Azimuthal asymmetry in the production processes of gluonic jets

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(Submitted January 6, 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 4, 251–254 (20 February 1979)

It is shown that the azimuthal asymmetry of the hadronic jets, which are formed in the decay of fast, linearly polarized gluons, is equal to zero. However, when events with a small multiplicity are selected an azimuthal correlation appears; we calculate it for the decay of the charge-parity ($^1S_0$ and $^3P_0$) states of the $Q\bar{Q}$ system, where Q is the heavy quark, for two jets with a small multiplicity.

PACS numbers: 12.40.Cc

The Yang-Mills glue, which binds the quarks in the hadrons, is a striking feature of quantum chromodynamics. The quantization of this glue leads to the appearance of new particles–gluons. A critical test of quantum chromodynamics can be performed in an experiment on the search for gluonic jets–narrow hadron beams which are produced as a result of fragmentation of fast gluons, which, like quarks, should be produced in the hard quantum chromodynamic processes. The gluonic jets are expected to occur in e^+e^- annihilation,[1] in the decay of the bound states of heavy (for example, t) quarks,[2] etc.

It would be of particular interest, therefore, to examine the predicted properties of gluonic jets. In this paper, we analyze the correlation between the polarization of the original gluon and the azimuthal distribution of hadrons in the jet. Although this problem was recently examined by Brodsky, de Grand, and Shwitters,[3] however we think that the results of this study are incorrect.

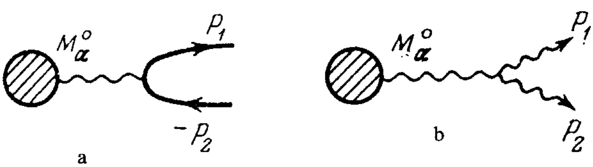

FIG. 1. Matrix elements for the decay of a polarized gluon.

Let us examine the decay of a fast gluon into a quark-antiquark pair (Fig. 1a) (only this type of decay was examined in Ref. 3) and into two gluons (Fig. 1b) (we assume that the original gluon is close to the mass surface, so that as a result of one or several such decays and a subsequent transformation of the quarks and gluons into hadrons, it goes over to the system of particles that move inside the cone with a fixed small angle–the δ jet of Sterman and Weinberg.[4]

The squares of the matrix elements in Figs. 1a and 1b have the form

$$|M|^2_{\text{Fig. 1a}} = -\frac{g^2 N_f}{2(p_1p_2)^2}[2p^1_\alpha p^1_\beta + g_{\alpha\beta}(p_1p_2)]M^\circ_\alpha M^{\circ *}_\beta, \quad (1a)$$

$$|M|^2_{\text{Fig. 1b}} = \frac{2g^2 c_V}{(p_1p_2)^2}\left[p^1_\alpha p^1_\beta - g_{\alpha\beta}(p_1p_2)\left(\frac{p^1_o}{p^2_o} + \frac{p^2_o}{p^1_q}\right)\right] M^\circ_\alpha M^{\circ *}_\beta , \quad (1b)$$

where N_f is the number of quarks and c_V coincides with the number of colors. In deriving Eq. (1b), we chose the density matrix of the outgoing gluons in three-dimensional transverse form: $\rho_{ij}(p) = \delta_{ij} - p_i p_j/p_0^2$.

The azimuthal asymmetry is represented by the terms proportional to $p^1_\alpha p^1_\beta$ in Eq. (1). It can be seen that if only the light quarks ($N_f = 3$) are taken into account, then these terms cancel out in Eqs. (1a) and (1b) (taking into account 1/2! from the phase volume of the gluons). The different signs in front of N_f and c_V resemble the different signs in front of N_f and c_V in the Gell-Mann–Low quantum chromodynamic function

$$\beta(a_s) = -\frac{a_s}{4\pi}\left(\frac{11c_V}{3} - \frac{2N_f}{3}\right) .$$

This may not be a simple coincidence. Since this structure is taken into account in the coefficient $\sim \ln\delta$ in the generalized Sterman-Weinberg equation for the production cross section of gluonic jets, which was derived from Eq. (1) after integration over the phase volume.[5]

Thus, we can see that the azimuthal asymmetry disappears completely if only the light quarks are taken into account; if we do not take into account the possiblilty of decay of a gluon into a pair of "charming" quarks, then the azimuthal asymmetry will appear, though it will be very small.

