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GLUEBALLS AND MEIKTONS: A STATUS REPORT

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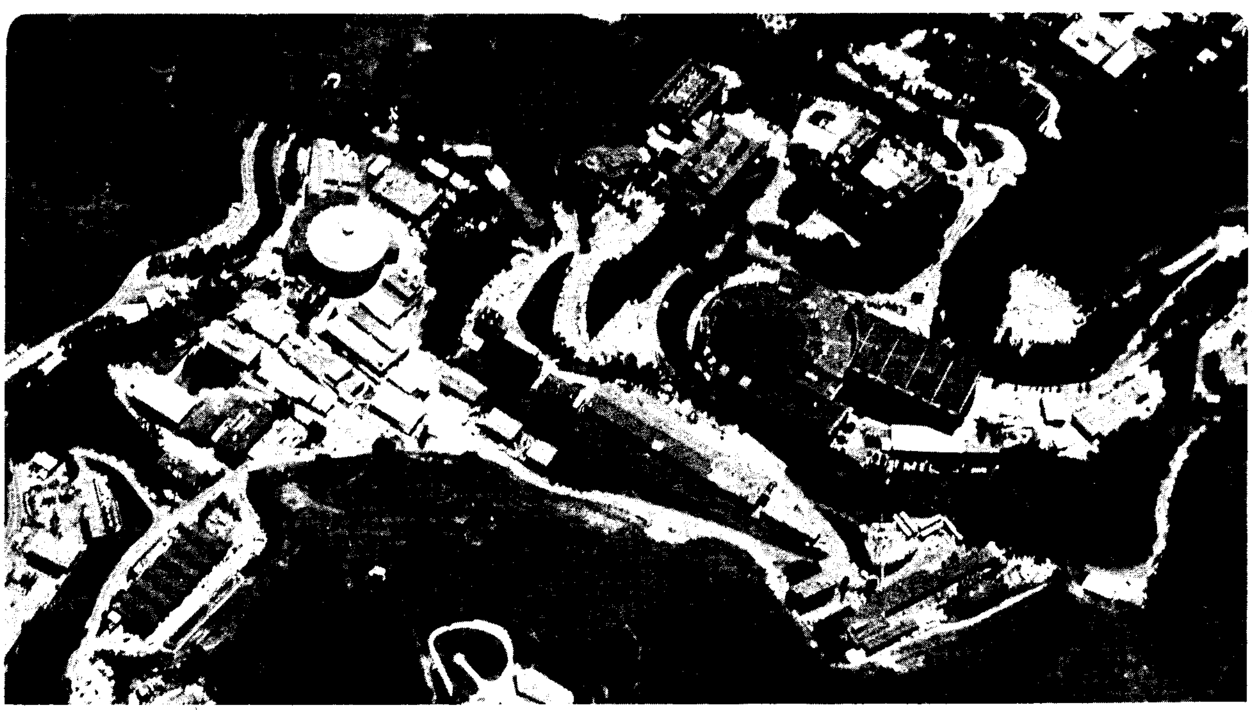

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Abstract

The search for gluonic states is reviewed. Criteria are given by which glueballs can be identified and are applied to the candidate states $\iota(1440)$ and $\theta(1700)$. The expected spectrum and phenomenology of $\bar{q}qg$ meiktons is presented. A class of excited meiktons and glueballs is discussed which have characteristic "signature" decays to multi-kaon final states, including some which would be OIZ forbidden for $\bar{q}q$ mesons of the same flavor content.

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I. Introduction

The discovery in 1980 of a large signal in $\psi \rightarrow \gamma(\bar{K}K\pi)_{1440}$ MeV marked the beginning of lively interest in the search for gluonic degrees of freedom in the hadron spectrum.[1] Given the present limitations of our theoretical and experimental tools, this search is a difficult undertaking – as was well illustrated by the inital confusion over the relationship of the $\bar{K}K\pi$ signal in ψ decay to similar signals seen in other processes. The problems are that the gluonic states are not known to have clear signatures by which they can be reliably identified, that they must be disentangled from a complex, densely spaced spectrum of $\bar{q}q$ mesons which is still only primitively understood above 1 1/2 GeV, and that experimental progress requires greatly increased statistics to do the necessary partial wave analyses. It is therefore not surprising that while more candidates for gluonic states have emerged since 1980, no definitive conclusions have been reached.

The problems are formidable but not insoluble. With high quality data from a variety of sources we can convincingly identify at least some gluonic states. Radiative ψ decay is an excellent channel for the search. Next month we will hear the first results of the 2 1/2 million ψ events taken by the Mark III detector at SPEAR. Because of the combined capability of the Mark III for charged and neutral particle detection, this represents a greater advance than the number of events alone would suggest. In the future we can hope for more ψ decay data from the Mark III, from DCI in Orsay, and from the e^+e^- ring to be constructed in Beijing. High statistics fixed target data is also crucial, since to identify the gluonic states we must understand the $\bar{q}q$ meson spectrum far better than we do now. We look forward to the results from LEAR and to the high statistics studies that will be possible if proprosals for the Brookhaven AGS, for LAMPF, and for TRIUMF are carried out. Photon-photon scattering in the resonance region and certain high energy hadron scattering experiments may also be valuable.

