THE FATE OF VALENCE QUARKS IN FRAGMENTATION PROCESSES

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Simple quark models for hadronic fragmentation processes are shortly reviewed. It is pointed out that the existing models differ most significantly in the assumptions concerning involvement of valence quarks in the first stage of interaction. By investigating x-distributions of produced hadron pairs one can test these assumptions experimentally.

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1. *Introduction*

In the last few years some attention has been paid to the simple quark models for low p_T hadronic fragmentation.

As observed experimentally [1] the ratio of positive to negative pion spectra in proton fragmentation at large Feynman x ($x = p_L/p_L^{max}$) is well described by the ratio of up to down quark distributions determined in deep inelastic lepton-proton interactions. This prompted many authors [2–5] to discuss the so-called quark recombination model (QRM) [6] in which one of the proton valence quarks (with the unchanged initial momentum) recombines with a small momentum sea antiquark to form the produced pion. Similar mechanisms apply for the production of other mesons, baryons, and for the meson fragmentation.

On the other hand, meson fragmentation spectra were also found to agree with the quark fragmentation functions derived from the analysis of leptoproduction and e^+e^- annihilation. This motivated the so-called quark fragmentation model (QFM) in which one of the initial valence quarks is "stuck" or "hold back" in the hadronic collision and the remainder of the original meson (carrying almost all the momentum) fragments in the same way as a single quark separated in a hard process [7]. Baryon fragmentation is related in a similar way to the diquark fragmentation. This approach can describe also spectra in the central region [8].

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Finally, observed grouping of the fragmentation processes into classes displaying similar x-dependence led to the development of so-called quark counting rules (QCR) determining shapes of x-spectra from simplified phase-space considerations for quark pair production and rearrangement into hadrons [9].

All the pictures presented above appeared to differ strongly from each other both in physical assumptions and in predictions. We will demonstrate this by presenting some relations between different fragmentation processes following from three models [10].

In QRM one expects the independence of spectra of recombined sea quarks. Therefore one has

$$\frac{d\sigma}{dx}(\pi^+ \to K^+) \propto \frac{d\sigma}{dx}(\pi^+ \to p) \tag{1}$$

and many other similar relations.

In QFM spectra should not depend on quantum numbers of initial hadron as long as the same quark (or diquark) fragmentation dominates the reaction. Therefore one expects e.g.

$$\frac{d\sigma}{dx}(K^- \to \bar{p}) \propto \frac{d\sigma}{dx}(\pi^- \to \bar{p}). \tag{2}$$

Finally, for the early version of QCR the same shape of spectra is expected e.g. for line reversal symmetric processes, as

$$\frac{d\sigma}{dx}(\pi^+ \to p) \propto \frac{d\sigma}{dx}(p \to \pi^+). \tag{3}$$

Recent data [11] appear to show that all the relations presented above are rather badly broken. Using power-law fits of the form

$$\frac{d\sigma}{dx} = c(1-x)^n \tag{4}$$

(acceptable in the limited x range, $0.3 \leqslant x \leqslant 0.7$) one finds n-values for the reactions (1) differing by a few standard deviations (1.28 ± 0.05 and 1.78 ± 0.14). Similar discrepancies occur for the relations (3), (4), and for many other model predictions [10].

Let us note that the discrepancies occur although x range has been already limited to exclude the influence of triple-Regge terms, apparently dominating highest x range in many processes [4] and treated here as independent contributions. Also the low x region, populated strongly by the resonance decay products (not included in standard analyses), has been excluded from considerations.

Obviously, relations (1)–(3) and their analogues follow from the simplest versions of discussed models. In more quantitative considerations all the models were modified by introducing additional factors, depending on other quantum numbers than the original formulae. In QRM there are two such factors: poorly known sea quark momentum distribution to be convoluted with valence distribution [2, 3] and the recombination probability, depending on quark- and final hadron momenta [2, 4, 12]. In QCR one can treat sea quark pairs necessary to form final hadrons as present in the initial hadron [9] or as created in the point-like interaction (with possible contributions from both mechanisms, yielding significantly different predictions) [13]. Finally, in QFM the distribution of the "stuck" quark momentum (reflected in the distribution of the fragmenting "hadron remainder" momentum) can be introduced and identified with "bare" or "dressed" quark distributions determined from deep inelastic processes or by Regge analysis, respectively [14].

