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GLUEBALL AND EXOTIC-MESON CANDIDATES

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Michael S. Chanowitz

Lawrence Berkeley Laboratory
and
Department of Physics
University of California
Berkeley, California 94720

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Glueball and Exotic Meson Candidates

Michael S. Chanowitz

Lawrence Berkeley Laboratory, Berkeley, California 94720

Invited talk presented at the 1981 meeting of the Division of Particles and Fields of the American Physical Society, Santa Cruz, California, September 9-11, 1981.

ABSTRACT

The states seen in radiative ψ decay at 1440 and 1640 MeV are discussed. It is argued that the former is almost certainly a glueball while the latter is probably either a glueball or a four quark $\bar{s}s(\bar{u}u + \bar{d}d)$ state. The present status and future verification of these assignments is discussed.

I. THE GLUEBALL M.O.

I will discuss the two states seen in radiative ψ decays reported by Coyne in the preceding, very exciting talk.¹ We want to consider whether they might be glueballs but first we have to examine the general problem of how to recognize a glueball. What is the experimental signature? Unfortunately the first glueball will not be delivered with a bright red glueball label. In fact, I believe² (see also Refs. 3 and 4) that we may have observed, but not recognized, the first glueball more than fifteen years ago in a $\bar{p}p$ annihilation experiment at CERN.⁵ The discoveries made in radiative ψ decays during the last year^{6,7} only recently pointed clearly to this interpretation^{2,3} of the earlier CERN data.

Quantitative theoretical understanding of the glueball spectrum is not yet at the point where predictions of masses, widths, and decay modes can serve as reliable guides.⁸ Lattice calculations are most promising for the future.⁹ For my money, at present the best guide is the Bag model,¹⁰ which Donoghue will discuss,¹¹ out even this approach has serious uncertainties. For instance, the bag constant B may well be different (larger) for glueballs, glueball spin splittings are even harder to estimate because color and spin Casimir values are larger for gluons, and the spherical cavity approximation is known¹² to fail in leading order.

Since quantitative dynamical models are not yet able to provide the necessary guidance we are forced to rely on the generic, qualitative properties which a glueball must have, almost just by definition. There are two such properties, which in police detective jargon I will call the glueball M.O. (modus operandi):

- A) Glueballs containing valence gluons will be produced prominently in hard gluon channels.
- B) Glueballs do not "fit" into $q\bar{q}$ multiplets.

This glueball M.O. is almost pure tautology. Indeed B) is a tautology and A) requires only the basic notions of quantum mechanics.

Other conjectured properties of glueballs might be useful but are less reliable than the M.O. For instance glueballs may well couple more weakly to photons,³ but this issue is inextricably linked to the related questions of decay widths and mixing with $\bar{q}q$ states which are not well understood.⁸ In addition the $\gamma\gamma$ coupling of radially excited $\bar{q}q$ states may also be suppressed by a factor which we can't estimate reliably. Naively we would expect glueballs to have flavor symmetric decay modes,¹³ but, as I will discuss below, this need not be true of a pseudoscalar glueball.^{2,3} Also, Donoghue has remarked (see the discussion following his talk) that η and η' may be produced preferentially in glueball decays. In general as we depart from the M.O. the possible uncertainties and exceptions increase.

Radiative ψ decays are important here because they are a prime glueball hunting ground--by modus operandus A). In perturbation theory¹⁴

$$\Gamma(\psi \rightarrow \gamma X) = \Gamma(\psi \rightarrow \gamma gg) + O(\alpha_s^3) \quad (1)$$

where the two gluons are in a color singlet and may resonate into a glueball. Therefore any prominent new state in this channel should be examined to see if it has a plausible assignment in the $\bar{q}q$ spectrum. In the spring of 1980 the Mark II collaboration announced a large signal,⁶ seen subsequently in the Crystal Ball⁷ with a rate¹

$$B(\psi \rightarrow \gamma (\bar{K}K^-)_{1.44}) \cong 4 \cdot 10^{-3}, \quad (2)$$

and now we have word from the Crystal Ball group of a second state,¹ seen in a weaker but very clean signal,

$$B(\psi \rightarrow \gamma (\eta\eta)_{1.64}) \cong 5 \cdot 10^{-4} \quad (3)$$

In the rest of this talk I will discuss these two states. I will argue that the 1440 is almost certainly a glueball and will discuss the future results, experimental and theoretical, which would allow us to delete the word "almost" from this sentence. For the 1640 I am less certain of an assignment. I believe it could be a glueball or a four quark state,¹⁵ depending on whether $B(1640 \rightarrow \eta\eta)$ is a small or large branching ratio.

