SLAC-PUB-2190
August 1978
(T/E)

QUARK FRAGMENTATION: SOME SIMPLE TESTS FOR QCD*

Roberto Suaya††

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

John S. Townsend

Department of Physics
Harvey Mudd College,††† Claremont, California 91711

and

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

The effect of quark and gluon spin on the fragmentation of energetic quarks into hadrons is discussed. Particle ratios and polarization for wide-angle mesons and baryons are given. In particular, we find $\rho/\pi = 1$ with the ρ's longitudinally polarized. It is found that circularly polarized photon beams can serve as a source of polarized quarks and that Λ's produced in the photon fragmentation region carry the same handedness as the photon.

(Submitted to Phys. Rev. D)

---

*Work supported in part by the Department of Energy.
††Present address: Fairchild Corporation, Mountain View, California.
†††Permanent address.

The testing of Quantum Chromodynamics (QCD) is an area of major concern in high energy physics. Among the successes of this theory are the constancy of the Drell ratio R in e^+e^- annihilation and the magnitude of the anomalous dimensions that are known to be present in deep inelastic lepton-hadron scattering.[1] The basic constituents of the theory are spin-1/2 quarks interacting through the exchange of spin-1 color gluons. The only clear, direct test of the spin-1/2 nature of the quarks is given by the $1 + \cos^2\theta$ angular distribution of jets in e^+e^- annihilation. In this paper we discuss some additional QCD predictions that rely strongly on the intrinsic angular momentum of quarks and gluons.

We first examine the fragmentation of quarks into hadrons. The distribution of the produced hadrons is known to be jet like, with a mean transverse momentum with respect to the quark direction of a few hundred MeV. The study of hadrons arising from quark decay with $k_\perp^2 \lesssim \langle k_\perp^2 \rangle$ lies outside the scope of perturbation theory. We limit ourselves to a consideration of those hadrons whose $k_\perp$ with respect to the quark direction is larger than 1 GeV. We can describe their production by the lowest order diagrams shown in Fig. 1. This is possible because the intermediate vector gluons are sufficiently far off shell to make perturbative calculations meaningful. We take the incoming quark to be in a definite helicity state and neglect terms of the form m/q, where q refers to relevant momenta in the problem and m labels the "quark mass." In this limit the vector character of the gluons guarantees that helicity is conserved at the quark-gluon vertex.

The production of a meson, shown in Fig. 1(a), can be described by two invariant amplitudes. We label these amplitudes M_{++} and M_{+-}, where the first subscript refers to the helicity of the incoming quark, taken to be right-handed, and the second subscript refers to the helicity of the produced antiquark. A simple calculation yields

$$|M_{+-}|^2 \propto p \cdot p_2 \; p_1 \cdot p_3$$
$$|M_{++}|^2 \propto p \cdot p_3 \; p_1 \cdot p_2 \qquad (1)$$

where we have only shown the Dirac spinor structure. The momenta p, p_1, p_2 and p_3 are indicated in the figure.

A zeroth order approximation to a meson wave function in a rapidly moving frame is given by requiring that the momentum of the q and the $\bar{q}$ be parallel. Therefore in comparison with other invariants $p_1 \cdot p_2 \approx 0$. This leads to a suppression[2] for M_{++}. Thus mesons originating at wide angles with respect to the jet axis are produced in a zero helicity state. We expect for this configuration that the ratio of vector to scalar mesons such as ρ/π or K^*/K is 1 and the produced vector mesons are longitudinally polarized.[3] This polarization can be confirmed, for example, by measuring the angular distribution of the 2π decay mode of the ρ. It should be noted that both particle ratios and polarization predictions are in fact independent of the helicity of the initial quark.

In the fragmentation of a quark into baryons (Fig. 1(b)) the same line of reasoning leads to $M_{+++} \approx 0$, where the subscripts refer to the helicities of the quarks forming the bound state and the momenta of the constituents are again taken to be parallel. This suppression can be seen in the angular distribution of decays of decuplet baryons produced at wide angles. Another consequence of this suppression manifests itself in the particle ratios of decuplet to octet baryons. For example, we predict $\Delta^+/p = \Delta^o/n = 5/4$ and $\Sigma^*/\Sigma = \Sigma^*/\Lambda = 1$. We have calculated these ratios by computing the overlap between the amplitudes to produce the three quark state and the SU(6) wave function of the hadron. These results may undergo modification if, on the average, the allowed helicity amplitudes are not equally probable.

