Is the $E(1420)$ in J/ψ Decay a Gluonic Bound State?

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Interpretations of the E meson (1420 MeV) in the radiative decay of the J/ψ are discussed. Information on the spin and parity assignment, and the two-photon decay rate of the E meson, will be sufficient for one to decide whether it is an ordinary quark-antiquark or a gluonic bound state.

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A clear new resonance[1] is seen in an inclusive photon spectrum and in exclusive processes such as $\gamma K\bar{K}\pi$ and $\gamma\eta\pi\pi$ of the J/ψ radiative decay in addition to the η, $\eta'(958)$, and $f(1270)$ (Table I).[2] One experiment finds $M=1.44^{+0.01}_{-0.015}$ GeV and $\Gamma=0.05^{+0.03}_{-0.02}$ GeV. The spin and parity of this state are not known. The interesting feature is a large radiative decay branching ratio into this state, larger than those into any other meson except the η'.[3] A resonance of this mass, width, and decay property has been seen in hadronic reactions, and called the $E(1420)$. Let us call the meson observed in the J/ψ decay as the E tentatively.

The quantum number of the E, although it was seen clearly in hadronic experiments, has been uncertain for several years.[4] In $\bar{p}p$ annihilation at rest, where the 1425 MeV $K\bar{K}\pi$ enhancement was originally observed, it is favored to be a 0^{-+} state and seems to have a large branching ratio into $\delta\pi$. The $D(1285)$ which is known to be a 1^{++} state was not seen there. In the $\eta\pi\pi$ channel in π^-p reactions,[5] there is an evidence for a 0^- at 1.4 GeV but no evidence for a 1^+ at 1.4 GeV.

However, in other experiments such as π^-p, K^-p, and $\bar{p}p$ annihilation in flight, one observes two peaks (the D and E) in the $K\bar{K}\pi$ mass spectrum. The E seems to have a large branching ratio[6] into $K^*\bar{K}$ and the new analysis by Dionisi *et al.*[7] gives convincing evidence that the E is a 1^{++} state. Then the 1^+ nonet is complete together with the A_1, some mixture of Q_1 and Q_2, and D.

TABLE I. Branching fractions of the radiative decay of the J/ψ to the resonances.

Mode	Branching fraction (10^{-3})
$\gamma\eta$	0.9 ± 0.4,[a] 1.2 ± 0.2,[a] 0.8 ± 0.2,[b] 1.3 ± 0.4[b]
$\gamma\eta'$	3.4 ± 0.7,[a] 6.9 ± 1.7,[a] 2.2 ± 1.7,[b] 2.4 ± 0.7[b]
γf	1.3 ± 0.3,[a] 2.0 ± 0.3,[b] 0.9 ± 0.3,[b] 1.5 ± 0.4[b]
γE	3.6 ± 1.4[a]

[a]Ref. 1. [b]Ref. 2.

Two conflicting experimental results might suggest the existence of two different mesons. In the J/ψ decay the E seems to be similar to the one seen in $\bar{p}p$ annihilation at rest from the following decay branching ratio:

$$B(E\to\delta\pi)B(\delta\to K\bar{K})/B(E\to K\bar{K}\pi)=0.8\pm0.2\,. \quad (1)$$

The E in J/ψ decay may be either a 0^{-+} or a 1^{++} state, or both, which is left open until the experiment decides. The E is known to be isoscalar. Moreover, because of the eixstence of only one state in J/ψ decay and of the narrow width this should be close to an SU(3) singlet.

Now, let us consider the possible interpretations of the E in the J/ψ decay. If the E is found to be a 1^{++} state, there seems nothing strange in assigning it to be an ordinary $q\bar{q}$ except for the large branching ratio. To see how large that branching ratio is, it is interesting to compare it with that of 2^+ isosinglet mesons, the f and f', because they have the same orbital angular momentum in a nonrelativistic quark model. The E production rate is larger than the f production rate by a factor of 2 or more. This is difficult to understand because a 1^{++} state cannot couple with two massless on-shell vector mesons.[8] An on-shell approximation for the two intermediate gluons gives a vanishing rate to the 1^{++} state, whereas there is no such suppression of the 2^{++}-state production.

