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THE ROLE OF VALENCE QUARKS IN PROTON FRAGMENTATION

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Abstract

Following earlier theoretical and experimental work (Kalinowski et al. [6], Bourquin et al. [7]), baryon production by fragmentation of incident protons in high energy hadron collisions is re-investigated in terms of a fragmentation-recombination mechanism similar to a model proposed by Fukuda and Iso [4]. The multiplicities $n_f(B)$ for the various types of baryons B produced in proton fragmentation are expressed in terms of the probabilities a_i for $i = 0, \dots, 3$ valence quarks of the incident proton to emerge in the baryon B and $3-i$ to emerge in mesons (following [7] we suppose that antibaryon production is mostly due to baryon-antibaryon pair production by a mechanism of non-fragmentation type, and this is taken into account in deducing $n_f(B)$ from baryon and antibaryon multiplicity data). The positivity of the a_i is found to impose remarkably narrow constraints on the $n_f(B)$ for (meta)stable B , and we find the data to satisfy these constraints. We show furthermore that the data are compatible with uncorrelated behaviour of the valence quarks of the incident proton, each of them having a probability ≈ 0.6 to emerge in the fragmentation baryon B , and a probability ≈ 0.4 to emerge in a meson. We also briefly discuss the relation of our analysis to previous work on the recombination model of proton fragmentation and its possible extension to meson fragmentation.

1. INTRODUCTION

Much work has been devoted in recent years to the description of low- p_T hadronic fragmentation in terms of quark partons, in particular the valence quarks of the incident hadrons. The models developed for this purpose fall broadly into two categories, based on quark recombination [1] and quark fragmentation [2], although it has been suggested in the framework of dual models that these mechanisms are not necessarily exclusive [3], and some models involve both fragmentation and recombination, in particular the quark cascade model with recombination mechanism of Fukuda and Iso [4]. Most of this work has dealt with inclusive x -distributions of one or two hadrons produced by the fragmentation of an incident hadron (x is as usual the fractional longitudinal c.m. momentum).

One can also address a more general question: what is the overall fate of the valence quarks of an incident hadron when the latter undergoes fragmentation in a low- p_T hadronic reaction? How often do they recombine with each other, and how often do they emerge in separate hadrons (mesons or baryons)? This type of question has been discussed by Ranft [5], the present author [1] and Kalinowski et al. [6]. The latter papers investigated the fate of the valence quarks in proton fragmentation by using as input the limited experimental information then available on baryon (B) and antibaryon ($\bar{B}$) production, more precisely on the mean multiplicities of B and $\bar{B}$ produced in the proton fragmentation region.

The method of Ref. [6] was recently adopted by the BGHORS Collaboration to interpret their new data on B and $\bar{B}$ production in fragmentation of 240 GeV protons [7], together with previous proton fragmentation data which their paper carefully compiles. They conclude that the present data require some modification and additions to the mechanisms considered in Ref. [6]. In the present paper, we reconsider the proton fragmentation problem in the light of the analysis of Ref. [7] and we are led to propose a simpler picture than reached in either [6] or [7]. Retaining the terminology of [7], this picture can be called a quark fragmentation - recombination model: each valence quark of the incident proton either recombines with an antiquark to give an outgoing meson (a process which can be regarded as a fragmentation quark $\rightarrow$ mesons(s) + quark), or it recombines with other quarks to give an outgoing baryon. This

type of model has much affinity with the quark cascade model of Ref. [4]. We shall find that the two above possible fates can be assumed to occur in an uncorrelated way for each valence quark of the incident proton, and they have probabilities P and $1-P$ of order 0.4 and 0.6 respectively.

The model has a simple extension to meson fragmentation which differs from the extension to meson fragmentation suggested at the end of Ref. [6]. This is a welcome change, because it avoids the difficulty pointed out recently by Chliapnikov in comparing the meson fragmentation prediction of [6] with experimental data (see Ref. [8], end of section 4).

The main principles of our approach remain the same as in Refs. [6] and [7]. The valence quarks of the incident proton are assumed to emerge as valence quarks of outgoing hadrons in the proton fragmentation region, and we assign probabilities for the various ways in which this can occur (note that this is an assumption which neglects the possible interference between amplitudes involving various recombinations of the incident valence quarks but leading to the same exclusive final state).

We depart from [6] in that we now neglect the recombinations where valence quarks of the incident proton emerge in two or three distinct baryons. This neglect is based on the finding of Bourquin et al. [7] that antibaryon production, even in the proton fragmentation region, can be attributed dominantly to $B\bar{B}$ pair production with local compensation of quantum numbers, as is believed to occur also in the central rapidity region ("local" means local in rapidity). This suggests that one can assume with good approximation all $\bar{B}$ to originate from $B\bar{B}$ pair production of non-fragmentation type, the B and $\bar{B}$ of the pair having opposite quantum numbers. We adopt this assumption.

We are thereby led to consider the mean multiplicity $n_f(B)$ of the fragmentation baryons of type B , i.e. the baryons of type B produced by the fragmentation of the incident proton. It can be expressed as

$$n_f(B) = n(B) - n(\bar{B}) \quad (1)$$

$n(B)$ and $n(\bar{B})$ being the observed mean multiplicities of B and $\bar{B}$ in the

proton fragmentation region defined as the corresponding c.m. hemisphere. Neglecting baryon exchange between forward and backward c.m. hemispheres (a reasonable assumption at high energy), we have

$$\sum_B n_f(B) = 1 \quad (2)$$

where the sum runs over all baryon types B . One will note that eqs. (1) and (2) hold not only for the average multiplicities, but also for each collision obeying our assumptions.

