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Baryon Production in QCD Jets

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Abstract. Recent data from several sources—Υ decays, high energy deep inelastic scattering, e^+e^- annihilation at PETRA—reveal substantial baryon production in QCD jets. We discuss the likely mechanisms within the context of QCD, and formulate experimental tests to distinguish amongst them.

1. Introduction

Recently data has become available on (anti-) baryon production in events which one believes to consist of high energy quark and gluon jets. The production of baryons, and in particular of very fast baryons, turns out to be substantial. Theoretically baryon production has received little attention in the past on the assumption that it would be small. Motivated by this new data we will discuss, in this paper, the production of baryons in several theoretical models of quark and gluon fragmentation.

The relevant data comes from DASP II [1] at DORIS, JADE and TASSO at PETRA [2, 3] and EMC [4] at the CERN SPS. In the next section we discuss this data, focussing on its unexpected features. Then we turn to a discussion of theoretical models, first for gluon jets and then for quark jets. Since in these models there are important parameters and functions that are not known we emphasize qualitative rather than quantitative predictions; and in particular we suggest a variety of ways in which the various models may be experimentally distinguished from each other. For the reader who wishes to see a numerical realization (however, untrustworthy!) of such models we include two Appendices. We also include some comments on several papers that have appeared as this paper was being written.

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2. Data and General Expectations

Before discussing the data it is useful to provide a framework for such a discussion by describing the general theoretical expectations for baryon production that preceded this data. Three of the most important expectations were as follows.

(*i*) The production of baryons at low momentum should be due to soft rather than hard dynamics, and so should be comparable in size to baryon production in normal soft hadron–hadron collisions. Since low momentum particles dominate total multiplicities, the total baryon multiplicity in QCD jets should also be similar to the produced baryon multiplicity in, for example, a proton jet at a comparable energy; and hence should be small, of the order of a few percent of the π^+ multiplicity [5].

(*ii*) Fragmentation spectra in general fall rapidly with increasing x: the momentum transfers involved in producing a hadron from an initial quark increase with the momentum fraction x of the hadron and hence the spectrum decreases with increasing x, just as the form-factor of the hadron decreases with increasing momentum transfer, Q^2. So one also expects the spectrum to decrease the more rapidly in x, the more complex a structure the hadron possesses. In particular the spectrum of fast produced baryons should decrease more rapidly than that of fast pions, just as the baryon form-factor decreases more rapidly than the pion form-factor. An explicit, widely used, QCD based realization of these intuitive expectations are the counting rules [6] which in their most naive form [6] lead us to expect

$$\frac{q \to P}{q \to \pi^\pm} \sim (1-x)^2; \frac{q \to \bar{P}}{q \to \pi^\pm} \sim (1-x)^6;$$
$$\frac{g \to P}{g \to \pi^\pm} \sim (1-x)^2 \tag{1}$$

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Of course from these general arguments it is not obvious at what value of x such behaviour should set in. In particular if the proton possesses a diquark substructure, its spectrum should not be so different from that of a pion until x becomes large enough that the structure of the diquark is resolved. Since the data we consider are for $x \lesssim 0.6$ this is an important question. It is generally believed that the behaviour exemplified in (1) should set in at small x, say for $x \gtrsim 0.1$, and one may support this belief with, for example, the following observations: the same hypothetical diquark scale which determines when the 3 quark structure of the baryon is revealed, also determines the Q^2 at which the proton acquires its full dipole form factor, and this scale is known to be $\sim m_p$, and so is similar to all other scales; the systematic application of the counting rules to, for example, large $p_\perp$ processes requires, for its success, that fragmentation functions follow these counting rules even at small x; in proton–proton collisions the $\bar{p}$ spectrum shows such a decrease from small x.

(*iii*) The produced baryon anti-baryon, $B\bar{B}$, pair should be close in rapidity and should tend to balance each other's transverse momentum. For $B\bar{B}$ pairs produced during the final state soft interactions, this is expected on the basis of the idea of short range correlations which is well-known to hold in ordinary soft hadronic interactions (with some reservations for transverse momentum) and which has also been recently confirmed for charge correlations in quark jets at PETRA [7]. At current values of Q^2 the hard (perturbative) production of a $B\bar{B}$ distant in phase space proceeds through diagrams very similar to those contributing to a diquark form-factor and hence would be severely suppressed. At asymptotic values of Q^2, distant $B\bar{B}$ pairs can be formed through the production of a $q\bar{q}$ pair early on in the perturbative branching of a quark jet; however, such a $B\bar{B}$ pair would still be close in longitudinal rapidity although distant in relative transverse momentum [8].

With the above remarks in mind we turn now to the data. The DASP II group [1] finds that anti-protons on the Υ (presumably three gluon jets) are produced at a rate about six times higher than on the neighbouring continuum (quark, antiquark jets) and the ratio of $\bar{p}$ to mesons is roughly independent of x. At PETRA [2, 3] the $\bar{p}$/meson, and Λ/meson ratio increases with x and becomes large. In deep inelastic processes (a quark jet) and in particular in the EMC data [4] the ratio of protons to pions increases up to $x \approx 0.5$ and is substantial. Moreover $p/\bar{p}$ increases rapidly with x.