By "gluonic states" I refer both to the glueballs and to the mixed states of quarks and glue[2,3,4] which we in Berkeley call meiktons[3] (pronouned "make-ton" from the classical Greek for a mixed thing) and which our English cousins like to call hermaphrodites.[4] (The editors of Nuclear Physics, in Solomonian fashion, prefer hybrid.) The ggg glueballs[5] and the $\bar{q}qg$ meiktons include in their number states with exotic quantum numbers, such as $J^{PC} = 1^{-+}$, which do not occur in the $\bar{q}q$ spectrum of the nonrelativistic quark model. This offers hope of a much-needed signature for gluonic states, though it should be borne in mind that such exotic quantum numbers might also be carried by $\bar{q}q$ states not describable in the nonrelativistic quark model. For instance, consideration of the bag model suggests that the radial excitation of the $J^{PC} = 0^{-+}$ and 1^{--} $\bar{q}q$ mesons may have respectively $J^{PC} = 0^{--}$ and 1^{-+} breathing modes.[6]

Recent work suggests another possible signature for certain gluonic states.[7] These are states that in the bag model contain TM (transverse magnetic) gluon modes, which in the usual spherical cavity approximation decay much more copiously to $\bar{s}s$ quarks than to $\bar{u}u + \bar{d}d$. Thus the $J^{PC} = 0^{-+}$ gg glueball, which contains one TM and one TE (transverse electric) mode, should decay predominantly to $\bar{K}K\pi$ (as $\iota(1440)$ is indeed observed to do). A $g_{TM}g_{TM}$ 2^{++} glueball would decay to $\phi\phi$. Four $\bar{q}qg_{TM}$ meikton nonets with $J^{PC} = 1^{+-}$, $(0, 1,2)^{++}$ contain many particles with striking decay modes. For instance, the $I = 1$ and $I = 0$ TM meiktons should decay prominently to $\phi\pi$, $\phi\rho$, and $\phi\omega$, which would be OIZ forbidden decays of $\bar{q}q$ mesons, while the strange TM meiktons would decay prominently to three kaon final states. With smaller branching ratios the ground state $\bar{q}qg_{TE}$ nonets, with $J^{PC} = 1^{--}$, $(0, 1, 2)^{-+}$, may also have such "signature" decays.[3]

The plan of the talk is as follows:

Section II is a brief, noncomprehensive update on the search for glueballs. Conservative criteria are given that can be used to identify some glueball states, along with other criteria which I do not think are reliable. Both are illustrated with a discussion of the two blue ribbon candidates, $\iota(1440)$ and $\theta(1700)$.

Section III concerns the meiktons, beginning with the conceptual issues underlying the prediction of their existence. Predictions for the ground state $\bar{q}qg_{TE}$ nonets are presented, with a discussion of an experimental meikton candidate, the A_3' with $J^{PC} = 2^{-+}$, for which there is some evidence from the ACCMOR collaboration.[8] Finally I review the excited $\bar{q}qg_{TM}$ nonets and the characteristic decays by which they may be identified.

Section IV is a discussion of the increased statistical level that is needed in future e^+e^- and fixed target studies.

An Appendix-Postscript contains a brief discussion of new results presented at the SLAC and Cornell meetings shortly after this talk was given.

II. Glueballs

The heart of our problem is that there are no reliable quantitative predictions for the masses, much less the widths and decay modes, of the expected glueballs. Bag[3,9,10] and potential[11] models are at best semi-quantitative guides to the spectrum. Lattice calculations[12] may ultimately succeed but for now the artifacts and uncertainties due to the small sizes of the lattices prevent them from being quantitatively reliable.

In this context it seems to me that there are only two properties which we can reliably use to identify glueball states. I call them the M.O. or modus operandi of the glueball. The first is a tautology: glueballs do not fit in the $\bar{q}q$ multiplets of the quark model. The second requires some quantum mechanics: glueballs are copiously produced in hard gluon channels. This second part of the M.O. is most evident if glueballs are made of valence gluons.

A good example of a hard gluon channel is radiative decay of $J/\psi(3095)$, $J/\psi \to \gamma + X$. In perturbation theory this decay is dominated by $J/\psi \to \gamma + gg$ where the two gluons are in a net color singlet. This is therefore a beautiful channel to look for glueballs with positive C-parity.

The good news is that the conservative M.O. is very powerfull. It applies to glueballs even when they are mixed with $\bar{q}q$ states. The bad news is that it is not easy to apply, because knowing that a particle is not a $\bar{q}q$ meson requires a thorough understanding of the $\bar{q}q$ spectrum. To apply the M.O. we need high statistics data from radiative ψ decay and fixed target experiments.

In the literature other properties have been proposed as a basis for identifying glueballs. One is that glueballs, being flavor singlets, should have flavor symmetric decays.[13] Another is that glueball widths should be the geometric mean of OIZ allowed and forbidden decays.[14] I do not believe either proposition is reliable. The first overlooks large symmetry breaking effects of both dynamical and kinematical

origin. The validity of the second depends on how a paradoxical feature of the OIZ rule is resolved.

The large flavor symmetry breaking that can occur in glueball decays is illustrated in the discussion of $\iota(1440)$ and $\theta(1700)$. For $\iota(1440)$ two effects may enhance the decays to $\bar{K}K\pi$. One is dynamical: the enhanced coupling of TM gluons to $\bar{s}s$ quarks found in the bag model.[7] The other is kinematical and applies to any $J = 0$ state annihilating to a fermion-antifermion pair, such as $\pi \to \mu\nu$, $e\nu$ or $J = 0$ glueball $\to$ $\bar{s}s$, $\bar{u}u + \bar{d}d$.[15,16] For $\theta(1700)$ large symmetry breaking may also be a consequence of kinematics, for the above reason if $J = 0$ and in general because of considerations having to do with the available phase space. These points are explained below. They illustrate the danger of using flavor symmetry to decide whether any particular resonance is a glueball.

The estimate[14] of glueball widths is based on the observation that in perturbative QCD, OIZ violating amplitudes are mediated by intermediate gluons. The initial state quarks annihilate to gluons which then create the final state quarks. For glueball decay only the latter occurs so we expect a suppression which is the square-root of full OIZ suppression. This estimate ignores the distinction between the two and three gluon channels which is phenomenologically important: the large deviation from ideal mixing of the light pseudoscalars shows that the OIZ rule is not honored in the $J = 0$ two gluon channel at ~ 1 GeV.

