Where can one see polarized-gluon fragmentation?

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We examine various reactions which may yield gluon jets of nonzero linear polarization and comment on the sort of experimental signals these jets may have.

A crucial prediction of quantum chromodynamics is the existence of gluon jets—jets of hadrons which are produced in the wake of a color-octet gauge vector gluon, just as in e^+e^- annihilation jets are produced by the separating $q\bar{q}$ pair. Gluon jets may be expected to be seen—or are thought to have been seen—in higher-order reactions such as $e^+e^- \to q\bar{q}g$, $e^-q \to eqg$, hadron scattering mediated by $qg \to qg$, $gg \to gg$, as well as in the Zweig-violating decays of heavy $Q\bar{Q}$ states: $\Upsilon \to ggg$, $\eta_\Upsilon \to gg$, etc.[1] The elucidation of the properties of these jets is an important problem in the understanding of quantum chromodynamics (QCD).

Gluon jets are thought to be distinguishable from quark jets in a variety of ways. Flavor correlations of leading particles in the jets should reflect the flavor-singlet nature of the gluon. The multiplicity of the jet may reflect the color charge of the gluon: The multiplicity of soft gluons emitted by separating octets is $\frac{9}{4}$ that emitted by triplets. It may be that soft-gluon multiplicity is related to hadronic multiplicity.[2]

An important question is whether or not gluon spin can affect the final-state distribution of hadrons in the jet. A possible scenario wherein this effect actually occurs has been recently proposed.[3] Production of leading hadrons in the gluon jet is assumed to proceed via the sequential reaction $g \to q\bar{q} \to$ hadrons. Now the gluon's spin axis is correlated with the decay plane of the $q\bar{q}$ pair: In lowest-order perturbation theory the distribution of quarks from the decay of a nearly on-shell gluon is

$$D_{q/g}(x, \epsilon) \sim 1 - 4x(1-x)(\hat{n}\cdot\vec{\epsilon})^2 , \qquad (1)$$

where x is the (light-cone) fraction of the gluon's momentum carried off by the quark, $\vec{\epsilon}$ is the direction of polarization, and $\hat{n}$ is the normal to the $q\bar{q}$ production plane. At high energy the transverse momentum of the quarks in this plane may be reflected in the distribution of fast hadrons in the gluon jet, whose momentum transverse to the jet axis would be the vector sum of quark momentum transverse to the gluon jet and of hadron momentum transverse to the quarks. Thus one might see an "oblate jet," one which has a larger intrinsic hadron momentum transverse to the jet in the $q\bar{q}$ plane than normal to that plane. From Eq. (1), the major axis of a polarized-gluon jet would be oriented preferentially perpendicularly to the direction of polarization of the gluon jet.

This prediction depends crucially on the assumption that the dominant sequential jet evolution is $g \to q\bar{q} \to$ hadrons, not $g \to gg \to$ hadrons. Smilga and Vysotsky[4] have pointed out that a cancellation of a polarization effect, on the parton level, between $g \to q\bar{q}$ and $g \to gg$ can occur if the number of flavors of massless quarks is three. Whether the polarization effect cancels on the hadron level depends on whether the spectrum of hadrons produced in the "final" evolution $g \to$ hadrons is equal to the spectrum of "final" evolution $q \to$ hadrons, and is *a priori* unknown. Thus polarization effects are not, strictly speaking, predictions of quantum chromodynamics; rathey they represent a possible scenario whose discovery would provide a useful set of parameters for distinguishing gluon jets.

Irrespective of these predictions, it is worth recalling that the only nonsinglet quantum numbers which a gluon jet carries and which are capable of being observed by a color-blind detector are those associated with its angular momentum. It is a worthwhile question to ask whether or not gluon polarization can influence the properties of hadrons produced in gluon fragmentation, and if so, where its effects can best be seen.[5]

A necessary requirement for observation of gluon spin effects is an underlying pointlike dynamics which produces gluons in definite spin states. For instance, in Zweig-violating decays of heavy $Q\bar{Q}$ pseudoscalar resonances which proceed via gg intermediate states, the gluon polarizations are preferentially perpendicularly polarized with respect to each other. Polarization effects may be seen by comparing the mean angle of $\langle p_{\rm out}\rangle$ in one jet with the $\langle p_{\rm out}\rangle$ of the other jet, where a sphericity or thrust analysis is used on each of the two separately in order to determine its planarity, if any.

