Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823
(Received 5 July 1978)

We point out that the polarization P of a scattered or produced quark is calculable perturbatively in quantum chromodynamics for $e^+e^- \rightarrow q\bar{q}$, large-$p_T$ hadron reactions, and large-Q^2 leptoproduction, and is infrared finite. The quantum-chromodynamics prediction is that $P=0$ in the scaling limit. Experimental tests are or will soon be possible in $pp \rightarrow \Lambda X$ [where presently $P(\Lambda) \simeq 25\%$ for $p_T > 2$ GeV/c] and in $e^+e^- \rightarrow$ quark jets.

In quantum chromodynamics (QCD), observables which are free of infrared divergences can be computed in terms of the running coupling constant α_s. For an asymptotically free theory, α_s is expected to be small in a scattering at large transverse momenta, so that observables can be computed perturbatively. Thus, provided we can relate quark observables to observed hadrons, QCD may be rigorously tested.

This approach has been proposed by Sterman and Weinberg[1] and by Politzer,[2] and recently used by others[3] in e^+e^- reactions or leptoproduction reactions. In this note we propose another observable which can be measured in e^+e^- reactions, leptoproduction, and large-p_T hadron collisions, namely, the polarization of the scattered or produced quark. More precisely, the relevant observable is polarization times cross section, which is given schematically by $\mathrm{Im}(NF^*)$. For a nontrivial result, one must have nonflip (N) and flip (F) amplitudes with a nonzero relative phase. Note that this is qualitatively different from other kinds of spin effects which could be obtained with relatively real amplitudes and Born terms.[4]

For large-p_T scattering this procedure is slightly less rigorous since the initial state involves quarks confined in hadrons. But it has increasingly been accepted[5] that at large p_T one is observing quark-quark scattering and that in fact large p_T is a domain where a perturbative treatment of $qq \rightarrow qq$, $qg \rightarrow qg$, and $gg \rightarrow gg$ (where g means gluon) can quantitatively predict jet and hadron distributions.

The polarization of a scattered quark is another observable which is infrared finite and can be computed perturbatively. A determination of the polarization of a scattered quark can both test the validity of the assumption that $qq \rightarrow qq$, $qg \rightarrow qg$, etc., dominate at large p_T, and serve as a significant test of QCD. The same remarks apply to the polarization of a produced quark in e^+e^- annihilation or in leptoproduction. We give the discussion in terms of large p_T because this may be the first place for an experiment test. We also predict the large-p_T left-right asymmetry on a polarized test.

Because of confinement, to test the QCD prediction we have to make some assumptions. For unpolarized beam and target, we assume that the initial quarks are unpolarized. To compute the left-right asymmetry on a polarized target, in general we need to know the wave function of the quarks in a proton. However, for the actual QCD prediction the individual qq scatterings produce only a small left-right asymmetry (see below), so that we necessarily predict a small left-right asymmetry on a polarized target independent of the details of the wave function. For production of light-quark jets in e^+e^- the predicted polarization is also very small and so any observable which could reflect polarization is satisfactory. (For production of massive quarks in e^+e^- the predicted polarization may not be small above threshold but below the scaling region, and we must assume that a hadron, which is a fragment of a polarized quark, will remember the polarization of the quark.) It is, of course, possible that light quarks could be produced with large polarization (contrary to our QCD prediction), but that the mechanism of quark fragmentation is such that the quark spin direction is not remembered. Because of such a possibility, the QCD prediction would be contradicted by observing large polarization effects; but an observation of small polarization effects, while consistent with the theory, is not a strong confirmation of the theory until quark fragmentation is better understood.

On the other hand, by a general parity argument, fragmentation will not induce polarization. An unpolarized produced quark has only its momentum direction associated with it, and so its fragments cannot know of the normal to the production plane, which is the only polarization direction allowed by parity. Although the fragments may define a plane in a particular event, when averaged over events no direction will remain unless the quark was originally polarized.

Before we give the analysis, we note that it should not be long before our prediction can be tested. For large-p_T reactions the region where it is assumed that $qq \to qq$, etc., dominate the cross section may begin around $p_T = 4$ GeV/c.[6] The transverse polarization of the Λ, $P(\Lambda)$, in $pp \to \Lambda +$anything is already measured[7] for $p_T \simeq 2$ GeV/c, and a proposal exists[8] to measure it for $p_T \lesssim 6$ GeV/c, perhaps in the region of large p_T. Intersecting-storage-ring data already show a trend toward scaling in this region.[6] In addition, to show that large-p_T polarization can be large, the Λ polarization at $p_T \simeq 2$ GeV/c is[7] about 25%. Thus the QCD prediction requires that $P(\Lambda)$ begin to decrease rapidly for $p_T \gtrsim 4$–5 GeV/c. If $P(\Lambda)$ is significantly different from zero, then either it is not valid to apply QCD in this region (in spite of the analyses of cross sections), or QCD cannot be applied perturbatively, e.g., because α_s is too large, or, conceivably, something is wrong with the present formulation of QCD itself. This latter alternative would only be taken seriously after the other two were convincingly dismissed. Future experiments at larger p_T will allow the analysis to be extended to smaller α_s.