There is also a more general difficulty. The estimate follows from the tacit assumption that the intermediate gluons in the Feynman diagram of an OIZ violating amplitude implies glueball dominance of the real intermediate states. For instance, in a glueball pole model $\phi \to G \to \rho\pi$ meson-glueball couplings appear twice, yielding the estimate $\Gamma_G \sim (\Gamma_{OIZ\ allowed} \cdot \Gamma_{OIZ\ forbidden})^{1/2}$ But the identification of intermediate gluons with intermediate glueballs overlooks the existence of what may be the dominant intermediate states. For instance $\phi \to \rho\pi$ can proceed via the OIZ allowed $\bar{K}K$ intermediate state, $\phi \to \bar{K}K \to \rho\pi$, since $\phi \to \bar{K}K$ and $\bar{K}K \to \rho\pi$ are both OIZ allowed.[17] This raises a "paradox",[18] which for $\phi \to \rho\pi$ is most crisply formulated with the unitarity equation,

$$\mathrm{Im} <\phi|\rho\pi> = <\phi|\bar{K}K> <\bar{K}K|\rho\pi> + \cdots.$$

The left side is OIZ suppressed though neither factor on the right side is. Cancellations are not possible, since the other intermediate states <u>are</u> OIZ suppressed, so $<\bar{K}K|\rho\pi>$ must be small though it is OIZ allowed. The OIZ rule is not self-contained, in the sense that some other dynamical principle is needed to make it consistent with unitarity. My view is that the small K:π ratios seen in the central region in hadron-hadron and e^+e^- collisions embody the physics of this unstated principle.

The real part of $<\phi|\rho\pi>$ has contributions from intermediate glueballs <u>and</u> from OIZ allowed channels like $\bar{K}K$. If the real part is small and/or if it is saturated by the $\bar{K}K$ contribution, then the glueball couplings could be much smaller than the simple estimate. Or, if there were big cancellations, the glueball couplings could be much larger. Another uncertainly is the distance to the relevant glueball poles, which is probably large in this example but in general would vary greatly from case to case. (The qualitative expectation that $\psi \to \gamma X$ is a glueball channel is not affected by these considerations because the $\bar{D}D$ threshold is well away from the glueball masses being considered.)

My conclusion is that we do not know how broad glueballs are or even that there is a single scale which characterizes the width of the ordinary "garden-variety" glueball. As illustrated below in the discussion of the branching ratios of $\theta(1700)$, the 1-2 GeV region is not an asymptopia in which we can ignore the kinematical peculiarities of different exclusive channels.

I will now briefly review the experimental status of $\iota(1440)$ and $\theta(1700)$. They are among the most prominent states in $\psi \to \gamma X$. $\theta(1700)$ has no prior history while $\iota(1440)$ was initially confused with the $J^P = 1^+$ E(1420). A close reading of the full experimental record suggested[15] that $\iota(1440)$ was not the $J^P = 1^+$ E(1420) but rather a $J^P = 0^-$ state discovered in $\bar{p}p$ annihilation at rest in 1966 (named "E" for Europe, as the first resonance found in Europe). This interpretation was subsequently supported by a spin-parity anlaysis of $\iota(1440)$ which yielded $J^P = 0^-$.[20] Nothing better illustrates the difficulty of finding the glueballs than the possibility that we actually discovered one in 1966, confused it with a $\bar{q}q$ meson, and remained blissfully unaware of its possible significance until its reemergence in $\psi \to \gamma X$ in 1980. (See however prescient remarks by Robson, Ref. 14.) This story dramatizes the importance of radiative ψ decay and the need to understand the $\bar{q}q$ spectum in detail. As discussed below, identification of $\iota(1440)$ as a glueball depends on finding a <u>third</u> $\bar{K}K\pi$ resonance, the ζ', which would complete the radially excited pseudoscalar nonet.

The $\iota(1440)$ is seen at a large rate,[1,20]

$$B(\psi \to \gamma\iota) \cdot B(\iota \to \bar{K}K\pi) \simeq 4.10^{-3}$$

large as a fraction ($\geq 5\%$) of all radiative ψ decays and as at least as prominent as the previously most prominent state, $\eta'(958)$, with $B(\psi \to \gamma\eta' = 3\ 1/2 \cdot 10^{-3}$. The other possible hadronic decays of ι are $\eta\pi\pi$ and $\pi\pi\pi\pi$. These have not yet been obseved and it is clear that they have substantially smaller branching ratios than $\bar{K}K\pi$.[21,22] Although a quantitative statement is not yet possible because no bound has been stated for $\iota \to \pi\pi\pi\pi$, it is already clear that $\bar{K}K\pi$ is the dominant decay.

This raises the issue of flavor symmetry, since naively we would expect a glueball to decay one third or less to $\bar{K}K\pi$. It suggests that ι might be a radially excited $\bar{s}s$ pseudoscalar, the ninth member of the π' nonet. I will argue that just the opposite is true. The predominance of $\bar{K}K\pi$ is what we would expect of a pseudoscalar glueball, while the hypothesis that ι is an $\bar{s}s$ state is incompatible with the full experimental picture.

The lowest order diagrams for decay of a two gluon glueball are shown in Figure (1). For a J = 0 initial state, Figure (1a) vanishes for massless quarks $m_q = 0$, while for massive quarks the amplitude is proportional to m_q.[15,16] This is a consequence of the familiar argument based on helicity consevation which explains $\Gamma(\pi \to \mu\nu) >> \Gamma(\pi \to e\nu)$. It applies both to J = 0 glueballs and to the pion because in both cases the interactions are helicity conserving (V and V-A respectively). Therefore Figure (1a) favors $\bar{s}s$ over $\bar{u}u$ and $\bar{d}d$ by a factor which is at least ~ 3 for constituent quark masses and could be as large as ~ 400 for current quark masses.

