Pseudoscalar-glueball production in $\psi \to \gamma X$, $\Upsilon \to \gamma X$, $e^+e^- \to e^+e^- X$, and $pp \to X$

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Saturation of the observed rate and spectrum of $\psi \to \gamma$ + hadrons by a 2-GeV 0^- "glueball" G, and the use of SU(3)×SU(3) Ward identities [incorporating the U(1) axial anomaly] implies the possibility of a substantial cross section (~0.5 nb) for the process $ee \to eeG$. As a consequence, the predominance of $K\bar{K}\pi$, $\eta(\eta')\pi\pi$, and/or 4π final states is expected in both these reactions. A discussion is presented of the role of G production in $\Upsilon \to \gamma$ + hadrons, and in the rise of σ_{pp}^{tot} at CERN ISR energies in the range $20 < \sqrt{s} < 50$ GeV.

Recent experiments[1,2] at SLAC have yielded data for the inclusive process $\psi \to \gamma$+ hadrons. The branching ratio $B = \Gamma(\psi \to \gamma + \text{hadrons})/\Gamma(\psi \to \text{hadrons})$, integrated over x $(\equiv 2E_\gamma/m_\psi)$ from $x=0.6$ to 1.0, is measured to be $(4.1 \pm 0.8)\%$, in reasonable agreement with quantum-chromodynamics (QCD) predictions: As calculated[3] from $(\psi \to \gamma gg)/(\psi \to ggg)$, the latter give $B \simeq 5\%$ for the same range of x. The experimental x distribution,[1] however, is in disagreement with QCD calculations: The latter predicts a peaking at large x, whereas the data[1] display a pronounced decrease in the event rate at large x, and a concomitant rise in the middle x range.

A possible explanation of this discrepancy is that the QCD process $\psi \to \gamma gg$ provides an integrated average (i.e., is dual) to the actual radiative decays $\psi \to \gamma$+ hadrons. If this were the case, it would be of interest to identify any exclusive channel in $\psi \to \gamma$+ hadrons which might provide a branching of ~5%, and which would populate the region of large missing mass ($x < 0.08$, or $m_X > 1.4$ GeV). Clearly, because of their small masses and small branching ratios, the η and η' are not relevant in this consideration.

One candidate of interest, given the basic QCD mechanism, is the hypothetical "glueball."[4] The definition of a glueball is rather vague, but generally speaking the term connotes a flavor-neutral meson whose valence structure has a large component of QCD glue. Since quarks and glue are coupled, there clearly must exist *some* $q\bar{q}$ component in any glueball. However, one expects that the density of glue in a glueball is larger than that in, say, the η'. In what follows I shall use the general characterization of a glueball just presented, in conjunction with methods developed previously[5] for the study of the glue content of the η and η' mesons, in order to obtain an estimate of the contribution of a (hypothetical) 0^- glueball to $\psi \to \gamma$+ hadrons.

In some recent publications,[5,6] the decays $\psi \to \eta(\eta')\gamma$ were conceptualized to proceed as in Fig. 1,[7] and the matrix elements were postulated to be proportional to the amplitudes A_η $(A_{\eta'})$, the glue "wave functions at the origin." The A's are defined for any pseudoscalar meson P by

$$A_p \equiv \left\langle 0 \left| \frac{g^2}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \right| P \right\rangle , \tag{1}$$

where $F^a_{\mu\nu}$ is the SU(3) color field tensor. In Ref. 5 I performed an analysis of the broken [SU(3) ×SU(3)] chiral Ward identities (WI's) (incorporating the Adler-Bell-Jackiw axial anomaly, as proposed by Crewther[8]). Together with an analysis of the 2γ decays of the π^0, η, and η', this yielded the following matrix elements of interest[9]:

$$\begin{aligned} A_{\eta'} &\simeq 0.66 F_\pi m_{\eta'}^2 (1 - 0.21\sigma) , \\ A_\eta &\simeq 0.67 F_\pi m_\eta^2 (1 - 0.096\sigma) , \end{aligned} \tag{2}$$

where σ, to be defined shortly, is nonzero if there is a QCD "surface term"[8] arising from the nontrivial topological nature of the gluon field. The ratio of $\psi \to \eta'\gamma$ to $\psi \to \eta\gamma$ was then calculated to be[5,6]

$$\frac{\Gamma(\psi \to \eta'\gamma)}{\Gamma(\psi \to \eta\gamma)} = \left(\frac{A_{\eta'}}{A_\eta}\right)^2 \left(\frac{1 - m_{\eta'}^2/m_\psi^2}{1 - m_\eta^2/m_\psi^2}\right)^3 . \tag{3}$$