The problem is now to express the $n_f(B)$ in terms of the probabilities for the valence quarks of the incident proton to recombine with each other and/or other quarks in order to produce the baryon B , or to fragment and emerge in mesons. This is done in the next section. The comparison with the experimental data is carried out in section 3 and the results are discussed in section 4.

2. EQUATIONS OF THE MODEL

2.1 Baryon Multiplicities in Terms of Recombination Probabilities

As mentioned above, under our assumptions the fragmentation of the incident proton (which we shall call p_{inc}) gives rise to one and only one baryon (which we call B). This baryon can contain $i = 0, 1, 2$ or 3 valence quarks of p_{inc} , and we denote by a_i the corresponding probabilities, with

$$a_0 + a_1 + a_2 + a_3 = 1 \quad (3)$$

This equation implies eq. (2). The classes of collisions corresponding to the various values of i are illustrated in Fig. 1, which only depicts the fragmentation of p_{inc} , not the remainder of the collisions. Full lines represent the valence quarks of p_{inc} , dashed lines other quarks or anti-quarks. In the usual recombination model [1] the latter are considered to come from the parton sea of p_{inc} (in the sense of deep inelastic lepton

scattering). We shall see later that this interpretation is not necessarily valid in our model. Since the "other" (anti)quarks are "picked up" by the incident valence quarks, we shall call them pick-up (anti)quarks. Fig. 1 shows for each class which incident valence quarks (full lines) fragment, i.e. pick up an antiquark to form a meson, and which recombine with other incident valence quarks and/or pick-up quarks to form the baryon B.

One sees in Fig. 1 that each of the classes $i = 1$ and $i = 2$ contains 3 subclasses. We shall attribute equal probabilities to them, $a_i/3$ and $a_2/3$, thereby neglecting differences which might follow from asymmetries between the u and d valence quarks of the proton. This is expected to be a good approximation for integrated quantities such as the mean multiplicities $n_f(B)$ we are studying, but it would not hold for x distributions, especially near $x = 1$.

We assume the pick-up (anti)quarks to be of u, d and s type with probabilities τ , τ and ξ respectively, and we neglect heavier flavours, so that

$$\tau = \frac{1}{2}(1 - \xi) \quad (4)$$

We expect ξ to be of order 0.1 as implied by the value of the K^+/π^+ ratio in the proton fragmentation region, which should be ξ/τ , see [6] and [7]*).

It is now a simple matter to calculate the mean multiplicity $n_f(B)$ for each quark composition of B. We list the expressions which we shall use later:

*) Chliapnikov [8] quotes a smaller suppression factor for strangeness based on a comparison of the cross section versus mass curves for the production of strange and non-strange mesons, see his Fig. 27. This factor can only be applied if supplemented with a further mass-dependent suppression factor. If one wants to use the data of Fig. 27 of [8], the ratio to be taken for ξ is $\sigma(\rho^0 + \omega^0)/\sigma(K_{892}^{*0}) \approx 2\sigma(\rho^0)/\sigma(K_{892}^{*0})$, which is ≈ 0.1 .

$$\begin{aligned}
 n_f(sss) &= \xi^3 a_0 \\
 n_f(dss) &= \xi^2 (3\tau a_0 + \frac{1}{3} a_1) \\
 n_f(dds) &= \xi \tau (3\tau a_0 + \frac{2}{3} a_1) \\
 n_f(uds) &= \xi (6\tau^2 a_0 + 2\tau a_1 + \frac{2}{3} a_2) \\
 n_f(uus) &= \xi (3\tau^2 a_0 + \frac{4}{3} \tau a_1 + \frac{1}{3} a_2) \\
 n_f(udd) &= \tau (3\tau^2 a_0 + \frac{4}{3} \tau a_1 + \frac{2}{3} a_2) \\
 n_f(uud) &= 3\tau^3 a_0 + \frac{5}{3} \tau^2 a_1 + \tau a_2 + a_3 \\
 n_f(uuu) &= \tau (\tau^2 a_0 + \frac{2}{3} \tau a_1 + \frac{1}{3} a_2)
 \end{aligned}
 \tag{5}$$

To go from these expressions to the $n_f(B)$ for actual baryons one must face the question of resonances ^{*)} for which no treatment of assured validity is known. Many resonances occur in final states of general hadronic collisions, including heavy ones which may have cascade decays involving lighter ones, and all such resonances have their own quark structure and decay schemes. There is obviously much arbitrariness in trying to apply a quark parton model to the production of all possible resonances. The situation may be simpler, however, when one concentrates on inclusive production of the lightest hadrons, because resonance decay, just as hadron production, involved the recombination of surviving incident valence quarks with other quarks, and inclusive distributions are averaged over all possible production and decay schemes. In the light of these considerations we have adopted the following simple rule for the inclusive multiplicities $n_f(B)$.

For each quark combination as occurs in eqs. (5), one considers the decomposition in pure states of isospin, and one identifies each such state with the lowest baryon of the corresponding isospin. This gives first

^{*)} The author is grateful to J.M. Gaillard and M. Jacob for valuable criticism and suggestions on this question, in particular concerning the Δ resonance.

$$\left. \begin{aligned} n_f(\Omega^-) &= n_f(s s s), & n_f(\Xi^-) &= n_f(d s s) \\ n_f(\Sigma^-) &= n_f(d d s), & n_f(\Sigma^+) &= n_f(u u s) \\ n_f(\Lambda^0) &= n_f([\bar{u} d]_0 s) = \frac{1}{2} n_f(u d s) \\ n_f(\Sigma^0) &= n_f([\bar{u} d]_1 s) = \frac{1}{2} n_f(u d s) \end{aligned} \right\} \quad (6)$$

where $[\bar{u} d]_I$ denotes the isospin I combination of u and d .