In analogy with this detection scheme, it is worthwhile to look for other reactions which produce gluon jets of high momentum and definite polarization in isolated regions of phase space.

We feel that one useful reaction for studying the properties of gluon jets is the production of large-mass dilepton pairs at large $p_\perp$ in $p\bar{p}$ collisions. The dominant subprocess in this reaction is $q\bar{q}\to\mu^+\mu^-g$. All hadrons produced at large $p_\perp$ opposite to the dilepton pair arise from the fragmentation of the gluon jet whose transverse momentum balances that of the dilepton pair. Since we wish to study the properties of the gluon jet we require that both the away side jet and dilepton pair be observed: Requiring that they emerge back-to-back and at an opening angle of 90° in the center-of-mass frame constrains the q and $\bar{q}$ momenta to be equal and opposite in that frame:

$$\frac{d\sigma}{dM_{\mu\mu}{}^2(d^3p_J/E_J)(d^3p_\mu/E_\mu)}\bigg|_{90°}\sim\frac{4\pi\alpha^2}{9}\sum_i e_i{}^2F_{q_i/p}(x)F_{\bar{q}_i/\bar{p}}(x)\,\frac{E}{d^3p_\mu}\,\frac{d\sigma}{dM_{\mu\mu}{}^2}(q\bar{q}\to\mu^+\mu^-g)\bigg|_{\hat{s}=x^2s,\,\hat{t}=xt,\,\hat{u}=xu}, \tag{2}$$

with $\hat{t}=\hat{u}=-(\hat{s}-M^2)/2$ and $x=2p_{\rm jet}/\sqrt{s}$.

By the measurement of the momentum of the virtual photon and the direction of the recoil jet, the kinematics of the scattering process are completely fixed (neglecting the primordial transverse momentum of the initial partons, whose effect is small in correlations). We define the momentum of the virtual photon $Q=(\omega,0,0,q)$ and the quark and antiquark momenta $p_q=E+p$ and $p_{\bar{q}}=E-p$, where $E=(p,0,0,0)$ and $p=(0,p,0,0)$. As independent variables we choose $\hat{s}=4p^2$ and $M^2=\omega^2-q^2$.

We would like to use the angular orientation of the dilepton pair to "tune" the gluon's polarization. To do this we define the muon momenta $\mu^+=Q/2+k$, $\mu^-=Q/2-k$. The initial reaction $q\bar{q}\to\gamma^*g$ takes place in the $(\vec{p},\vec{q})$ plane. The reaction $q\bar{q}\to\mu^+\mu^-g$ shows a correlation between $\vec{\epsilon}$, the polarization of the gluon jet, and k:

$$M^4\frac{E_\mu}{d^3P_\mu}\,\frac{d\sigma}{dtdM^2}\bigg|_{90°}\equiv F(\hat{s},M^2,k,\epsilon)$$
$$\sim 4(p\cdot\epsilon)^2[M^4+16(p\cdot k)^2]+(E\cdot k)^2(16M^2)+(k\cdot\epsilon)^2(\hat{s}-M^2)^2+16(\hat{s}-M^2)(k\cdot p)(p\cdot\epsilon)(k\cdot\epsilon). \tag{3}$$

Defining $\hat{n}$ as the normal to the $(\vec{p},\vec{Q})$ plane, $\hat{n}\cdot\vec{\epsilon}=\cos\theta$, and defining k via light-cone variables v, $k_\perp$, and φ, the azimuthal angle of k to the $(\vec{p},\vec{Q})$ plane,

$$k=\left((v-\tfrac{1}{2})\frac{\sqrt{\hat{s}}}{2}+\frac{k_\perp{}^2}{4\sqrt{\hat{s}}}\,\frac{1-2v}{v(1-v)},\ k_\perp\sin\varphi,\ k_\perp\cos\varphi,\ (v-\tfrac{1}{2})\frac{\sqrt{\hat{s}}}{2}-\frac{k_\perp{}^2}{4\sqrt{\hat{s}}}\,\frac{1-2v}{v(1-v)}\right),$$

Eq. (2) reduces to

$$F(s,M^2,k,\epsilon)\sim M^2\hat{s}\sin^2\theta[M^2+4\hat{s}v(1-v)\sin^2\varphi]+M^2(\hat{s}-M^2)^2[\tfrac{1}{4}-v(1-v)\sin^2(\theta-\varphi)]$$
$$-4v(1-v)\hat{s}M^2(s-M^2)\sin\varphi\sin\theta\cos(\varphi-\theta). \tag{4}$$

