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Gluonic mesons in J/ψ radiative decay

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Abstract. Two–gluon coupling of gluonic mesons is estimated in a spectator model to be considerably larger than that of $Q\bar{Q}$. As an example of a gluonic meson that may be produced in J/ψ radiative decay, we analyse $\eta(1760)$. We deduce from experimental data that its branching ratio to two gluons is bounded, $0.4 \pm 0.3 \lesssim BR(\eta(1760) \to gg) \lesssim 0.9 \pm 0.3$, consistent with a gluonic meson, but not compelling it. We propose further tests, and estimate the two–photon coupling of $\eta(1760)$ to be 1.4 ± 0.7 keV.

We cannot be content whilst the strong dynamics of gluonic degrees of freedom remain an area of substantial ignorance. The existence of glueballs and hybrids (mesons with explicit gluonic excitation) remains unconfirmed. J/ψ radiative decay has yielded glueball candidates $f_0(1500)$, $f_J(1710)$, $f_J(2220)$ [1] and would *a priori* serve as an ideal isoscalar gluonic meson production mechanism. It is tempting to restrict analysis of the branching ratio of a resonance R into two gluons to the expected extremes of the allowed range, i.e. to glueballs where $BR(R \to gg) \sim 0.5 - 1$ or to quarkonia where $BR(R \to gg) \sim O(\alpha_S^2) \approx 0.1 - 0.2$ [2]. It is, however, imperative to consider the possibility of hybrid admixture. This is especially true in the pseudoscalar sector where both states in $\eta(1440)$ possess $BR(\eta(1440) \to gg) = 0.5 - 1$ [2,3], not compatible with pure $Q\bar{Q}$. We are thus motivated to determine the two–gluon coupling of hybrids. This is done in a model calculation which constitutes the first attempt in the literature to estimate two–gluon coupling of hybrids quantitatively.

Theoretical estimates for the two–gluon coupling of both hybrids and $Q\bar{Q}$ are made, which indicate that hybrid coupling is substantially larger than that of $Q\bar{Q}$, consistent with expectations. This underlines the importance of taking account of the possibility of hybrid production in J/ψ radiative decay. In addition to $\eta(1440)$, the state $\eta(1760)$ has also been reported in J/ψ radiative decay. Since hybrids are expected at $\approx 1.8 - 1.9$ GeV [4], we study the example of $\eta(1760)$ in more detail to accertain whether it exhibits hybrid character. Firstly, we investigate its radiative production in J/ψ decay, and show how this can be used to obtain a lower bound on the two–gluon coupling of $\eta(1760)$. The bound is consistent with a gluonic admixture in the state, but does not require it. We then show that a sensible and constrictive upper bound on the two–gluon coupling of $\eta(1760)$ can be obtained from Υ radiative decay, corroborating the validity of the methods used. The expectation that there should be an isoscalar analogue of the hybrid candidate $\pi(1800)$ also indicates that there may be gluonic admixture in $\eta(1760)$. Moreover, we then expect hybrid as opposed to glueball admixture. Given that we are still not able to definitively pinpoint whether $\eta(1760)$ has substantial hybrid admixture we propose further tests. We show how the two–photon coupling of $\eta(1760)$ can be used in conjunction with its two–gluon coupling to establish whether $\eta(1760)$ is dominantly gluonic or $Q\bar{Q}$. The two–photon coupling is estimated using vector meson dominance, showing that detection is a realistic prospect.

We start with the theoretical estimation of the width $\Gamma(R \to gg)$, where R is a hybrid. The production of a hybrid is calculated assuming that one of the gluons radiated in $J/\psi \to \gamma R$ acts as a spectator.

The physical picture for $\Gamma(R \to gg)$ is as follows. For a hybrid meson which possesses an excited gluonic degree of freedom, the quark and antiquark reside in a colour–octet state instead of a colour singlet state as for regular mesons. For convenience, we evaluate $\Gamma(R \to gg)$ in the valence–gluon picture [5]. In this description, the colour state of the hybrid can be written as $|\bar{Q}_i \lambda^a_{ij} Q_j A^a >$ where we suppress other quantum numbers such as spin.