We now determine $n_f(p)$ under the above rule. A proton can either result directly from the isospin $\frac{1}{2}$ combination $[\bar{u} d]_{\frac{1}{2}}$, or occur as decay product of a Δ resonance resulting from the isospin $\frac{3}{2}$ combinations uuu , $[\bar{u} u d]_{\frac{3}{2}}$, $[\bar{u} d d]_{\frac{3}{2}}$. For the "direct" proton we have

$$n_f(p_{\text{dir}}) = n_f([\bar{u} d]_{\frac{1}{2}}) = \frac{2}{3} n_f(u u d) \quad (7)$$

For the protons from Δ decay we have three channels

$$\left. \begin{aligned} n_f(\Delta^{++} \rightarrow p) &= n_f(\Delta^{++}) = n_f(u u u) \\ n_f(\Delta^+ \rightarrow p) &= \frac{2}{3} n_f(\Delta^+) = \frac{2}{3} n_f([\bar{u} u d]_{\frac{3}{2}}) = \frac{2}{9} n_f(u u d) \\ n_f(\Delta^0 \rightarrow p) &= \frac{1}{3} n_f(\Delta^0) = \frac{1}{3} n_f([\bar{u} d d]_{\frac{3}{2}}) = \frac{1}{9} n_f(u d d) \end{aligned} \right\} \quad (8)$$

The total $n_f(p)$ is then the sum of the 4 multiplicities in (7) and (8) :

$$n_f(p) = n_f(u u u) + \frac{8}{9} n_f(u u d) + \frac{1}{9} n_f(u d d) \quad (9)$$

Combining eq. (5) to (9) we obtain

$$n_f(\Omega^-) = \xi^3 a_0, \quad n_f(\Xi^-) = \xi^2 (3 \tau a_0 + \frac{1}{3} a_1) \quad (10)$$

$$\left. \begin{aligned} n_f(\Sigma^-) &= \xi \tau (3 \tau a_0 + \frac{2}{3} a_1) \\ n_f(\Lambda^0) &= n_f(\Sigma^0) = \xi (3 \tau^2 a_0 + \tau a_1 + \frac{1}{3} a_2) \\ n_f(\Sigma^+) &= \xi (3 \tau^2 a_0 + \frac{4}{3} \tau a_1 + \frac{1}{3} a_2) \end{aligned} \right\} \quad (11)$$

$$n_f(p) = 4 \tau^3 a_0 + \frac{62}{27} \tau^2 a_1 + \frac{35}{27} \tau a_2 + w a_3, \quad w = \frac{8}{9} \quad (12a)$$

In the last equation the factor $w = \frac{8}{9}$ in front of a_3 may be regarded as a rather unnatural consequence of our assumption concerning the role of the Δ resonance. When all three valence quarks of p_{inc} recombine with each other, they are expected to give (almost) always a proton rather than a Δ^+ . If they do always the value of w in eq. (12a) is replaced by

$$w = 1 \quad (12b)$$

We shall see in the next section that this change of w has only minor effects on the results. In eqs. (9-12) no spin factors are included, which is one more aspect of our simplifying assumption to avoid the problem of resonances.

Regarding resonances, we mention briefly that other rules could be envisaged. For example, for the Λ^0 and Σ , one could make the (rather extreme) assumption that resonance effects tend to mix them completely in charge and isospin. This would give

$$n_f(\Lambda^0) = n_f(\Sigma^+) = n_f(\Sigma^0) = n_f(\Sigma^-) \quad (13)$$

$$n_f(\Lambda^0 + \text{all } \Sigma) = c n(uus + uds + dds)$$

with c presumably a little smaller than 1 to take into account the rare decays of strangeness -1 resonances into nucleon + $\bar{K}$. The experimental data mentioned in section 3 exclude eq. (13).

Also for protons a similar mixing can be envisaged. It would assume that for the classes $i = 0, 1$ and 2 of Fig. 1, the B's without strange quarks are protons or neutrons with equal probabilities, class $i = 3$ still giving dominantly protons. Eq. (12) is then replaced by

$$n_f(p) = 4\tau^3 a_0 + 2\tau^2 a_1 + \tau a_2 + w a_3, \quad w \approx 1 \quad (14)$$

With $w \approx 1$, this formula is sufficiently close to (12) to lead to similar conclusions and is therefore compatible with the data.

2.2 Hyperon Multiplicities

We shall see in section 3 that the version of our model embodied in eqs. (10 - 12) is in good agreement with the data in Ref. [7]. This agreement is made more significant by the remarkable fact that the equations of the model combined with the positivity of all a_i impose severe constraints on the multiplicities $n_f(B)$. One set of such constraints concerns the Λ^0 and Σ hyperons and will be discussed now.

