Hadronic Signature of the Three-Gluon Coupling

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It is argued that an excess of η' mesons in gluon jets may be a clear indication for the three-gluon vertex of quantum chromodynamics.

Present data[1] on scaling violations in deep-inelastic lepton-hadron scattering are not sensitive[2] to the three-gluon (3G) coupling of quantum chromodynamics (QCD). Several quantitative tests for the existence of the 3G coupling have been recently suggested.[3,4]

In this note we suggest a *qualitative* test for the existence of a 3G coupling, which might be simpler to observe experimentally than the tests previously proposed. It has been argued that isoscalar mesons possess a *constituent* gluon component;[5] notable among these is the η' which should have a dominant gluon contribution in its constituent decomposition.[6,7] Parametrizing

$$\eta' = N'(-\sin\theta'|\eta_8\rangle + \cos\theta'|\eta_1\rangle + \epsilon'|G\rangle),$$

where $|\eta_8\rangle$, $|\eta_1\rangle$, and $|G\rangle$ are octet, singlet, and gluon components, respectively, it has been found[6] that $|\epsilon'| \simeq 1.6$, i.e., the η' has a 72% probability of being a "glue ball."

Before analyzing the consequences of the above result as related to the problem of the 3G coupling, let us point out that the dominance of gluons in η' can be checked independently in heavy 1^- quarkonium decay into $\eta'\gamma$. It is well known that the large branching ratio[8] $B(J/\psi \to \eta'\gamma) = 2.5\times10^{-3}$ could be explained with a large[9] (5% to 9%) $c\bar{c}$ admixture in the η' [see Fig. 1(a)]. However, if we adopt the dominance of gluons in η' then $J/\psi \to \eta'\gamma$ proceeds through the diagram in Fig. 1(b), which is of the same order of magnitude as Fig. 1(a).[10] Since the η' is expected to contain much less $b\bar{b}$ than $c\bar{c}$, and certainly even less of higher flavors,[11] one predicts from a model such as in Fig. 1(a) that $\Upsilon \to \eta'\gamma$ (and similarly for higher 1^- quarkonium states) would be suppressed in comparison with $J/\psi \to \eta'\gamma$. However, if the η' is mainly gluons, we predict substantial $\eta'\gamma$ decays for all 1^- quarkonium states, as evident from Fig. 1(b).

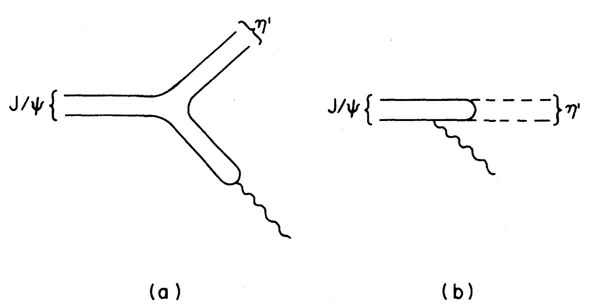

FIG. 1. (a) $J/\psi \to \eta'\gamma$ through the $c\bar{c}$ component of η'. (b) The same decay through the gluon component of η'.

Let us now assume that η' has a dominant gluon component. Since gluon jets decay mainly to gluons in a theory with a 3G coupling,[12] we expect that the fraction of η' mesons in the fragmentation products of gluon jets is larger (by a factor $\sim 1/\alpha_s$) than the fraction of other mesons, say pions. This can be clearly seen by counting the number of (hard) vertices in Fig. 2(a) as compared with (c) and (d). In contrast, the η' and π content of quark jets is of the same order as can be seen by comparing Fig. 2(e) with (f).

In a theory without a 3G coupling, the situation for quark jets is the same as before [compare again Fig. 2(e) with 2(f)], *but* gluon jets have now an equal share of η' and π as can be seen by comparing Fig. 2(b) with 2(d). As a possible signature for the presence of η' in a jet, note that about 60% of η' decays include energetic photons (25% of which result from $\eta' \to \eta\pi\pi$, $\eta \to \gamma\gamma$).