In the low $k_\perp$ region where the majority of the produced hadrons lie, $p_1 \cdot p_2$ cannot be considered negligible in comparison with the other invariants. Therefore, the suppression of particular helicity states is no longer tenable. In addition, nonperturbative effects are bound to be important. Since the number of available mechanisms to produce a given helicity state should in this case be large, it is reasonable to suggest that in this region particle ratios will be given by statistical phase space, that in the limit $m/E \to 0$, reduce to $(2J_1+1)/(2J_2+1)$, i.e., $\rho/\pi = 3$ etc.[4]

Large transverse momentum hadronic production as well as e^+e^- annihilation constitute the most natural reactions in which to study these phenomena. In both cases events must be selected with a well defined jet structure. One should study the energetic hadrons produced at $k_\perp \gtrsim 1$ GeV with respect to the jet axis. A potentially troublesome source of background is given by hadrons originating from hard gluon bremsstrahlung. Detailed calculations[5] show this background to be negligible up to the higher energies available at PETRA/PEP.

Our previous results, though dependent on quark spin, do not require the use of polarized quarks. The need for quark jets is, however, clearly evident. We would now like to consider an independent test of the underlying theory that can be performed at low energies where the jet structure is unlikely to be present. This test relies on the use of polarized quark beams. It is generally thought that detailed studies of the dynamics of quark spin dictate the use of polarized beams and targets, and the observation of the resulting angular asymmetries.[6] These asymmetries vanish in lowest order when only one of the initial quarks is polarized. There is, nonetheless, a simple experiment that can be done using polarized beams on unpolarized targets, provided that measurement is made of the polarization of the produced final state hadron. A very convenient source of polarized quarks turns out to be circularly polarized photon beams. Such beams, for example, are available at SLAC with almost 100% polarization.

For low transverse momentum photon-hadron physics, the photon can be thought of as a superposition of vector mesons. On the other hand for high transverse momentum, the photon interaction with hadronic matter is predominantly mediated by the bare $q\bar{q}$ component in the photon wave function (when seen in a rapidly moving frame).[7] If the photon is polarized, so will be the quarks. In particular, the probability that a photon in a positive helicity state will fragment into a polarized q carrying a fraction z of the photon momentum is given by[8]

$$P_{\gamma_+\to q_+}(z) = \frac{\beta z^2}{2} , \qquad P_{\gamma_+\to q_-}(z) = \frac{\beta}{2}(1-z)^2 \tag{2}$$

where β depends on the transverse momentum and coupling constant e. The secondary quark beam will undergo a hard scattering subprocess with a constituent of the target, before turning into a large $p_\perp$ hadron. The vector nature of QCD is reflected in the conservation of quark helicity regardless of the type of hadron constituent from which the quark scatters.

The selection of final state hadrons at large Feynman x and $p_\perp$ insures that they have originated from quarks with a large fraction z of the photon momentum. These hadrons should reflect the high degree of polarization of the secondary quark beam. What is needed is a monitor of this polarization. Ideal candidates are strange baryons which decay weakly with large parity violating parameters such as $\Lambda \to p + \pi^-$ or $\Sigma^+ \to p + \pi^o$. The angular distribution of the decay nucleons (or pions) then allows the determination of the degree of polarization of the strange baryon along the direction of motion.[9]

In the $p_\perp$ regime $1 < p_\perp < 6$ GeV/c we find that the most economical way to produce Λ's or Σ's in the photon fragmentation region is to use s quarks from the photon wave function and combine them with u and d quarks from the target. This is often referred to as a constituent interchange mechanism (CIM).[10] The contribution to the differential cross section for these constituent interchange processes is given by[10,11]

$$E \frac{d^3\sigma}{d^3p} = \frac{\varepsilon^P f(\theta_{cm})}{(p_\perp^2 + m^2)^N} \tag{3}$$

where $\varepsilon = 1 - \frac{E^*}{E^*_{max}}$ with E^* the cm energy of the detected particle and E^*_{max} its maximum kinematically allowed value, and

$$P = 2n^{hadronic}_{passive} + n^{em}_{passive} - 1$$

$$N = n_{active} - 2 \quad .$$

The fundamental CIM process in forward photoproduction of baryons is $qB \to qB$ or $\gamma + (qq) \to B + \bar{q}$ (see Fig. 2). Processes in which the s quark is taken from the nucleon wavefunction necessarily involve two more spectators or passive quarks (with the same number of active quarks) than when the s quark is directly taken from the photon wavefunction. Photoproduction data[12] prefer small values of P and hence favor the use of s quarks from the photon.