Bag model dynamics suggests an additional enhancement of $\bar{K}K\pi$ which would apply to both Figures (1a) and (1b).[7] In cavity perturbation theory the vertices are proportional to the overlap integrals of the cavity mode eigenfunctions. The lowest gluon mode, TE, has roughly flavor symmatric s-channel couplings to $\bar{u}u$, $\bar{d}d$, and $\bar{s}s$, but the TM mode couples much more strongly to $\bar{s}s$ (by ~ 5 in the amplitude). The TE mode has $J^{PC} = 1^{+-}$ while the TM gluon has $J^{PC} = 1^{--}$, so a $J^{PC} = 0^{-+}$ glueball is constructed from one TE and one TM mode. This contributes an additional enhancement of $\bar{s}s$ pairs in Figure (1a) and assures that one of the $\bar{q}q$ pairs in Figure (1b) is predominantly $\bar{s}s$.

Admittedly these arguments lean heavily on perturbation theory, and, in the second instance, on details of the bag model. But at the very least they demonstrate how kinematics and dynamics could create large violations of flavor symmetry. They show that we need not be surprised if we find a pseudoscalar glueball which decays predominantly to $\bar{K}K\pi$.

Does $\iota(1440)$ follow the glueball modus operandi? It is certainly prominent in radiative ψ decay, and the remaining question is whether it has a place as a $\bar{q}q$ state.

There is a natural opening: the ninth member of the radially excited pseudoscalar nonet, consisting of $\pi'(1270)$, K'(1425), the I = 0 $\zeta(1275)$, and the as yet undiscovered ζ'. Could ι be the missing ζ'?

The difficulty with this hypothesis is that there is no possible mixing between ζ nd $\iota = \zeta'$ which is consistent with all the experimental constraints. Consider for example the predominance of $\iota \to \bar{K}K\pi$ which suggests approximate ideal mixing, i = $\zeta' \sim \bar{s}s$ and $\zeta \sim 1/\sqrt{2}\,(\bar{u}u + \bar{d}d)$. But then we expect $\Gamma(\psi \to \gamma\zeta) \sim 2\,\Gamma(\psi \to \gamma\zeta')$ whereas experimentally we see from $\psi \to \gamma\eta\pi\pi$ and $\psi \to \gamma\bar{K}K\pi$ that $\Gamma(\psi \to \gamma\zeta) << \Gamma(\psi \to \gamma\iota)$ by at least an order of magnitude. Ideal mixing would also suggest[6,23] a larger mass than 1440 MeV: $m_{\bar{s}s} \sim 2m_{K'} - m_{\zeta}$. If we are instead led by the observation $\Gamma(\psi \to \gamma\iota) >> \Gamma(\psi \to \gamma\zeta)$ to 1-8 mixing, as for η and η', $\iota = \zeta' \simeq \zeta_1$ and $\zeta \simeq \zeta_8$, then we cannot understand the predominance of $\iota \to \bar{K}K\pi$ nor the ratio $\sigma(\pi p \to \iota n \to \eta\pi\pi n)/\sigma(\pi p \to \zeta n \to \eta\pi\pi n)$ which we would expect to be ~ 2 though the experimental upper limit appears to be ≤ 0.4.[15] It also seems surprising in either case that $\Gamma(\psi \to \gamma\iota) \geq \Gamma(\psi \to \gamma\eta')$ despite the smaller phase space and wave function at the origin for the putative radial excitation. (Bethe-Salpeter calculatons have given conflicting results on the latter point.)[24]

It is clear that what we need is not more arguments from theorists but some good experiments. If ι is not ζ', then ζ' should be discovered. The approximate degeneracy of π' and ζ suggests ideal mixing in which case $m_{\zeta'} \simeq 2m_{K'} - m_{\pi'}$). More generally, good channels for the ζ' search are $\pi^- p \to \bar{K}K\pi n$, $\eta\pi\pi n$, and $\eta'\pi\pi n$, and $\bar{p}p \to (\bar{K}K\pi)\pi\pi$, $(\eta\pi\pi)\pi\pi$, $(\eta'\pi\pi)\pi\pi$. No experiment reported to date would have been able to detect the ζ' in these channels above 1450 MeV. In fact the $\zeta(1275)$ has only been seen so far by one experiment[25] because only this experiment studied the channel $\pi^- p \to \eta\pi\pi n$ with enough statistics to perform a partial wave analysis and discover the 70 MeV wide $\zeta(1275)$ beneath the narrowere $J^P = 1^+$ D(1280). Previous experiments which only looked at the $\eta\pi\pi$ mass histogram undoubtedly confused these two states, so the properties ascribed to D(1280) in the Particle Data booklet cannot be taken at face value without looking back critically at the experimental sources. With enough statistics it would also be possible to see ζ and ζ' in radiative ψ decay, presumeably at a rate much smaller than $\Gamma(\psi \to \gamma\iota)$.

The second blue ribbon candidate is $\theta(1700)$. It was first seen in $\psi \to \gamma\eta\eta$[26] at B.R $\sim 1/2 \cdot 10^{-3}$, subsequently in $\psi \to \gamma\bar{K}K$[27] at $\sim 1.10^{-3}$ and perhaps in $\psi \to \gamma\rho^0\rho^0$ [22] at $\sim 1\ 1/4 \cdot 10^{-3}$. The spin is not conclusively measured but there is a reported preference[26] for $J = 2$ (which could be due to an $f' \to \eta\eta$ contaminant). If we add the rates for these three modes, including $\theta \to \rho^+\rho^-$ as expected for $I = 0$, we find an enormous signal, $B(\psi \to \gamma\theta) \geq 5.10^{-3}$, even bigger than $\iota(1440)$ and therefore the most prominent state in $\psi \to \gamma X$ to date. Half of the glueball modus operandi is then well satisfied, though we should keep in mind that this conclusion rests heavily on the $\rho\rho$ signal which is the least clearly established. Other likely θ decay modes are $\omega\omega$ and $\eta\pi\pi$.