If the E is found to be a 0^{-+} state, then it could be a radial excited state of the SU(3)-singlet pseudoscalar η',[9] or a gluonic bound state (GBS).[10] The radial-excited-state production with a sizable rate was pointed out by Cohen and Lipkin[11] and the GBS production was predicted by many authors.[10] It is not easy to distinguish between these two interpretations generally, but one test exists, which shall be discussed later. Before going into the details of that test, let us show that there is no problem in the GBS assignment for the E.

The large radiative decay rate from the J/ψ is easy to understand from the GBS interpretation because the GBS couples strongly with two gluons. Furthermore, a duality hypothesis[12] between resonances (GBS) and a perturbative calculation,[13] which is known to be satisfied in the electromagnetic current matrix element, encourages the idea. The total radiative decay rate into the two 0^{-+} gluons is calculated by Billoire *et al.*[14] and is equal to 0.95 keV by using 0.2 as α_s based on the perturbative calculation. The sum of the decay rates into the $\gamma\eta$, $\gamma\eta'$, and γE is equal to 0.47 $\pm$0.13 keV and the value could be larger than this value by an inclusion of the $\eta\pi\pi$ decay mode of the E. The improvement of the saturation due to the addition of the E is large so the GBS assignment seems to be reasonable.

The next point to be discussed is the decay properties, the decay final state, and the total width. The present author has exhibited[15] a decay characteristic of the 0^- GBS, K meson excess in the final state, in a previous paper. The lowest-order diagram described in Fig. 1 was investigated and the existence of a large flavor violation and an enhancement of $S\bar{S}$ quark production from helicity suppression was pointed out. The decay branching ratio to $K\bar{K}$+pions or η +pions is about 50% if we use constituent quark masses or almost 100% if we use current quark masses. Experimentally, the $K\bar{K}\pi$ and $\eta\pi\pi$ are the known decay modes,[16] and agree with the expectation based on the GBS interpretation.

The total decay width was also estimated in the same paper based on a potential model of the GBS. The value was between 50 MeV and 1 GeV with use of a naive lowest-order calculation. Because of the uncertainty of the calculation, the observed width would be consistent with the theoretical estimate.

Thus the GBS interpretation seems to have no problem in the J/ψ decay. In the inclusive hadronic reactions, a sizable production of the GBS is expected. But the cross section of the exclusive two-body reactions such as $\pi^- p \to \mathrm{GBS}\, n$ are expected to be very small because of the nonexistence of an exchanged Regge pole. In these reactions all valence quarks in one of the initial particles are transferred to the other. By writing the quark lines we see no resonances in s channel, consequently there is no Regge pole to be exchanged from the resonance-Regge duality. It would be consistent not to see any signature of the GBS in high-statistics $\pi^- p \to En$ experiments of Dionisi *et al.*[7] from this reason.

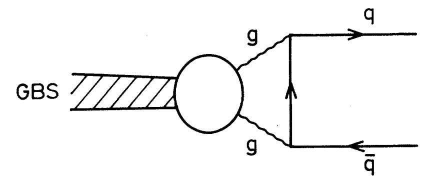

FIG. 1. The lowest-order diagram which gives a GBS decay.

Now I describe one test to distinguish the two interpretations. Hereafter I assume that the E in J/ψ decay is confirmed as a 0^{-+} state and an SU(3) singlet. We shall study two ideal cases: (1) $q\bar{q}$ and (2) a GBS for both particles of the η' and E, which give lower and upper values of $\Gamma(E\to\gamma\gamma)$. First we assume the η' and E to be an SU(3)-singlet $q\bar{q}$ resonance.

Electromagnetic and gluonic couplings of the η' and E are defined as

$$A_{\eta'(E)} = \langle 0 | F_{\mu\nu}\tilde{F}^{\mu\nu} | \eta'(E)\rangle, \qquad (2)$$
$$B_{\eta'(E)} = \langle 0 | G_{\mu\nu}{}^{a}\tilde{G}^{a;\mu\nu} | \eta'(E)\rangle,$$

where $E_{\mu\nu}$ and $G_{\mu\nu}{}^a$ are the electromagnetic and gluonic tensor, respectively. The ratio between $A_{\eta'}$ and A_E is expressed by the two-photon decay rates[17] and the ratio between $B_{\eta'}$ and B_E is expressed by the J/ψ radiative decay rates[18,19] as follows:

$$\left|\frac{A_E}{A_{\eta'}}\right|^2 = \frac{\Gamma(E\to\gamma\gamma)}{\Gamma(\eta'\to\gamma\gamma)}\left(\frac{m_E}{m_{\eta'}}\right)^5, \qquad (3)$$
$$\left|\frac{B_E}{B_{\eta'}}\right|^2 = \frac{\Gamma(J/\psi\to E\gamma)}{\Gamma(J/\psi\to\eta'\gamma)}\left(\frac{m_{J/\psi}{}^2 - m_{\eta'}{}^2}{m_{J/\psi}{}^2 - m_E{}^2}\right)^3.$$