The interaction for $R(\bar{Q}Qg) \to gg$ can be depicted as an annihilation of $Q\bar{Q}$ into a gluon with the valence gluon acting as a spectator. This picture is similar to semileptonic and non–leptonic decays of mesons, which are discussed in [6]. In meson decays, a quark (antiquark) undergoes a weak transition, while another antiquark (quark) maintains its identity unchanged as a spectator, although

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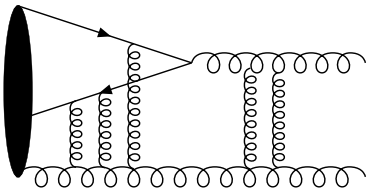

Fig. 1. Non–perturbative interactions of $O(1)$ in the spectator model

it was in the parent meson and later transits to the daughter meson. Although its kinematic states in the parent and daughter mesons are very different, it is believed that a non–perturbative QCD effect of order unity can make them match. In our case, the valence gluon is a spectator while the $Q\bar{Q}$ turn into an off–shell gluon. The quark diagram is shown in Figure 1. Both the gluon coming from the $Q\bar{Q}$ and the spectator gluon are off–shell. The two off–shell gluons can exchange many soft gluons via non–perturbative QCD interactions and finally turn into two free gluons emerging as the final colour–singlet state. This non–perturbative effect provides a factor whose precise evaluation is beyond our present ability, but as argued elsewhere [6], must be of order unity. We take the factor $O(1)$ to be 1 in our numerical calculations.

Now we need to evaluate the subprocess pertaining to the annihilation of $(Q\bar{Q})^a \to g^a$. It is well known that e^+e^- annihilation into a final state F can be realized via an off–shell photon γ^* as

$$\sigma(e^+e^- \to F) = \frac{4\pi\alpha}{s^{3/2}} \Gamma(\gamma^* \to F) \tag{1}$$

where $\sqrt{s}$ is the s–channel invariant mass. For example, for $e^+e^- \to \mu^+\mu^-$, one has

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s} \tag{2}$$

where

$$\Gamma(\gamma^* \to \mu^+\mu^-) = \frac{\sqrt{s}}{3}\alpha \tag{3}$$

is the decay width of an off–shell virtual photon into a $\mu^+\mu^-$ pair. The expression neglects the muon mass.

Since the $Q\bar{Q}$ resides in a bound state and constitutes a colour octet, a form factor is needed to reflect the binding effect. In a non–relativistic scenario [7], one can describe this as

$$\begin{aligned} &< 0|J|Q\bar{Q} > \\ &\quad \propto \int d^3p_1 d^3p_2 \psi(\mathbf{p}_1 - \frac{1}{2}\mathbf{p}_c, \mathbf{p}_2 - \frac{1}{2}\mathbf{p}_c)\delta(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_c) \\ &\quad = (2\pi)^3 \psi(\mathbf{r}_1 = 0, \mathbf{r}_2 = 0) \end{aligned} \tag{4}$$

which is just the wave function at the origin. Here $\mathbf{p}_1$ is the 3–momentum of the quark, and $\mathbf{p}_c$ the centre of mass momentum of the $Q\bar{Q}$ system.

In a close analogy, considering colour and other quantum numbers with a proper normalization, we obtain

$$\Gamma(0^{-+}\ Q\bar{Q}g \to gg) = \frac{16\pi(s+2m^2)\alpha_S}{s^2(s-4m^2)^{1/2}}\ \Gamma_g |\psi_H(0)|^2 \tag{5}$$

where m is the constituent quark mass of about 0.33 GeV and

$$\psi_H(0) = \frac{1}{R^{3/2}} \tag{6}$$

with R is the radius associated with the simple harmonic oscillator (S.H.O.) wave function.

If Γ_g is the decay width of the off–shell gluon, we have similarly to $\gamma^* \to \mu^+\mu^-$ that

$$\Gamma_g = \frac{4(M^2_{Q\bar{Q}} - 4m^2)^{1/2}\alpha_S}{3M^2_{Q\bar{Q}}}\ (M^2_{Q\bar{Q}} + 2m^2), \tag{7}$$

where the extra factor of 4 is due to quark colour and $M_{Q\bar{Q}}$ is the mass of the $Q\bar{Q}$ system.