What of the other half of the glueball M.O.: does θ have a home in the $\bar{q}q$ spectum? If it were a $J = 2$ $\bar{q}q$ state, θ would have to be the radial excitation of f(1270). This seems most unlikely if the $\theta \to \rho\rho$ signal is genuine, since then $\Gamma(\psi \to \gamma\theta)$ is about three times larger than $\Gamma(\psi \to \gamma f)$, contrary to what we would expect of a radial excitation. If on the other hand θ does not decay to $\rho\rho$, it still is not a plausible radial excitation of f because of the predominance of $\theta \to K^+K^-$ over $\theta \to \pi^+\pi^-$ (still unobserved) by at least a factor of 2. In this case we might want to say that θ is the radial excitation of f', but the mass splitting is far too small for this to be tenable. If θ is a scalar, it seems equally unlikely to be a $\bar{q}q$ state, since it seems from inspection of $\psi \to \gamma\pi^+\pi^-$ that $\Gamma(\psi \to \gamma\theta)$ is much larger than $\Gamma(\psi \to \gamma\varepsilon(1400))$ which is still unseen.

Further striking evidence comes by comparing $\psi \to \gamma\bar{K}K$[27] with $\gamma\gamma \to \bar{K}K$,[28] from which we learn that

$$\Gamma(\psi \to \gamma\theta)/\Gamma(\psi \to \gamma f') > \sigma(\gamma\gamma \to \theta)/\sigma(\gamma\gamma \to f')$$

with the $\bar{K}K$ branching ratios cancelling. In fact $\gamma\gamma \to \theta \to \bar{K}K$ is not seen at all and probably ">" will eventually be replaced by ">>". Since f' is mostly an $\bar{s}s$ state it has an extremely small coupling to $\gamma\gamma$, making the inequality even more striking. As it stands the inequality already excludes a $\bar{u}u + \bar{d}d$ assignment for θ. If it becomes ">>", it would be very strong evidence against any $\bar{q}q$ assignment for θ but would be just as expected for a pristine, unmixed glueball. Models to explain θ as a mixture of $\bar{q}q$ meson and glueball have not been very successful, requiring for instance mixing with f but not with the much nearer f'.[29] It may simply be that θ mixes very little with $\bar{q}q$ states.

Flavor symmetry is also an issue in the interpretation of θ since $\Gamma(\theta \to \pi^+\pi^-) \leq 1/2\, \Gamma(\theta \to K^+K^-)$,[21] contrary to what we would naively expect for a flavor singlet. However the phenomenology of exclusive final states is among the most poorly understood aspects of QCD. Here I will consider a simple model, not because I think it is a really adequate model of the physics, but just because it illustrates a point: that flavor symmetry in QCD need not imply flavor symmetery of the exclusive final states. The model shows that $\pi\pi$ could be a smaller mode than $\bar{K}K$ even if θ is a $J = 2$ glueball and a flavor singlet.

The model is just Figure (1a). That is, I assume the decay begins with the flavor symmetric annihilation of the gluons to a single $\bar{q}q$ pair, given by $1/\sqrt{3}(\bar{u}u + \bar{d}d + \bar{s}s)$, which subsequently hadronizes to form the observed final states (if θ has $J = 0$ the $\bar{q}q$ pair would be mostly $\bar{s}s$ as discussed above for ι). Now we must consider how the $\bar{u}u + \bar{d}d$ and $\bar{s}s$ pairs hadronize. I will assume that no additional $\bar{s}s$ pairs are formed in the process of hadronization (a conservative assumption for the purpose at hand). Then the $\bar{u}u + \bar{d}d$ pairs will materialize as $(\pi\pi)_2$, $(\eta\eta)_2$, $(\eta\pi\pi_3)$, $(\pi\pi\pi\pi)_2 = (\rho\rho)_0$, and $(\pi\pi\pi\pi\pi\pi)_4 = (\omega\omega)_0$. The subscripts denote the least possible units of orbital angular momentum and I have indicated the dominant resonant combinations of the 4π and 6π states. Similarly the $\bar{s}s$ pairs materialize as $(\bar{K}K)_2$, $(\eta\eta)_2$, $(\bar{K}K\pi)_3 = (\bar{K}^*K)_2$, and $(\bar{K}K\pi\pi)_2 = (\bar{K}^*K^*)_0$.

The point is that for the $\bar{s}s$ decays the three and four body final states are heavily penalized by phase space and the corresponding quasi-two-body channels ($\bar{K}K^*$ and $\bar{K}^*K^*$) are actually forbidden. But for the $\bar{u}u + \bar{d}d$ decays the four and six body decays proceed with no inhibition in the quasi-two-body s-wave channels $\rho\rho$ and $\omega\omega$, while $\eta\pi\pi$ has more available phase space than the corresponding $\bar{K}K\pi$. Therefore simply because of the available phase space we expect a much larger fraction of the $\bar{s}s$ decays to hadronize to $\bar{K}K$ than $\bar{u}u + \bar{d}d$ to $\pi\pi$. Flavor symmetry at the level of the quarks is not incompatible with the flavor symmetry breaking observed for the exclusive final states.