Combining this mechanism with our knowledge of the SU(6) wave functions of Λ's and Σ's, we find that Λ's are particularly suited as probes. The u and d quarks in the Λ wave function are in a spin singlet state and therefore the helicity of the Λ is directly given by that of the s quark. Thus, in the limit $x \to 1$ the Λ follows the handedness of the photon, i.e., the longitudinal polarization $P_\Lambda \to 1$.[13] As we see in Eq. (2), the contribution of quarks with opposite handedness to the photon is suppressed by $(1-x)^2$ in this limit. The magnitude of the longitudinal polarization will decrease with decreasing x and will vanish for low x.

For the Σ's for which the u and d quarks are in a spin triplet state, the polarization is given by $P_\Sigma = -\frac{1}{3} P_\Lambda$. Care must be taken experimentally since $\Sigma^o \to \Lambda + \gamma$ thereby contaminating the Λ signal, in a way that will reduce the magnitude of the Λ polarization.[14] Calculations support the feasibility of detecting this polarization at SLAC.

Finally we should note that for ρ photoproduction (exclusive or inclusive at large x and large transverse momentum), a mechanism of the type described for photoproduction of Λ's should occur. The joining of a q and a $\bar{q}$ to form a ρ in this region should be described as in Fig. 1(a) with the quark leg p_3 crossed so that p and p_3 are incident. Our arguments show that ρ's formed in this way should exhibit longitudinal polarization only, independent of the polarization of the photon.[15] This prediction leads to a striking result when using a polarized photon beam since for low t, diffraction dominates and ρ photoproduction is known to conserve s-channel helicity.[16] The polarization of the ρ's should thus change markedly at larger momentum transfer where the point-like coupling of the photon to quarks predominates.

We acknowledge illuminating discussions with members of the SLAC Theory Group and Group BC, particularly with J. Ballam, J. Bjorken, S. J. Brodsky, R. Blankenbecler, R. Horgan, G. P. Lepage and K. Moffeit. One of us (J.S.T.) would like to thank S. D. Drell for the hospitality of SLAC and the Associated Western Universities, Inc. for their support. This work was supported in part by the Department of Energy.

REFERENCES

1. J. Ellis, "Applications of QCD," Stanford Linear Accelerator Center preprint SLAC-PUB-2121 (1978).
2. This analysis provides an alternative explanation of the result of G. Farrar and D. Jackson, Phys. Rev. Lett. 35, 1416 (1975) that the leading quark within a nucleon in a deep inelastic reaction carries the same helicity as the nucleon. This is easily seen by crossing the quark line p_3 in Fig. 1(a), i.e., there is a zero in the amplitude M_{++} when the two incident particles carry the same momentum.
3. In relating the matrix elements of Eq. (1) to the spin states of the mesons in the rest frame, we have used the time-honored assumption of treating this system as loosely bound.
4. Measurements at DESY for the ρ/π ratio are in agreement with this result. J. Bürger, Invited talk at the XIII Rencontre de Moriond, March, 1978.
5. T. A. DeGrand, Y. J. Ng and S.-H. H. Tye, Phys. Rev. D 16, 3251 (1977).
6. J. Babcock, E. Monsay and D. Sivers. Phys. Rev. Lett. 40, 1161 (1978).
7. A discussion of this point is given by R. Rückl, S. J. Brodsky and J. F. Gunion, Stanford Linear Accelerator Center preprint SLAC-PUB-2115 (1978).
8. J. Bjorken, J. Kogut and D. Soper, Phys. Rev. D 3, 1382 (1971). G. Altarelli and G. Parisi, Nucl. Phys. B126, 298 (1977).
9. This component of the polarization can only be different from zero if polarized beams or targets are used.
10. R. Blankenbecler, S. J. Brodsky and J. F. Gunion, Phys. Lett. 39B, 649 (1972); Phys. Rev. D 6, 2652 (1972); Phys. Lett. 42B, 461 (1973).
11. S. J. Brodsky and G. Farrar, Phys. Rev. Lett. 31, 1153 (1973); Phys. Rev. D 11, 1309 (1975).