A strong correlation is seen between the azimuthal orientation of the dilepton pair (with respect to the $q\bar{q}g$ scattering plane and the direction of polarization of the gluon jet. For instance, at $\varphi=0$

$$F(\varphi=0)=\cos^2\theta[v(1-v)M^2(\hat{s}-M^2)^2-M^4\hat{s}]$$
$$+M^2(\hat{s}-M^2)^2[\tfrac{1}{4}-v(1-v)]+M^4\hat{s}, \tag{5a}$$

while at $\varphi=\pi/2$

$$F(\pi/2)=\sin^2\theta\{M^4\hat{s}+v(1-v)[M^2(\hat{s}-M^2)^2+4M^4\hat{s}]\}$$
$$+M^2(\hat{s}-M^2)^2[\tfrac{1}{4}-v(1-v)]. \tag{5b}$$

Particularly if $v=\frac{1}{2}$, the gluon polarization prefers to be oriented parallel to the dilepton plane when that plane is normal to or parallel to the $q\bar{q}g$ scattering plane.

The experiment will probably be straightforward to carry out. One triggers on a massive dilepton pair accompanied by an away-side jet, both at $\theta=90°$ in the c.m. frame. According to Eq. (5), the gluon jet will then be predominantly polarized either in or out of the scattering plane, depending on the azimuthal angle of the muon. If gluon polarization affects gluon fragmentation, one would expect to see an "oblate" gluon jet—production of hadrons at a transverse momentum $\vec{p}_\perp$ to the gluon jet—which will show a functional dependence on $\vec{p}\cdot\vec{\epsilon}$. With the choice of kinematics selected here, that corresponds to a correlation of $\langle p_{\rm out}\rangle$, the mean transverse momentum of hadrons in the gluon jet out of the $q\bar{q}g$ scattering plane, with the orientation of the dilepton pair. One can, for example, look for a change in $\langle p_{\text{out}}\rangle$ when one triggers on a dilepton pair lying in the $q\bar{q}g$ scattering plane versus a trigger on a dilepton pair oriented at $\varphi=\pi/2$ with respect to the scattering plane. Any observed change in $\langle p_{\text{out}}\rangle$ will be a signal for a correlation between hadron production and polarization orientation in the gluon jet.

This effect may also be seen in $p\bar{p}\to\gamma_{\text{pol}}+\text{jet}+X$, where the subprocess is $q\bar{q}\to g\gamma$, and the polarization of the gluon is correlated with that of the photon.

At $\theta=90°$ in the center-of-mass frame one finds

$$\frac{d\sigma}{d\Omega}(q\bar{q}\to\gamma g)\sim\frac{\alpha\alpha_c}{2s}[1-(\vec{\epsilon}_1\cdot\vec{\epsilon}_2)^2 +4(\vec{\epsilon}_1\cdot\vec{\epsilon}_2)(\hat{p}\cdot\vec{\epsilon}_1)(\hat{p}\cdot\vec{\epsilon}_2) -4(\hat{p}\cdot\vec{\epsilon}_1)^2(\hat{p}\cdot\vec{\epsilon}_2)^2]\,, \tag{6}$$

where $\hat{p}$ is a unit vector along the beam direction and $\epsilon_1(\epsilon_2)$ is the photon (gluon) polarization. When the photon's polarization is required to be either parallel to or perpendicular to the scattering plane, the gluon's polarization is forced to be perpendicular to that of the photon's, with $\cos^2\theta$ probability. The same trigger as the Drell-Yan case could be applied here: Look for a change in $\langle p_{\text{out}}\rangle$ in the gluon jet for different orientations of the photon's polarization. At present energies and transverse momenta, this experiment is probably prohibitively difficult.

This reaction may be considered to be the progenitor of the Drell-Yan case, since in both cases the gluon's polarization correlates with that of the photon, be it real or virtual. This correlation transfers into a preferential orientation between the plane of the lepton pair and the gluon polarization, because the polarization of the virtual photon correlates with the plane of the pair, as in Eq. (1).

