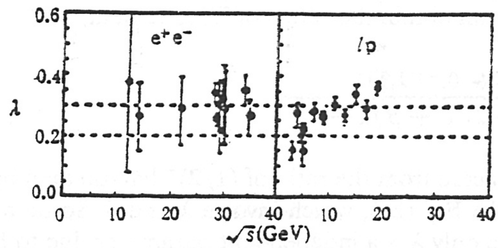

Fig.2

The strangeness suppression λ in e^+e^- (left side) and 1 h (right side) collisions [3].

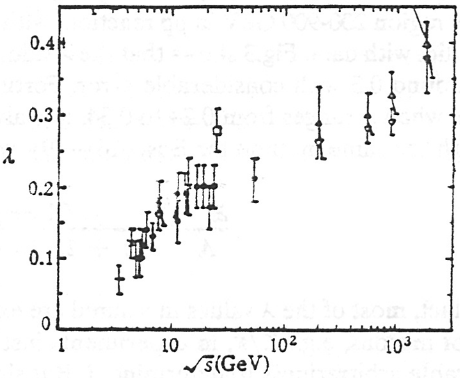

Fig.3

Energy dependence of the observed strangeness suppression factor λ in hp collisions [8]. ○ K^+pNA22; × K^{-p}; ● pp; □ ppNA23; ▽ $p\bar{p}$ (s & s); △ $p\bar{p}$ (A & K); + π^{-p}.

3. COMPARISON WITH AVAILABLE DATA

As mentioned above, in terms of Eq.(15), we can calculate β with the measured λ values in any reaction types and energies, and test it experimentally. Figs. 2 and 3 give the measured λ values in various reactions and energies up to now [8]. Fig.2 shows that the measured λ values remain ~0.3 and do not vary with $\sqrt{s}$ at the energy region 10 GeV < $\sqrt{s}$ < 40 GeV in e^+e^- reaction. Put λ = 0.3 into Eq.(15), we have β = 0.36. Note that the measured rates of the $(1/2)^+$ in experiments have involved the contribution from $(3/2)^+$ decays, so when we compare them with experimental results, we have to count this contribution according to the particle property table [9]. For example,

$$\frac{\Xi^{*-}}{\Xi^-} = \frac{\beta}{1+\beta+0.09\lambda\beta} = 0.26. \tag{16}$$

$$\frac{\Sigma^{*-}}{\Sigma^0} = \frac{\Sigma^{*+}}{\Sigma^0} = \frac{\beta}{1+0.12\beta} = 0.34. \tag{17}$$

$$\frac{\Sigma^{*\pm}}{2\Lambda} = \frac{\Sigma^{*-}}{\Lambda} = \frac{\beta}{2+2.76\beta+2(1+\beta)\lambda+\beta\lambda^2} = 0.09. \tag{18}$$

$$\frac{\Delta^{++}}{p} = \frac{2\beta}{2+4\lambda+2\lambda^2+\beta(4+3\lambda+2\lambda^2+\lambda^3)} = 0.138. \tag{19}$$

These predictions are drawn in solid line in Fig.1; they are in good agreement with the data.

Fig.3 gives the measured λ value at various energies in h—h reactions. When $\sqrt{s}$ rises from 4 GeV to 1.8 TeV, λ value grows from 0.1 to 0.35. Note that even if the probability (1) for a qq pair created in the QCD vacuum excitation may vary with $\sqrt{s}$, $\langle N_u \rangle$, $\langle N_s \rangle$ measured according to Eq.(2) may contain not only quarks created according to Eq.(1), but also the quark components coming from initial hadrons in h—h or 1—h reactions. With $\sqrt{s}$ rising, the proportion of the former also grows. So it is not difficult to understand the change of λ with $\sqrt{s}$ [10]. I have not seen any experimental report about decuplet yields in h—h reactions. Recently, however, UA5 collaboration has published the yields of Ξ^- and Λ baryons, including the contribution from $(3/2)^+$ baryon decays at energy region 200-900 GeV in $p\bar{p}$ reaction, with which we can test whether β predicted by Eq.(15) is in conflict with data. Fig.3 shows that the λ values measured at $\sqrt{s}$ = 200, 546, 900 GeV by SP$\bar{\text{P}}$S are all around 0.3 with considerable error. Fortunately, β is not sensitive to the change of λ. For example, when λ ranges from 0.24 to 0.34, it is always consistent with 0.36.

With the same method for Eqs. (16)-(19), we can obtain the ratios of Ξ^- to Λ yield

$$\frac{\Xi^-}{\Lambda} = \frac{(1+\beta+0.09\lambda\beta)\lambda}{2+2.76\beta+2(1+\beta)\lambda+\beta\lambda^2}. \tag{20}$$

In fact, most of the λ values measured are extracted from the ratio of $(1/2)^+$ baryon members or that of mesons, e.g., K/π, in experiments just like Eq. (20), which involve λ and β. So there is considerable arbitrariness to determine β. But since only λ is a independent parameter due to Eq. (21), the arbitrariness of β does not exist. For instance, put Eq. (15) into (20), we can obtain

$$\frac{\Xi^-}{\Lambda} = \frac{(4-0.91\lambda-3\lambda^2-0.09\lambda^3)\lambda}{8.76+6\lambda-7.76\lambda^2-6\lambda^3-\lambda^4}. \tag{21}$$

so we can improve the reliability of the measured λ value. Put λ = 0.3 obtained in e^+e^- annihilation and in $p\bar{p}$ reaction at SP$\bar{\text{P}}$S energies into Eq. (21), we can obtain the theory value

$$\frac{\Xi^-}{\Lambda} = 0.10. \tag{22}$$

The yields of Ξ^- and Λ have no contribution from charm baryon decays in pp reaction and γ resonance of e^+e^- annihilation, so it can be compared with Eq.(22) directly. Recently, ARGUS collaboration gave Ξ^-/Λ = 0.090 ± 0.016 in γ resonance [9]. UA5 collaboration gave Ξ^-/Λ = 0.065 ± 0.069, 0.189 ± 0.107, 0.092 ± 0.062 at $\sqrt{s}$ = 200, 546, 900 GeV in $p\bar{p}$ reaction [11]. None of them is in conflict with 0.10 predicted by Eq. (22). In $e^+e^- \to$ h's continuum, the initial c and b quarks created from elector-weak interactions may have some probability to be combined into c and b baryons, which may decay into Λ through Λ_c with the probability of about 27% [9]. This makes the rate of Λ increase and the ratio Ξ^-/Λ decrease. HRS and TASSO collaborations have measured Ξ^-/Λ = 0.083 ± 0.017 [3] and 0.064 ± 0.014 [12], respectively, which reflects this trend. However, the patterns of the production and decays of c and b baryons are model dependent. I will not discuss them here.

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