These features of the data are displayed in Fig. 1. In Fig. 1a we plot the average anti-proton multiplicity per event for Υ decays [1] and for the neighbouring continuum [1]. For comparison purposes we plot the same quantity, $\langle n_{\bar{p}} \rangle$, for pp collisions [5] at $\sqrt{s} = 2m_\Upsilon$. (We take $\sqrt{s} = 2m_\Upsilon$ rather than $\sqrt{s} = m_\Upsilon$ in an attempt to account for the leading baryon

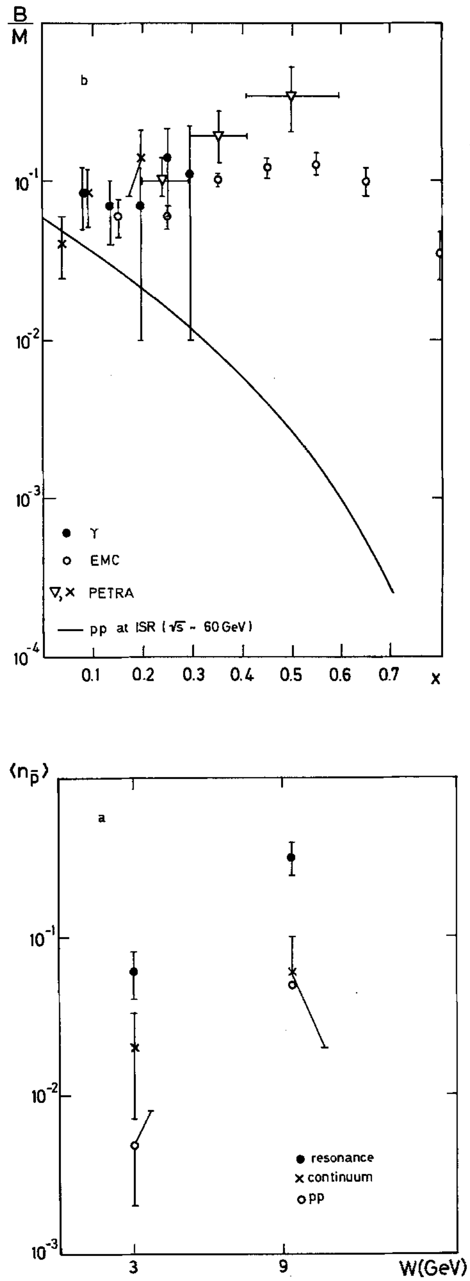

Fig. 1. a The average number of $\bar{p}$ per event on the J/ψ [9] and Υ [1] resonances (·), the neighbouring continua [1, 9] (x), and at the appropriate energies (see text) in pp collisions [5] (0). **b** The ratio of baryons to mesons (see text for precise definitions) as a function of Feynman x, on the Υ [1] (•), in PETRA jets [2, 3] (x, ∇), in the EMC [4, 11] data (0); also plotted is the curve for pp collisions derived from ISR data [10] (——)

effect; on average in a pp collision only about half the *c.m.* energy is available for particle production). We repeat this procedure for the ψ [9]; except that we now show the range of values $\langle n_{\bar{p}} \rangle$ takes in pp collisions for $\sqrt{s}$ between $2m_\psi$ and $2(m_\psi + 2m_p)$—the range of values about $2m_\psi$ attempts to include the effects of the masses of the two leading protons on the relatively low available energy.

In Fig. 1b we plot baryon to meson ratios, B/M, as a function of x, for the Υ data [1] (where B = number of produced protons and antiprotons $= 2\bar{p}$, and M = total number of charged pions, kaons and baryons $= \pi^{\pm} + K^{\pm} + 2\bar{p}$), for PETRA jets (for the data marked x (2) B and M are defined as for the Υ data; the data marked ∇ [3] have different definitions, with $B = \Lambda + \bar{\Lambda}$ and $M = \pi^{\pm}$), for the EMC data [4] (where $B = p$, M = all positive hadrons) and for pp collisions [10] (where $B = p + \bar{p}$, $M = \pi^{\pm}$). We use here pp data at $\sqrt{s} \sim 60$ GeV; lower energy data has lower values of $\bar{B}/M$ at small x (e.g. $\frac{2\bar{p}}{\pi^{\pm}} \sim \frac{1}{150}$ at $x \approx 0$ and $p_{\text{lab}} \approx 24$ GeV/c) and this should be borne in mind when comparing small x normalizations in the figure.

The reader will note that B and M are not the same quantities for all the data; however, they are similar enough for a comparison to be meaningful.

The data possesses some striking features.

(*i*) Small momentum baryons (which dominate the values of $\langle n_{\bar{p}} \rangle$) are much more copiously produced on the Υ than in quark jets, or in pp collisions. Soft baryon production in quark jets, on the other hand, is comparable to that in pp collisions, in accordance with our theoretical expectations.

(*ii*) In quark jets the baryon to meson ratio rises with x, becoming perhaps of $O(1)$ by $x \approx 0.5$ for PETRA energies; and on the Υ it is perhaps constant: both differ drastically from the rapid fall observed in pp collisions. (For the EMC data one can compare $\bar{p}/\pi^{\pm}$ with the same ratio in pp collisions; now the $\bar{p}$ shares none of the initial quanta in either reaction, but the same observation is still valid.)

(*iii*) There is some sign for a change in the size of B/M when one goes from the EMC data ($W \sim 10$ GeV) to the TASSO data ($W \sim 36$ GeV). Also the highest x EMC point might indicate the start of a decreasing B/M ratio as $x \to 1$.

To summarize: the large multiplicity of soft baryons in gluon jets, and the constant or increasing size of the ratio B/M with increasing x in quark and gluons jets, are the main surprises of the data since they contradict our naive theoretical expectations.

3. Models

What is the source of all these baryons? Since the Υ is supposed to decay via a 3 gluon intermediate state, and since high Q^2 quark jets possess a substantial perturbative fast gluon component (see below), one suspects that the common denominator amongst all these phenomena may be glue. One expects glue to be a more efficient producer of baryons than normal soft interactions on fairly general grounds: the flux tube trailing a gluon possesses an energy density about twice that of a quark flux tube, and hence the production of heavy particles, such as baryons, should be much less severely suppressed (naively the suppression in a gluon flux tube would be only the square root of the suppression in the quark flux tube). A second general observation is that in any high Q^2 process, after the four momentum squared of the quanta degrades below a Q_0^2 up to which we have calculable perturbative dynamics, the system then necessarily passes through energy densities and "temperatures" higher than those that occur in ordinary hadron–hadron collisions (except as rare fluctuations). So once again one would expect a greater production of heavier particles in regions of phase space occupied by such moderately hard quanta; in particular away from $x = 0$, since $x = 0$ is dominated by soft quanta.