If we assume that $\sqrt{s} = M_{Q\bar{Q}}$ (so that $\sqrt{s} = M_{Q\bar{Q}} = 1 - 1.5$ GeV), we have

$$\Gamma(0^{-+}\ Q\bar{Q}g \to gg) = \frac{16\pi(s+2m^2)\alpha_S}{s^2(s-4m^2)^{1/2}R^3}\ \Gamma_g \tag{8}$$

Note that $BR(0^{-+}\ Q\bar{Q}g \to gg) \sim \Gamma(0^{-+}\ Q\bar{Q}g \to gg)/\Gamma_g \sim O(\alpha_S)$ as expected for a hybrid. For $\alpha_S = 0.3 - 0.4$ and $R^2 = 10 - 12$ GeV^{-2} [5] we find $\Gamma(0^{-+}\ Q\bar{Q}g \to gg) \sim 180 \pm 110$ MeV.

It should be noted that all the expressions given above are based on relativistic field theory, except for the wave function at the origin which stands for the necessary form factor. This is almost universally assumed [2].

For conventional second radially excited S–wave (3S) meson production in the non–relativistic limit [2,3,7]

$$\Gamma(0^{-+}\ 3S\ Q\bar{Q} \to gg) = \frac{8}{3}\frac{\alpha_S^2}{M_R^2}|\Psi_{3S}(0)|^2 = 5\frac{\alpha_S^2}{M_R^2}\frac{1}{R^3} \tag{9}$$

where M_R is the mass of the resonance. For the purpose of calculation we use the naïve S.H.O. expression

$$\Psi_{3S}(0) = \sqrt{\frac{15}{8R^3}} \tag{10}$$

We obtain for the same parameters as before that $\Gamma(0^{-+}\ 3S\ Q\bar{Q} \to gg) \sim 6 \pm 2$ MeV. In addition, if we assume that the gg coupling of 3S is similar to 2S, we can obtain from $BR(\eta(1295) \to gg) \sim 0.25$ [2] that $\Gamma(0^{-+}\ 3S\ Q\bar{Q} \to gg) \sim 10$ MeV, independently supporting our estimate.

We deduce that the two–gluon coupling of a hybrid is considerably larger than that of 3S $Q\bar{Q}$, strongly discriminating between the two cases. From (11) and (13) it follows that the branching ratio of a hybrid in radiative J/ψ or Υ decay is substantial relative to that of 3S $Q\bar{Q}$.

Having established the prominent production of hybrids in J/ψ or Υ radiative decay, we proceed to analyse

the possibility that $\eta(1760)$ has substantial hybrid admixture.

Experimentally, $\eta(1760)$ has a mass of 1760 ± 11 MeV and a width of 60 ± 16 MeV, as well as $BR(J/\psi \to \gamma\eta(1760))\ BR(\eta(1760) \to \rho^0\rho^0) = (0.13 \pm 0.09) \times 10^{-3}$ [8], all derived from DM2 data [9]. Even though these results are used throughout, they are in need of confirmation. Mark III data [9] on $\eta(1760) \to \rho\rho$ have been re–analysed [1] incorporating the neglected $(\pi\pi)_S\ (\pi\pi)_S$ mode in the original analysis. The re–analysis eliminated the $J^{PC} = 0^{-+}$ resonance, indicating that improved data analysis of DM2 data is also needed, although it was admitted that the parametrization used in the re–analysis "may be patching up 0^- contributions well above 1500 MeV" [1]. It is, however, significant that $\eta(1760)$ was initially observed in the relatively clean $\omega\omega$ channel [10].

In [2,3] a formalism was presented which successfully connects the two-gluon width $\Gamma(R \to gg)$ of a pseudoscalar resonance to the radiative J/ψ branching ratio $BR(J/\psi \to \gamma R)$. Here

$$10^3 BR(J/\psi \to \gamma R) = \frac{M_R}{1.8\ GeV} \frac{\Gamma(R \to gg)}{50\ MeV} \frac{x|H_{PS}(x)|^2}{37} 1 \tag{11}$$

where $x \equiv 1 - \frac{M_R^2}{M_{J/\psi}^2}$ and the function $H_{PS}(x)$ is explicitly evaluated in [3] (17). From (11) we obtain

$$BR(\eta(1760) \to gg)\ BR(\eta(1760) \to \rho^0\rho^0) = \frac{6.6 \pm 4.6\ MeV}{60 \pm 16\ MeV} = 0.11 \pm 0.08 \tag{12}$$