II. E(1420) AND G(1440)

Since the E(1420) decays to $\bar{K}K\pi$ it is first necessary to consider whether it could be the state seen in $\psi \rightarrow \gamma \bar{K}K^-$. (1420) was established in πp scattering as a $J^P = 1^+$ state which decays to $\bar{K}K\pi$ predominantly via K^*K .¹⁶ But $J = 1$ states are the last we would expect to find strongly produced in a two gluon channel, because of the Landau-Yang theorem. Motivated by this discrepancy and by preliminary findings¹⁷ that the $(\bar{K}K\pi)_{1440}$ signal is dominated by $\phi\pi$ rather than K^*K (now confirmed by the Crystal Ball¹), I reviewed² the experimental record on the E(1420).

The experimental picture is confusing. In πp scattering and $\bar{p}p$ annihilation in flight ($p_{\text{LAB}} \gtrsim 700$ MeV.) E(1420) is produced

together with D(1285) and with $\sigma_D \gg \sigma_E$, consistent with the interpretation of D and E as approximately ideally mixed $I = 0$ partners of the $J^P = 1^{++}$ nonet. But in $\bar{p}p$ annihilation at rest where the highest statistics "E" signal was seen there was no sign of D. In $\bar{p}p$ annihilation in flight a 50 signal for $\eta\pi\pi$ was observed in the E mass region, but in πp scattering a very sensitive experiment saw no $J^P = 1^+$ $\eta\pi\pi$ signal in the E region, though it did see the $J^P = 1^+$ $D \rightarrow \eta\pi\pi$ signal very clearly.¹⁸ The very high statistics experiment in $\bar{p}p$ annihilation which first saw the $(KK\pi)_{1420-40}$ enhancement reported⁵ a convincing spin-parity determination of $J^P = 0^-$, based on the distribution in production angle. But an equally convincing CERN pion experiment¹⁶ found $J^P = 1^+$. It is these most recent πp scattering results which have led to the designation of E(1420) as an established 1^+ state in the PDG tables.

This is all summarized in Table I, where I have outlined the conclusions that can be drawn from the most reliable of the experiments (more details and experimental references may be found in reference (2)).

TABLE I: E vs. G

	$\bar{K}K\pi$	$\eta\pi\pi$	J^P	D(1285)
πp	K^*K	No	1^+	$D \gg E$
$(\bar{p}p)_{\text{rest}}$	$(+ K^*K?)$		0^-	No
$(\bar{p}p)_{\text{flight}}$		Yes ($\delta\pi$)	$1^+/0^-$	$D \gg E$
$\pi \rightarrow \gamma X$	$\delta\pi$	Indication ($\delta\pi$)	0^-	No

The reader can find other apparent inconsistencies if he scans the table, but he will also notice that the table has a consistent interpretation if two different states are involved. One is the E(1420) of the Particle Data Group table, a $J^P = 1^+$ state which decays primarily to K^*K and is probably predominantly an ss state. E(1420) does not decay strongly to $\eta\pi\pi$ or to $\delta\pi$. The second state, which I and the MIT group¹⁰ called G(1440), is a $J^P = 0^-$ state which

decays to $\bar{K}K\pi$ and $\eta\pi\pi$ —both with substantial $\delta\pi$ components—and does not decay copiously to K^*K . The $\pi\pi$ data is dominated by the E while $\bar{p}p$ annihilation at rest and $\psi \rightarrow \gamma X$ are dominated by the G. The results for $\bar{p}p$ annihilation in flight are consistent with substantial production of E and G.