One can now conceive of the following typical experiments:

1. Assume that three jets are produced in e^+e^- collisions, of which one is a gluon jet and two are quark jets. One could then look at η'/π ratios. If $\eta'/\pi \sim 1$ in all three jets, then no 3G coupling is present; if, however, the η'/π is observed to be enhanced in one of the three jets, then this obviously signals the 3G coupling.

2. Since heavy 1^- quarkonium states decay mainly into three gluons, one could measure the η'/π ratio as it changes from ~ 1 off resonance (where two quark jets dominate) to a higher value on resonance, assuming a 3G coupling. In a theory without a 3G coupling no rise of the η'/π ratio is expected.

On the basis of counting rules[13] one expects in case of a 3G coupling that the η' mesons in the gluon jet are harder than the pions there, and

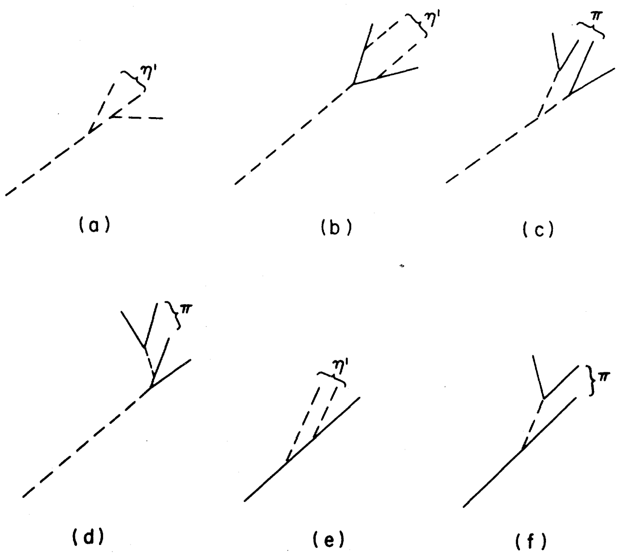

FIG. 2. η' and π production from gluon and quark jets; only lowest-order diagrams are considered. Each diagram stands for all possible crossed diagrams, e.g., (b) represents six diagrams with two gluons emitted from the same quark or from two quarks. (a) η' production from a gluon jet, in a theory with a 3G coupling. (b) As above, in a theory without a 3G coupling. (c) π production from a gluon jet, with a 3G coupling. (d) As above, in both theories. (e) η' production from a quark jet, in both theories. (f) As above, for π production.

harder than the η' in the quark jet, while in a theory with no 3G coupling all decay products have a similar momentum distribution. Therefore, to get clean signals for the effect we are looking for, it is advisable to look especially at the hard decay products for which the above-mentioned phenomenon of large η'/π ratios in gluon jets will be greatly enhanced.

Our conclusions depend heavily on the large fraction of gluons in the η'.[6,7] Therefore, failure to observe an excess of η' mesons in gluon jets may alternatively indicate the failure of this picture for the η'. However, excess of η' in gluon jets will strongly indicate both the existence of a 3G coupling *and* of constituent gluons in η'.

Models for the mixing of η and η' in the spirit of Ref. 6 have also been suggested[14] in which the large two-gluon component $\epsilon'|G\rangle$ in the wave function of η' is replaced by other 0^- meson states, by radially excited $q\bar{q}$ states with $I=Y=J=0$ and/or by daughter trajectories of η and η'. The papers by Lipkin and Cohen[15] and by Inami, Kawarabayashi, and Kitakado[16] are special realizations of the last two possibilities, respectively. Further mixing schemes departing from the standard one but not invoking a two-gluon component in the wave functions of η and η' were studied by Lipkin[17] and by Filippov.[18] Obviously in all these schemes one does not expect the gluon to fragment strongly into η or η' nor does one expect substantial $\eta'\gamma$ decays for heavier 1^- quarkonium states. Let us note, however, that in QCD the original scheme of Ref. 6 seems to be a most natural and tempting one and that our proposed experiments can surely help to test it.