These modifications can easily bring models to the good agreement with data. However, they spoil the predictive power of models, allowing for definite predictions only with additional ad hoc assumptions which may be indefinitely modified. Moreover, the modifications force all the models inevitably to converge. It becomes therefore impossible to decide if "bare quark recombination", "dressed quark fragmentation" or "pair production and recombination" is the best picture of fragmentation processes. In fact, some considerations suggest that QRM and QFM are 2 equivalent (at least at $x \simeq 1$) "dual" approaches to the same process [15].

These difficulties motivated us to look for some simple tests concerning the basic assumptions adopted in different models. Such a basic assumption distinguishing QFM from other models is the necessary interaction of one of the initial valence quarks, removing it from the group of partons involved in the formation of "fragmentation" hadrons. Therefore we can ask a simple question: Is there any evidence for processes, in which *all* the initial valence quarks participate in fragmentation into final hadrons with high x? If answer is positive (as QRM predicts), QFM would require significant corrections (maybe by reinterpreting different diagrams [15]). Otherwise, QRM will need serious changes to explain the absence of such processes. In fact, finding the right answer to our question seems to be very interesting independently of particular models.

The purpose of this note is to propose a test of the existence of the processes defined above by studying the $\Lambda\pi^+$ and $\Lambda\pi^-$ pair distributions. We discuss this proposal in the next section. In Section 3 the existing evidence for other processes of fragmentation of all the valence quarks is critically discussed. Our conclusions are listed in the last section.

2. *Investigation of $p \to \Lambda\pi^\pm$ fragmentation as a test of quark models*

We are looking for the evidence of processes, where all the valence quarks from the initial hadron are present in the final state hadrons at high x. If they are all contained in a single hadron, we have to deal usually with important diffractive contribution, not included in the quark models (and described e.g. by the triple Pomeron vertex in the triple-Regge language). We postpone the discussion of such data to the next section.

Better results can be obtained by investigation of hadron pairs produced at high x. Let us compare x-distribution for such a pair which may contain all the initial valence quarks with a pair in which one of the initial quarks is missing. We expect from QFM similar x-dependence for both distributions, whereas in QRM second spectrum should be significantly suppressed at high x.

To get a meaningful test of quark models from such comparison we should fulfil few important conditions. First, we have to be sure that our process is investigated in the kinematic region, in which it can be discussed as a well separated single hadron fragmentation. Therefore no dependence on energy or quantum numbers of second colliding hadron should be observed. Recent investigations [16] have shown that this is not the case in meson–baryon collisions below NAL energies. Therefore baryon–baryon collisions at high energy are best suited for our test.

Secondly, to have for our test as wide x-range as possible, we should choose a process for which triple-Regge terms are not expected to dominate at x close to 1. This rules out not only the diffractive transitions peaking at $x \simeq 1$ ($n \to p\pi^-$ etc.), but also charge-exchange transitions ($p \to p\pi^{\pm}$ etc.) which may proceed via non strange meson M exchange yielding at small $p_{\perp}$ a flat x-distribution from a triple-Regge formula

$$\left.\frac{d\sigma}{dx}\right|_{p_{\perp}\simeq 0} \simeq c(1-x)^{2\alpha_M(0)-1} \simeq c(1-x)^0. \tag{5}$$