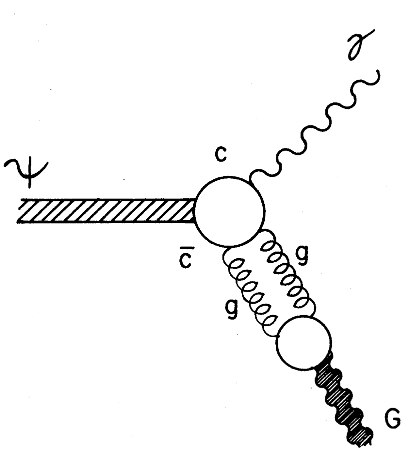

FIG. 1. Diagram illustrating final-state interaction leading to glueball production in radiative ψ decay.

The second factor on the right-hand side arises from phase-space considerations, and is assumed to represent the major energy variation of the $\psi \to \gamma + 0^-(gg)$ amplitude before final-state interaction.

The ratio on the left-hand side of the equation is not yet very well determined experimentally. In a recent experiment,[10] a ratio 5.9 ± 1.5 was obtained. In such a case, Eq. (2) inserted into (3) gives $\sigma = 0.8 \mp 0.8$.

Now, let G represent a 0^- glueball. If values of A_G and m_G were available, one would be able to extend this model to predict

$$\Gamma(\psi \to G\gamma)/\Gamma(\psi \to \eta\gamma) = (A_G/A_\eta)^2[(1 - m_G{}^2/m_\psi{}^2)/(1 - m_\eta{}^2/m_\psi{}^2)]^3 . \quad (4)$$

We have no way at present of predicting m_G. Various estimates[4] place m_G in the range 1–2 GeV, and I shall adopt 2 GeV as a working value.[11] In what follows, I present the theoretical arguments leading to a connection between A_G and F_{0G}, the coupling of G to the U(1) axial-vector quark current.

I rewrite here the two WI's [Eqs. (14) and (15) in Ref. 5] which are relevant to the discussion. Define the quark isoscalar currents

$$A_\mu^a = \bar{q}\gamma_\mu\gamma_5(\lambda^a/2)q, \quad q = (u,d,s), \quad a = 0, 8 , \quad (5)$$

$$\tilde{A}_\mu^0 = A_\mu^0 - (\tfrac{3}{2})^{1/2}K_\mu , \quad (6)$$

where $\lambda^0 = (\frac{3}{2})^{1/2}1$ and $\partial^\mu K_\mu = (g^2/16\pi^2)F_{\mu\nu}^a\tilde{F}_a^{\mu\nu}$. $\tilde{A}_\mu^0$ is the "symmetry current"[8] whose divergence is soft. Define also the matrix elements to the isoscalars $P = \eta, \eta', G, \ldots$:

$$\langle 0|\partial^\mu A_\mu^a|P\rangle \equiv F_{aP}m_P{}^2, \quad a = 0, 8 \quad (7)$$

$$\langle 0|\partial^\mu \tilde{A}_\mu^0|P\rangle \equiv \tilde{F}_{0P}m_P{}^2 , \quad (8)$$

$$\langle 0|\partial^\mu K_\mu|P\rangle \equiv A_P . \quad (9)$$

From (6)–(9)

$$A_P = (\tfrac{2}{3})^{1/2}(F_{0P} - \tilde{F}_{0P})m_P{}^2 . \quad (10)$$

The relevant WI's read[5]

$$\sum_P F_{8P}(F_{8P} + \sqrt{2}\,\tilde{F}_{0P})m_P{}^2 = (F_\pi m_\pi)^2 , \quad (11)$$

$$\sum_P (F_{8P} + \sqrt{2}\,\tilde{F}_{0P})^2 m_P{}^2 = 3[(F_\pi m_\pi)^2 + \bar{S}] , \quad (12)$$

where $\bar{S} \equiv -i(\frac{2}{3})^{1/2}\int d^4x\, \partial^\mu\langle TK_\mu(x)\partial^\mu\tilde{A}_\mu^0(0)\rangle_{\text{vac}}$ is a possible surface term arising from the nontrivial vacuum topology of QCD. In Ref. 5 P ran over η and η'. An analysis of the 2γ decays was performed, and it was deduced that $F_{8\eta} = F_{0\eta'} = 1.1F_\pi$, $F_{8\eta'} = -F_{0\eta} = 0.17F_\pi$ provided a reasonable fit to the data. When inserted into Eqs. (11) and (12), and use is made of (10), we find the results (1), with $\sigma \equiv [1 + \bar{S}/(F_\pi m_\pi)^2]^{1/2} - 1$.

