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Quark dynamics of polarization in inclusive hadron production

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The parton-recombination model plus SU(6) symmetry is used to relate polarizations in inclusive baryon production to those of the underlying constituent subprocesses. A large number of predictions are given, none of which disagrees with experiment. It is suggested that the polarization arises via Thomas precession of the quarks' spins in the recombination process. This description accounts for all of the qualitative features of the baryon and antibaryon polarization data.

The unexpected discovery[1] of large polarization effects in inclusive Λ^0 production by unpolarized protons at high energy and small transverse momentum has shown that important spin effects exist in high-energy collisions. In this paper we study the quark dynamics underlying polarization within the framework of the parton-recombination model.[2] Assuming minimal complexity for the quark transitions and using SU(6) symmetry we relate the polarizations of numerous baryon-to-baryon transitions. The obtained relations test the basic recombination picture but are independent of how the polarization arises on the quark level. We then propose a model in which this polarization is due to a Thomas-precession effect in the quark-recombination process. Our model suggests that polarization of leading particles in multiparticle jets should be seen not only in hadron-initiated jets but also in quark jets produced in e^+e^- annihilation or deep-inelastic lepton-hadron scattering.

The data which we wish to explain are[3] the following.

(a) Λ^0's produced in pp and p-nucleus scattering are polarized transverse to the production plane and preferentially along the $(\vec{p}_\Lambda \times \vec{p}_p)$ axis.

(b) This polarization is independent of the beam energy and nearly independent of x_F, the fraction of the proton's longitudinal momentum carried off by the Λ^0.

(c) The polarization increases in magnitude linearly with the transverse momentum of the Λ^0.

(d) $\bar{\Lambda}^0$'s produced in pp and pA collisions are *not* polarized.

(e) Recent measurements of polarizations of Ξ^0, Ξ^-, and Σ^+ hyperons produced by a proton beam[4] suggest that the Ξ^0 and Ξ^- have *the same* polarization as the Λ^0, whereas the Σ^+ and the Λ^0 polarizations have *the same size but opposite signs.*

Of the above observations, (b) suggests that the proper framework to analyze the polarizations is the parton-recombination model, which has been applied with good success to many small-transverse-momentum fragmentation processes. In this model, a proton in the infinite-momentum frame is built up by three valence quarks plus a large number of sea partons; in the collision the slow or "wee" partons interact with the target, destroying the coherence of the wave function, which then decays into a many hadron final state. The partons-into-hadrons transformation takes place semilocally in rapidity and is pictured as proceeding via quark recombination: $q\bar{q}$ pairs and qqq triplets form mesons and baryons, respectively. The fastest particles are formed by the recombination of the beam's valence quarks with other valence quarks or sea partons. For example, fast Λ^0's (Σ^+'s) are produced by the recombination of a valence ud (uu) pair with an s quark from the sea of the proton (VVS recombination). In processes in which the minimal number of exchanged quarks is two, such as $p \to \Xi^0$ and $p \to \Xi^-$, VVS recombination is not possible and the production of fast particles proceeds through *VSS* recombination. Finally, if the fragmenting and the secondary particles have no common valence quarks, only *SSS* recombination is possible. In this case the cross sections are expected to be small and have steep x dependences, in agreement with experiment.

For analyzing Λ^0 polarization, it is convenient to apply the recombination model in the rest frame of the fragmenting beam proton. In that frame the proton's wave function is simple, just three valence quarks *uud*. The $p \rightarrow \Lambda^0$ transition proceeds through a slow strange quark in the fast-moving target particle scattering from the beam proton and combining with a *ud* pair in the beam proton to form the Λ^0. Since the *ud* pair in the Λ^0 is in a spin-singlet state, the spin and the polarization of the Λ^0 are those of the strange quark. The hypothesis of (approximate) short-range order of parton forces[5] implies that the distribution of slow quarks in the target particle and the *low-energy* subprocess s quark + proton $\rightarrow u$ quark + Λ^0 in which the Λ^0 polarization arises should be nearly independent of the target-particle energy. Hence the Λ^0 polarization should not depend on the total collision energy, in agreement with experiment.