The investigation of hadron pairs which may contain all the initial valence quarks, but differ from the initial hadron by strangeness (or other such quantum number) has one additional advantage. If the mass distribution of such a pair includes significant resonance contributions, we obtain from the QRM a specific surprising prediction

$$\lim_{x\to 1} \frac{\dfrac{d\sigma}{dx}\left[h \to (h'h'')_{\text{resonance}}\right]}{\dfrac{d\sigma}{dx}\left[h \to (h'h'')_{\text{background}}\right]} = 0, \tag{6}$$

i.e., the resonance peaks should disappear at high x. Indeed, let us discuss $B \to MB'$ fragmentation. According to QRM, non-resonant pair may use all the initial valence quark's momentum, as it is formed by $(q_1q_2q_3) \to (q_1q_2q_4)+(q_3\bar{q}_5)$ transition. For the resonance production we use only two of the initial valence quarks. Therefore a non--resonant pair distribution should be nearly flat in x, whereas for resonance the x-distribution should decrease as in all the non-diffractive $B \to B'$ transitions, i.e. as $(1-x)^n$ with $n \gtrsim 0.5$. Let us note that both QFM and QCR predict, instead of (6), the same x-distribution for non-resonant pairs and resonances.

Finally, an obvious practical advice is to avoid processes, for which cross-section is very small or final particles difficult to detect and identify.

All this discussion suggests that the best process for our test is the strangeness-exchange fragmentation $p \to \Lambda\pi^{\pm}$. Let us define the ratio

$$R = \frac{d\sigma}{dx}(p \to \Lambda\pi^-) \Big/ \frac{d\sigma}{dx}(p \to \Lambda\pi^+). \tag{7}$$

We can list immediately the following predictions:

(*i*) QRM gives flat x-distribution for denominator (all initial valence quarks can be used) and $(1-x)^{0.5}$ or $(1-x)^1$ dependence for numerator in analogy to single Λ spectrum.

(*ii*) Triple Regge terms should vanish faster than QRM predictions for both processes — n-values are above 0.5 for denominator (K* exchange) and above 2 for numerator (exotic exchange). They will not obscure our test.

(*iii*) QFM predictions depend on the ratio of ud and uu fragmentation into $\Lambda\pi^+$ pair, which can be measured in neutrino experiments. If these two processes are similar, R should approach a constant at high x; otherwise one gets predictions as in QRM.

(*iv*) QCR predict in all versions decrease of denominator, numerator and R at high x, although n-values vary.

TABLE I

Model predictions for p fragmentation into $\Lambda\pi^\pm$ pairs

p →		$\Lambda\pi^+$	$\Lambda\pi^-$	Y^{*+}	Y^{*-}
QRM	N° of common quarks	3	2	2	1
	n-value	0	0.5÷1	0.5÷1	1÷2
QFM	a) diquark fragmentation as in QRM N° of common quarks	2	2	2	1
	n-value	0.5÷1	0.5÷1	0.5÷1	1÷2
	b) diquark fragmentation from QCR N° of spectators in uu fragmentation	1	5	1	5
	ud fragmentation	3	3	3	3
	minimal n-value from QCR (9)	1	5	1	5
	from QCR (13)	0	2	0	2
QCR	N° of spectators	2	4	2	4
	n-value from (9)	3	7	3	7
	n-value from (13)	1	3	1	3
Triple-Regge n-values at $p_\perp = 0$		>0.5	>2	>0.5	>2

All the predictions are summarized in Table I, where different versions of QFM are motivated by QRM or QCR prescriptions for (yet unknown) diquark fragmentation. We see that data may be compatible with QRM and QFM simultaneously, if the diquark fragmentation obeys "new" counting rules [13]. Clear distinction between models, however, can be made by considering spectra of resonant and non-resonant $\Lambda\pi^+$ pairs.

Indeed, assuming the availability of all initial valence quarks in the final state (as in QRM) we have for resonance

$$\frac{d\sigma}{dx}(\mathrm{uud} \to \mathrm{uus}) \propto (1-x)^{0.5 \div 1} \tag{8}$$

and for non-resonant pair

$$\frac{d\sigma}{dx}(\mathrm{uud} \to \mathrm{uds}+\mathrm{u\bar{d}}) \propto (1-x)^{0} \tag{9}$$

because in the first case we lose the momentum of initial d quark, and in second case all the initial valence quarks are used. Therefore QRM predicts

$$\lim_{x\to 1} R'(x) = \lim_{x\to 1} \frac{d\sigma}{dx}(\mathrm{p} \to \mathrm{Y}^{*+} \to \Lambda\pi^{+}) \Big/ \frac{d\sigma}{dx}(\mathrm{p} \to \Lambda\pi^{+}) = 0 \tag{10}$$

i.e. the resonance/background ratio should decrease to zero with increasing x.