But why should only G be seen in $\bar{p}p$ annihilation at rest while G, E, and D are all produced for $p_{\text{LAB}} \geq 700$ MeV? This conclusion may seem contrived, but on further reflection it confirms the impression that we have found how the pieces of the puzzle fit together. It is in fact just what we would expect for the proposed J^{PC} assignments. Consider the reaction

$$(\bar{p}p)_{\text{rest}} \rightarrow X\pi\pi \quad (4)$$

where X is a positive charge conjugation eigenstate, $C(X) = +$. (The final state $X\pi^0$ is not allowed by J, P, and C if $C(X) = +$ and if X has abnormal spin-parity, $J^{\text{PC}} = 0^-, 1^+, \dots$.) The initial $\bar{p}p$ state may have quantum numbers $J^{\text{PC}} = 0^{++}$ or 1^{--} . For the dipion in an s-wave the initial $\bar{p}p$ state must be $J^{\text{PC}} = 0^{++}$ by C invariance and then only for $J^{\text{PC}}(X) = 0^-$ can X be in an s-wave relative to the dipion. For $J^{\text{PC}}(X) = 1^+$ either the dipion must be in (at least) a p-wave (possible for $\pi^+\pi^-$ but not for $\pi^0\pi^0$) or X must be in a p-wave relative to the s-wave dipion. In either case (and especially in the latter) there is a formidable angular momentum barrier for $\bar{p}p$ annihilation at rest into $E\pi\pi$ and $D\pi\pi$, which is no longer effective in $X\pi^+\pi^-$ for $p_{\text{LAB}} \geq 700$ MeV. In the $X\pi^0\pi^0$ channel we would expect the suppression of E and D to hold for larger values of p_{LAB} than for $X\pi^+\pi^-$.

The assignment $J^{\text{PC}}(G) = 0^-$ is also suggested by two theoretical considerations. The first^{2,10} is that the dominant partial waves for the two gluons in $\psi \rightarrow \gamma gg$ are $1^-, 0^+, 2^+$, of which only 0^- is consistent with abnormal spin-parity required by $G \rightarrow \delta\pi$. The second^{2,3} is the special preference for $\bar{K}K\pi$ decays which a pseudoscalar glueball might uniquely have, because at the quark level it would prefer annihilation to $\bar{s}s$ over $\bar{u}u$ or $\bar{d}d$ by a factor m_s/m_u in the amplitude (like $\pi \rightarrow \mu\nu$ is enhanced over $\pi \rightarrow e\nu$). The $\bar{s}s$ pairs would often hadronize to s-wave $\bar{K}K\pi$, which by final state interaction would form $\delta\pi$ some but not all of the time. Therefore, in contrast to Ref. (13), we do not expect G to decay in an SU(3) symmetric fashion nor do we require the ratio $G \rightarrow \bar{K}K\pi / G \rightarrow \eta\pi\pi$ to correspond precisely to $\delta \rightarrow \bar{K}K / \delta \rightarrow \eta\pi$ (which is not very well known in any case). Rather the first ratio should be $\geq$ the second and there may be more K mesons than predicted by SU(3) symmetry. These are special properties of a pseudoscalar glueball and are consistent with what is known experimentally.

The two state hypothesis is confirmed by the spin-parity result reported by Coyne,¹ which is entered in the table. The assignment of E(1420) to the $J^{\text{PC}} = 1^{++}$ nonet is not controversial. We turn next to the possible assignments of G(1440).

III. $G(1440)$ and $\zeta'(\?)$: IS G A GLUEBALL?

Section II was devoted to the evidence that $G(1440)$ and $E(1420)$ are different states. This section is devoted to showing that G is distinct from still another state, a pseudoscalar ζ' , which has yet to be discovered. ζ' is the name I will use for the ninth member of the radially excited pseudoscalar $\bar{q}q$ nonet. Its discovery will fill the last available slot for a $\bar{q}q$ pseudoscalar in the relevant mass range and will therefore verify *modus operandus B*) for the G . I will argue on the basis of what is already indicated experimentally that G does not have the properties of ζ' and therefore that already the most plausible assignment is for G to be a glueball.

Eight of the nine members of the radially excited pseudoscalar nonet have already been observed. They are $\pi'(1270)$, $K'(1400-1500)$, and $\zeta(1275)$.⁸ The latter, $\zeta(1275)$, is an unbaptized isoscalar named in honor of the ZGS where it was discovered in a very nice experiment¹⁸ which studied the reaction $\pi^-p \rightarrow \eta\pi^+\pi^-n$. This is the same high statistics experiment which observed no signal for $E \rightarrow \eta\pi\pi$.

Data from this experiment is shown in Figure (1). $D(1285)$ and $\zeta(1275)$ are clearly visible in the $IJ^P = 01^+ \text{ and } 00^- \delta\pi$ channels

Results of the phase shift analysis. (a)-(f) Intensities of the labeled partial waves. (g) Phase of $01^+ \delta\pi$ relative to $11^+ \delta\pi$ ($M^N = 0^\circ$). (h) Phase of $00^- \delta\pi$ relative to $00^- \epsilon\eta$. The curves are discussed in the text.