To deduce the two–gluon coupling of $\eta(1760)$, its $\rho^0\rho^0$ coupling needs to be estimated. We assume naïve branching ratios for $\eta(1760) \to \rho\rho,\ \omega\omega$ which are consistent with the experimental value of $BR(J/\psi \to \gamma\rho\rho)/BR(J/\psi \to \gamma\omega\omega) = (4.5 \pm 0.8)/(1.59 \pm 0.33) \approx 3$, i.e. we take $BR(\eta(1760) \to \rho^0\rho^0) \lesssim \frac{1}{4}$. From (12) we hence deduce that $BR(\eta(1760) \to gg) \gtrsim 0.4 \pm 0.3$. Following [2] the favoured conclusion is that $\eta(1760)$ has gluonic admixture and is not pure $Q\bar{Q}$, even though the latter possibility is allowed given the size of experimental errors. If the $\eta(1760)$ is $Q\bar{Q}$, it is expected on mass grounds to be the 3S η. Such a state at 1.8 GeV decays dominantly to $\rho\rho$ with a branching ratio of approximately 40% (see Table B4 of [11]), yielding a 4π signal. It should be noted that if the state is *pure* 3S $Q\bar{Q}$, (12) implies that $BR(\eta(1760) \to gg) \gtrsim 0.8 \pm 0.6$, which weakens the hypothesis (here we used a branching ratio to $\rho^0\rho^0$ of $\frac{1}{3}$ 40%). So we expect mixing with either the predicted glueball at 2.22 ± 0.32 GeV [12] or the hybrid at $\approx 1.8 - 1.9$ GeV [4]. Although it is possible that there is significant glueball mixing given the substantial errors in the mass estimate [12], the nearness of $\eta(1760)$ to predicted hybrid masses, and the necessity of an isoscalar analogue to the hybrid candidate $\pi(1800)$ (see below), henceforth motivate us to concentrate on hybrid admixture in $\eta(1760)$.

It is also possible to obtain an upper bound [3] on $BR(\eta(1760) \to gg)$ if we assume the CUSB limit [8,13] of $BR(\Upsilon \to \gamma X) \lesssim 8 \times 10^{-5}$ for inclusive resonance production. The relevant relation, similar to (11), is [2]

$$BR(\Upsilon \to \gamma R) = \frac{4\alpha}{5\alpha_S}\left(1 - 2.6\frac{\alpha_S}{\pi}\right) \frac{M_R}{M_\Upsilon^2}\ \Gamma(R \to gg)\ \frac{x|H_{PS}(x)|^2}{8\pi(\pi^2 - 9)} \tag{13}$$

where $x \equiv 1 - \frac{M_R^2}{M_\Upsilon^2}$. Taking $\alpha_S(m_b) = 0.18$, we estimate that $BR(\eta(1760) \to gg) \lesssim 0.9 \pm 0.3$, although we note that $H_{PS}(x)$ may be unreliable for the value of x used [2]. The upper bound is sensible and constrictive, underlining the validity of the methods used, and indicating that the window for detection of $\eta(1760)$ in Υ radiative decay at a B–factory could be small.

Even if the experimental information from Mark III and DM2 [9,10] is unreliable, there is a second indicator of the gluonic admixture in $\eta(1760)$. Evidence [14] that the $\pi(1800)$ is dominantly an isovector hybrid [15] has recently emerged in diffractive π production. The state has width 212±37 MeV [8], and detailed ratios of widths for its various decay modes are known[1]. The $\pi(1800)$ has strong hybrid features, including suppressed decays to S–wave mesons [15–17], and is inconsistent with a 3S $Q\bar{Q}$ interpretation [11]. Moreover, an especially interesting feature of $\pi(1800)$ is its decay to $f_0(1500)\pi$ [14], where $f_0(1500)$ is observed in the small $\eta\eta$ decay mode. We estimate from experiment that $BR(\pi(1800) \to f_0(1500)\pi) \approx 10 \pm 6\%$ (see Footnote 1), indicating significant decay to the glueball candidate $f_0(1500)$. A new analysis [18] implies that the branching ratio can be two times larger. Amongst the dominant decay modes of $\pi(1800)$ is $f_0(980)\pi$, as well as below threshold $K_0^*(1430)K$, yielding a significant $KK\pi$ coupling [14]. We naturally expect an isoscalar analogue of $\pi(1800)$. For the isoscalar analogue, the dominant decays are expected to be to $a_0(1450)\pi$ and $a_0(980)\pi$, yielding a large $\eta\pi\pi$ and a substantial $KK\pi$ width. It is tantalizing that the $J/\psi \to \gamma a_0(980)\pi$ data in [19] appear to have resonance behaviour in the 0^{-+} wave in the region $1.8 - 1.9$ GeV with width 0.1 GeV, most notably in Fig. 7a, and that the branching ratio to $a_0(980)\pi$ appears to be similar to that of $\eta(1440)$. Moreover, Fig. 1a of [20] appears to be consistent with an excess of $K_S^0 K^\pm\pi^\mp$ events at ~ 1.9 GeV. It is hence surprising that [19,20] make no reference to structures in the $1.8 - 1.9$ GeV region. The observations are consistent with expectations for an isoscalar analogue of the $\pi(1800)$. The VES collaboration has put a limit on the K^*K signal for $\pi(1800)$ (see Footnote 1). It is imperative that the behaviour of K^*K in J/ψ radiative decay