Now, let us suppose that there is, in addition to the η and η', an additional heavy isoscalar G, with $m_G \sim 2$ GeV. The characterization of G as a glueball implies $F_{8G} = 0$, and hence only Eq. (12) is affected by G. Let us assume, in addition, that $3\bar{S} \ll F_\pi{}^2 m_G{}^2$ [which is certainly true if our model for $\psi \to (\eta, \eta')\gamma$ is valid]. In that case Eq. (12) necessitates $(F_{8G} + \sqrt{2}\,\tilde{F}_{0G})^2 \ll F_\pi{}^2$, or, since $F_{8G} = 0$, $\tilde{F}_{0G} \simeq 0$. From Eq. (10) we then obtain

$$A_G \simeq (\tfrac{2}{3})^{1/2}F_{0G}m_G{}^2 . \quad (13)$$

From (1), (4), and (13), and with $\Gamma(\psi \to \eta\gamma) \simeq 1.2 \times 10^{-3}\Gamma(\psi \to \text{hadrons})$,[12] we obtain

$$\Gamma(\psi \to G\gamma)/\Gamma(\psi \to \text{hadrons}) = 7.0\% \times (F_{0G}/F_\pi)^2(1 - 0.096\sigma)^{-2} . \quad (14)$$

If we take $\bar{S} = 4(F_\pi m_\pi)^2$ ($\sigma = 1.24$), which gives [via Eq. (3)] $\Gamma(\psi \to \eta'\gamma)/\Gamma(\psi \to \eta\gamma) \simeq 5$, we find from Eq. (14)

$$\Gamma(\psi \to G\gamma)/\Gamma(\psi \to \text{hadrons}) = 9.0\%(F_{0G}/F_\pi)^2 . \quad (15)$$

The QCD estimate for $(\psi \to \gamma X)/(\psi \to \text{hadrons})$, integrated over all x, and including effects of $\psi \to \gamma^* \to$ hadrons, is 8.3% for $\alpha_s = 0.2$.[2] In order that $\psi \to G\gamma$ *totally* saturate this result [with $\eta(\eta')\gamma$ subtracted], we assign

$$F_{0G} = 0.90F_\pi = 0.82F_{0\eta'} . \quad (16)$$

The result (16) combined with Eqs. (13) and (1) (with $\sigma = 1.24$) shows that *in view of the simultaneous fulfillment of the conditions $A_G \gg A_{\eta'}$ and $F_{0G} < F_{0\eta'}$ the designation of G as an approximate glueball is amply motivated.*

Hence I conclude that a 2-GeV 0^- glueball could very well saturate the QCD-predicted branching ratio for $\psi \to \gamma +$ hadrons, and, given its mass, roughly produce the observed x distribution. From the observed breadth of the x distribution, we expect $\Gamma_G \gtrsim 400$ MeV, making its detection as a Breit-Wigner peak rather difficult. Nevertheless, a measurement of the γ-ray energy distribution between $x = 0.4$ and $x = 0.6$, with a view toward detecting a decrease in this region, would be of great interest.

I conclude with several observations and predictions, and a summary.

(1) If indeed $\psi \to \gamma +$ hadrons is saturated with a 0^- glueball, I predict a predominance of 4π, $\eta(\eta')\pi\pi$, and/or $K\bar{K}\pi$ in the final state, and a suppression of 2π and 3π events. Quasi-two-body states include $\rho^\circ\rho^\circ$, $\delta\pi$, $A_2\pi$, and $(K^*\bar{K} + \bar{K}^*K)$.

(2) The WI's imposed a correlation between F_{0G} and A_G [Eq. (13)]. The value of F_{0G} ($\sim F_{0\eta'}$) obtained in Eq. (16) implies *that there is "normal" short-range coupling of the G to light $q\bar{q}$ pairs*, and perhaps[13] $\Gamma_{G\to 2\gamma} \approx (m_G/m_{\eta'})^3\Gamma_{\eta'\to 2\gamma} \simeq 50$ keV. For a hadronic width $\Gamma_G = 1$ GeV, I obtain $\sigma(\gamma\gamma \to G \to \text{hadrons}) = 120$ nb at $\sqrt{s_{\gamma\gamma}} = 2$ GeV. The G would

be detected as a broad enhancement in the final states mentioned in (1).

(3) The large width required for G ($\geq$400 MeV) is not implausible. For example, if the 2γ decay width ($\simeq$50 keV) estimated in the preceding paragraph were interpreted in terms of a vector-dominance model, it would imply a hadronic width

$$\Gamma(G\to 2\rho^\circ)\simeq(m_\rho{}^2/eg_\rho)^4(1-4m_\rho{}^2/m_G{}^2)^{3/2}\Gamma(G\to 2\gamma)\simeq 1.5\text{ GeV}. \qquad (17)$$

While this is not to be taken as a prediction, it does lend credence to a large width for the G.