Figure 1 (from Ref. 18)

$\Gamma(\psi \rightarrow \gamma G)$ is very large but $\psi \rightarrow \gamma \zeta'$ is not seen, either in $\bar{K}K^*$ or in $\eta\pi\pi$ (as indicated by the absence of $\zeta' \rightarrow \gamma D$ in Table 1). So assuming $G = \zeta'$ the data requires

respectively. In addition there might be a small structure in the $00^- \epsilon\eta$ channel²⁰ near 1.4 GeV., which however depends crucially on the single low bin at 1280. If this bin were raised by only 2σ the structure at 1.4 would disappear. On the other hand if the dip at 1280 is a real effect, there might be a particle at 1.4 GeV. which decays to $\epsilon\eta$. I will refer to this possible particle as the "glitch" or "gl(1.4)." Notice that there is no indication of gl(1.4) in the $00^- \delta\pi$ channel. Finally the reader should be warned that the experimental acceptance drops

by roughly a factor 2 between 1.27 and 1.4 GeV.²¹

Could G be the ζ' , the missing ninth member of the nonet? Suppose for the moment that it is.

$$\Gamma(\psi \rightarrow \gamma \zeta') \gg \Gamma(\psi \rightarrow \gamma \zeta) \quad (5)$$

which in turn requires the mixing to be approximately singlet-octet²² like η' and η ,

$$\begin{aligned} \zeta' &\cong \zeta_1 \\ \zeta &\cong \zeta_8, \end{aligned} \quad (6)$$

where

$$\begin{aligned} \zeta_1 &= \frac{1}{\sqrt{3}} (\bar{u}u + \bar{d}d + \bar{s}s) \\ \zeta_8 &= \frac{1}{\sqrt{6}} (\bar{u}u + \bar{d}d + 2\bar{s}s) \end{aligned} \quad (7)$$

Next we consider the implications of singlet-octet mixing for pion scattering. Using Eqs. (6), (7) and the OIZ rule we expect²³

$$\frac{\sigma(\pi^- p \rightarrow \zeta' n)}{\sigma(\pi^- p \rightarrow \zeta n)} \cong 2 \quad (8)$$

Since $\eta\pi\pi$ is only an OIZ allowed decay for the $\bar{u}u + \bar{d}d$ components, naively we would also expect $B(\zeta' \rightarrow \eta\pi\pi)/B(\zeta \rightarrow \eta\pi\pi) \cong 2$. In fact this is probably an overestimate, because $\zeta \rightarrow \bar{K}K\pi$ is severely constrained by the available phase space. Assuming $\bar{K}K\pi$ and $\eta\pi\pi$ are the dominant modes ($\pi\pi\pi\pi$ being even more suppressed by phase space) and taking account of three body phase space, I find $B(\zeta' \rightarrow \eta\pi\pi)/B(\zeta \rightarrow \eta\pi\pi) \cong 1.1$. Then for the cross sections measured at the ZGS we expect

$$\frac{\sigma(\pi^- p \rightarrow \zeta' n \rightarrow \eta\pi\pi n)}{\sigma(\pi^- p \rightarrow \zeta n \rightarrow \eta\pi\pi n)} \cong 2 \quad (9)$$

The experimental situation appears to be quite different than Eq. (9). If $g(1.4)$ is actually $G(1440)$ (which, remember, we are assuming for the moment is ζ') then including acceptance corrections, a rough estimate for the experimental ratio is ~ 0.4 ,²¹ a factor 5 smaller than Eq. (9). In fact the discrepancy is probably much greater, since the absence of $g(1.4)$ in the $\delta\pi$ channel strongly suggests that $g(1.4)$ is not $G(1440)$. If $g(1.4)$ is not $G(1440)$ or if it is not even a real effect, then the experimental value for Eq. (9) is $\ll .4$ and the discrepancy is $\gg 5$. The conclusion is that the hypothesis $G = \zeta'$ does not allow a consistent interpretation of the data from both $\psi \rightarrow \gamma X$ and $\pi p \rightarrow \eta\pi\pi n$. $G(1440)$ is not a plausible partner for $\zeta(1275)$ in the π' nonet.