Let us illustrate this fact. We calculate the integral $\int |M|^2 p_\perp\, dV$ phase, where $p_\perp$ is the modulus for projection of the momentum of the decay product on the perpendicular plane to the direction of the momentum of the decaying gluon, and the integration is carried out over the polar angle θ in the region $0 \leqslant \theta \leqslant \delta \ll 1$ at a fixed azimuthal angle ϕ:

$$W(\phi) = \int [|M|^2_{q\bar{q}} + |M|^2_{2\gamma_s}] p_\perp dV_{\text{phase}} \sim \int_0^1 dx$$

$$\times \left\{ N_f\left(\frac{1}{2} - 2x(1-x)\cos^2\phi\right) \right. \quad (2)$$

$$\left. + c_V\left[2x(1-x)\cos^2\phi + \frac{x}{1-x} + \frac{1-x}{x}\right]\right\} x(1-x),$$

where x is a fraction of the energy of one of the particles to which the linearly polarized gluon decays.

The quantity (2) was obtained by the folowing experimental procedure: we chose a direction in the perpendicular plane to the axis of the gluonic jet, along which the sum of the projection moduli of the transverse momentum of the particles $T_\perp = \Sigma_i |\mathbf{p}_{i\perp} \mathbf{n}_\phi|$[1)] is maximum; we determined the angle ϕ between this direction and the polarization vector of the gluon (Fig. 2) and established a dependence between the number of events and the angle ϕ; moreover, each event was assigned the weight $T_\perp$. The integral over x in Eq. (2) is changed to a convergent integral by multiplying it by $p_\perp$. Thus we obtain

$$W(\phi) = 1 - 4\frac{N_f - c_V}{5(N_f + 8c_V)} \quad . \tag{3}$$

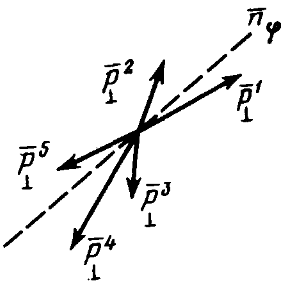

FIG. 2. Projection of the gluonic jet on the perpendicular plane.

Even for $N_f = 5 W(\phi) \approx 1 - 0.05 \cos^2\phi$, which is too small for experimental observation. Such small asymmetry is attributed mainly to the large azimuthal-symmetric "log-log" contribution from $|M|^2_{2\gamma_s}$. The contribution from the diagram in Fig. 1a, however, can be enhanced compared with that in Fig. 1b by specially selecting the events with small multiplicity,[2)] since the multiplicity in the gluonic jet should be approximately a factor of 2 larger than that in the quark jet.[8] Let us examine the azimuthal correlation of the planes of separation of the jets with a small multiplicity for the decay of the charge-parity bound states of the heavy quarks along the channel $(Q\bar{Q}) \to 2\gamma_s \to 2(q\bar{q})$. A simple calculation yields

$$B_{{}^1S_0}(\phi) = 1 + \frac{2}{3}\sin^2\phi, \tag{4a}$$

$$B_{{}^3P_0}(\phi) = 1 + \frac{2}{3}\cos^2\phi \tag{4b}$$

respectively, for ${}^1S_0$ and ${}^3P_0$ states. Equation (4a) can be obtained from the expression describing the decay $\pi^0 \to e^+e^-e^+e^-$ by a limiting transition to small scattering angles.[9] The expression for $B_{{}^1S_0}(\phi)$ in Ref. 3 is incorrect; the error is attributable to multiplying the squares of its parts rather than squaring the entire amplitude. This rather typical error indicates that the concept of the "oblate gluonic jet" is unsuitable. It is much better to imagine two quark jets or two gluonic jets with a small scattering angle, so that a general fan-shaped structure can be observed instead of two individual cones.

We thank L.B. Okun' for his interest in this work and for the useful discussion.

[1)]This quantity is analogous to that introduced in the two-jet e^+e^- annihilation.[6] $T_\perp$, which is linear with respect to the momenta, is an infrared stable quantity.[7]

[2)]This remark was made by L.B. Okun'.

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