We now describe several mechanisms that may contribute to baryon production. These mechanisms are necessarily convolutions of hard and soft dynamics, so precise calculations are not possible for the time being. We try to compensate for his weakness by suggesting experimental signatures that may serve to distinguish between the possible mechanisms.

Gluon Jets

1) Consider Υ decays to begin with. These proceed via the almost pointlike creation of three fast gluons, and just before hadronization the final state will usually consist of these three fast gluons, together with perhaps several more perturbatively radiated gluons that will be in general much slower. Now as a fast gluon leaves the interaction region it trails behind it a flux tube. In a world without dynamical triplets of colour, the flux tube would break up into a sequence of glueball resonances (in the same way as a quark flux tube typically decays into string bits that are usually taken to be low lying meson resonances) as in Fig. 2. Estimates of lowest-lying glueball masses range from about 0.75 to 2 GeV [12]. So low lying glueball resonance masses should be in the range 1.5–2 GeV. Including dynamical fermion triplets is not expected to alter these numbers very much and hence the mass of a gluon string bit is expected to follow some distribution centred on a mean in the range of 1.5 to 2 GeV. In the real world with quarks we may represent such a gluonstring bit as a flux tube with $q\bar{q}$ pairs at each end, in the octet representation. Since the flux tube has a length ~ 1 fermi and a similar width, it is in fact less a tube than a rather symmetric interaction region containing 2 quarks and 2 antiquarks. With a mean mass in the region of 1.5 to 2 GeV the purely *kinematical* suppression of the evolution of such a string bit into a baryon antibaryon pair of mass ~ 2 GeV will not be severe. Whether the *dynamics* of such a massive interacting multiquark system allows substantial $B\bar{B}$ production is a much less straightforward question; however, just the fact that any kinematic suppression is much weaker here than in usual soft processes (including quark flux tubes—see below) leads us to expect enhanced baryon to meson production ratios. Some

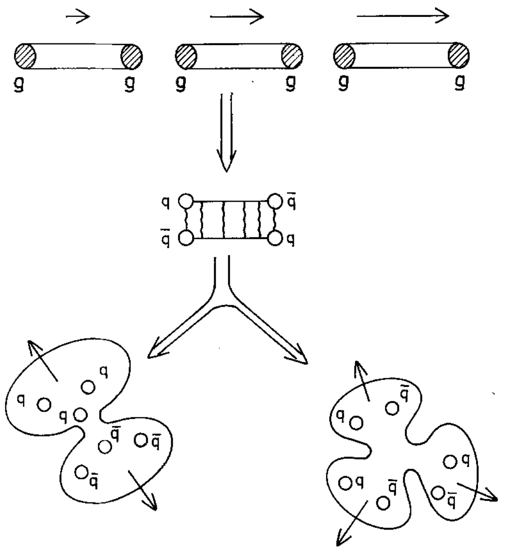

Fig. 2. An isolated fast gluon trails an octet flux tube that breaks up into "glueball" string bits as shown. Such a string bit evolves (if not originally so) into a strongly interacting system containing two quarks and two antiquarks, and this can either decay into a $B\bar{B}$ system or a purely mesonic system (a three meson system in the figure)

insight into the effect of the dynamics may be gained by looking at low energy $p\bar{p}$ annihilations. At $\sqrt{s}=2$ GeV the relative kinetic energy is low enough that the intermediate state will at some point consist of 2 quarks and 2 antiquarks mixed together in a strongly interacting region of total mass 2 GeV (just like our glue string bit). The annihilations correspond to the case when this system decays into mesons; the cross-section is 77 ± 3 mb [13]. The cross-section for producing a $B\bar{B}$ pair may be estimated by taking $p\bar{p} \to p\bar{p}$ or $n\bar{n}$ and subtracting the pp value. This gives [13] ~ 38 mb. Thus there appears to be no particular dynamical suppression of this mode: and our best guess is that the decay of a gluon string bit into $B\bar{B}$ will also not exhibit any marked dynamical suppression. This holds also for fast baryons.

The reason is that fast baryons (and mesons) require a large relative momentum difference between the two (octet) $q\bar{q}$ pairs created from the vacuum which leads to the same suppression factor for baryon *and* meson production. So, we expect $B/M \sim (1-x)^0$ (rather than $B/M \sim (1-x)^2$ suggested by the counting rules (1)) in this picture.

2) The above accounts for the baryons that arise from pieces of individual gluon flux tubes. However, on the Υ most of the total $\langle n_{\bar{p}} \rangle$ comes from slow antiprotons. That is where the gluon flux tubes merge. Here, after the flux tubes break, we are left with a system of 3 $q\bar{q}$ colour octet pairs immersed in a strongly interacting region of mass $\sim 3/2(1.5-2)$ GeV ≈ 2.2 to 3 GeV; as in Fig. 3. In Fig. 3 we show how the system might decay into $B\bar{B}$. The mass is now such that we expect no kinematical suppression at all. Moreover, an argument analogous to the one

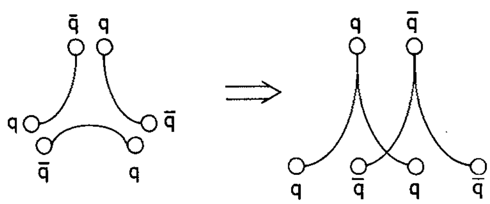

Fig. 3. The six quark system at the origin of the 3 gluon state; and its possible decay into $B\bar{B}$

above using $p\bar{p}$ data at $\sqrt{s}=2$ GeV, suggests that at 2 GeV the ratio of $B\bar{B}$ to mesonic modes is even larger. This is consistent with the data on the Υ which tells us that more than half Υ decays produce a $B\bar{B}$ pair. Whether such a separate mechanism for slow $p\bar{p}$ production is really occurring should be experimentally tested as follows. If we consider that subset of Υ decays which are 2 jet like (high thrust), as will occur when two of the gluons are essentially collinear, then the colour will go via a single flux tube and there will be no *slow* vertex of the kind shown in Fig. 3. Hence in such events we expect fewer slow antiprotons. This effect will be even more clear-cut in radiative decays of the Υ; where $\Upsilon \to \gamma gg$.