Before discussing the polarization dynamics of the underlying constituent interactions, we wish to relate the polarizations of various baryon-to-baryon transitions.[6] We make four simplifying assumptions: (i) The transverse momenta of each of the quarks are more or less parallel to that of the final-state baryon, (ii) quark polarization is correlated with its transverse momentum and is flavor independent, (iii) the wave functions of the quarks common to the fragmenting and secondary baryons, such as the *ud* pair in $p \rightarrow \Lambda^0$, are identical, and (iv) valence quarks are not depolarized by the recombination. Let us first express the polarizations of transitions which proceed through *VVS* recombination in terms of two amplitudes for producing the baryon at some $p_\perp$ with the sea quark with spin up ($A_\uparrow$) and down ($A_\downarrow$) in the scattering plane. A straightforward SU(6) calculation gives

$$P(B \rightarrow B') = C\frac{|A_\uparrow|^2 - |A_\downarrow|^2}{|A_\uparrow|^2 + |A_\downarrow|} , \quad (1)$$

where C is given in Table I and interference between $A_\uparrow$ and $A_\downarrow$ is forbidden (these terms are odd under a parity × space-rotation transformation, hence zero). To fit the Λ data we need $|A_\uparrow|^2 \sim A(1-\epsilon)$, $|A_\downarrow|^2 = A(1+\epsilon)$. However, this model fails in its predictions for Σ^+: $C = -\frac{1}{3}$ is predicted while $C = -1$ is indicated by experiment.

Of course, the *uu* diquark of the Σ^+ is a $J=1$ state, in contrast to the *ud* diquark of the Λ. Since we have assumed a spin-$p_\perp$ correlation for the s quark in the Λ, it is natural to assume the same kind of correlation for the leading diquark. This is equivalent to an assumption that the recombination probability for the

TABLE I. Polarizations for various transitions predicted by the leading-partons–trailing-partons model. The constant C in the model of Eq. (1) for *VVS* recombination is the coefficient of $-\epsilon$.

$B \rightarrow B'$ transition	Polarization
$p \rightleftarrows n$, $\Sigma^- \rightleftarrows \Xi^-$, $\Sigma^+ \rightleftarrows \Xi^0$	$-\frac{20}{21}\epsilon + \frac{1}{42}\delta$
$p \rightleftarrows \Sigma^+$, $n \rightleftarrows \Sigma^-$, $\Xi^- \rightleftarrows \Xi^0$	$\frac{1}{3}\epsilon + \frac{2}{3}\delta$
$p,n \rightleftarrows \Lambda^0$	$-\epsilon$
$\Sigma^+, \Sigma^-, \Xi^-, \Xi^0 \rightleftarrows \Lambda^0$	$-\frac{2}{3}\epsilon + \frac{1}{6}\delta$
$p,n \rightleftarrows \Sigma^0$	$\frac{1}{3}\epsilon + \frac{2}{3}\delta$
$\Sigma^+, \Sigma^-, \Xi^-, \Xi^0 \rightleftarrows \Sigma^0$	$-\frac{20}{21}\epsilon + \frac{1}{42}\delta$
$p \rightleftarrows \Xi^0, \Xi^-, \Sigma^-$ $n \rightleftarrows \Xi^0, \Xi^-, \Sigma^+$	$-(\frac{1}{3}\epsilon + \frac{2}{3}\delta)$
$\pi, K^+ \rightarrow \Lambda$	$-\frac{1}{2}\delta$
$K^- \rightarrow \Lambda$	ϵ

diquark in a state (j,m) is different for different m (cf. Fig. 1). If we assume $|A_{1,1}|^2 = B(1+\delta)$, $|A_{1,-1}|^2 = B(1-\delta)$, $|A_{1,0}|^2 = |A_{00}|^2 = B$ we find

$$P(p \rightarrow \Sigma^+) = \tfrac{1}{3}\epsilon + \tfrac{2}{3}\delta \quad (2)$$

with $\delta = \epsilon$ demanded by data. Recombination pre-

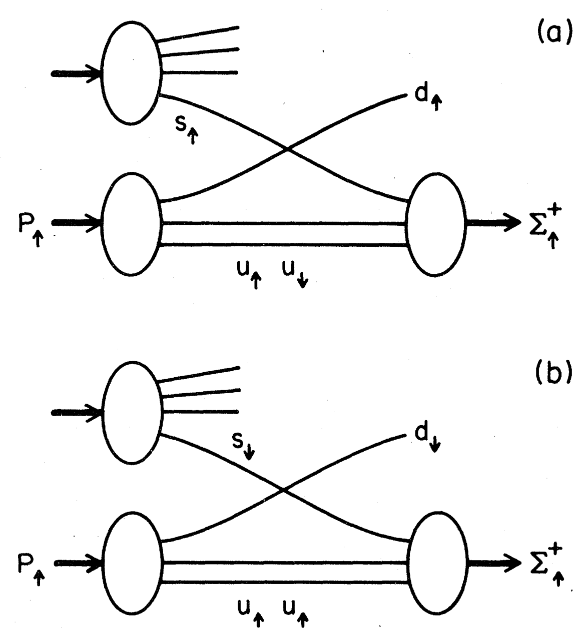

FIG. 1. Diagrams for $p \rightarrow \Sigma^+$ corresponding to the two amplitudes (a) $A_\uparrow A_{10}$ and (b) $A_\downarrow A_{11}$. The partons-into-hadrons transition occurs in the blob.

ferentially occurs when the trailing s quark is spin down and the leading diquark has $m_j = +1$ in the scattering plane.