In QFM both processes should proceed mainly by uu fragmentation. This should not distinguish between resonant and non-resonant pairs, whatever prescription for power counting is used. Triple Regge terms are also the same for both processes and should vanish approximately as $(1-x)^{0.5}$. Therefore relation (10) is a good test of the assumption stating that *all* the initial valence quarks can contribute simultaneously to the formation of final hadrons at high x. If confirmed, it would support strongly this assumption. Otherwise, we would be led to assume that at least one of the initial valence quarks undergoes a significant loss of energy, as QFM predicts.

The only relevant data on $\Lambda\pi^{\pm}$ production published till now [17] do not allow for the systematic investigation of x-dependence for non-resonant pairs. As expected, the Σ^{*+} spectrum is roughly of the same shape as Λ spectrum, whereas the Σ^{*-} spectrum falls down more steeply at high x. However, the resonance/background ratio for $\Lambda\pi^{+}$ pairs seems to be *lower* for $|x| < 0.4$ than for the full data sample, although the data are far from conclusive. If this effect contradicting prediction (10) will be confirmed in more precise future experiments, QRM will require significant modifications to describe the data.

3. *Other existing data and tests of quark models*

We may ask now if the existing data on single and double hadron spectra do not prove or disprove the existence of processes, in which all the initial valence quarks recombine into final hadrons with large x. Investigating single particle spectra one finds conflicting evidence supporting apparently both possibilities. In the meson "elastic" fragmentation $\mathrm{M} \to \mathrm{M}$ (with diffractive peak removed) an observed x-dependence appears to be similar to that in $\mathrm{M} \to \mathrm{M}'$, where M and M′ contain one common valence quark [7]. This suggests that non-diffractive recombination of valence $\mathrm{q\bar{q}}$ pair is negligible. However, subtracting diffraction is not really well defined procedure and the real errors can be larger than quoted, allowing for quite large corrections. On the other hand, a detailed analysis of baryon fragmentations $\mathrm{B} \to \mathrm{B}'$ within QRM frame suggests an important contribution of three valence quark recombination [4]. This follows e.g. from the relative flatness of p spectra in pp collisions as compared to n or Λ spectra. Again, however, diffraction may have obscured the results. Thus single particle spectra do not allow for a clear answer to our question. Let us note also that even in QRM recombining all the initial valence quarks into one hadron may be suppressed in non-diffractive processes, as suggested by an analogy with the Zweig rule.

The data on pair production are rather scarce. However, the idea of comparing the x-spectrum of a pair containing all the initial valence quarks with the spectrum of pair without one of these quarks has been already exploited.

The first test of this type has been performed by ACCMOR collaboration [18] which has measured

$$R_1(x) = \frac{d\sigma}{dx}(\mathrm{K}^- \to \pi^-\pi^-)\Big/\frac{d\sigma}{dx}(\pi^- \to \pi^-\pi^-) \tag{11}$$

finding $(1-x)^1$ behaviour consistent with QRM. Indeed, since both u and $\bar{\mathrm{d}}$ from the initial π^- can be used in forming $\pi^-\pi^-$ pair, we expect here a flat x-distribution. From K^-, however, only d can be used, and we expect for $\pi^-\pi^-$ spectrum a $(1-x)^1$ or $(1-x)^2$ shape, as seen in most $\mathrm{M} \to \mathrm{M}'$ processes, for which M and M′ have one common valence quark.