Similar remarks apply to the transverse polarization of a quark produced in $e^+e^- \to q\bar{q}$, or a quark struck by a current in leptoproduction. Again, in e^+e^- the polarization could in principle be of order α_s but is small in QCD. The prediction can be tested by studying Λ (or other resonance) polarizations as well. Another method is available, which can also be applied at large p_T, or in leptoproduction. The procedure is as follows. Define a quark jet axis by some method, giving a jet momentum direction $\vec{q}$, and let the beam direction be $\vec{b}$. Then consider the normal $\vec{b}\times\vec{q}$. If there were polarization in the direction of $\vec{b}\times\vec{q}$, one would expect that particles in the jet could remember that direction and preferentially have the component of their momentum transverse to $\vec{q}$ pointing up (or down) relative to $\vec{b}\times\vec{q}$. If $P=0$ one would expect no net momentum in the direction $\vec{b}\times\vec{q}$.

Ideally we would define an observable which was zero whenever the polarization was identically zero and which could be directly related to the quark polarization. Because we do not yet know how to calculate the way in which a polarized quark fragments into hadron, we cannot do that. Presumably one should test an observable such as the following one. Let

$$r_i = (\vec{p}_i \times \hat{q}) \cdot \hat{n},$$

where $\hat{n}$ is a unit vector in the direction $\vec{b}\times\vec{q}$, $\hat{q}$ is a unit vector in the jet direction, and $\vec{p}_i$ is the momentum of the ith particle in the jet. Then

$$\alpha = \sum_i r_i |r_i|$$

is an asymmetry which could signal the transverse polarization. In a future publication we will give results for such observables for the case of charmed-quark jets where $P \neq 0$ (see below). We emphasize here that since the QCD prediction is that P is numerically small for large-p_T reactions, light-quark jets, and leptoproduction, the details of how one relates the quark polarization to an observable are not important.

Consider $qq \to qq$. In QCD the leading contribution to each helicity amplitude is given by single-gluon exchange, and the next order is the two-gluon–exchange box diagram, plus crossed box, etc., as shown in Fig. 1. There is a nonzero imaginary amplitude from the box diagram, and thus

$$P \propto g^4 \times g^2/g^4.$$

For $\alpha_s = g^2/4\pi$ of order $\frac{1}{3}$, there could be sizable polarization. However, because QCD is a vector-gluon theory the quark helicities are preserved for zero quark mass (m_q) so that $P \equiv 0$.

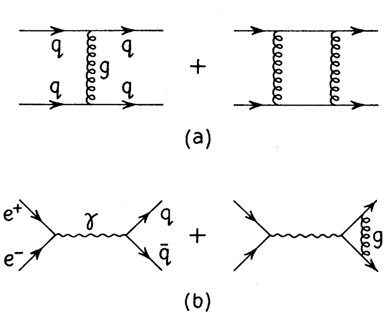

FIG. 1. The polarization of the produced quark is calculated to order α_s from the contributions shown; other contributions, such as soft-gluon emission, do not contribute to the polarization because they give a real amplitude.

These remarks hold if all quantities involved are free of infrared singularities. The important one for us is the behavior for $m_q \to 0$. It is easy to see by writing down the part of the box diagram which contributes to the polarization (see below) that it is finite and free of mass singularities in this limit. When $m_q \to 0$ there is no helicity flip in the Born diagram or box diagram, so that we immediately find $P=0$ for all our reactions. This is easily verified by direct computation.

It is necessary to check that the results are also finite for zero gluon mass. That is slightly more subtle since the imaginary part of the box diagram is *not* infrared finite. What happens[9] is that the box-diagram amplitude can be written in a form

$$M_{\text{box}} = BI + R,$$

where B is equal to the Born term, I is an infrared-divergent, complex, but spin-independent integral, and R is a spin-dependent remainder whose imaginary part is infrared finite. This is easily shown by writing the box-diagram amplitude, and subtracting the part with the loop momentum set equal to zero in the numerator. Then it becomes clear that the term BI does not contribute to the polarization arising from interference with the Born term B. No other contributions such as the crossed box or soft-gluon emission can matter since they do not give nonvanishing imaginary parts. A similar procedure allows one to see that to order α_s in all the reactions $qq \to qq$, $qg \to qg$, and $e^+e^- \to q\bar{q}$ the scattered-quark polarization or the asymmetry on a polarized target is zero for $m_q = 0$.

It is interesting to calculate the deviation from zero for $m_q \neq 0$, to order α_s. The explicit result for $e^+e^- \to q\bar{q}$ is, for arbitrary m_q and large Q^2,

$$P = \left(\frac{4\alpha_s}{3}\right)\frac{m_q}{Q^2}\frac{\sin\theta\cos\theta}{1+\cos^2\theta}.$$

Whatever observable is used, the variation with Q^2 and the c.m. scattering angle θ can be tested. P is the polarization transverse to the scattering plane, calculated through order α_s in QCD.