(4) In a more speculative direction, a glueball width $\Gamma_{G\to 2g}\simeq 1$ GeV inserted into a standard Drell-Yan calculation[14] gives a cross section $\sigma_{pp\to G+\text{anything}}\simeq 1.2$ mb at $\sqrt{s}=50$ GeV, with an effective threshold at $\sqrt{s}=20$ GeV. Can glueball production constitute a sizable portion of the rise of $\sigma_{pp}^{\text{total}}$ at CERN ISR energies above 20 GeV?

(5) With the set of parameters obtained, some speculation may be made concerning the radiative decays of the Υ(9.5 GeV). For instance, suppose that $\Upsilon\to\gamma+$hadrons is again saturated by our 2-GeV 0^- glueball. Because the charge of the b quark is $-\frac{1}{3}$, we expect

$$\Gamma(\Upsilon\to G\gamma)/\Gamma(\Upsilon\to\text{hadrons})\simeq\Gamma(\Upsilon\to gg\gamma)/\Gamma(ggg)\simeq 0.02. \qquad (18)$$

From equations similar to (4) and through the use of Eqs. (1), (13), and (16) (with $\sigma=1.24$) we find

$$\Gamma(\Upsilon\to\eta\gamma)/\Gamma(\Upsilon\to\text{hadrons})\simeq 6\times 10^{-5} \qquad (19)$$

and

$$\Gamma(\Upsilon\to\eta'\gamma)/\Gamma(\Upsilon\to\text{hadrons})\simeq 3\times 10^{-4}. \qquad (20)$$

The peak due to the 2-GeV glueball will occur at $x=0.96$, and, depending on the total width of the G, the γ-ray spectrum in $\Upsilon\to\gamma X$ could well resemble that predicted by the QCD calculation. Of course, if more massive glueballs are present, then the analysis becomes rapidly more complex.

To summarize: We have used the broken SU(3) $\times$SU(3) Ward identities (with anomaly) to relate the gluon and quark coupling of a heavy SU(3) singlet 0^- meson G. By means of a final-state-ineraction model, we have shown that a 2-GeV 0^- glueball (in the sense $A_G\gg A_{\eta'}$) could be responsible for entirely saturating the inclusive radiative decay $\psi\to\gamma X$ predicted by QCD, as well as displaying the seeming peaking of the decay spectrum near $x=0.6$. In order for this to be so, we must have $F_{0G}\sim F_\pi$, and hence a substantial two-photon cross section for $e^+e^-\to e^+e^-G$ is predicted. Finally, speculations were made concerning the role of G in radiative γ decay and in pp scattering at high energies.

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[11]This value of m_G will produce the seeming rise of the observed x distribution at $x=0.6$ (Ref. 1). A 2-GeV glueball has previously been proposed, and its role in ψ decay stressed by K. Ishikawa, Phys. Rev. D 20, 731 (1979); 20, 2903 (1979); Report No. UCLA/80/TEP/6 (unpublished). The author would like to thank Dr. Ishikawa for bringing these works to his attention, and regrets their omission from the references in the original report version of this work.

[12]Comparison with $\eta\gamma$ (rather than $\eta'\gamma$) is preferable for at least two reasons: (a) Experimental data on the branching ratio $(\psi\to\eta\gamma)/(\psi\to\text{all})$ seem to be settling down to a consistent value of $\sim1.0\times10^{-3}$; (b) A_η is sensitive than $A_{\eta'}$ to the surface term τ [see Eq. (1)]. We have used a value of 1.2×10^{-3} for $\Gamma(\psi\to\eta\gamma)/\Gamma(\psi$

$\rightarrow$ hadrons), corresponding to $\Gamma(\psi \rightarrow \eta\gamma)/(\psi \rightarrow \text{all}) \cong 10^{-3}$.

[13]I have not yet carried out a consistent analysis of the $(\eta, \eta', G) \rightarrow 2\gamma$ amplitudes, which would involve a study of the simultaneous interpolating equations $\partial^\mu A_\mu^0 = \sum F_{0P} m_P^2 \phi_P +$ em anomaly, $\partial^\mu A_\mu^8 = \sum F_{8P} m_P^2 \phi_P$ + em anomaly, and $\partial^\mu K_\mu = \sum A_P \phi_P$. Very delicate sum rules on the 2γ decay amplitudes result, and the "state of the art" does not justify taking these seriously. In the absence of such an analysis, the estimate for $\Gamma(G \rightarrow 2\gamma)$ stated in the text is probably to be taken as an upper limit.

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