Similar x-dependence is seen also for $\pi^+\pi^-$ pairs (both resonant and non-resonant ones)

$$R_2(x) = \frac{d\sigma}{dx}(\mathrm{K}^- \to \pi^+\pi^-)\Big/\frac{d\sigma}{dx}(\pi^- \to \pi^+\pi^-). \tag{12}$$

Here the authors of Ref. [18] claim that both QRM and QFM predict no or little x-dependence, as π^+ contains no common valence quark with initial particle. This conclusion seems to be really justified in QFM, but in QRM it follows only from the additional rule suppressing the recombination in single hadron (in analogy to Zweig rule, as mentioned above). Such a rule is not included in standard QRM, in which we can expect that R_2 will behave similarly to the ratio of single spectra

$$R_3(x) = \frac{d\sigma}{dx}(\mathrm{K}^- \to \pi^-)\Big/\frac{d\sigma}{dx}(\pi^- \to \pi^-) \tag{13}$$

since the steepness of π^+ spectra will favour always the lowest value of x accepted by the trigger. Data for R_3 are not too useful (in the $(1-x)^n$ fit n-values for numerator vary for different experiments between 1 and 2.5, and for denominator removing diffraction introduces ambiguities). Nevertheless, they are certainly compatible with $R_2 = R_3$, as QRM predicts. Thus the data of Ref. [18] seem to favour clearly QRM and a positive answer to our main question.

Unfortunately, these results cannot be regarded as a decisive test answering our question. If we look more closely on the ratios R_1 and R_2 (Fig. 1) we find that their x-dependence is very weak (compatible with a constant) up to $x = 0.8$. Only the last two points (at $x = 0.85$ and 0.95) lay significantly lower and determine the n-values quoted as a fit. This is just a region excluded usually from QRM fits due to the possible dominance of triple Regge terms. In fact, observed decrease of R_1 and R_2 is compatible with triple Regge formula

$$R_1 \propto R_2 \propto R_3 \propto (1-x)^{2[\alpha_{A_2}(0)-\alpha_{K^*}(0)]} \simeq (1-x)^{0.6}. \tag{14}$$

Therefore the data should be significantly improved for lower x to check more precisely the behaviour of R_1 and R_2. Alternatively, one can check if triple Regge terms do really take over at high x by the investigation of shapes of numerator and denominator in R_1

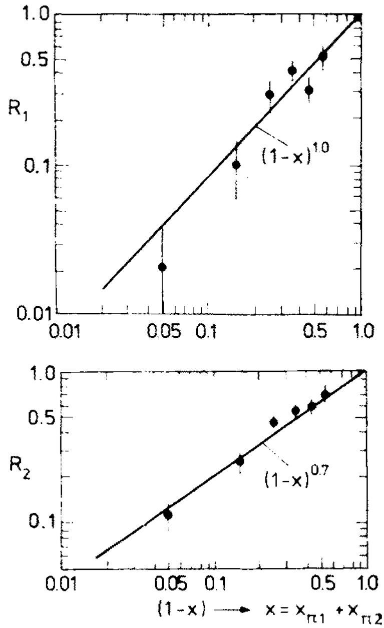

Fig. 1. Ratio R_1 (11) and R_2 (12). Data are from Ref. [18], straight line fits are to guide the eye

and R_2, separately. Common x-dependence for pairs with masses in- and outside of the resonance region (noted in Ref. [18]) suggests that triple Regge mechanism is really dominating — all the quark models predict $R_2 \xrightarrow[x\to 1]{} \text{const} = 1/2$ for resonant pairs.

As we have seen, the test is not unambiguous, mainly because of possible important triple-Regge contribution. Also the relatively low momentum (59 GeV/c) could introduce non-negligible corrections to the limiting fragmentation, obscuring the results. Therefore we conclude that our test proposed in Section 2 is significantly superior to the analysis, which can be performed on the other existing data.

4. *Conclusions*

We have discussed various quark models of hadron fragmentation processes. Serious discrepancies between data and naive model predictions have been observed for all the models. Therefore instead of testing more refined (and less predictive) versions of various models we discuss the simple question of the existence of processes, in which *all* the initial valence quarks contribute to the final state hadrons at high x. Existing models differ here strongly: in QRM such processes are very important, whereas in QFM one of the quarks is always "stuck" in the first stage of interaction and does not contribute.

We have shown that investigating the $\Lambda\pi^{\pm}$ pair production in proton fragmentation region we may answer our question, testing most basic assumptions of the discussed models. Such a test will be important for any future model building. Existing data on single- and double particle distributions were shown to be insufficient to perform similar tests unambiguously.

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