Quark Jets

3) We now turn our attention to energetic quark jets. An energetic isolated almost on-shell quark will trail a colour (triplet) flux tube behind it; $q\bar{q}$ pairs will be excited from the vacuum and will split the flux tube into string bits of perhaps 0.75 to 1 GeV mass each. In this picture [14] a $B\bar{B}$ pair can be formed if colour triplet diquark, antidiquark are excited out of the vacuum instead of a $q\bar{q}$ pair, and if they split the quark flux tube as in Fig. 4. Qualitatively this will be suppressed relative to $q\bar{q}$ excitation as follows. Suppose we excite a pair of triplet objects $A, \bar{A}$ from the vacuum to split the flux tube. Initially the $A\bar{A}$ will be close together and the energy uncertainty will be $O(M(A\bar{A}))$. As the $A\bar{A}$ separate they replace an everlengthening piece of the flux tube until at some point the gain in diminishing the flux tube length outweighs the cost of the $A\bar{A}$ energies, and then the flux tube may be considered permanently broken. The energy deficit in the initial stage is related directly to the masses, m_A, the scale is set by the string tension ε, and so generically we expect a suppression factor of the type $\exp\{-\text{const.}\, m_A/\varepsilon\}$ in the amplitude for the process (the precise form of the suppression factor will depend on the dynamics). Since $\varepsilon \sim 1$ GeV/fermi and since these are the kinds of energy density occurring in ordinary hadron–hadron collisions, we might expect B/M to be comparable in the central regions of pp collisions at ISR and e^+e^- annihilation at PETRA. This turns out to be the case experimentally (see Fig. 1). Fast baryons (i.e., $x \to 1$), on the other hand, require a large relative momentum difference between the diquarks and the antidiquark which leads

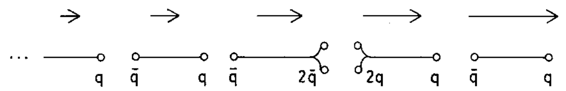

Fig. 4. The colour flux tube trailing a quark breaks up into meson and baryon, anti-baryon string bits. The lengths of the arrows represent the velocities of the bits (pictorially)

to $B/M \sim (1-x)^2$ in agreement with the counting rules* (1) and other models. The data, however, exhibits a quite different behaviour.

We now suggest two mechanisms for fast baryon production that make use of the substantial perturbative gluon emission that already occurs at PETRA energies (the 3-jet events are the large angle tail of these emissions). Indeed the momentum in glue roughly equals the momentum lost by the quark. In the leading log. approximation [15] (LLA) the final momentum fraction of the quark is

$$\langle x_v \rangle = \left[\frac{\alpha(Q^2)}{\alpha(Q_0^2)}\right]^{32/3(33-2N_f)} \tag{2}$$

where α is the strong coupling constant, N_f is the number of flavours, and Q_0^2 is a value chosen such that when the 4 momentum squared of a quantum drops below Q_0^2, it no longer participates in the perturbative branching. This quantity is sensitive to the values of Q_0 and Λ chosen; if we choose $Q_0 = 2\,\Lambda = 1$ GeV, then

$$x_v \approx \begin{cases} 0.49 \;\; (0.67) & Q = 30\,\text{GeV} \\ 0.56 \;\; (0.77) & Q = 10\,\text{GeV} \end{cases} \tag{3}$$

while for $Q_0 = 2.5$ GeV, $\Lambda = 0.5$ GeV we find the bracketed values. Moreover, typically most of the emitted momentum will be carried by a single fast gluon.

4) This immediately suggests the first mechanism: if a fast gluon is emitted at a wide enough angle that the forward pieces of the quark and gluon flux tubes don't overlap, then the gluon flux tube can decay into a $B\bar{B}$ pair as discussed earlier in the context of Υ decays. As the following argument shows, hard gluons are indeed emitted at relatively wide angle. In the LLA the probability for finding all but a fraction $\varepsilon/2$ of the total (parton) energy outside two oppositely directed cones of (full) opening angle δ is given by [16]

$$P_{\varepsilon,\delta} = 1 - \exp\left\{-\frac{16}{3}\frac{\alpha_s}{\pi}\ln\varepsilon\ln\frac{\delta}{2}\right\} \tag{4}$$

This translates into the probability for finding hard gluons of (total) energy not less than 1/3 and 1/2, respectively, the total jet energy radiated at an angle δ or larger ($Q = 30$ GeV, $\Lambda = 0.5$ GeV):

δ	$P_{1/3,\delta}$	$P_{1/2,\delta}$
5°	0.69	0.52
10°	0.60	0.44
15°	0.53	0.38
20°	0.48	0.34
30°	0.39	0.27

(5)

Most of the gluon energy will be carried by a single gluon as can be checked by comparison with the lowest order formula.