By taking the ratios between $A_{\eta'(E)}$ and $B_{\eta'(E)}$, I consider the effect of the wave function canceled, and I have

$$\frac{A_{\eta'}}{B_{\eta'}} = \mathrm{const}\,\frac{\alpha}{\alpha_s(\eta')} \qquad (4)$$

and the same one for the E. The numerical constants are regarded as being equal in both particles. Combining Eqs. (3) and (4), I have

$$\left(\frac{\alpha_s(E)}{\alpha_s(\eta')}\right)^2 = \left(\frac{m_{J/\psi}{}^2 - m_{\eta'}{}^2}{m_{J/\psi}{}^2 - m_E{}^2}\right)^3\left(\frac{m_{\eta'}}{m_E}\right)^5 \frac{\Gamma(J/\psi\to E\gamma)\,\Gamma(\eta'\to\gamma\gamma)}{\Gamma(J/\psi\to\eta'\gamma)\,\Gamma(E\to\gamma\gamma)}. \qquad (5)$$

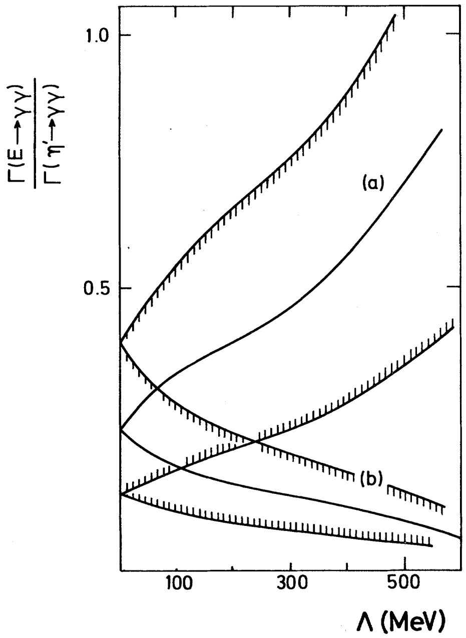

FIG. 2. The two-photon decay rate of the E for two cases. The η' and E are assumed to be: line a, an SU(3)-singlet 0^{-+} $q\bar{q}$; line b, a GBS. The most error is due to the error of $\Gamma(J/\psi \to E\gamma)$. 1.42 GeV was used for m_E.

The ratio $\alpha_s(E)/\alpha_s(\eta')$ should be smaller than 1 from both the asymptotic freedom of quantum chromodynamics and the observed better realization of ideal mixing in heavier resonances. Conversely, a small value for the right-hand side of Eq. (5), smaller than 1, would be consistent with the $q\bar{q}$ meson interpretation.

Secondly, we assume that the both are GBS. The two-photon decay of GBS occurs as a higher-order effect through a quark box; therefore, the right-hand sides of Eq. (4) should be replaced with const $\alpha\alpha_s[\eta'(E)]$, if they are GBS. Consequently the left-hand side of Eq. (5) is replaced with $[\alpha_s(\eta')/\alpha_s(E)]^2$ for this case under the assumption of the equal magnitude of the constant.[20]

Thus, the ratio for the two ideal cases $\Gamma(E \to \gamma\gamma)/\Gamma(\eta' \to \gamma\gamma)$ is calculated and given in Fig. 2 for line a the SU(3)-singlet $q\bar{q}$ assumption and for line b the GBS assumption. We use the standard form for α_s as a function of the mass together with a strong interaction scale Λ. The large error comes from mainly the large error of $\Gamma(J/\psi \to E\gamma)$. A mixing of the gluonic component to the η' in the line a enhances the ratio and a mixing of the $q\bar{q}$ component to the η' in the line b reduces it. Thus the E-meson two-photon decay rate is expected to be above the line a if the E is $q\bar{q}$, or below if the E is GBS. A use of 500 MeV and 6 keV for Λ and $\Gamma(\eta' \to \gamma\gamma)$ leads $\Gamma(E \to \gamma\gamma)$ to the following value: line a, ~3 keV; line b, ~0.4 keV.