It is clearly important to reexamine the process $\pi p \rightarrow \eta\pi\pi n$ with an experiment optimized for the G mass region. It would be best to be able to detect $\eta\pi\pi$ and $\bar{K}K\pi$ in a mass range from 1.27 to 1.7 GeV. If the π' nonet is ideally mixed, as suggested by the coincidence of masses $m_{\zeta} = m_{\pi} = 1.27$ GeV., then we would expect $m_{\zeta'} = 2m_{\bar{K}} - m_{\zeta}$. For $m_{\bar{K}}$ between 1.4 and 1.5 GeV.,⁸ the ζ' would be between 1.5 and 1.7 GeV. and would decay predominantly to $\bar{K}K\pi$. Another possibility, if $g(1.4)$ is confirmed but established not to be the G , is that it is the ζ' of a non-ideal nonet.

As radial excitations it is plausible that neither ζ nor ζ' are produced very strongly in $\psi \rightarrow \gamma X$. Naively they are expected

at substantially smaller rates than the ground states η and η' . This is a second reason why $G = \zeta'$ is an implausible assignment. Assuming again that $G = \zeta'$, Eqs. (5) and (6) mean ζ' is essentially the radial excitation of η' . But we already know just from the $\bar{K}K\pi$ decay of G (compared to all decays of η') that

$$\Gamma(\psi \rightarrow \gamma G) \geq \Gamma(\psi \rightarrow \gamma \eta')$$

This is the opposite of what we expect if $G = \zeta'$, because of the smaller available phase space for G and because the radial excitation should couple more weakly to two gluons (a la the van Royen-Weisskopf model for $\bar{q}q$ meson annihilation²⁴).

This remark can be made quantitative. The rate for radiative decay of a vector quarkonium $V(\bar{Q}Q)$ to a pseudoscalar quarkonium of a different flavor $P(\bar{Q}'Q')$, $V(\bar{Q}Q) \rightarrow \gamma + P(\bar{Q}'Q')$, has been computed²⁵ in weak binding approximation. Applied to η' and its excitation ζ' the result is²⁶

$$\frac{\Gamma(\psi \rightarrow \gamma \zeta')}{\Gamma(\psi \rightarrow \gamma \eta')} = \left(\frac{k_{\zeta'}}{k_{\eta'}} \right)^3 \left(\frac{M_{\eta'}}{M_{\zeta'}} \right)^2 \frac{E_{\zeta'}}{E_{\eta'}} \cdot \left| \frac{\psi_{\zeta'}(0)}{\psi_{\eta'}(0)} \right|^2 \quad (10)$$

where K_p and E_p are the pseudoscalar momentum and energy in the rest frame and $\psi_p(0)$ is the pseudoscalar $\bar{q}q$ wave function at the origin. If $G = \zeta'$ then Eq. (10) and the experimental inequality $\Gamma(\psi \rightarrow \gamma G) \geq \Gamma(\psi \rightarrow \gamma \eta')$ together imply

$$|\psi_{\zeta'}(0)|^2 \geq 3 |\psi_{\eta'}(0)|^2 \quad (11)$$

which makes G a most unlikely candidate to be the excitation of η' .

The argument is not complete because the binding corrections may be of the same order as the essentially kinematic factors in Eq. (10). It is important to know the approximate magnitude or even just the sign of the binding corrections. It is however reassuring that Eq. (10) gives a reasonable account of the ratio $\Gamma(\psi \rightarrow \gamma \eta')/\Gamma(\psi \rightarrow \gamma \eta)$; using²⁷ $|\psi_{\eta'}(0)/\psi_{\eta}(0)|^2 = \cot^2(11^\circ)$, Eq. (10) gives 7 for the η' to η ratio.

One specific model²⁸ of ζ' and ζ might²⁹ accommodate a small ratio for $\sigma(\pi^+p \rightarrow \zeta'n)/\sigma(\pi^+p \rightarrow \zeta n)$ without assuming ζ' to be mostly $\bar{s}s$. But this model predicts too large a rate for $\Gamma(\psi \rightarrow \gamma \zeta)$ and too small a rate for $\Gamma(\psi \rightarrow \gamma \zeta')$ if $G = \zeta'$ is assumed,³⁰ and in the context of the model the SPEAR 1440 $\bar{K}K\pi$ enhancement was initially interpreted¹³ as $E(1420)$.