We then would expect: (*i*) equal cross-sections versus x for baryons and antibaryons; (*ii*) independence of the initial quark flavour, i.e. equal densities of protons and neutrons despite the fact that the initial quark is more frequently a u than a d; (*iii*) fast baryon production occurs predominantly in fatter jets. This is because the piece of gluon flux tube giving the $B\bar{B}$ pair should not overlap with the quark flux tube. So say the (anti-) baryon have $x_B \sim 1/2$, $x_{\bar{B}} \sim 1/5$, then we require $p_{\perp B}$, $p_{\perp \bar{B}} > \langle p_\perp \rangle$ and if most of this $p_\perp$ is the appropriate fraction of the gluon momentum we thus have

$$p_{\perp B} \simeq 2.5\, p_{\perp \bar{B}} > 2.5 \langle p_\perp \rangle \sim 1\,\text{GeV} \tag{6}$$

and the jet looks fat. (*iv*) $B/M \sim (1-x)^0 +$ higher terms as compared to $B/M \sim (1-x)^2$ given by the counting rules (1). Indeed from the Υ data we know that the B/M ratio resulting from a gluon is roughly constant in x. Coupling this with the fact that Υ spectra are no softer (for $x \gtrsim .2$) than neighbouring continuum spectra [17] tells us directly that this model gives $B/M \sim$ const.

These signatures are sufficiently restrictive that we can already state that fast (anti-) baryon production in the EMC data is *not* dominated by this mechanism. This is on the basis of (*i*). Since the EMC data is at relatively lower energies, $Q \sim 10$ GeV, this may be because of the sparse fast gluon production at those energies (see (3)). At PETRA one can test (*iii*) immediately; (*i*) can be tested by taking events with two $B\bar{B}$ pairs and seeing if their orientations are uncorrelated; (*ii*) would require neutron identification, while there is already some evidence [3, 4] for (*iv*). We observe that if this mechanism dominates then inputting the appropriate QCD matrix elements one can predict fast B/M ratios in 2 jet events from those observed on the Υ (the present data is, however, too coarse).

5) The second mechanism is illustrated in Fig. 5 [18]: an energetic off-shell quark goes almost on-shell by emitting a fast almost collinear gluon which is almost on-shell, $p_g^2 \lesssim Q_0^2 \sim 1\,\text{GeV}^2$, and which then converts into a $q\bar{q}$ pair. When the quark of this pair is the faster it recombines with the initial quark into a diquark with x close to 1, which then produces a fast baryon through a cascade mechanism. When the $\bar{q}$ is faster it recombines with the original quark to give a fast meson (resonance). The baryon cross-section may

* In [14] the calculated B/M ratio is roughly constant in x. However, in that calculation the composite nature of the diquark is disregarded, and since it is precisely this compositeness that leads to a ratio of B/M that falls with x, we believe that a more complete calculation would produce such a decreasing ratio, and this would then lead to difficulties with the data we have been focussing on here

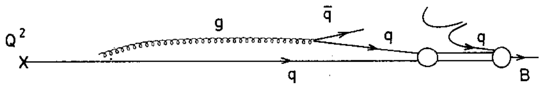

Fig. 5. A fast, off-shell, quark emits perturbatively a fast collinear gluon with $Q_0^2 \sim 1\ \mathrm{GeV}^2$ which converts into a fast quark and a slow antiquark. The two quarks form a diquark which gives a fast baryon

be written

$$\frac{dN_B}{dx} = \int_0^1 dx_g P_1[q(x=1) \to g(x_g)]$$
$$\cdot \int_0^{x_g} dx_{\bar{q}} P_2[g(x_g) \to \bar{q}(x_{\bar{q}})] \tag{5}$$
$$\cdot P_3[q(1-x_g) + \bar{q}(x_{\bar{q}}) \to B(x)]$$

where the p_i represent probabilities for the various fragmentation processes. One can trivially generalize this formula to the case of multigluon emission; however, at our energies most of the emitted gluon momentum is carried by the fastest gluon. p_1 can be estimated in the LLA; it varies with Q^2 and is sensitive to one's choice of Q_0 and Λ. If we choose $Q_0 = 2\Lambda = 1$ GeV, then glue carries about half of the momentum and p_1 is roughly flat in x_g. The $g \to q\bar{q}$ mass kinematics is very similar to $\rho \to \pi\pi$ so we expect this spectrum to be also flat [19] (in $x_{\bar{q}}/x_g$). p_3 includes both the recombination of q and $\bar{q}$ and the subsequent decay into a baryon. For the recombination to be probable we require that $x_q = 1 - x_q$ be not too distant from $x_{\bar{q}}$: p_3 will fall rapidly with the rapidity gap $\sim |\ln x_q/x_{\bar{q}}|$ with a scale of $1-2$ units. So typically the initial quark will recombine with whichever is the faster decay product of the gluon. The total momentum of these two quanta will clearly be close to unity (e.g. $1 - x_g + x_{\bar{q}} \approx 1$). If they are two quarks then the final baryon might typically carry $\sim 2/3$ of the momentum. If they are a $q\bar{q}$ then the mass kinematics will favour a meson resonance rather than a light π, and so once again the fastest meson decay product will carry about 2/3 of the $q\bar{q}$ momentum. Hence this mechanism will produce a B/M ratio at large x that is close to unity: $\frac{B+\bar{B}}{\text{mesons}} \sim O(1)$. With the parameters Q_0 and Λ such that p_1 is flat in x_g (as in our discussion here) it is clear that this mechanism for meson production will dominate over the direct cascade of the quark at large enough x (because the q spectrum is flat in x and $q \to \pi \sim (1-z)^2$ typically). So in this case we expect at PETRA energies

$$\left.\frac{B+\bar{B}}{\text{mesons}}\right|_{\text{larye } x} \approx 1 \tag{6}$$

However, this result is obviously sensitive to Q_0 and Λ: also (see (3)) it will be considerably weaker at EMC energies.