[1] The widths of $\pi(1800)$ are assumed to be in the ratio [14, 23] 1 $(f_0(980)_{\pi^+\pi^-}\pi^-)$, 0.6 ± 0.2 $(f_0(1300)_{\pi^+\pi^-}\pi^-)$, 0.3 ± 0.1 $(K^+K^-\pi^-)$, 0.4 ± 0.1 $(a_0^-(980)_{\eta\pi^-}\eta)$, 0.12 ± 0.05 $(\eta\eta'\pi^-)$, 0.04 ± 0.02 $f_0(1500)_{\eta\eta}\pi^-$, < 0.18 $(\rho^0\pi^-)$, < 0.06 (K^*K) and 0.4 ± 0.2 $(\rho^-\omega)$. If a mode is in subscript the branching ratio to the mode has not been included. Correcting for these branching ratios [8] we estimate the width ratios 1.9 ± 0.1 $(f_0(980)\pi)$, 0.9 ± 0.3 $(f_0(1300)\pi)$, 1.0 ± 0.3 $(K_0^*(1430)K)$, 0.9 ± 0.2 $(a_0(980)\eta)$, 0.12 ± 0.05 $(\eta\eta'\pi)$, 0.6 ± 0.3 $(f_0(1500)\pi)$, < 0.36 $(\rho\pi)$, < 0.06 (K^*K) and 0.4 ± 0.2 $(\rho\omega)$

in the 1.8 GeV region [19] (Fig. 7a) be studied in more detail to accertain whether there is also weak coupling to K^*K.

The $KK\pi$ data [19,20] can be explained as arising from the presence of the isoscalar analogue of $\pi(1800)$ as a component of $\eta(1760)$. If this is indeed the case, and if the observations of $\eta(1760)$ in $\rho\rho$ and $\omega\omega$ [9,10] are reliable, we would also expect a $Q\bar{Q}$ component in $\eta(1760)$. This is because the isoscalar analogue of $\pi(1800)$ only couples weakly to $\rho\rho$ and $\omega\omega$, due to the small coupling of $\pi(1800)$ to $\rho\omega$ (see Footnote 1).

We are still not able to definitively pinpoint whether $\eta(1760)$ has substantial hybrid admixture. Improvement in experimental errors would have significant consequences here. We now propose further tests.

We compare two–gluon to two–photon coupling. For isoscalar mesons, written in flavour singlet and octet components as $\cos\theta|8\rangle + \sin\theta|1\rangle$, the ratio between the $\gamma\gamma$ and gg coupling is [2,21]

$$\frac{\Gamma(R\to\gamma\gamma)}{\Gamma(R\to gg)} = \frac{1}{4}(\frac{\alpha}{\alpha_S})^2 \frac{1}{1+\frac{8.2\alpha_S}{\pi}} \frac{\cos^2(\theta-\tau)}{\cos^2\theta} \qquad (14)$$

where $\tau \equiv \tan^{-1}\frac{1}{2\sqrt{2}} \approx 19.5^\circ$. Since this relation is only valid for $Q\bar{Q}$, and since we already have a lower bound for $\Gamma(\eta(1760)\to gg)$, we can use it to obtain a lower bound on $\Gamma(\eta(1760)\ Q\bar{Q}\to\gamma\gamma)$. Thus if experiment finds a $\gamma\gamma$ coupling below this value, the state is not pure $Q\bar{Q}$, since $Q\bar{Q}$ are expected to be strongly coupled to $\gamma\gamma$ [22]. Using the value $\alpha_S \approx 0.48\pm0.05$ obtained by fitting the above relation to the data on $f_2(1270)$ and $f_2(1525)$ [2], together with the value $\Gamma(R\to gg) \gtrsim 4\times(6.6\pm4.6)$ MeV (see (12)), we find

$$\Gamma(\eta(1760)\ Q\bar{Q}\to\gamma\gamma) \gtrsim (0.68\pm0.50)\frac{\cos^2(\theta-\beta_c)}{\cos^2\theta}\ \text{keV} \qquad (15)$$

