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η-η' mixing and gluons

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Experimental data on electromagnetic decays of the η' meson, combined with quark-model estimates, indicate that η' has no appreciable two-gluon component in its wave function. It is argued that this is consistent with recent data on the η/π production ratio in hadronic high-P_T inclusive processes. It is shown why previous estimates of the two-gluon component of η and η', based on application of the quark-line (Okubo-Zweig-Iizuka) rule, are unreliable for the isoscalar 0^- mesons.

I. INTRODUCTION

A popular explanation[1,2] for the departure of the isoscalar 0^- mesons η and η' from ideal mixing is that intermediate two-gluon states are responsible for strong flavor mixing in these mesons. For vector mesons at least three intermediate gluons are needed[1] and since the quark-gluon coupling α_s is small, $\alpha_s \simeq 0.2$–0.4, flavor mixing in this case is suppressed. Numerically the suppression in the vector-meson sector is larger than α_s but the qualitative trend is well accounted for by the model.

Extending this model one can conceive of a situation where the isoscalar 0^- mesons contain the two gluons not just as intermediate particles responsible for the flavor mixing but also as true constituents.[3] In fact this is needed if one wants to explain the observed η/η' production ratio in hadronic collisions of nonstrange particles with the help of the quark-line rule (QLR). Then one finds[3,4] that $\simeq 50\%$ of the η' wave function consists of either a two-gluon component or a radially excited $q\bar{q}$ state[4,5] or of a daughter trajectory of η and η'.[4,6] It was pointed out[7] that if η' indeed carries a large two-gluon component in its wave function then one expects gluon jets to fragment preferentially into η' and subsequently into η mesons. It was then suggested to look for this effect in high-energy e^+e^- experiments and to test in this way the two-gluon dominance in η' as well as the three-gluon coupling in quantum chromodynamics (QCD).

The purpose of this note is to see what evidence one can already draw on the two-gluon content of η and η' from existing data. In Sec. II we shall study the question whether the data on η'/η production rates in nonstrange hadronic collisions really imply a large two-gluon component in η' while in Sec. III we shall ask whether a large two-gluon component is compatible with existing data on the radiative decays of η'. Section IV is devoted to indirect evidence on gluon fragmentation into η' and η. In Sec. V our conclusions are finally summarized.

II. CONSEQUENCES OF THE QUARK-LINE (OZI) RULE

Writing

$$\eta = S_1(\cos\theta_1\eta_8 - \sin\theta_1\eta_0) + S_1'\xi\,,$$
$$\eta' = S_2(\sin\theta_2\eta_8 + \cos\theta_2\eta_0) + S_2'\xi\,, \quad (2.1)$$

where

$$\eta_8 = \frac{1}{\sqrt{6}}\,(u\bar{u} + d\bar{d} - 2s\bar{s})\,,$$
$$\eta_0 = \frac{1}{\sqrt{3}}\,(u\bar{u} + d\bar{d} + s\bar{s})\,, \quad (2.2)$$

one has a generalization[4] of the simple mass-mixing scheme where $S_1' = S_2' = 0$, $S_1 = S_2 = 1$, $\theta_1 = \theta_2 = \theta_P$. In the simple mass-mixing scheme one gets from the quadratic SU(3) mass formula $\theta_P = \pm(11° \pm 1°)$, while the linear SU(3) mass formula yields $\theta_P = \pm(24° \pm 1°)$ but gives no information on the sign of θ_P.

In Eq. (2.1) ξ may correspond to a two-gluon state[3,4] to a radially excited $q\bar{q}$ system[4,5] with $I = Y = J = 0$ or is related[4,6] to the η and η' daughter trajectories. The possibility of ξ being a two-gluon state is a very natural[3] and tempting one in QCD, especially in view of the popular picture of Ref. 1 for the flavor-mixing mechanism in the isoscalar sector.

We shall now turn to the study of the quark-line rule. Defining

$$Z = \frac{M(A + B \to C_1 + \cdots + C_n + (s\bar{s}))}{M(A + B \to C_1 + \cdots + C_n + (u\bar{u} + d\bar{d})/\sqrt{2}\,)}\,, \quad (2.3)$$

$$Z' = \frac{M(A + B \to C_1 + \cdots + C_n + \xi)}{M(A + B \to C_1 + \cdots + C_n + (s\bar{s}))}\,, \quad (2.4)$$

one obtains[4]

$$\frac{M(A + B \to C_1 + \cdots + C_n + \eta')}{M(A + B \to C_1 + \cdots + C_n + \eta)} = \frac{S_2[\cos(\theta_0 - \theta_2) + Z\sin(\theta_0 - \theta_2)] + S_2'Z'}{S_1[\sin(\theta_0 - \theta_1) - Z\cos(\theta_0 - \theta_1)] + S_1'Z'}\,, \quad (2.5)$$

where $\theta_0 = \tan^{-1}(1/\sqrt{2}) = 35.26°$.