The theoretical uncertainties, particularly in the factors p_1 and p_3 in (5) make a quantitative calculation unrewarding. Instead we concentrate on other experimental signatures that may serve to distinguish amongst the above machanisms. However, for the reader who would like to see a more numerical realization of the above qualitative arguments, we present in Appendix A such a numerical calculation — only on the understanding, however, that we claim the detailed assumptions and results to be no more than merely illustrative.

Differences with the previously discussed pure glue mechanism include: (*i*) since most of the gluon transverse momentum recombines with the equal and opposite transverse momentum of the original quark, there will be no tendency for a jet with a fast (anti-) baryon to be fat (unlike the pure glue case); (*ii*) in a quark jet (e.g. EMC data) the baryon will be faster than the antibaryon [20]; in annihilation events one would expect that in events with two $B\bar{B}$ pairs, their orientations should be usually the same, (pure glue implies no correlation); (*iii*) the fast baryon contains the initial quark and hence reflects its flavour. From a ratio $u:d = 4$ we expect $p:n = 13:7$ with some dilution from charm decays.

The above properties are common to the recombination model and to the soft model of Fig. 4, except perhaps some small differences with respect to (*i*) above.

Some differences between the model of Fig. 4 and the above recombination model are as follows. (*i*) For large x the recombination model predicts $B/M \sim O(1)$; the flux tube model typically gives [14] $B/M \sim O(.1)$, and as discussed earlier this ratio should fall at larger x. (*ii*) The recombination mechanism turns on with increasing Q^2 like the fast perturbative branching; we expect significant increases in B/M at larger x as we go from EMC to higher PETRA energies. In contrast the flux tube model will predict rough scaling from lower SPEAR energies upwards. (But comparisons at low energies may be masked by ambiguities associated with the large baryon mass, e.g. use of $x = 2p/\sqrt{s}$ versus $x_0 = 2E/\sqrt{s}$.) In Fig. 1a the PETRA baryon ratios at large x do indeed seem to be larger than the EMC ratios. Such a Q^2 dependence at fixed x argues for a perturbative contribution to baryon production.

(*iii*) Gluon bremsstrahlung off charm quark is weaker than off low mass quarks. Hence in the recombination mechanism the fast baryon production will also be weaker. In annihilation events a semileptonic decay is a good trigger of a charm quark: one then looks at the B/M ratio in the opposite jet which is also necessarily charmed.

4. Discussion

In this paper we have discussed a number of theoretical ideas for obtaining large amounts of fast produced baryons in quark and gluon jets. Since high energy quarks are generally accompanied by energetic gluons from the perturbative branching of the initial far off-shell quark, the most economic model would be one in which fast baryon production in both quark and gluon jets involved glue in an essential way. However, this need not be the case, so it is important also to consider the possibility that fast baryons in quark jets are produced entirely by non-perturbative soft mechanisms. To this end we have considered a soft flux tube model (Sect. 3(3)) and have contrasted it against the perturbative models.

An evident distinction between soft and hard models is that the latter should show a Q^2 dependence from the onset of perturbative branching, while the former should show very little change at high Q^2. This requires better data, but there appears to be a hint of some Q^2 dependence in comparing the EMC data ($W \sim 10$ GeV) and the TASSO data ($W \sim 36$ GeV) in Fig. 1b. It would also help if the different groups presented data that could be more directly compared with each other (i.e. same B and M).

We have argued that in a soft model the B/M ratio should fall with increasing x. The data would then argue against such a soft mechanism. The way out would be to argue that the full 3 quark structure of the baryon manifests itself only at a rather high Q^2, i.e. that there is a rather high mass scale involved in the quark binding. We have argued that this option would be hard to reconcile with the undelayed onset of the dipole behaviour of the proton form factor (and for other reasons too). It is amusing that the highest x EMC point in Fig. 1b suggests that the B/M ratio may have begun to decrease at about $x \sim 0.6$. This is at best rather tenuous evidence; nonetheless it is worth emphasizing that the point at which B/M begins to decrease with x contains dynamical information about a higher mass scale, and should be searched for experimentally.

The question of whether fast baryons are produced preferentially in fat jets is accessible to immediate experimental verification, and would distinguish between the hard mechanisms we have proposed; it would also, if answered in the affirmative, rule out the soft mechanism.

The EMC data has more baryons than antibaryons at large x and this means that the baryons are not being produced by a flavour blind process, such as gluondecay, there.

Since the EMC data has important implications for baryon production dynamics, it is important to know to what extent the fast baryons are indeed produced (in $B\bar{B}$ pairs) and to what extent they are due to the initial baryon number of the photon–proton interaction (this is of course not a consideration in e^+e^- interactions). In Appendix B we perform a sample calculation, and the result is that a substantial fraction of fast baryons might be just the initial struck proton. This means that the change in B/M spectra in going from EMC to TASSO energies may be greater than suggested by Fig. 1b. It also puts into some uncertainty our conclusion that because there are more fast baryons than antibaryons, a gluon decay mechanism is ruled out at EMC energies. These questions clearly require better understanding.

Finally we mention some papers on baryon production that arrived as this work was being completed. Hofmann [21] considers a recombination mechanism. The mechanism is flavour blind and would predict equal numbers of baryons and antibaryons in a quark jet. Eilam and Zahir [22] consider a perturbative recombination model in which the baryon is produced from three perturbatively produced quarks: they find very small cross-sections. However, another similar calculation [23] finds larger cross-sections. Meyer [24] extends the Field–Feynman Monte Carlo model to include baryons. The model *assumes* similar baryon and meson fragmentation functions and hence does not add to our theoretical understanding of B/M ratios, but does well its intended job of describing the data. Andersson et al. [14] fit the data within a soft colour flux tube model, but they treat the diquark as a point particle.