The equality of $n_f(\Lambda^0)$ and $n_f(\Sigma^0)$ is a clear prediction but it cannot be tested at present, since the data refer to all Λ^0 including those from $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ decay, and give no information on Σ^0 production. From now on, we shall therefore consider $n_f(\Lambda^0 + \Sigma^0)$, for which eq. (11) gives

$$n_f(\Lambda^0 + \Sigma^0) = 2\xi(3\tau^2 a_0 + \tau a_1 + \frac{1}{3} a_2) \quad (15)$$

More interesting are the consequences obtained from solving the eqs. (11)

$$\left. \begin{aligned} a_0 &= \left[n_f(\Lambda^0 + \Sigma^0) + n_f(\Sigma^-) - 2n_f(\Sigma^+) \right] / (3\xi\tau^2) \\ a_1 &= 3 \left[2n_f(\Sigma^+) - n_f(\Lambda^0 + \Sigma^0) \right] / (2\xi\tau) \\ a_2 &= 3 \left[n_f(\Lambda^0 + \Sigma^0) - n_f(\Sigma^+) - n_f(\Sigma^-) \right] / \xi \end{aligned} \right\} \quad (16)$$

These expressions must be positive, which gives

$$n_f(\Sigma^+) + n_f(\Sigma^-) \leq n_f(\Lambda + \Sigma^0) \leq 2 n_f(\Sigma^+) \leq n_f(\Lambda^0 + \Sigma^0) + n_f(\Sigma^-)$$

Note that these inequalities are independent of ξ . They are depicted graphically in Fig. 2 in terms of the ratios

$$v_0 = n_f(\Lambda^0 + \Sigma^0)/n_f(\Sigma^+), \quad v_- = n_f(\Sigma^-)/n_f(\Sigma^+) \quad (17)$$

The point v_-, v_0 must fall in the triangle ABC which is quite narrow in the v_0 direction ($1.5 \leq v_0 \leq 2$), and the sides of which correspond to $a_i = 0$ ($i = 0, 1, 2$) as indicated in the figure. As seen from the experimental point, the data in Ref. [7] fulfil this condition. We note that eqs. (13) would give vertex B of the triangle.

A quantity which is readily expressible in the variables v_-, v_0 is the ratio $n_f(\Omega^-)/n_f(\Xi^-)$, for which eqs. (10) and (16) give

$$3 \tau \xi^{-1} n_f(\Omega^-)/n_f(\Xi^-) = 2(v_0 + v_- - 2)/(v_0 + 2v_- - 2) \quad (18)$$

The righthand side is constant along straight lines passing through the point A in the v_-, v_0 plane of Fig. 2, e.g. the line AD which corresponds to the experimental estimate in Ref. [7].

2.3 Uncorrelated Behaviour of Incident Valence Quarks

In the framework of our model, there is a further simplification which suggests itself naturally. It consists in assuming that in the diagrams of Fig. 1 the valence quarks of p_{inc} behave in a statistically uncorrelated way. In making this assumption, we must exclude the small subset of diffraction dissociation collisions, or at least those where the incident proton p_{inc} itself does not dissociate. This subset corresponds to a small fraction $1 - \bar{a}$ of all inelastic collisions, and contributes only to a_3 . For the main fraction $\bar{a}$, the uncorrelated behaviour means that each valence quark of the incident proton has a probability P of

fragmenting and emerging in a meson, and a probability $1-P$ of emerging in the baryon B , these processes being statistically independent for the three valence quarks. In formulae this gives:

$$\left. \begin{aligned} a_0 &= \bar{a}^3 P^3, & a_1 &= 3 \bar{a}^2 P^2 (1-P), & a_2 &= 3 \bar{a} P (1-P)^2 \\ a_3 &= 1 - (a_0 + a_1 + a_2) = 1 - \bar{a} + \bar{a}(1-P)^3 \end{aligned} \right\} \quad (19)$$

and leads to the constraint

$$a_1^2 = 3 a_0 a_2 \quad (20)$$

For $\bar{a}$ and P one has

$$\bar{a} = (a_1 + a_2)^3 / (3a_1 a_2), \quad P = a_1 / (a_1 + a_2) \quad (21)$$

This value of $\bar{a}$ gives an additional constraint

$$\bar{a} \leq 1 \quad \text{or} \quad (a_1 + a_2)^3 \leq 3a_1 a_2 \quad (22)$$

As mentioned above we expect $1 - \bar{a} \ll 1$.

The constraint (20) is easily translated into a constraint on the ratios v_0 , v_- . With eqs. (16) and (17) it becomes

$$v_0 = 2(1 - v_- + v_-^2)^{\frac{1}{2}} \quad (23)$$

and is represented by the full curve in Fig. 2. Note that this curve is close to the line AD . Using (21) and (23) we obtain

$$\bar{a} = \frac{n_f (\Lambda^0 + \text{all } \Sigma)}{6 \xi (1 - \xi)^2} \frac{\{1 - v_- - \xi [2(1 - v_- + v_-^2)^{\frac{1}{2}} - 1 - v_-]\}^3}{(1 - v_-)^2 [1 - (1 - v_- + v_-^2)^{\frac{1}{2}}]} \quad (24)$$

The second, v_- dependent fraction goes to 2 for $v_- \rightarrow 1$ and diverges as $2(1 - \xi) / v_-$ for $v_- \rightarrow 0$, so that (22) excludes very small values of v_- .

We shall see in the next section that the uncorrelated version of our model is compatible with the data in [7], the probability P being of order 0.4.