Although I will argue in the next section that $\theta(1640)$ might be a $\bar{q}\bar{q}qq$ state, this is an even less likely explanation for G than the hypothesis that $G = \zeta'$. Four quark states would not be produced at larger rates than normal $\bar{q}q$ states in $\psi \rightarrow \gamma X$. And a pseudoscalar $\bar{q}\bar{q}qq$ cannot be constructed from the orbital ground state, $L = 0$, but requires at least $L = 1$. Such states cannot easily be studied in the bag model because of the inadequacy⁸ of the static cavity approximation for $L > 0$. Like the $L = 0$ $\bar{q}\bar{q}qq$ states,³¹ most of these states are probably too broad to be observable as ordinary resonances.

I have argued that $G(1440)$ is a glueball because it is a good match to the glueball M.O. and, in particular, because it does not have the properties of the relevant $\bar{q}q$ meson, the ζ' . Discovery of the real ζ' would be the best verification of this argument. This means constructing a $G - \zeta'$ table, Table II, analogous to the $E - G$ table discussed in Section II.

TABLE II: ζ' vs. G

	$\bar{K}K\pi$	$\eta\pi\pi$	$\gamma\gamma/\rho\gamma$	$\zeta(1275)$	
$\bar{p}p$ (esp. at rest)	$\Gamma \sim 80 \pm 10$ $\delta\pi(+K^*K?)$				$G + \zeta'?$
πp		$c\eta?$		Yes	$\zeta'?$
$\psi \rightarrow \gamma X$	$\delta\pi$	$\delta\pi?$		No	G
Kp					

Right now most of Table II is empty and of the six entries, three are speculative. I have made (premature) guesses in the right column about the dominant states in each reaction. G and ζ' may both appear in $\bar{p}p$ annihilation because of the anomalously large width and the need for $\delta\pi$ and K^*K in the fit to the Dalitz plot.^{5,32} The other guesses are based on the preceding discussion. If ζ and ζ' are ideally mixed ζ' will be suppressed relative to ζ in πp , $\bar{p}p$ and $\gamma\gamma$ scattering but not in Kp scattering.

Premature guesses aside, the important point is that by completing Table II we can disentangle G from ζ' , including the difficult question of mixing. The success of the naive prediction for $\eta' \rightarrow \gamma\gamma$ and two estimates of $\eta' - G$ mixing³³ all suggest that $\eta' - G$ mixing is small. But $\zeta' - G$ mixing could be appreciable if $m_G - m_{\zeta'}$ is very small.

IV. $\theta(1640)$

The signal for $\psi \rightarrow \gamma(\eta\eta)$ ₁₆₄₀ is clean and convincing but is significantly smaller, by an order of magnitude, than $\Gamma(\psi \rightarrow \gamma(\bar{K}K\pi)$ ₁₄₄₀). Consequently it is not yet clear whether the

glueball M.O. A) is satisfied. If the branching ratio for $\theta \rightarrow \eta\eta$ is $\lesssim 10\%$, then $\Gamma(\psi \rightarrow \gamma\theta)$ is large, of the order of $\Gamma(\psi \rightarrow \gamma G)$, and the glueball interpretation becomes attractive. Furthermore, a statistical approach and experience with other hadrons of comparable mass, such as $\rho'(1600)$, suggests that a branching ratio much larger than 10% for a two body mode is unexpectedly large. For instance, Bjorken's estimate³⁴ for $\psi \rightarrow \gamma + \text{glueball} + \gamma\eta\eta$ is an order of magnitude smaller than the observed rate at 1640 because he assumed $\sim 1\%$ for $B(\text{glueball} \rightarrow \eta\eta)$.

Let's now suppose that $\theta \rightarrow \eta\eta$ has a large branching ratio, much larger than even 10%. Then $\Gamma(\psi \rightarrow \gamma\theta)$ is much smaller than $\Gamma(\psi \rightarrow \gamma G)$ or $\Gamma(\psi \rightarrow \gamma\eta')$ and more or less comparable to the ratio of more typical hadrons such as f and η . In this case θ might have a natural interpretation as a $\bar{q}q\bar{q}q$ state. First, this would explain the large branching ratio into a two body final state, since $\bar{q}q\bar{q}q$ states decay predominantly by "falling apart", when they can, into two $\bar{q}q$ mesons. Second, a typical hadronic rate for $\psi \rightarrow \gamma\theta$ is what we naively expect for a four quark state, since the amplitudes for $g\bar{g} \rightarrow \bar{q}q$ and $g\bar{g} \rightarrow \bar{q}q\bar{q}q$ both begin in order $O(\alpha_s)$.