If both the 0^- and 1^+ exist and are produced in J/ψ decay, then we are unable to obtain the simple relation like Eq. (5). However, because 1^+ does not couple with two on-shell gluons and decays with a p wave to $\delta\pi$, its contribution may be small.

As a summary, let me stress again two crucial experiments to distinguish between three possible interpretations of the E in the J/ψ decay: the spin and parity analysis and the two-photon decay observation. If the E is found to be a 1^{++} state, then it must be a $q\bar{q}$ bound state. On the other hand, if it turns out to be a 0^{-+} state and the two-photon decay rate is larger than or equal to 3 keV, it must be the radial excited state of the ordinary pseudoscalar. Finally, the existence of a small photon-decay rate, much smaller than 3 keV, would suggest strongly that the E is a GBS.

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[2] First observations were made at the Deutsches Electron-Synchrotron, see W. Bartel *et al.*, Phys. Lett. 66B, 489 (1977); W. Braunschweig *et al.*, Phys. Lett. 67B, 243 (1977); W. Bartel *et al.*, Phys. Lett. 64B, 483 (1976); G. Alexander *et al.*, Phys. Lett. 72B, 493 (1978); R. Brandelik *et al.*, Phys. Lett. 74B, 292 (1978).

[3] The number of the E production in the table comes from the $K\bar{K}\pi$ mode only. It is known that there is a peak in the $\eta\pi\pi$ channel too, but the decay rate is not known.

[4] See L. Montanet, in Proceedings of the Twentieth International Conference on High Energy Physics, Madison, Wisconsin, July 1980 (to be published), CERN Report No. CERN-EP-80-163.

[5] N. R. Stanton *et al.*, Phys. Rev. Lett. 42, 346 (1979).

[6] The ratio $B(E \to K^*\bar{K})/B(E \to K^*\bar{K} + \delta\pi) = 0.86 \pm 0.12$,

where $\delta \to K\bar{K}$ is assumed, is given by C. Dionisi *et al.*, Nucl. Phys. B169, 1 (1980).

[7]See Dionisi, Ref. 6.

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[9]Here we neglect the small mixing angles between the singlet and the octet.

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[16]From the quantum number of the E, 4π is the crucial final state. The author thanks T. Yanagida for this point.

[17]Two-photon reactions might give the decay rates [see F. Low, Phys. Rev. 120, 582 (1960)]. Reviews have been given by H. Terazawa, Rev. Mod. Phys. 45, 615 (1973); V. M. Budnev *et al.*, Phys. Rep. 15C, 181 (1975).

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[19]In order to avoid a double counting of the gluon-mediated transition, it is unnecessary to include the $c\bar{c}$ component in the η' and E.

[20]This assumption may be plausible because of the smooth behavior of the box diagram in the energy region under consideration and to the nearly equal masses of the η' and E.

Have We Seen Our First Glueball?

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Evidence is presented that there are at least two states near 1.4 GeV which decay to $\bar{K}K\pi$. One is $E(1420)$, an axial vector, and the other is $G(1440)$, probably a pseudoscalar. The pseudoscalar is likely to be a glueball.

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The discovery of gluonium states would be dramatic confirmation of quantum chromodynamics (QCD). But their identification is an extremely challenging problem, because of the usual experimental difficulties of meson spectroscopy in the likely 1–2-GeV region, compounded by our inability to predict reliably the dynamical properties which might provide useful experimental signatures.[1] Lacking a reliable, detailed understanding of the gluonium spectrum and dynamics, the experimental search can rely only on the most generic features of the theoretical picture. One such property is that gluonium states do not fit into $\bar{q}q$ multiplets. Another is that their production is enhanced in channels which are rich in gluons.

Since the radiative decays $\psi \to \gamma X$ are dominated in perturbation theory[2] by $\psi \to \gamma + 2$ gluons, they provide an excellent channel for the search. The prominent appearance of a $\bar{K}K\pi$ enhancement at 1440 MeV is therefore very striking.[3-5] It is produced at a rate comparable to the other most prominent hadron in the channel, the $\eta'(958)$. In contrast, the $E(1420)$, with which we are tempted to identify the 1440, has been an obscure, difficult state to study in hadronic reactions. This contrast provides *prima facia* grounds for examining the 1440 as a gluonium candidate.