3. COMPARISON WITH EXPERIMENTAL DATA

3.1 Analysis Using the Hyperon Data for $\xi = 0.1$

Our analysis is based on the data contained in Ref. [7]. All mean multiplicities refer to the fragmentation hemisphere of one incident proton, and they are defined with respect to the class of all inelastic collisions. The data give us the experimental values of the quantity defined in eq. (1) for the following cases:

$$\left. \begin{aligned} n_f(p) &= 0.65 \pm 0.06, & n_f(\Lambda^0 + \Sigma^0) &= 0.050 \pm 0.0094 \\ n_f(\Sigma^+) &= 0.025 \pm 0.005, & n_f(\Sigma^-) &= 0.009 \pm 0.0025 \end{aligned} \right\} \quad (25)$$

This implies

$$n_f(\Lambda^0 + \text{all } \Sigma) = 0.084 \pm 0.011 \quad (26)$$

The relevant multiplicities of Ω^- and Ξ^- are not known, but the considerations at the end of section 4 of Ref. [7] provide an estimate for the ratio

$$n_f(\Omega^-) / n_f(\Xi^-) \approx 0.0375 \quad (27)$$

This number is obtained by combining eq. (13) of Ref. [7] with the following equations in section 4 of this paper. No error is quoted; this is understandable because the estimate requires a guess of the x-dependences of Ξ^- , Ω^- which are not reliably measured.

If we adopt the value of ξ deduced from meson production data, $\xi = 0.1$, we can use the eqs. (16) to determine the probabilities a_i from the multiplicities $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm)$. We find :

$$\left. \begin{aligned} a_0 &= 0.15 \pm 0.23, & a_1 &= 0 \pm 0.46, \\ a_2 &= 0.48 \pm 0.32, & a_3 &= 0.37 \pm 0.61 \end{aligned} \right\} \quad (28)$$

The errors are disappointingly large, as a result of compensations between the various terms of (16). This inaccuracy is not surprising if one considers the experimental point in the v_- , v_0 plane of Fig. 2, especially the fact that the error of v_0 covers much more than the full height of the allowed triangle.

Better accuracy is obtained if we adopt the uncorrelated version of our model as described in subsection 2.3. We rewrite eq. (23) as

$$n_f(\Lambda^0 + \Sigma^0) = 2 \{ [n_f(\Sigma^+)]^2 - n_f(\Sigma^+) n_f(\Sigma^-) + [n_f(\Sigma^-)]^2 \}^{\frac{1}{2}} \quad (29)$$

and introduce it into eqs. (16). Using the experimental values of $n_f(\Sigma^\pm)$ and keeping $\xi = 0.1$ as before, we now find

$$\left. \begin{aligned} a_0 &= 0.05 \pm 0.03, & a_1 &= 0.20 \pm 0.04 \\ a_2 &= 0.30 \pm 0.16, & a_3 &= 0.45 \pm 0.17 \end{aligned} \right\} \quad (30)$$

We have one theoretical and one experimental check on these values, given by eqs. (22) and (27). The values (30) give

$$\bar{a} = 0.69 \pm 0.30, \quad n_f(\Omega^-)/n_f(\Xi^-) = 0.036 \pm 0.012 \quad (31)$$

and satisfy them very well. As to the probability P in eq. (21), it is found to be 0.41 ± 0.14 .

3.2 Analysis with ξ as Free Parameter

We now proceed to use the experimental value $n_f(p)$ and first show that it allows us to deduce $\xi \approx 0.1$ using the baryon data alone. To do this we treat ξ as a variable in (16) and insert the values of a_i into (12a - b), a_i being taken from (3). This gives $n_f(p)$ as a function of ξ , $n_f(\Lambda^0 + \Sigma^0)$ and $n_f(\Sigma^\pm)$. Inserting the experimental values and errors for the latter quantities, we obtain the ξ dependence of $n_f(p)$ shown in Fig. 3a - b, where 3a corresponds to $w = 8/9$ and 3b to $w = 1$. One sees the small dependence on w . The graphs also contain the experimental value and error of $n_f(p)$. They lead to $\xi \approx 0.08 - 0.1$, compatible with the value deduced from meson production data.

We have also calculated $n_f(p)$ as function of ξ for the uncorrelated model of subsection 2.3. We have done this using the experimental value (26) of $n_f(\Lambda^0 + \text{all } \Sigma)$ and the experimental value of v_- deduced from (25). The resulting curves are very close to those shown in Fig. 3a - b, and are plotted without errors in Fig. 3c for the two values of w . Fig. 3c also shows $\bar{a}$ as function of ξ , calculated from eq. (24). It is remarkable that the constraint $0 < 1 - \bar{a} \ll 1$ imposes $\xi \approx 0.08 - 0.1$ and hence gives for $n_f(p)$ a range close to the experimental one.

3.3 Further Discussion of the a_i

It is also interesting to study the a_i for given values of $n_f(p)$, $n_f(\Lambda^0 + \text{all } \Sigma)$ and ξ . In the version of subsection 2.1, the model has then one free parameter left, which we take to be a_0 . Its range turns out to be limited to $a_0 \lesssim 0.2$ by the positivity condition for a_1 and a_2 . Figs. 4 and 5 show the variations of the a_i ($i = 1, 2, 3$), the $n_f(B = \Lambda^0 + \Sigma^0, \Sigma^\pm, \Xi^-, \Omega^-)$ and the ratio $n_f(\Omega^-)/n_f(\Xi^-)$ as functions of a_0 ,

using as input

$$w = 8/9, \quad n_f(p) = 0.67, \quad n_f(\Lambda^0 + \text{all } \Sigma) = 0.084, \quad \xi = 0.1 \quad (32)$$

The figures show that a_3 and the $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm)$ hardly vary with a_0 , the $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm)$ agreeing with the experimental values which are reproduced on the right of Fig. 5. In contrast, the ratio $n_f(\Omega^-)/n_f(\Xi^-)$ changes rapidly with a_0 . Its estimated experimental value, shown by the circle on the right of Fig. 5, leads to $a_0 \approx 0.05$.