Since θ decays to $\eta\eta$, it has $J^{PC} = 0^{++}, 2^{++}, \dots$. The preference for 2^{++} from the Crystal Ball analysis¹ is far from definitive, since it hangs on a 2 σ accumulation in the last angular bin. Jaffe's shopping list¹⁵ of $\bar{q}q\bar{q}q$ states contains many possibilities. However it is the rare $\bar{q}q\bar{q}q$ state which can give rise to an observable state; most are above their "fall-apart" threshold and are too broad to observe as ordinary resonances.^{31,8} Of Jaffe's low lying crypto-exotic nonet, only $S^*(980)$ and $\delta(980)$ are likely to be observable. $S^*(980)$ is the clearest example: it is a $(\bar{u}u + \bar{d}d)\bar{s}s$ state which is below $K\bar{K}$ and $\eta\eta$ threshold so that its width is $O(12)$ suppressed and therefore small enough to observe. On the other hand there is no trace of Jaffe's predicted $\epsilon(650)$ and $\nu(900)$ in standard phase shift analyses, presumably because their widths are of the order of their masses.

We must therefore look for states on the shopping list which might be as narrow as the ~ 200 MeV width quoted for θ . Since the bag model estimates of the masses assume the bag ansatz and single gluon exchange, they are only semiquantitative (eg S^* is predicted at 1100 MeV). Therefore I have considered all $I = 0$ states within 300 MeV of 1640. The $J = 0$ states are, in the notation of Ref. 15., $C^S(36, 1550)$, $C^{SS}(36, 1950)$, $C^S(9^*, 1800)$, $C^0(9^*, 1450)$ and $C^0(36^*, 1800)$. The quark contents are $C^0 = \bar{u}u\bar{d}d$, $C^S = (1/\sqrt{2})(u\bar{u} + \bar{d}d)\bar{s}s$, and $C^{SS} = \bar{s}s\bar{s}s$. Of these $C^S(36)$ and $C^{SS}(36)$ are ruled out because they have unsuppressed fall-apart decays to $(K\bar{K}, \eta\eta)$ and $\eta\eta$ respectively. $C^0(9^*)$ is ruled out because it decays so copiously to $\pi\pi$, $\Gamma(\pi\pi)/\Gamma(\eta\eta) = 12$,³⁵ and such a large $\pi\pi$ signal is ruled out experimentally.¹⁷ $C^0(36^*)$ is also unlikely to be as narrow as 200 MeV because it has unsuppressed fall-apart decays to $\omega\omega$ and $\rho\rho$; for $M_\omega = 1640$ the s-wave phase space suppression is only $\beta = .3$ which is not enough to account for $\Gamma_\theta \approx 200$ MeV if the unsuppressed width is $\sim M_\theta$.

Among these five $J = 0$ states my favorite candidate is $C^S(9^*)$. If $\theta(1640) = C^S(9^*)$ it is below threshold for its fall-apart decays,

$\bar{K}^*K^*$ and $\phi\omega$. The decays to two pseudoscalars are suppressed by¹⁵ the "recoupling coefficient" of $(.178)^2$, so a very crude guess for the width

$$\Gamma_\theta \cong \left(\frac{.178}{.743}\right)^2 M_\theta \cong 100 \text{ MeV}$$

gives a reasonable result. (Here .743 is the recoupling coefficient for $C(9)$ to two pseudoscalars and I have used as input that $\epsilon(600)$ or $\kappa(900)$ have widths of order their masses.) In this case the other dominant modes are K^+K^- and $\bar{K}^0K^0$ in the ratio³⁵

$$\Gamma(\theta \rightarrow K^+K^-) = \Gamma(\theta \rightarrow \bar{K}^0K^0) = \Gamma(\theta \rightarrow \eta\eta). \quad (12)$$

Then

$$B(\theta \rightarrow \eta\eta) \cong \frac{1}{3} \quad (13)$$

and

$$\Gamma(\psi \rightarrow \gamma\theta) \cong (1.5) \cdot 10^{-3} \quad (14)$$

If $\theta = C^*(9)$, it is not the state seen in $\gamma\gamma \rightarrow \pi\pi$.³⁶