The tests we have discussed should help to discriminate between the possible mechanisms for baryon production in quark and gluon jets. It is clear that baryon production provides a rather subtle handle on the interplay between soft and hard QCD dynamics.

Appendix A

In this Appendix we shall calculate a fast baryon spectrum using the perturbative recombination model of Sect. 3(5). We have already emphasized that the parameters and functions that go into such a calculation are not well-known and hence a wide variety of final baryon spectra are possible. Hence we have not attempted to fit the data with such a model. The purpose of the calculation in this Appendix is to show in detail how this mechanism works, so that the reader can then recalculate the fast baryon spectrum with his own favourite assumptions. The assumptions we use are thus chosen with the aim of making a simple analytic calculation possible rather than being the best theoretical ones: however, they will not be grossly unreasonable. Since we wish to exemplify this mechanism our detailed assumptions will be such as to enhance the mechanism, and consequently we shall not be surprised to find that we overestimate the fast baryon spectrum.

The model goes through the following sequence of steps:

$$q \to q + g \to q + (\tilde{q}\bar{\tilde{q}})$$

$$\to \begin{cases} \text{if } x_{\tilde{q}} > x_q : (q\tilde{q}) + \ldots = \text{diquark} + \to B + \ldots \\ \text{if } x_{\tilde{q}} < x_q : (q\bar{\tilde{q}}) + \ldots = \dfrac{\text{meson}}{\text{resonance}} + \ldots \to M + \ldots \end{cases} \tag{7}$$

For the first step we choose

$$\frac{dN}{dx_q dx_g} = \delta(x_q + x_g - 1) \tag{8}$$

Integrating, this is equivalent to

$$\frac{dN}{dx_q} = 1; \frac{dN}{dx_g} = 1 \tag{9}$$

If we use the leading log jet calculus [15] with $\Lambda = 0.5$ GeV, $Q_0 = 1$ GeV then a flat quark spectrum at PETRA energies is about right. Our gluon spectrum corresponds to one gluon per event. Actually there could be further soft gluons, and as long as their total momentum were small (8) and (9) would be good approximations. However, in practice the real gluon spectrum should be softer than the one we use.

The next step in (7) may be written as:

$$\frac{dN}{dx_q dx_{\bar{q}}} = \int_{x_{\bar{q}}}^{1} dx_g \frac{dN}{dx_q dx_g} \frac{1}{x_g} \frac{d\bar{P}}{dz}\bigg/_{z = x_{\bar{q}}/x_g} \tag{10}$$

where $d\bar{P}/dz$ is a fragmentation probability density for gluon to quark. We choose

$$\frac{d\bar{P}}{dz} = 1 \text{ for } 0 \leqq z \leqq 1 \tag{11}$$

which is not unreasonable since the kinematics is similar to a $\rho \to \pi\pi$ decay [15]. So

$$\frac{dN}{dx_q dx_{\bar{q}}} = \frac{1}{1 - x_q}; x_q + x_{\bar{q}} \leqq 1 \tag{12}$$

At the next step we obtain the diquark spectrum

$$\frac{dN_D}{dx_D} = \int_0^1 dx_q \int_{(1-x_q)/2}^{1-x_q} dx_{\bar{q}} \frac{dN}{dx_q dx_{\bar{q}}} \delta(x_D - x_q - x_{\bar{q}}) \tag{13}$$

where the lower limit on the $x_{\bar{q}}$ integration follows from our requirement that the qq system is only considered to be a diquark if $x_{\bar{q}} > \frac{1}{2} x_g = \frac{1}{2}(1 - x_q)$. Using (12) in (13) we obtain

$$\frac{dN_D}{dx_D} = \begin{cases} \ln\left(\frac{1}{1 - x_D}\right) & \text{if } x_D < \frac{1}{2} \\ \ln 2 & \text{if } x_D \geqq \frac{1}{2} \end{cases} \tag{14}$$

The baryon spectrum is then

$$\frac{dN_B}{dx_B} = \int_{x_B}^{1} \frac{dx_D}{x_B} \cdot \frac{dN_D}{dx_D} \frac{dP}{dz}\bigg)_{z = x_B/x_D} \tag{15}$$

We choose

$$\frac{dP}{dz}\bigg)_{z = x_B/x_D} = 1 \tag{16}$$

which corresponds to $\langle x_B/x_D \rangle = 1/2$ in the diquark fragmentation. For kinematic reasons one expects $\langle x_B/x_D \rangle$ to be large. Putting together (14–16) gives

$$\frac{dN_B}{dx_B} = \int_{x_B}^{1} \frac{dx_D}{x_D} \frac{dN_D}{dx_D} = \begin{cases} \ln 2 \cdot \ln \frac{1}{x_B} & \text{if } x_B \geqq \frac{1}{2} \\ (\ln 2)^2 + \int_{x_B}^{1/2} \frac{dx_D}{x_D} \ln\left(\frac{1}{1 - x_D}\right) & \text{if } x_B \leqq \frac{1}{2} \end{cases} \tag{17}$$

as our final baryon spectrum.

The main features of this spectrum are as follows: (*i*) The total number of $B\bar{B}$ pairs/event from this mechanism is 1/2 since in half the gluon decays the quark carries more than half the gluon momentum and hence a diquark is formed. This is already too large a number since the total observed number of $B\bar{B}$ pairs is less than 1/2, and most of these are slow. (*ii*) The baryon spectrum is relatively flat and for large x_B behaves as

$$\frac{dN_B}{dx_B}_{x_B > 1/2} \approx (\ln 2) \cdot (1 - x_B) \tag{18}$$

(*iii*) At $x_B = 1/2$ the spectrum gives $dN_B/dx_B \approx 0.5$ which is about 10 times larger than the EMC data [4].