Restricting the model further to the uncorrelated version of subsection 2.3 now fixes all parameters, and it is remarkable that one finds $a_0 = 0.047$. As to $\bar{a}$, it is found to be 0.77.

If in (32) we had taken $n_f(p) = 0.65$ the uncorrelated model would have given $\bar{a} > 1$. This results from the tight constraints of the model which become particularly visible if we vary $n_f(p)$ while keeping $n_f(\Lambda^0 + \text{all } \Sigma)$ and ξ fixed. Positivity of the a_i restricts $n_f(p)$ to a narrow interval, which is narrowed down further by the condition $\bar{a} < 1$ for the uncorrelated version of the model. This is shown in Figs. 6 and 7 for w , $n_f(\Lambda^0 + \Sigma^0)$ and ξ as in eq. (32).

In Fig. 6 the shaded areas show the allowed values of $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm)$ as functions of $n_f(p)$ for the model as defined in subsection 2.1. These areas extend over the allowed range of $n_f(p)$, outside which some of the a_i become negative. The dashed lines of Fig. 6 give $\bar{a}/10$ and $n_f(\Omega^-)/n_f(\Xi^-)$ for the uncorrelated version of the model, showing how $\bar{a} < 1$ further reduces the range of $n_f(p)$. The relevant experimental values are also shown, confirming again the compatibility of the data with the uncorrelated model and the constraint $0 < 1 - \bar{a} \ll 1$. Fig. 7 plots the a_i , $\bar{a}$ and P versus $n_f(p)$ for the uncorrelated model.

In Figs. 6 and 7 the region where $0 < 1 - \bar{a} \ll 1$ is the relevant one. It gives $n_f(p) \approx 0.665$ and

$$a_0 \approx 0.04, \quad a_1 \approx 0.20, \quad a_2 \approx 0.36, \quad a_3 \approx 0.40, \quad P \approx 0.37 \quad (33)$$

If the same analysis is done with $w = 1$ instead of $w = 8/9$ the above figures become $n_f(p) \approx 0.705$ (one standard deviation above the measured value) and

$$a_0 \approx 0.04, \quad a_1 \approx 0.20, \quad a_2 \approx 0.38, \quad a_3 \approx 0.38, \quad P \approx 0.35 \quad (34)$$

If one uses $\xi = 0.08$ instead of $\xi = 0.1$, one finds $n_f(p) \approx 0.635$ for $w = 8/9$ and $n_f(p) = 0.67$ for $w = 1$, while for both $w = 8/9$ and 1 one obtains

$$a_0 \approx 0.07, \quad a_1 \approx 0.27, \quad a_2 \approx 0.36, \quad a_3 \approx 0.30, \quad P \approx 0.43 \quad (35)$$

Our analysis has shown the interest of having production data concerning Ξ , Ω and their antiparticles; this is illustrated by the rapid variation of the ratio $n_f(\Omega^-)/n_f(\Xi^-)$ in Figs. 5 and 6. In fact, we can deduce from (33-35) the following predictions

$$\left. \begin{array}{l} \xi = 0.1 : \quad n_f(\Xi^-) = 1.2 \times 10^{-3}, \quad n_f(\Omega^-) = 4 \times 10^{-5} \\ \xi = 0.08 : \quad n_f(\Xi^-) = 1.2 \times 10^{-3}, \quad n_f(\Omega^-) = 3.6 \times 10^{-5} \end{array} \right\} \quad (36)$$

Using our definition (1) and the antibaryon multiplicities in Table 3 of Ref. [7] this gives the multiplicities

$$n(\Xi^-) = 3.1 \times 10^{-3}, \quad n(\Omega^-) = 3.4 \times 10^{-4} \quad (37)$$

With these values, most of $n(\Omega^-)$ and about one third of $n(\Xi^-)$ would come from $B\bar{B}$ pair production of non-fragmentation type. This is due to the low ξ value (ξ may be larger in the central region, see [7], section 4.1).

3.4 The Δ^{++} Multiplicity

We end this section with a brief discussion of the multiplicity of Δ^{++} in the proton fragmentation region. This is known to be around $\frac{1}{2}$ or $\frac{1}{3}$ of the proton multiplicity for $0.6 < x < 0.9$ and to have about the same x-distribution at large x, except for the diffractive proton peak at $x > 0.9$ [9]. It is expected that if the distributions would differ at lower x, it would be in the direction of a higher Δ^{++}/p ratio. We therefore expect $n(\Delta^{++}) \gtrsim \frac{1}{3} n(p)$ and therefore also, since the $\bar{\Delta}^{++}$ and $\bar{p}$ multiplicities are small,

$$n_f(\Delta^{++}) \gtrsim \frac{1}{3} n_f(p) = 0.22 \pm 0.02 \quad (38)$$

This is too large to be accounted for in our model if one identifies $n_f(\Delta^{++})$ with $n_f(uuu)$ as given by eq. (5), because the last eq. (5) implies $n_f(uuu) \leq \tau/3 \approx 0.15$ for all possible values of the a_i . For the values (33) of the a_i one has $n_f(uuu) = 0.085$.