For a state containing no strange quarks ($\theta = 35.3^\circ$) we obtain $\Gamma(\eta(1760)\ Q\bar{Q}\to\gamma\gamma) \gtrsim (0.9\pm0.7)$ keV. For the partner $s\bar{s}$ state ($\theta = -54.7^\circ$) production is suppressed: $\Gamma(\eta(1760)\ Q\bar{Q}\to\gamma\gamma) \gtrsim (0.15\pm0.11)$ keV. $Q\bar{Q}$ two–photon widths of O(keV) would generate a prominent signal in $\gamma\gamma\to4\pi$. Specifically, if the branching ratio to $\rho\rho$ is 40% as mentioned before, we have $\Gamma(\gamma\gamma\to\eta(1760)\to4\pi) \gtrsim 0.4\pm0.3$ keV. Conversely, the confirmation of $BR(J/\psi\to\gamma\eta(1760)) \gtrsim 4\times(0.13\times10^{-3})$ together with the absence of a signal in $\gamma\gamma$ at $\gtrsim 0.9$ keV could support the $\eta(1760)$ as dominantly gluonic rather than $Q\bar{Q}$.

We now explicitly evaluate $\gamma\gamma$ widths. From information on the $\rho\omega$ coupling of $\pi(1800)$ we can make an estimate of $\gamma\gamma$ coupling of $\pi(1800)$ and $\eta(1760)$ using VMD, independent on whether the state is a hybrid or $Q\bar{Q}$. We use the following VMD relation pertaining to states containing only u and d quarks, which incorporates the effects of phase–space

$$\Gamma(R\to\gamma\gamma) = (\frac{\pi\alpha}{\gamma_\rho^2})^2 \frac{\Gamma(\pi(1800)\to\rho\omega)}{8(1-4(\frac{m_{\rho\omega}}{M_R})^2)^{L+\frac{1}{2}}} (\frac{M_R}{\tilde{M}_B})^2 \times \begin{cases} 4\mathcal{R}_\omega^2 & \text{for } \frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d}) \\ (1+\mathcal{R}_\omega^2)^2 & \text{for } \frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d}) \end{cases} \qquad (16)$$

where we make the approximation that the mass of ρ and ω are the same (with $m_{\rho\omega}$ their average mass), and that the isoscalar and isovector resonances have the same mass. $\tilde{M}_B = 720$ MeV takes account of hadronic P–wave ($L=1$) phase space [17,22], $\mathcal{R}_\omega = 0.30$ [22] denotes the photon coupling of ω relative to that of ρ, and the VDM coupling is $\gamma_\rho^2/4\pi = 0.507$ [22]. We can estimate that $\Gamma(\pi(1800)\to\rho\omega) = BR(\pi(1800)\to\rho\omega)\ \Gamma_T(\pi(1800)) = 15\pm8$ MeV (see Footnote 1). From (16) we obtain $\Gamma(\pi(1800)\to\gamma\gamma) = 0.4\pm0.2$ keV and $\Gamma(\eta(1760)\to\gamma\gamma) = 1.4\pm0.7$ keV. The predicted $\gamma\gamma$ coupling of $\eta(1760)$ is sizable, making its detection in the $KK\pi$ and $\eta\pi\pi$ channels a realistic prospect. If these expectations are correct, comparison with $\Gamma(\eta(1760)\ Q\bar{Q}\to\gamma\gamma) \gtrsim 0.9\pm0.7$ keV derived above leaves the issue of the gluonic content of $\eta(1760)$ unresolved. Improvement in experimental errors should have significant consequences here.

It has been argued that $\pi(1800)$ can influence $p\bar{p}$ annihilation data [23] and enhance CP violating modes in Cabibbo suppressed D^0 decays [24] due to mixing with $p\bar{p}$ and D which both have similar mass. Clearly the $\eta(1760)$ will have similar effects. Especially interesting here are the $\eta\pi\pi$ and 4π channels which cannot result from mixing with $\pi(1800)$. Also interesting is that $D^0\to(K^0K^-\pi^+)_S$ and $(\bar{K}^0K^+\pi^-)_S$ are superficially different [8], though with large errors, possibly indicating CP violation.