In leptoproduction, because the photon is spacelike, the gluon effects induce no imaginary amplitudes so that the polarization is identically zero to order α_s. To the present order in QCD perturbation theory, color does not play a significant role. The color averaging involved introduces numerical coefficients of order 1, but no qualitative features. Up to color factors the same analysis holds for lepton reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, etc., and so similar results hold there; we have been unable to find any polarization predictions for these reactions in the literature.

It has recently been argued[10] for large-p_T processes that rigorously in QCD one should indeed calculate with the parton-model formulas, but (with nonscaling distributions and) with the lowest-order term for the $qq \to qq$ scattering cross section calculated using the running coupling constant $g(p_T^2)$. We assume that this is also the correct procedure for us to follow. We assume that for large Q^2, instanton effects (which can flip helicity) are irrelevant for our analysis.

In this note we have pointed out that the asymmetry off a polarized target, and the transverse polarization of a produced quark in $e^+e^- \to q\bar{q}$, or in $qq \to qq$ at large p_T, or in leptoproduction, should all be calculable perturbatively in QCD. The result is zero for $m_q = 0$ and is numerically small if we calculate $m_q/\sqrt{s}$ corrections for light quarks. We discuss how to test the predictions. At least for the cases when P is small, tests should be available soon in large-p_T production [where currently $P(\Lambda) = 25\%$ for $p_T \gtrsim 2$ GeV/c], and e^+e^- reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.

One of us (G.L.K.) appreciates helpful remarks from J. Ellis and M. Einhorn, and we are grateful for discussions with York-Peng Yao. This research is supported in part by the U. S. Department of Energy and in part by the National Science Foundation.

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New, Generalized Cabibbo Fit and Application to Quark Mixing Angles in the Sequential Weinberg-Salam Model

Robert E. Shrock
Physics Department, Princeton University, Princeton, New Jersey 08540

and

Ling-Lie Wang
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

(Received 12 September 1978)

We carry out a new, generalized analysis of nuclear β decay and semileptonic hyperon and K_{e3} decays. The results are used to determine two quark mixing angles in the sequential Weinberg-Salam model.

The Weinberg-Salam (WS) $SU(2)_L \otimes U(1)$ gauge theory[1] has been quite successful in accounting for a wide variety of weak-interaction data. The four-quark version of the model, due to Glashow, Iliopoulos, and Maiani (GIM),[2] gained strong support with the discovery of charmed hadrons. Recently, the version of the model with three doublets of leptons and quarks, first discussed by Kobayashi and Maskawa (KM),[3] has gained prominence, since it incorporates the τ lepton[4] and the $(Q=-\frac{1}{3})$ Υ-constituent quark,[5] b. We assume that any additional fermions will transform under $SU(2)_L \otimes U(1)$ in the same way as the known ones, and we denote the corresponding model as the sequential WS model.

The mixing angles which describe how the weak-gauge-group eigenstates of the fermions are composed of mass eigenstates are of fundamental significance. With more than two quark doublets the old Cabibbo theory must be generalized. In this Letter we report the results of a new analysis of nuclear β decay and semileptonic hyperon and K_{e3} decays which makes use of the most up-to-date data to determine two quark mixing parameters and corresponding angles in the sequential WS model. Previous bounds on mixing angles[6,7] have been based on the standard 1974 Cabibbo fit by Roos.[8] Since several of the experimental inputs have changed since that time, it is clearly important to carry out a new analysis.

Consider the sequential WS model with $n_f = 2n$ flavors of quarks. Denoting the vectors of $Q=-\frac{1}{3}$ left-handed components of quark mass and gauge-group eigenstates, respectively, as $\psi_L = (d, s, b, \dots)^T$ and $\xi_L = (d', s', b', \dots)^T$, we have $\xi_L = V\psi_L$, where V is the unitary $n \times n$ quark mixing matrix. With no loss in generality one can define V_{11} and V_{12} to depend, respectively, on just one and two rotation angles. In a KM-type parametrization $V_{11} = c_1$ and $V_{12} = s_1 c_3$, where $c_1 \equiv \cos\theta_1$, $s_1 \equiv \sin\theta_1$, etc. If the Cabibbo-GIM structure of the charged current were exact, the submatrix consisting of V_{ij}, $i, j = 1, 2$ would be unitary by itself. This would require that a number of new mixing angles must vanish and would imply the existence of at least one new stable quark[9]; for the WS-KM model this would be the b quark. However, two recent experiments[10] have established that, given a reasonable assumption about the hadronic production cross section for b-flavored hadrons, such particles are unstable, with lifetimes $\tau_b < 5 \times 10^{-8}$ sec. This implies that there must be finite