The fact that $n_f(\Delta^{++})$ is substantially larger than $n_f(uuu)$ has no ready-made explanation in the model, which contains no prescription on how to calculate the multiplicities of resonances. A rather obvious source of additional Δ^{++} may result from the fact that a π^+ and a p produced as separate hadrons in the quark fragmentation - recombination process have a substantial probability to resonate when their effective mass is in the Δ^{++} range. This would correspond to a resonance effect as final state interaction in the final hadronic phase of the collision whereas the quark fragmentation - recombination mechanism refers to the parton phase preceding hadronization. Good data on x-distributions of resonances would probably help to get a better grasp of the resonance problem.

4. DISCUSSION AND CONCLUDING REMARKS

4.1 Questions of Dynamical Interpretation

The analysis of section 3 has concentrated on the consequences of the model equations, in particular on the surprisingly narrow constraints which they imply for the measurable quantities $n_f(B)$ and on the fact that they are well satisfied by the experimental values (25 - 27). We now address the question of possible dynamical interpretations of the model.

The simplest one follows the picture proposed by Fukuda et al. [4] in their quark cascade model with recombination mechanism. Its principle can be described by completing the diagrams of Fig. 1 with the quark fragmentation mechanism of Fig. 8. It says that the fragmentation baryon B is composed of valence quarks of p_{inc} and/or quarks occurring in the fragmentation of (the other) valence quarks of p_{inc} . In contrast with the usual application of quark fragmentation models, the fate of the quark resulting from such fragmentation is here specified; it emerges in the fragmentation baryon B . In this interpretation, our assumption of uncorrelated behaviour of the incident valence quark is very natural.

On the other hand, our model does not preclude other mechanisms, such as the exchange of an even number of "quark ladders" between the incident hadrons illustrated in Fig. 9. Such processes induce correlations between the fragmentation of the two incident hadrons and may also imply correlations between the behaviour of the valence quarks of either incident hadron. We note that the processes illustrated in Figs. 1 and 8, on the one hand, and 9, on the other, are not mutually exclusive, and nature may be sufficiently complicated to have contributions of both types even at very high energies.

The diagrams illustrated in Fig. 9 also specify a mechanism for particle production in the central region of rapidity. In the case of Figs. 1 and 8, particle production in the central region is not specified in the diagrams and is expected to be of gluonic origin (no exchange of quarks or quark ladders).

The dual topological unitarization scheme, adopted e.g. by Capella et al. [2] and Cohen-Tannoudji et al. [10], relies entirely on diagrams of the type of Fig. 9a. In our approach it corresponds to $a_2 = 1$, all other a_i vanishing. With eqs. (9 - 12) this gives:

$$n_f(\Lambda^0 + \Sigma^0) = 2n_f(\Sigma^+) = \frac{2}{3} \xi, \quad n_f(p) = \frac{35}{27} \tau \quad (39)$$

$$n_f(\Sigma^-) = n_f(\Xi^-) = n_f(\Omega^-) = 0 \quad (40)$$

Eq. (39) is reconcilable with the data (one standard deviation) for $\xi \approx 0.06 - 0.09$, but other sources must then be found for production of Σ^- , Ξ^- and Ω^- .

4.2 Meson Fragmentation

Returning to our model and taking it in the uncorrelated version (subsection 2.3), we discuss its extension to the fragmentation of incident mesons. The most natural extension follows Ref. [4] and considers the fragmentation diagrams given in Figs. 10 and 8, with the corresponding probabilities a_i^m expressed in analogy with eqs. (19) :

$$a_0^m = \bar{a} P^2, \quad a_1^m = 2\bar{a} P(1 - P), \quad a_2^m = 1 - \bar{a} + \bar{a}(1 - P)^2 \quad (41)$$

Using $\bar{a} = 0.9$, $P = 0.4$, this gives

$$a_0^m = 0.14, \quad a_1^m = 0.43, \quad a_2^m = 0.43 \quad (42)$$

in contrast with a tentative extension to meson fragmentation considered in Ref. [6] which gave $a_2^m \approx 0.75$. A recent estimate by Chliapnikov [8] rules out such a large value and suggests $a_2^m \lesssim 0.5$

It should be noted, however, that the above extension to mesons is not the only one possible. Whereas the proton fragmentation diagrams of Fig. 1 are distinct without the special interpretation in Fig. 8, this is not so for meson fragmentation. In Fig. 10 the diagrams with $i = 0$ and 1 are undistinguishable without further specification, for example the specification in Fig. 8. A detailed study of meson fragmentation will therefore be required before coming to conclusions, and it may be difficult to circumvent the problem of resonance production as we did for baryons where we were helped by the fact that a baryon resonance has almost always a single baryon among its decay products.

4.3 Relation to Recombination Model

We now discuss the relation of our proton fragmentation model with some aspects of the recombination model [1]. As shown by the present author [1], data on meson production in proton fragmentation give the estimate

$$P_1 \approx 0.2 - 0.4, \quad (43)$$

where P_1 is the probability that a valence quark of p_{inc} recombines with an antiquark to give a meson. From consideration of Fig. 1 one immediately derives that in our model

$$P_1 = a_0 + \frac{2}{3} a_1 + \frac{1}{3} a_2 \quad (44)$$

This gives with eqs. (33 - 35) the following estimates

$$P_1 \approx 0.29 \text{ for } \xi = 0.1, \quad P_1 \approx 0.37 \text{ for } \xi = 0.08 \quad (45)$$

both compatible with (43).

We mentioned at the beginning of section 2 that in our model the pick-up quarks and antiquarks represented by dashed lines in Fig. 1 are not necessarily sea quarks (in the sense of deep inelastic lepton-hadron scattering), which they are supposed to be in the recombination model [1]. The reason is found in Fig. 8, where the pick-up (anti)quarks are (anti)quarks occurring in the fragmentation process of a valence quark (this is entirely analogous to the situation in Ref. [4]). There is no reason to assume that these (anti)quarks pre-existed as sea partons in the incident proton. The present interpretation eliminates the need to introduce the so-called sea enhancement factor required to account for the meson multiplicity in the recombination model [1].