The final topic in this section is the TM^2 glueballs[7,10] with $J^{PC} = (0,2)^{++}$. As mentioned in the preceding discussion of $\iota(1440)$ the TM gluons decay dominantly to $\bar{s}s$ quarks.[7] From Table 3, taken from Ref. (7), we see that the 0^{++} TM^2 gleuball may lie between 1.1 and 1.9 GeV depending on the value of the parameter C_{TE}/C_{TM} (if $\theta(1700)$ is the 2^{++} TE^2 glueball than $C_{TE}/C_{TM} = 1/2$ while if θ is the 0^{++} TE^2 glueball then $C_{TE}/C_{TM} = 2$ – see Table 2). The 2^{++} TM^2 glueball lies between 1.9 and 2.5 GeV. If above threshold the 2^{++} TM^2 state would decay prominently to $\phi\phi$ in an s-wave and might be identified with one of the candidate $\phi\phi$ resonances seen at Brookhaven.[30] The 0^{++} TM^2 state being below the $\phi\phi$ thresold would decay chiefly to $\bar{K}K$ and $\eta\eta$. There are two candidate 0^{++} resonances in K_sK_s at 1240 and 1770 MeV[31]; if either is the TM^2 state it should also decay to $\eta\eta$ and appear strongly in $\psi \to \gamma X$.

The last comment suggests another possible interpretation of $\theta(1700)$. If it turns out that $\rho\rho$ is not a principal decay mode of θ and if θ is also found to have zero spin, than θ might be the TM^2 0^{++} glueball.

To summarize this section, all that we now know about ι and θ is compatible with the glueball M.O. but not with simple $\bar{q}q$ assignments. For ι the central task is to find ζ', the ninth member of the π' nonet, with a mass probably greater than 1450 MeV, decaying to $\bar{K}K\pi$ and perhaps also to $\eta\pi\pi$ and $\eta'\pi\pi$. For θ the central issues are determination of the spin, verification of the possibly large $\rho\rho$ decay mode, and observing or improving the upper limit on $\gamma\gamma \to \theta \to \bar{K}K$. In the next section I will comment on whether ι and θ could be qqg meiktons. I believe that this is unlikely for ι but possible for θ if the $\rho\rho$ decay mode is not confirmed.

III. Meiktons

The gluonic degrees of freedom might also be observed by finding the mixed $\bar{q}qg$ states[2,3,4] which I will call meiktons. I will briefly describe the bag model predictions for the ground state meikton nonet[3,4] and for a class of excited nonets which would have characteristic, experimentally distinguishable decays.[7] If these meiktons are found it would confirm the existence of valence gluons, in the very particular form required by the bag model.

The idea of valence gluons is a controversial one. In fact we do not understand why there are even valence quarks! – though the regularities of the meson and baryon spectra leave no doubt about the usefulness of the concept of valence quarks. The question is why mesons have many of the properties of $\bar{q}q$ states rather than say $\bar{q}\bar{q}qq$, $\bar{q}\bar{q}\bar{q}qqq$ ... as one might expect of very strongly interacting quark quanta. I want to suggest an answer based on two facts we have learned in recent years.[6] First, deep inelastic scattering experiments have taught us that asymptotic freedom extends out to larger distances than we had previously thought, to about one fermi rather than to a fraction of a fermi. Second, lattice studies show that the transition from strong to (asymptotically free) weak coupling occurs very abruptly as a function of distance and that the change ocurs at about one fermi. Since hadron radii are about one fermi, this all suggests that perturbation theory may be a reasonable qualitative or even semi-quantitative guide to the physics of hadron interiors. Hence valence quarks and gluons may exist because of the surprising relevance of perturbation theory. In cavity perturbation theory, as done in the bag model, additional convergence is gained because the vertices are not point-like but are proportional to small overlap integrals of cavity eigenfunctions.

In the bag model the lowest energy quark mode has $J^P = 1/2^+$ and energy $E = 2.04/R$ where R is the cavity radius. The lowest energy gluon mode is the transverse electic (TE) mode with, surprisingly, axial vector quantum numbers $J^P = 1^+$ and

energy $E = 2.74/R$. The ground state meiktons are constructed from a $\bar{q}q$ pair, either the spin singlet with $J^{PC} = 0^{-+}$ or triplet with $J^{PC} = 1^{--}$, combined with the TE gluon with $J^{PC} = 1^{--}$. The result is four nonets having $J^{PC} = 1^{--}, (0,1,2)^{-+}$. Three groups[3,4] have now computed the masses of these nonets through $0(\alpha_s)$ in cavity perturbatin theory and are in agreement except for differences in the treatment of quark and gluon self energies. The results from Reference (3) are shown in Table 1 for three values of the ratio of gluon mode self energies $C_{TE}/C_{TM} = 2, 1, 1/2$. This ratio is fixed if we assume that $\theta(1700)$ is the TE^2 glueball, with $C_{TE}/C_{TM} \sim 1/2$ if θ has spin 2 and $C_{TE}/C_{TM} \sim 2$ if θ has spin 0. Table 2 shows the predicted glueball spectrum from the same calculation.

For the preliminary indication that θ is a tensor, the masses range from 1.2 to 2.1 GeV. The 1^{--} nonet complicates the already complicated situation expected in the nonrelativistic quark model which may have <u>two</u> $\bar{q}q$ nonets in this region: the radial excitation, L = 0, N = 2, and the d-wave orbital excitation, L = 2, N = 1. The 0^{-+} nonet falls in the range of the radially excited π' $\bar{q}q$ nonet with L = 0, N = 2. The 2^{-+} nonet is near the region of the d-wave spin singlet $\bar{q}q$ nonet, L = 2, N = 1. But the 1^{-+} nonet is a quark model exotic; that is, $J^{PC} = 1^{-+}$ does not appear in the spectrum of the nonrelativistic $\bar{q}q$ model (although 1^{-+} states do appear as cavity excitations of $\bar{q}q$ states in the bag model).[3,6] It is therefore particularly interesting to look for the states of the 1^{-+} nonet. The quantum numbers of these four ground state nonets, 1^{--} and $(0, 1,2)^{-+}$, are a specific test of the bag model because they follow from the axial vector quantum numbers of the TE gluon mode.