Finally Fritzsch and Streng[19] pointed out that η' *and* η mesons should be preferred in the fragmentation of gluons; however, it seems[6] that η' would be much more enhanced.[6] Furthermore, the importance of the $1^- \to \eta'\gamma$ decays as a test for the gluon content of the η', and then of the η'/π ratio in gluon jets as a test of the 3G coupling of QCD are not mentioned there.

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[10]$B(J/\psi\to\eta\gamma) < B(J/\psi\to\eta'\gamma)$ in this picture since the η contains many fewer gluons than the η' (Ref. 6).

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Observation of $J/\psi(3100)$ Production by 209-GeV Muons

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Interactions of 209-GeV muons within a magnetized-steel calorimeter have produced 1000 ± 80 $\mu^+\mu^-$ pairs from $J/\psi(3100)$ decay. Redundant systems of proportional and drift chambers maintained uniform acceptance and 9% mass resolution. Above 30 GeV, the cross section for ψ production by virtual photons is found to rise less steeply with energy than predicted by a quantum chromodynamics calculation. Its dependence on Q^2 fits the vector-dominance form $(1+Q^2/M^2)^{-2}$ with $M = 2.7 \pm 0.5$ GeV.

Traditionally, photon-hadron interactions have been discussed[1] within the framework of vector-meson dominance (VMD) at low Q^2, and in terms of the constituent structure of hadrons at higher Q^2. The production of $J/\psi(3100)$ by photons,[2] if damped by a VMD propagator $(1+Q^2/m_\psi^2)^{-2}$, requires description over a range in Q^2 spanning both domains. Elements of quantum chromodynamics (QCD) have been used in calculations attempting to provide this description.[3-5]

This Letter is based on 1000 ± 80 examples of $\mu \mathrm{Fe} \to \mu\psi X$, $\psi \to \mu^+\mu^-$, the first reported observation of ψ production by spacelike photons. The events are drawn from a sample of 16 834 fully reconstructed 3μ final states produced by 209-GeV muons at Fermilab. ψ production by real photons has been observed by Knapp *et al.*,[6] Nash *et al.*,[7] Camerini *et al.*,[8] and Gittelman *et al.*[9]

The spectrometer in Fig. 1, in part described elsewhere,[10] was illuminated by 4×10^{11} beam muons. 12% of the data are reported here. The beam intensity ranged from 0.03 to 0.11 per 19-nsec rf period. For 3μ final states, the trigger demanded three or more hits in each of three consecutive trigger scintillator banks (Fig. 1). Events were vetoed by additional beam (halo) muons within 28 (10) nsec. The trigger efficiency was uniform near the ψ mass, with a threshold below ~1 GeV.

Beam tracks were momentum analyzed by two separate upstream bends. Accepted outgoing tracks, registering four or more proportional chamber hits in two views and three or more hits in the third, were required to intersect at a common vertex optimized by iteration. The result of a combined fit to the track momentum and Coulomb scattering angle in each module was used to reject background hits. The 3μ events were subjected to a one-constraint fit which conserved energy, including hadron shower energy. A Monte Carlo program modeled the spectrometer, including detector resolutions and efficiencies, and scattering and energy-loss straggling in the steel plates. Using randomly sampled beam muons, it simulated interactions with nucleons in Fermi motion, or coherently with Fe nuclei. Shadowing and minimum-momentum-transfer-squared ($|t|_{min}$) effects were included.

The mass spectrum of $\mu^+\mu^-$ pairs is exhibited in Fig. 2(a). If the two like-sign muons differed by more than a factor of 2 in energy, the unpaired muon was chosen to be the more energetic; other-