One of the main arguments in favour of the recombination model rests on the similarity between the x -distribution of $\pi^\pm$ produced in the fragmentation of an incident proton and the x -distribution of the valence quarks which they share with this proton, i.e. the proton structure functions $u(x)$ for π^+ and $d(x)$ for π^- . This similarity holds in the region $0.4 \lesssim x \lesssim 0.8$ and applies to $u(x)$, $d(x)$ as determined in deep inelastic lepton-nucleon scattering at moderate Q^2 ($Q^2 = \text{a few GeV}^2$).

The recombination model proposes a simple explanation for this similarity, and one can ask whether it still applies in the present model. The answer is yes if in the diagrams of Fig. 1 it is assumed that for $x \gtrsim 0.4$ each outgoing pion containing a valence quark of p_{inc} has a x -value distributed as $u(x)$ for π^+ and $d(x)$ for π^- , i.e. as the x -value of this valence quark in p_{inc} . The picture would then be as follows. In valence quark fragmentation (Fig. 8), the original quark (presumably a constituent quark) first gives a meson through combination of its valence quark (as probed in deep inelastic scattering) with a low x anti-quark ^{*)}. The rest of the fragmentation then produces mesons and a

^{*)} Note that the similarity does not hold for pions with lower x -values, nor for x very close to 1. At low x it is broken by the contribution of resonances and by the fact that the collision is expected to affect the x -value of incident valence quarks mainly at low x (the "wounded" quarks are expected to have mainly low x ; see G. Berlad et al. [11]). At $x \approx 1$, the similarity is broken by the triple Regge contribution (see L. Van Hove [1]).

remaining quark, mostly at lower x than the first meson. The remaining quark emerges in baryon B (Fig. 1), contributing only a small amount to its x -value. In this way, for $i = 1, 2, 3$, the x -value of B is mainly determined by the x -values of the incident valence quarks which it contains, as in the recombination model.

To go further one needs a formalism to describe x -dependences in the fragmentation and recombination mechanisms of the model. Formalisms of this type have been developed by Fukuda et al. [4]. It would be interesting to combine them with the results of the present paper and of the recombination model. As stressed earlier, the problem of resonance production also requires further study.

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ADDENDUM

After this paper was written, P.V. Chliapnikov drew the author's attention to the appendix of the paper by I.V. Ajinenko et al., Z. Physik C4, 181 (1980), which gives estimates for the inclusive cross sections of $\Lambda^0 + \Sigma^0$, Σ^0 , $\bar{\Lambda}^0 + \bar{\Sigma}^0$, $\bar{\Sigma}^0$ in K^+p interactions at 32 GeV/c. Although they refer to the whole of phase space rather than to the c.m. hemisphere of the incident proton, we can use them in our eq. (1) to estimate the corresponding $n_f(B)$ and we find

$$n_f(\Sigma^0)/n_f(\Lambda^0 + \Sigma^0) = 0.29 \pm 0.18.$$

This is to be compared to the value 0.5 predicted from our eq. (11).

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FIGURE CAPTIONS

- Figure 1 Diagrams for production of baryon B by fragmentation of incident proton p_{inc} . Full lines denote valence quarks of p_{inc} , dashed lines "pick-up" quarks or antiquarks (see text).
- Figure 2 Allowed domain for the point v_0, v_- (shaded area) and experimental point with errors. The full curve AB corresponds to the uncorrelated model, the dotted line AD to the experimental value of $n_f(\Omega^-)/n_f(\Xi^-)$.
- Figure 3 The proton multiplicity $n_f(p)$ as function of ξ calculated from the experimental values of $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm)$ with $w = 8/9$ (a) and $w = 1$ (b), and in the uncorrelated model from the experimental values of $n_f(\Lambda^0 + \text{all } \Sigma)$ and v_- (c). Fig. 3c also shows the quantity $\bar{a}$. Each figure shows the experimental value of $n_f(p)$.
- Figure 4 The probabilities a_1, a_2, a_3 versus a_0 for the parameters of eq.(32). The value $\frac{2}{a_0}$ corresponds to the uncorrelated model.
- Figure 5 The multiplicities $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm, \Xi^-, \Omega^-)$ and the ratio $n_f(\Omega^-)/n_f(\Xi^-)$ versus a_0 for the parameters of eq.(32). Experimental values and errors (when known) are indicated on the right. The value $\bar{a}_0$ corresponds to the uncorrelated model.
- Figure 6 The allowed values of $n_f(\Lambda^0 + \Sigma^0, \Sigma^\pm)$ versus $n_f(p)$ for $w, n_f(\Lambda^0 + \text{all } \Sigma), \xi$ as in eq.(32), and the values of $\bar{a}, n_f(\Omega^-)/n_f(\Xi^-)$ for the uncorrelated model. Experimental values and errors (when known) are also indicated.
- Figure 7 The quantities shown are plotted versus $n_f(p)$ for $w, n_f(\Lambda^0 + \text{all } \Sigma), \xi$ as in eq.(32), for the uncorrelated model.

Figure 8 The quark fragmentation diagrams following ref. [4].

Figure 9 Proton fragmentation diagrams with exchange of quark
ladders.

Figure 10 Extension of Fig. 1 to meson fragmentation.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG.10