Supposing now that $A, B, C_1, \ldots, C_n$ are nonstrange hadrons, then the exact quark-line rule implies $Z = Z' = 0$ and

$$k \equiv \frac{\bar{\sigma}(A+B \to C_1 + \cdots + C_n + \eta')}{\bar{\sigma}(A+B \to C_1 + \cdots + C_n + \eta)} = \left[\frac{S_2 \cos(\theta_0 - \theta_2)}{S_1 \sin(\theta_0 - \theta_1)}\right]^2, \tag{2.6}$$

where $\bar{\sigma}$ represents the cross section σ divided by the phase-space volume available in the final state. In the standard mass-mixing case one has $S_1 = S_2 = 1$ ($S_1' = S_2' = 0$) and Eq. (2.6) is reduced to the original version of Alexander *et al.*[8]

Experimentally[9] $k \simeq 0.5$ for a wide range of high-energy reactions and for $\theta_1 = -6°$, $\theta_2 = -20°$ (Refs. 4 and 6) one gets $(S_2/S_1)^2 \simeq 0.67$. Fuchs,[3] using similar mixing angles but a lower value for k, $k \simeq 0.27$—extracted from older low-energy data—derives, using Eq. (2.6), $(S_2/S_1)^2 \simeq 0.27$. Assuming $S_1 = 1$ (Ref. 3) this means $(S_2')^2 = 0.33$ or 0.73, respectively, i.e., a two-gluon component in η' of 33% or 73%. This conclusion, however, is not compelling. In fact it is even logically inconsistent, since according to the approach of Refs. 1 and 2, the mass mixing of the 0^- isoscalars is actually due to strong violations of the QLR through the two-gluon intermediate states. For the same reason a hadronically produced outgoing $u\bar{u}$ or $d\bar{d}$ line can pass over to an outgoing $s\bar{s}$ line via a two-gluon intermediate state. One, therefore, expects Z to be non-negligible for 0^--meson production. It is, therefore, perfectly consistent within the framework of Ref. 1 to assume

$$S_1 = S_2 = 1 \quad (S_1' = S_2' = 0), \quad \theta_1 = \theta_2 = \theta_P, \quad Z \not\ll 1.$$

For $\theta_P = -11°$ and $k = 0.5$ one then obtains, using Eq. (2.5), that $Z = -0.15$, while for $\theta_P = -24°$ one obtains $Z = 0.08$. These values are close to the relative magnitude of the off-diagonal terms in the corresponding mass-mixing matrices.[1,2]

It is obvious from these considerations that it is quite meaningless to draw any conclusions on S_1', S_2' from the measured ratio k as long as one does not have independent information on Z which *a priori* needs not be small for 0^- mesons. Note that in our picture of Z it is *not* expected to change randomly in phase or magnitude with varying reaction channels.[4] Since $Z \neq 0$ is assumed to originate in a mixing process taking place in a free *outgoing* $q\bar{q}$ line, it should not strongly depend on how this line has been produced.

III. ELECTROMAGNETIC DECAYS OF η'

Having failed to get clear-cut information on $S_{1,2}$ by the methods of Sec. II, it may be hoped that electromagnetic decays of η and η' are more suited for this purpose, since photons can only couple to the charged quarks in the mesons. This way the measured decay widths are directly proportional to $(S_{1,2})^2$.

The total width of η' has been measured recently[10] and is

$$\Gamma(\eta' \to \text{all}) = 0.28 \pm 0.10 \text{ MeV}. \tag{3.1}$$

Combined with the known branching ratios[11] for $\eta' \to \gamma\gamma$ and $\eta' \to \rho\gamma$ one gets

$$\Gamma(\eta' \to \gamma\gamma) = 5.4 \pm 2.1 \text{ keV} \tag{3.2}$$

and

$$\Gamma(\eta' \to \rho\gamma) = 83 \pm 30 \text{ keV}. \tag{3.3}$$

Theoretically one expects (e.g., Ref. 2 and references therein)

$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} = 18\left(\frac{m_{\eta'}}{m_{\pi^0}}\right)^3 \left(\frac{F_\pi}{F_{\eta'}}\right)^2 (S_2)^2 \times \left(\sin\theta_2 \frac{e_u^2 + e_d^2 - 2e_s^2}{\sqrt{6}} + \cos\theta_2 \frac{e_u^2 + e_d^2 + e_s^2}{\sqrt{3}}\right)^2, \tag{3.4}$$

$$\Gamma(\eta' \to \rho\gamma) = \frac{4\alpha}{3} k^3 \left(\frac{e_u - e_d}{\sqrt{2} m_{u,d}}\right)^2 \Omega^2 (S_2)^2 \sin^2\theta_2, \tag{3.5}$$