The above ideas may be extended in a straightforward way into production via *VSS* recombination. Here the V quark is leading and the *SS* diquark nonleading. If we make the same assumptions for recombination probabilities as above *except* that we change the signs of ϵ and δ so that the leading parton again prefers to be spin up we find

$$P(p \rightarrow \Xi^0, \Xi^-, \Sigma^-) = -(\tfrac{1}{3}\epsilon + \tfrac{2}{3}\delta) \quad . \tag{3}$$

The data of Ref. 4 show $P(p \rightarrow \Xi^0) = P(p \rightarrow \Xi^0) = P(p \rightarrow \Lambda)$ again in agreement with this prediction for $\delta = \epsilon$.

So we see that all data are accounted for by the assumption that the leading constituents in the beam preferentially recombine with their m_j positive in the scattering plane while the nonleading constituents preferentially recombine with their m_j negative. Predictions of the model for other reactions are shown in Table I.

We have chosen to speak of diquark-quark recombination rather than of three-quark recombination because the two quarks with similar wave functions—the *VV* pair for example—probably interact with each other during recombination rather differently than they interact with the quark of a different wave function. Our ignorance about these interactions is most easily handled by treating the two similar quarks as one object, a diquark. All wave functions are given by exact SU(6).

The above predictions follow from the quark-recombination picture plus SU(6) symmetry and are independent of the dynamical mechanism by which the recombining sea quarks acquire their polarization. Now we wish to suggest a model for this polarization.[7] Consider again the $p \rightarrow \Lambda^0$ transition, this time in the infinite-momentum frame. Let the strange quark's longitudinal momentum before recombination be $x_i p$ and its transverse momentum $k_{\perp s}$. Since the x distribution of the sea quarks is very steep $\sim (1-x)^n$, $n = 7$–9, a fast Λ^0 must get most of its momentum from the valence *ud* quark pair. For $x_\Lambda = 0.6$, say, a typical share of the initial momenta is $x_i \lesssim 0.1$ and $x_{ud} \gtrsim 0.5$. *After* recombination, however, the three quarks share the Λ^0's momentum $x_\Lambda p$ roughly equally: for $x_\Lambda = 0.6$ the s quark's final momentum fraction is $x_f \approx 0.2$ (see Fig. 2). Thus the strange quark feels a force which tends to make its momentum more parallel to the beam axis. Since this force $\vec{F}$ is *not* parallel to the s quark's velocity $\vec{\beta}$, the quark will feel a Thomas precession—an effective interaction $U = \vec{s} \cdot \vec{\omega}_T$ where $\omega_T \propto [\gamma/(\gamma+1)] \times (\vec{F} \times \vec{\beta})$.[8]

The amplitude for production of a Λ of spin s will

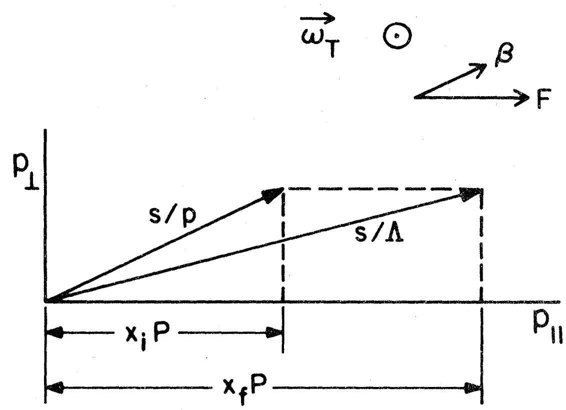

FIG. 2. Vectorial directions of the s quark in the proton (s/p) and in the Λ (s/Λ). The s quark carries longitudinal momentum $x_i p$ in the proton and $x_f p$ in the Λ. The direction of $\vec{\omega}_T \propto \vec{F} \times \vec{\beta}$ is up and out of the paper.