These $\bar{q}qg$ states are likely to decay by formation of a $\bar{q}q$ pair from the gluon, $g \to \bar{q}q$, followed by disassociation of the resultant $\bar{q}\bar{q}qq$ state into two $\bar{q}q$ mesons. Because of parity the TE gluon does not couple to an s-wave pair $\bar{q}_s q_s$ (we use j – j coupling in the bag) but to $\bar{q}_p q_s$ or $\bar{q}_s q_p$. The result then is either two L = 0 mesons in a relative p-wave or an L = 0 and an L = 1 meson in a relative s-wave,

$$\bar{q}_s q_s g(TE) \rightarrow \begin{cases} (\bar{q}q)_s + (\bar{q}q)_s & L = 1 \\ (\bar{q}q)_s + (\bar{q}q)_p & L = 0 \end{cases}$$

Examples of these two kinds of decays for the isovector member of the exotic 1^{-+} nonet are

$$\text{"}\rho\text{"}(1^{-+}) \rightarrow \begin{cases} \pi\eta & L = 1 \\ \pi D(1280) & L = 0 \end{cases}$$

The $\pi\eta$ channel is particularly nice because it is an experimentally clean two body channel and because $\pi\eta$ in a p-wave uniquely signals the 1^{-+} quantum numbers.

Since the TE gluon s-channel couplings to $\bar{q}q$ are approximately flavor symmetric, (see Table 1 of Ref. (3)), the $\bar{q}qg_{TE}$ meiktons may have characteristic multi-kaon and apparent OIZ violating decays. As for the $\bar{q}qg_{TM}$ states discussed below, but to a lesser extent, the $\bar{q}qg_{TE}$ states may have decays such as "ρ"$(1^{-+}) \rightarrow \pi E, \bar{K}K^*$; "$\rho$"$(1^{--}) \rightarrow \pi\phi, \bar{K}K$; and "$\rho$"$(2^{-+}) \rightarrow \pi f', \bar{K}K^*$. The latter are of particular interest for the A_3-A_3' candidate discussed below.

Here even more than for the glueballs we depend upon the results of high quality, fixed target experiments. For instance, too many states of a given quantum number could indicate the existence of meikton nonets. There is an intriguing example of this already in the experimental literature. The ACCMOR collaboration at CERN accumulated 600,000 events in the reaction $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$ from which many interesting results were obtained – on the previously controversial A_1 meson, on the radially excited π' and K', and on a 2^{-+} isovector the $A_3(1700)$.[8]

They confirmed the existence of $A_3(1700)$, primarily in the $f\pi$ s-wave, though they saw it less clearly also in the $f\pi$ d-wave, $\rho\pi$ p-wave, and $\varepsilon\pi$ d-wave. And they saw a second bump in the 2^{-+} channel at 1850 MeV, which I will call the A_3', only 150 MeV above the A_3! This second bump appeared in $(f\pi)_d$, $(\rho\pi)_p$, and $(\varepsilon\pi)_d$ but not in the $f\pi$ s-wave. From Table I with $C_{TE}/C_{TM} = 1/2$ as for $J(\theta) = 2$, the "ρ"(2^{-+}) meikton is expected in just this region, at 1790 MeV. Now if the 2^{-+} meikton and the 2^{-+} d-wave $\bar{q}q$ isovectors had nearly equal masses between 1750 and 1800 MeV they would mix strongly. The mixing might naturally be dominated by the s-wave $f\pi$ intermediate state in which case the levels would "repel" and one of the eigenstates would tend to decouple from the $f\pi$ s-wave, leaving a picture like what is perhaps obseved.

I say "perhaps" because the mass and even the existence of the A_3' are by no means clear. The experimenters have found a second interpretation of their data in which the bump at 1850 results from the interference of $A_3(1700)$ with a second state at ~ 2100 MeV. My private suspicion, which I have not yet been able to confirm with the principals, is that they were moved to find this second solution by the perception that nobody would love a second I, $J^{PC} = 1, 2^{-+}$ state just 150 MeV above the A_3. Indeed such a state could not be explained in the $\bar{q}q$ model as an excitation of the A_3. Even the 400 MeV splitting corresponding to an $A_3'(2100)$ seems rather small for a radial excitation.

Another experiment with even more statistics is probably needed to decide the existence and mass of the A_3'. It would also be interesting to look for the characteristic meikton decay modes $\pi f'$ and $\bar{K}K^*$, as dissussed above. The initial results from ACCMOR are a good case study in how careful study of the meson spectrum may turn up the new physics we are seeking.

The TM (transverse magnetic) gluon mode has vector quantum numbers, $J^{PC} = 1^{--}$, and mode energy 4.49/R. For R ~ 1 fm., the $\bar{q}qg_{TM}$ nonets should be a few hundred MeV heavier than the $\bar{q}qg_{TE}$ nonets. They are of special interest because, as seen in Table 1 of Ref. (3), the s-channel coupling $g_{TM} \to \bar{s}s$ is bigger by ~ 5 in amplitude than $g_{TM} \to \bar{u}u, \bar{d}d$. In taking this result seriously we are escalating our reliance on the spherical cavity approximation to the bag model but with a potentially great reward: if the predicted enhancement is even qualitatively correct than many $\bar{q}qg_{TM}$ meiktons will have spectacular decay signatures by which they can be clearly distinguished from $\bar{q}q$ mesons of the same quantum numbers. As already discussed in Section II, the dominance of $\iota \to \bar{K}K\pi$ is consistent with the TM $\to \bar{s}s$ enhancement and the interpretation of ι as a $J^{PC} = 0^{-+}$ TE-TM glueball.