where k is the photon energy, Ω an overlap integral, and $m_{u,d} = 0.34$ GeV taken from the static magnetic moments of the baryons. Starting with $\Gamma(\eta' \to \gamma\gamma)$ one obtains[2] from (3.4) (setting $S_2 = 1$, $\theta_2 = -11°$, and $F_{\eta'} = F_\pi$), $\Gamma(\eta' \to \gamma\gamma) = 6.3$ keV in good agreement with (3.2). Taking $S_2 = 1$, $\theta_2 = -24°$ [the value from the linear SU(3) mass formula], and $F_{\eta'} = F_\pi$ one gets $\Gamma(\eta' \to \gamma\gamma) = 4.5$ keV again in agreement with (3.2). However, with $\theta_2 = -18°$ and $(S_2)^2 = 0.3$ of Ref. 3 one predicts $\Gamma(\eta' \to \gamma\gamma) = 1.6$ keV which is obviously too small. Even taking $(S_2)^2 = 0.5$ together with $\theta_2 = -18°$ gives only $\Gamma(\eta' \to \gamma\gamma) = 2.7$ keV. It seems that the large two-gluon component in η' derived from a strict ($Z = 0$) application of the QLR is incompatible with $\Gamma(\eta' \to \gamma\gamma)$.

However, since the present data are listed with 40% errors, they are not precise enough to definitely determine the gluon-bound-state component of η'. For example, with the above mentioned $\theta_2 = -11°$ and $(S_2)^2 = 0.5$, $\Gamma(\eta' \to \gamma\gamma) = 3.15$ keV, still in agreement with the measurement.

Turning now to $\Gamma(\eta' \to \rho\gamma)$ one finds[2] with $S_2 = 1$, $\theta_2 = -11°$ that $\Gamma(\eta' \to \rho\gamma) = 141$ keV. This allows for $(S_2)^2 \geq 0.6$ if $\Omega = 1$ or for $(S_2)^2 \geq 0.8$ for a typical $\Omega = 0.7$ (see Table I of Ref. 2). An $(S_2)^2$ as small as 0.3 (Ref. 3) seems, however, to be excluded. Note, however, that for $\Omega = 0.85$ and $\theta_2 = -11°$, $(S_2)^2 = 0.5$, the predicted $\eta' \to \rho\gamma$ width is 51 keV, still in agreemwnt with the experimental value of 83 ± 30 keV. It seems that a better understanding of Eqs. (3.4) and (3.5), e.g., the factor Ω or possible modifications due to QLR violations of the type discussed in Sec. II, as well as better data on $\eta' \to \rho\gamma$, $\eta' \to \gamma\gamma$ are needed before the indicated absence of a *dominant* gluon-bound-state component in η' is definitely established. Note that the modifications of Eqs. (3.4) and (3.5), due to QLR-violating effects, i.e., $u\bar{u} \to s\bar{s}$ transitions, are expected to be small due to extra factors of α_s or the appearance of $(e_s/m_s)^2$ in (3.5) while the effect of *small* QLR violation, i.e., $Z = O(\alpha_s) \neq 0$ on $(S_2/S_1)^2$ in Sec. II was non-negligible.

IV. INDIRECT EVIDENCE ON THE HADRONIC CONTENT OF GLUON JETS

Direct data on the hadronic content of gluon jets do not exist since clean gluon jets have not yet been produced. It is believed,[12] however, that gluon jets are produced in high p_T inclusive processes alongside the quark jets. Moreover, these gluon jets are believed[12] to be produced predominantly at low p_T ($p_T \simeq 2$ GeV/c), whereas for $p_T \gtrsim 10$ GeV/c quark jets are dominant. It follows that at low p_T one has an excess of gluon jets as compared to the higher p_T region. If one believes the arguments of Ref. 7, this implies that one expects a larger η/π production ratio at lower p_T than at the higher p_T region mentioned above *provided* that η' has a large two-gluon component in its wave function. This comes about since $B(\eta' \to \eta\pi\pi) = 66\%$, combined with an excessive η' production in the gluon jet according to Ref. 7, implies an enhanced η signal in the (gluon) jet.

Recent experiments[13] show, however, that the ratio of η to π production R is almost constant, i.e., $R \simeq 0.5$ over the whole range $2 \leq p_T \leq 11$ GeV/c for a wide range of energies and even for pion beam experiments. Combining this with the expectations of Ref. 12 mentioned above, this implies that the η-meson content of gluon jets is the *same* as that of quark jets contrary to the expectations of Ref. 14. According to Ref. 7, however, this means only that $S'_{1,2}$ in (2.1) are small, as was already inferred from the analysis of Sec. III.

V. CONCLUSIONS

We have seen that present data on the radiative decays of η' as well as recent data on η production in hadronic high-p_T experiments suggest that η and η' do *not* contain a large two-gluon component in their wave function.

We have further learned that a strict application of the QLR is not justified in studying isoscalar 0^--meson production. For the weakly mixed isoscalar vector mesons, however, the implications of this rule[4,5] can be better trusted.

Finally, since our conclusions rely heavily on theoretical models whose validity is not absolutely guaranteed and on rather imprecise data, it is obviously still interesting to look at the η content of gluon jets as soon as they are cleanly produced, e.g., in heavy-quarkonium decays.

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