12. A. M. Boyarski et al., Phys. Rev. D 14, 1733 (1976).

13. This polarization should not be confused with the transverse polarization observed in Λ production in pp collisions.

14. This background can be subtracted by looking at charged Σ's.

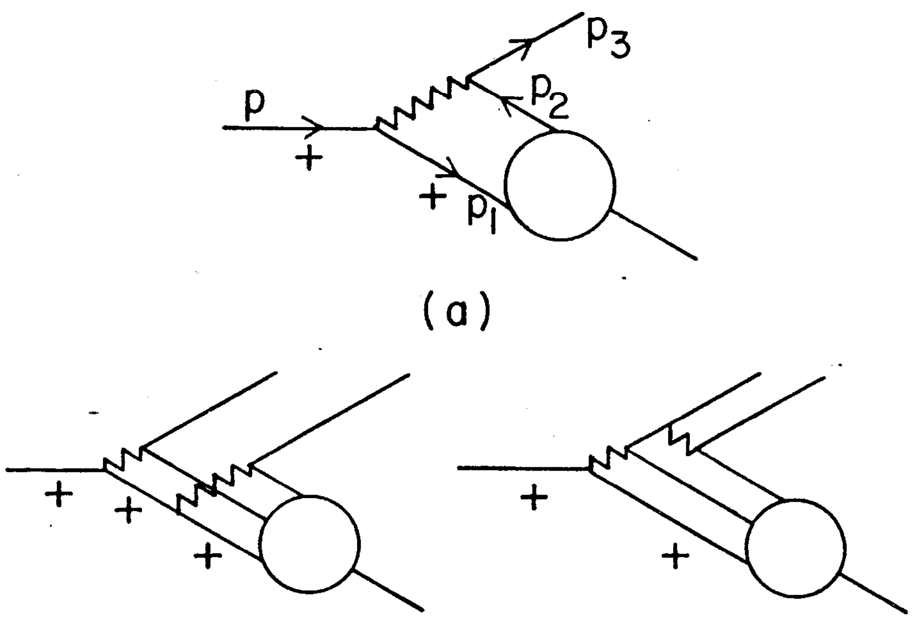
15. This result also holds for pion production of ρ's.

16. J. Ballam et al., Phys. Rev. Lett. 24, 960 (1970). M. Davier et al., Phys. Rev. D 1, 790 (1970).

FIGURE CAPTIONS

1. Lowest order QCD diagrams that contribute to the fragmentation of a quark into (a) mesons and (b) baryons. There is a third diagram of the form of (b) in which the quark produced by gluon bremsstrahlung itself radiates. The + sign refers to the helicity.

2. The leading CIM process contributing to the photoproduction of Λ's.



10–78 (b) 3463A3

Fig. 1

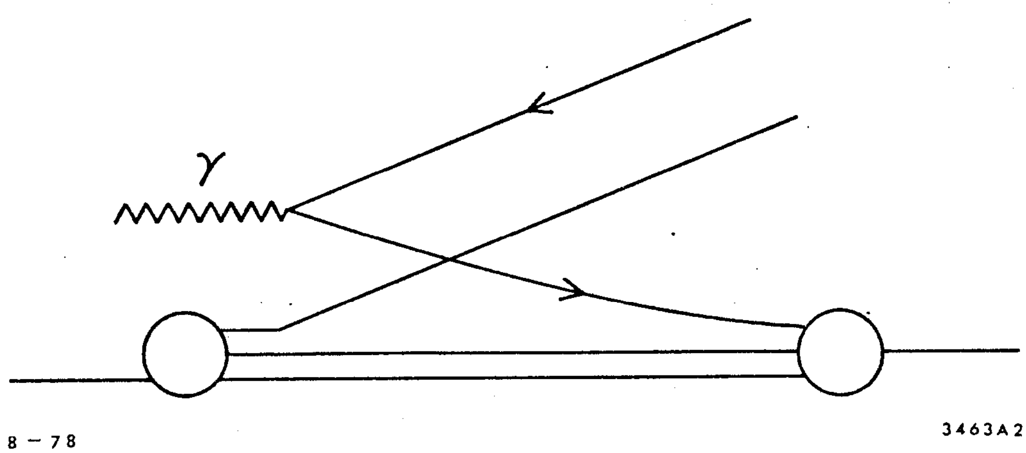


Fig. 2