The experimental data on 0^{-+} production in radiative J/ψ decays need clarification and confirmation before strong conclusions can be drawn. This should be a high priority at a τ–charm factory or BEPC. An immediate challenge for experimental analysis includes confirmation of a resonance in the 1.8 GeV region in $J/\psi\to\gamma\ (KK\pi,\rho\rho,\omega\omega)$. Comparison with signals in $\gamma\gamma\to4\pi$, $KK\pi,\eta\pi\pi$ should also be made at facilities like Babar, CLEO II, LEP2 and LHC.

Progress towards the resolution of the nature of $\eta(1760)$ can be made by using the techniques presented.

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References

1. D.V. Bugg et al. (Crystal Barrel Collab.), Phys. Lett. **B353** (1995) 378
2. F.E. Close, G.R. Farrar, Z.-P. Li, Phys. Rev. **D55** (1997) 5749
3. M.B. Çakir, G.R. Farrar, Phys. Rev. **D50** (1994) 3268
4. T. Barnes, F.E. Close, E.S. Swanson, Phys. Rev. **D52** (1995) 5242
5. A. Le Yaouanc et al., Z. Phys. **C28** (1985) 309
6. M. Bauer, B. Stech and M. Wirbel, Z. Phys. **C34** (1987) 103; D. Fakrov and B. Stech, Nucl. Phys. **B133** (1978)

315; M. Bauer and B. Stech, Phys. Lett. **B152** (1985) 380
7. A. Le Yaouanc, L. Oliver, O. Pène, J.-C. Raynal, "Hadron Transitions in the Quark Model" (Gordon and Breach, New York London Paris, 1988), pp. 66, 77; ibid. Phys. Rev. **D8** (1979) 2223
8. Particle Data Group, Phys. Rev. **D54** (1996) 1
9. D. Bisello et al. (DM2 Collab.), Phys. Rev. **D39** (1989) 701; R.M. Baltrusaitis et al. (Mark III Collab.), Phys. Rev. **D33** (1986) 1222
10. D. Bisello et al. (DM2 Collab.), Phys. Lett. **B192** (1987) 239; R.M. Baltrusaitis et al. (Mark III Collab.), Phys. Rev. Lett. **55** (1985) 1723
11. T. Barnes, F.E. Close, P.R. Page, E.S. Swanson, Phys. Rev. **D55** (1997) 4157
12. F.E. Close, M. Teper, unpublished. Earlier, 2156 ± 270 MeV appeared in OUTP-96-35P, RAL-96-040
13. P.M. Tuts, Proc. of ICHEP88 (Munich, 1988), eds. K. Kosthauss et al. (Springer, Berlin), paper 723
14. D.V. Amelin et al. (VES Collaboration), Phys. Lett. **B356** (1995) 595; ibid. Jad. Fiz. **59** (1996) 1021; D.I. Ryabchikov, Proc. of HADRON'95, eds. M.C. Birse et al.; A.M. Zaitsev, Proc. of 27^{th} ICHEP (1994), p. 1409, eds. P. Bussey et al.; ibid. Proc. of 28^{th} ICHEP (1996)
15. P.R. Page, Proc. of PANIC'96, ed. C. Carlson (1996), p. 500, hep-ph/9607476
16. P.R. Page, Phys. Lett. **B402** (1996) 183
17. F.E. Close, P.R. Page, Nucl. Phys. **B443** (1995) 233; ibid. Phys. Rev. **D52** (1995) 1706
18. A. Abele et al. (Crystal Barrel Collab.), Nucl. Phys. **A609** (1996) 562
19. J.-E. Augustin et al. (DM2 Collab.), Phys. Rev. **D46** (1992) 1951
20. Z. Bai et al., (Mark III Collab.), Phys. Rev. Lett. **65** (1990) 2507
21. W. Kwong et al., Phys. Rev. **D37** (1988) 3210
22. P.R. Page, Nucl. Phys. **B495** (1997) 268
23. A.M. Zaitsev, private communication; Proc. of NAN95 (Moscow, 1995), Jad. Fiz. **59** (1996) 1674
24. F.E. Close, H.J. Lipkin, Phys. Lett. **B372** (1996) 306