There are four possible $J = 2$ states in the 1640 ± 300 MeV. mass range. They are $C^0(9, 1650)$, $C^0(36, 1650)$, $C^S(9, 1950)$, and $C^S(36, 1950)$. $C^0(9)$ and $C^0(36)$ are unlikely for the same reason as the $J = 0$ $C^0(36^*)$ discussed above: they could fall apart to $\pi\pi$ and $\omega\omega$ and would therefore probably be much broader than 200 MeV. The other two states, $C^S(9)$ and $C^S(36)$, would have no allowed fall-apart decays if their masses were 1640 MeV. They would be below the $\phi\omega$ and $\bar{K}^*K^*$ thresholds and in the approximation of Ref. (15) they do not decay to two pseudoscalars. Such decays could occur by virtue of (as yet uncalculated) gluon exchange corrections. Then as for the $J = 0$ $C^S(9^*)$ state, $\bar{K}K$ and $\eta\eta$ would be the dominant two body decay modes. If θ were either the $J = 2$ $C^S(9)$ or $C^S(36)$ but not both then K^+K^- , $\bar{K}^0K^0$ and $\eta\eta$ would occur equally as in Eq. (12). But if both states were degenerate at 1640, interference effects could change the relative amounts of $\bar{K}K$ and $\eta\eta$. Another difference from the $J = 0$ $C^S(9^*)$ possibility is that for these $J = 2$ states there might be a larger proportion of multibody decays, since the two body decays occur by virtue of gluonic corrections which could give rise to three body decays in the same order.

Finally we cannot neglect the possibility that θ is a garden variety $\bar{q}q$ state. There are many more such possibilities in the θ mass range than in the mass range of the G . For instance an $I = 1$ $J^P = 2^{++}$ $\pi\pi$ resonance has been found at 1.7 GeV, which could be a radial excitation of the f or an $L = 3$ state. θ could be an $I = 0$ member of one of these nonets. In this respect the θ is less tightly constrained than the G whose only conceivable $\bar{q}q$ assignment is in the nearly complete π' nonet. The reasons for not preferring a $\bar{q}q$ assignment for θ are indirect and have been alluded to above: either $B(\theta \rightarrow \eta\eta)$ is small and $\Gamma(\psi \rightarrow \gamma\theta)$ is too large for an ordinary hadron, or $B(\theta \rightarrow \eta\eta)$ is very large which is also implausible for a typical 1.64 GeV $\bar{q}q$ hadron. However it will be much harder to rule out definitively a $\bar{q}q$ assignment for θ than for G .

V. CONCLUSION

$G(1440)$ has all the properties expected of a glueball. It is the most prominent state in a prime glueball production channel, $\psi \rightarrow \gamma X$, and it is not well accounted for as a radially excited $J^P = 0^- \bar{q}q$ meson. Final confirmation requires the following tasks:

1) Reexamine $\pi^- p \rightarrow \eta \pi \pi n$ to verify the indication from Ref. (18) that G is produced too weakly to be the ninth member of the $J^P = 0^-$ radially excited nonet.

2) Examine the strong binding corrections to $\psi \rightarrow \gamma + \eta'/\zeta'$ to verify the nonrelativistic intuition that a radial excitation cannot be produced here with a rate $\geq$ the rate of the ground state.

3) Fill in the entries of Table II and thereby discover the ζ' and unravel the extent of $\zeta' - G$ mixing.

In the case of $\theta(1640)$ the proper assignment is far less clear. The meson spectrum in the 1600 - 1700 GeV region is more complex and more poorly known, which means it will be harder to exclude definitively a conventional $\bar{q}q$ interpretation. Nonetheless the already known facts suggest two nonconventional interpretations:

1) If $B(\theta \rightarrow \eta\eta) \lesssim 10\%$, then $\Gamma(\psi \rightarrow \gamma\theta)$ is extremely large and the glueball interpretation is attractive.

2) If $B(\theta \rightarrow \eta\eta)$ is appreciably larger than 10%, then $\Gamma(\psi \rightarrow \gamma\theta)$ is not unusually large. The big two body decay modes would then be naturally explained if θ were a $\bar{q}qqq$ state. My favorite candidate is an $\bar{s}s(\bar{u}u + \bar{d}d)$ state which would also have large $\bar{K}K$ decay modes.

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