Other reactions with gluons in the final state can be very good sources of polarized gluons. *All* soft gluons of momentum k emitted at small angles from a quark of momentum p are polarized in the $(\vec{k},\vec{p})$ plane simply because their matrix element is proportional to $\epsilon\cdot p/k\cdot p$. But as the gluon becomes harder and harder, it depolarizes. The fragmentation function for a polarized gluon to carry off a (light-cone) momentum fraction x from a quark is, in lowest-order perturbation theory,

$$D_{g/q}(x,\vec{k}_\perp,\epsilon)\sim\frac{k_\perp^2}{(k_\perp^2+x^2M_q^2)^2}\,\frac{x^2+4(1-x)\cos^2\varphi}{x}\,, \tag{7}$$

where $\cos\varphi=\vec{k}_\perp\cdot\vec{\epsilon}/|k_\perp|$.

So essentially all reactions which are gluon radiative corrections to quark-jet production are potential sources for polarized gluons. However, these reactions can also be more difficult to study because of the presence of quark jets in addition to gluon jets: Ambiguities associated with the misidentification of quark jets for gluon jets can only dilute possible observed effects.

For example, we have studied the reaction $e^+e^-\to q\bar{q}g$, which is presumed to be the source of multijet events seen at the upper range of PETRA ($\sqrt{s}\sim30$ GeV).[6] Here it would be interesting to observe a variation of the event shape due solely to a change in the gluon polarization by tuning the kinematic variables, thrust and/or the angle θ between the normal to the event plane and the e^+e^- axis, in analogy with μ-pair production. We find that

$$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma_\perp}{dx_1dx_2}\,d\cos\theta=\frac{\alpha_c}{4\pi(1-x_1)(1-x_2)}\left[(x_1-x_2)^2(1+\tfrac{1}{2}\sin^2\theta)+4(1-x_1)(1-x_2)(1-\tfrac{1}{2}\sin^2\theta)\right] \tag{8a}$$

and

$$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma_\parallel}{dx_1dx_2}\,d\cos\theta=\frac{\alpha_c}{4\pi(1-x_1)(1-x_2)}\left[(x_1+x_2)^2(1+\tfrac{1}{2}\sin^2\theta)-4(1-x_1)(1-x_2)(1-\tfrac{1}{2}\sin^2\theta)\right]\,, \tag{8b}$$

where $x_1=2|P_q|/\sqrt{s}$, $x_2=2|P_{\bar{q}}|/\sqrt{s}$ are the light-cone momentum fractions carried by the quark and the antiquark ($x_g=2-x_1-x_2$) and $\sigma_\parallel(\sigma_\perp)$ is the cross section for the production of a gluon polarized in (perpendicular to) the event plane. One would again imagine measuring $\langle p_{\text{out}}\rangle$ of hadrons with respect to the plane of the three jets, as one passed from one configuration to another, due to the rotation of the gluon's mean direction of polarization. For example, keeping $x_1\approx x_2\approx x_g\approx\frac{2}{3}$ and varying θ, $\sigma_\perp/\sigma_\parallel$ changes from $\frac{1}{3}$ to $\frac{1}{11}$ as θ changes from 0° to 90°, and the contribution of the gluon jet to $\langle p_{\text{out}}\rangle$ may change accordingly. Of course, as we have already remarked, the identification of quark jets versus gluon jets may prove to be a difficult task, while treating the events globally will dilute the effect.

This reaction, integrated over θ, has also recently been studied by Olsen, Ostlund, and Øverbø[5] who note that polarization is strong over a large range of the thrust variable, where the cross section is dominated by small x_g.

We conclude by summarizing. The only nonzero quantum number carried by a gluon jet which is capable of being detected is its spin. The evolution of a polarized-gluon jet into hadrons may be correlated with the degree of polarization of the gluon: In order to see it, one needs reactions which produce polarized gluons in isolated regions of phase space. A possible experimental signal is a $\langle p_{\text{out}}\rangle$ correlated with the degree of polarization of the gluon jet, whose polarization should be alterable by the experimentalist *via* his choice of kinematics or acceptances. A possible candidate for observation is the reaction $p\bar{p} \rightarrow \mu^+\mu^- +\text{jet} + X$, for which the polarization direction of the gluon is correlated with the azimuthal orientation of the dilepton. All soft gluons produced as radiative corrections to quark-jet reactions are strongly polarized in the quark-gluon scattering plane. Other reactions, such as $e^+e^- \rightarrow q\bar{q}g$, yield polarized gluons, and may be used to look for polarization effects, but the difficulties associated with differentiating quark and gluon jets might make these reactions less useful.

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[1]For a review of the present theoretical and experimental status of perturbative QCD, see, for example, the contribution of J. Ellis, in Proceedings of the 1979 International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979 (unpublished).

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