be proportional to the difference in energy $(\Delta E_0 + U)^{-1}$, where ΔE_0 (>0) is the energy denominator between the quark's intermediate and final energies in the absence of spin effects. Thus the cross section for production of Λ's is enhanced when $\vec{s} \cdot \vec{\omega}_T$ is negative. $\vec{\omega}_T$ is oriented in the $(\vec{p}_p \times \vec{p}_\Lambda)$ direction in the infinite-momentum frame, so that the cross section is bigger when the spin of the s quark, and hence the spin of the Λ^0, is oriented opposite to that direction, exactly as observed. Explicit evaluation of the asymmetry shows that the polarization is weakly dependent on x_F but proportional to the transverse momentum of the Λ^0—essentially a consequence of the wide disparity in size of $p_\parallel$ and $p_\perp$ in the problem. Thus Thomas precession accounts for all of the qualitative features of the $p \rightarrow \Lambda^0$ polarization data.

It is now easy to understand when $P(p \rightarrow \overline{\Lambda}^0) = 0$. The production of $\overline{\Lambda}^0$'s by a proton beam proceeds entirely through sea-sea-sea recombination. In this case, there will be equally many configurations in which the s quark is *faster* then the *ud* diquark as in which it is slower. Hence, in averaging over the configurations, the forces will cancel and the average $\vec{\omega}_T$ will vanish.

In summary, we have presented a model for quark polarization in which this polarization arises via Thomas precession in the quark-recombination process. We have derived a large number of relations between polarizations in inclusive baryon-to-baryon transitions. These relations test the quark-recombination picture independently of the quark polarization mechanism. It is straightforward to apply our technique to other inclusive processes, such as the octet-baryon-to-decuplet-baryon, baryon-to-vector-meson,

meson-to-baryon, and meson-to-vector-meson transitions.[9] Finally, completely analogous arguments to those presented here suggest that when the leading baryon or vector meson in a quark jet in e^+e^- annihilation or deep-inelastic electroproduction has transverse momentum with respect to the jet axis, it will be polarized, too. Thus we see that polarization effects should be a pervasive (though subtle) effect of *all* hadronic fragmentation and recombination.

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[1]G. Bunce *et al.*, Phys. Rev. Lett. 36, 1113 (1976).

[2]The parton-recombination model is a lineal descendant of quark-spectator models which have been applied to high-energy collisions for more than a decade. For reviews to modern work with references see: R. Hwa, invited talk presented at the XI International Symposium on Multiparticle Dynamics, Bruges, Belgium, 1980 (unpublished); H. I. Miettinen, plenary session talk at the XXth International Conference on High Energy Physics, Madison, Wisconsin, 1980 (unpublished).

[3]An incomplete list of references to experimental data is: K. Heller *et al.*, Phys. Lett. 68B, 480 (1977); Phys. Rev. Lett. 41, 607 (1978); S. Erhan *et al.*, Phys. Lett. 82B, 301 (1979); G. Bunce *et al.*, *ibid.* 86B, 386 (1979); F. Lomanno *et al.*, Phys. Rev. Lett. 43, 1905 (1979); and Paper No. 492 contributed to the XXth International Conference on High Energy Physics, Madison, Wisconsin, 1980 (unpublished); K. Rayachauduri *et al.*, Phys. Lett. 90B, 319 (1980).

[4]Results from a Fermilab experiment by the Michigan-Minnesota-Rutgers-Wisconsin Collaboration, presented by K. Heller at the XXth International Conference on High Energy Physics, Madison, Wisconsin, 1980 (unpublished).

[5]See, for example: R. P. Feynman, *Photon-Hadron Interactions* (Benjamin, New York, 1972); M. Le Bellac, CERN Report No. CERN 76-14, 1976 (unpublished).

[6]An earlier application of SU(6) symmetry to relating baryon polarizations is: K. Heller, University of Michigan Report No. UM-HE-77-38, 1977 (unpublished).

[7]Our model is completely different from that of Ref. 6 but has similarities with the semiclassical color-flux-tube model of B. Andersson, G. Gustafson, and G. Ingelman, Phys. Lett. 85B, 417 (1979). For hard-scattering models see: G. L. Kane, J. Pumplin, and W. Repko, Phys. Rev. Lett. 41, 1689 (1978). Predictions of the triple-Regge model are reviewed in: S. N. Ganguli and D. P. Roy, Phys. Rep. (to be published).

[8]L. H. Thomas, Philos. Mag. 3, 1 (1927). See, for example, J. D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, New York, 1978).

[9]A much more detailed analysis is in preparation.