As we remarked earlier on our assumptions while not grossly unreasonable were all biased to obtaining as large a baryon spectrum as possible: one may regard the spectrum in (17) as a rough upper bound on what can be achieved with the model. The fact that it lies considerably higher than the experimental spectrum indicates that a suitably conservative set of assumptions could produce a spectrum roughly consistent with the data.

Finally some remarks concerning the fast meson spectrum. Its calculation proceeds just as for baryons except that we pick those events where $x_{\bar{q}} \geqq x_{\bar{q}}$ in the gluon decay. The $(q + \bar{q})$ system will be a low lying meson resonance and its decay will typically give two mesons with a flattish spectrum [15] not dissimilar to our $D \to B$ spectrum. Hence for large x this mechanism readily produces

$$B/M \approx \text{const} \approx O(1)$$

Of course mesons can also be produced directly from quark fragmentation, but since the quark spectrum is flat such mesons would have a spectrum like $(1 - x)^2$ or $(1 - x)^3$ for large x, and hence would be dominated by the recombination mechanism which gives a more slowly falling spectrum as in (18).

Appendix B

We would like to calculate the spectrum of fast non-produced baryons resulting from a collision between a virtual photon and a proton, i.e. how often does the initial baryon end up in the struck quark c.m. hemisphere after the interaction? In order to properly evaluate the EMC data [4] it is important to know the answer to this question.

Unfortunately our understanding of the soft dynamics is not precise enough to enable us to perform a definitive calculation. What we shall do is to perform a sample calculation using simple but not unreasonable assumptions.

Consider, then, the parton final state just prior to the soft hadronization. The struck quark will typically have $x \sim .8$ (not $x=1$ because of prior perturbative bremsstrahlung) and the other two quarks of the initial proton will have a total x of $x_D \approx -0.4$. During the soft hadronization these partons will change their momenta with a final distribution that falls exponentially in y (rapidity) from their original momentum [25]. The final baryon may be then obtained either by the fragmentation or the recombination of these quarks.

We assume that the two quarks other than the struck quark behave as a unit diquark. This is not unreasonable [25]. An analysis [25] of ν and $\bar{\nu}$ data then tells us that the diquark spectrum in the struck quark c.m. hemisphere will, after the soft interactions, be (for y_D not too large)

$$\frac{dN_D}{dy_D} \approx \frac{2}{W} e^{-y_D} \tag{20}$$

where W is the c.m. energy in GeV and y_D is the diquark rapidity. We further neglect the small probability that the struck quark ends up in the target hemisphere. Since whenever the quark and diquark both end up with $x>0$, the final baryon will also have $x>0$, we immediately have a lower bound on the total non-produced baryon multiplicity with $x>0$:

$$N_B(x>0) > \int_0 dy_D \frac{dN_D}{dy_D} = \frac{2}{W} \underset{W\approx 10\,\mathrm{GeV}}{\approx} 0.2 \tag{21}$$

The total number of forward protons observed in the EMC data is of the same order.

The next step is to estimate the shape of the spectrum. It is reasonable to assume that if the quark and diquark are within about 2 units of rapidity they recombine into a baryon, and otherwise the diquark fragments. More generally we assume recombination takes place if x_q lies between c and $(1-c)$ of the baryon fraction x_B: we shall choose c later. The baryon spectrum is then

$$\frac{dN_B}{dx_B} \approx R \int_{cx_B}^{(1-c)x_B} dx_q \int_{cx_B}^{(1-c)x_B} dx_D \frac{dN}{dx_q dx_D} \cdot \delta(x_q + x_D - x_B) \tag{22}$$

where we ignore baryons obtained from diquark fragmentation and when $x_D < 0$ (such baryons would typically be slow). R is a recombination normalization factor such that $\int_0^1 \frac{dN}{dx_B} dx_B$ has the correct normalization, i.e. it equals the total number of diquarks with $x_D > 0$ subject to the constraint that the quark has an x_q lying between $\frac{c}{1-c}$ and $\frac{1-c}{c}$ of x_D.

Now (20) may be rewritten as

$$dN/dx_D = \frac{2m_{\perp D}}{W^2} \cdot \frac{1}{x_D^2} \tag{23}$$

$$\left(\text{where we use } y_D = \ln\left(\frac{E+P}{m_{\perp D}}\right) \approx \ln \frac{2E}{m_{\perp D}} = \ln \frac{x_D W}{m_{\perp D}} \right)$$

so we choose to try

$$\frac{dN}{dx_q dx_D} = \frac{A}{x_D^2} \Theta(1 - x_q - x_D) \tag{24}$$

Substituting in (22) gives

$$\frac{dN_B}{dx_B} = \frac{1-2c}{c(1-c)} \frac{AR}{x_B} \tag{25}$$

Using our normalization requirement gives finally:

$$\frac{dN_B}{dx_B} \approx \frac{\ln\left(\frac{c}{1-c} \frac{W}{2m_{\perp D}}\right)}{\frac{W}{2m_{\perp D}} - \ln \frac{W}{2m_{\perp D}}} \frac{2}{W} \cdot \frac{1}{x_B} \tag{26}$$

as a good approximation for the range of variables we shall consider. This result is insensitive to c; a reasonable choice for c would be $c = 1/5$ (allowing the q and D to be up to some 1.5 units in rapidity apart) and then for $m_D = 0.5$ GeV, $W = 10$ GeV we obtain

$$\frac{dN_B}{dx_B} \approx \frac{0.026}{x_B} \tag{27}$$

which at large x_B is close to the observed EMC proton spectrum.

Our above estimates both for the integrated forward baryons (less model-dependent) and the very fast baryons (much more model-dependent) show that many of the fast baryons may in fact not come from produced $B\bar{B}$ pairs, but may be remnants of the initial target proton.

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