In Ref. (7) the spectum of $\bar{q}qg_{TM}$ meiktons and TM^2 glueballs was computed to $0(\alpha_s)$ in cavity perturbation theory, using the same approximations and parameters that were applied in Ref. (3) to the $\bar{q}qg_{TE}$, TE^2, and TE-TM states. The results for the specrtum are shown in Table 3, as a function of C_{TE}/C_{TM} as before. There are four $\bar{q}qg_{TM}$ nonets with the same quantum numbers as the p-wave $\bar{q}q$ states, $J^{PC} = 1^{+-}$, $(0, 1, 2)^{++}$ (mixing with the $\bar{q}q$ p-wave is incorporated to $0(\alpha_s)$ and is small). Their masses range between 1.8 and 2.5 GeV for $C_{TE}/C_{TM} = 1/2$ and between 1.4 and 2.2 GeV for $C_{TE}/C_{TM} = 2$.

Some "signature" decay modes are shown in Table 4. The ϕ-like TM meiktons decay to final states with four K's including $\phi\phi$, so the "ϕ"(2^{++}) might be identified with one of the Brookhaven $\phi\phi$ candidates.[30] The strange $\bar{q}qg_{TM}$ states decay to three kaon final states, including ϕK and ϕK^*; these are the natural prey of high statistics kaon beam experiments such as LASS. The isovectors and ω-like isoscalars decay to final states containing a $\bar{K}K$ pair. The $\bar{K}K$ pair may materialize as a ϕ meson, either by final state interaction or directly by soft gluon emission from the color octet $\bar{s}s$ pair created by the $J^{PC} = 1^{--}$ TM gluon. These decays, such as "ρ" $(1^{+-}) \to \phi\pi$ or "ρ" $((0,1,2))^{++}0 \to \phi\rho$ are unmistakeable, since they would be OIZ forbidden decays for

$\bar{q}q$ isovectors. Similarly "ω" $((0, 1, 2)^{++}) \to \omega\phi$ would be an OIZ forbidden decay for either an ω-like or a ϕ-like $\bar{q}q$ isoscalar.

There are some TM meikton candidates in the recent experimental literature. I have already mentioned "ϕ"(2^{++}) in connection withe BNL data.[30] The 0^{++} K_sK_s resonance at 1770 MeV[31] might be identified with "ω" (0^{++}). Together with E(1420) the recently claimed 1^{++} $\bar{K}^*K$ resonance, D′(1526),[32] makes too many states for the A_1 nonet; either D′ or E or a mixture of both could be the "ω" (1^{++}). Unfortunately both D′(1526) and the 1770 MeV K_sK_s resonance are below threshold for the characteristic $\phi\omega$ decay.

IV. More Statistics

It is clear that the discovery and identification of hadrons with gluon constituents requires a much more thorough experimental exploration of the meson spectrum. This will be so even if our theoretical understanding improves, because even if we did have reliable predictions of glueball and meikton masses and decays, positive identification of the new gluonic states would still in most cases require disentangling them from nearby $\bar{q}q$ mesons with the same quantum numbers. This in turn means that we still would need to know in detail the composition of the $\bar{q}q$ nonets.

High statistics is as much a frontier as high energy. In particle physics we go to higher energy to be able to resolve structure and dynamics at smaller distances. But in order to resolve the structure and dynamics of the meson spectrum, which is fundamental to QCD, we need not higher energy but higher statistics. In the past five years each increase in statistics has brought important new results. There is no reason to think that this progression has reached an end. Many fundamental questions, such as the existence and nature of gluonic states, remain to be answered.

The particular statistical level required for the next step will vary from case to case. For example, the questions about iota and the π' nonet could probably be settled by experiments in $\pi^- p \to \bar{K}K\pi n$, $\eta\pi\pi n$ with good acceptance out to $\leq$ 1.7 GeV and with statistical power comparable to or perhaps even less than that of the ACCMOR experiment. But higher statistical levels will probably be needed to map the spectrum at higher masses, say from 1.5 to 2.5 GeV. For instance, to settle the question of the possible meikton candidate A_3' (1850/2100) raised by the ACCMOR collaboration, considerably more than their 600,000 event sample would be needed. Here we move into the realm where higher intensity beams may be needed, such as LEAR, an upgraded AGS, and the new facilities proposed at LAMPF and TRIUMF. The new beams may in turn require new detector development, perhaps with very

sophisticated on-line triggers. To go beyond the statistical level of the ACCMOR experiment, increased off-line computing power is also needed.

Radiative ψ decay is crucial both because gluonic states are produced there with large rate and signal-to noise ratio and because their prominence in that channel is one of the few signals we have to distinguish glueballs from other states. As we know from fixed target studies, mass histograms alone will not often suffice to discover the new states in the 1 1/2 – 2 1/2 GeV mass region. Partial wave analysis is essential to find all but the sitting ducks, and it is in any case essential to understand whatever is found. This means a significant increase over the present level of statistics is required.

As a statistical calibration point, the Crystal Ball study of ι(1440) was based on a sample of about 150 observed $\iota \to K^+K^-\pi^0$ decays,[20] Among glueball candidates ι(1440) is the quintessential sitting duck: it appears at a large rate (~ 1/2 % of all ψ decays!) in the relatively background free $\psi \to \gamma\bar{K}K\pi$ channel, so that it could be discovered[1] in the $\bar{K}K\pi$ mass histogram without partial wave anlysis. θ(1700) was also found without partial wave analysis, in the sparser and cleaner $\eta\eta$ mode,[26] requiring more statistics than for ι. θ and ι are the exceptions, not the rule. Other glue state candidates will be harder to find, requiring partial wave analysis just to bring them out of the background. In this case we must surpass the statistical level of the Crystal Ball – $2{\cdot}10^6$ ψ's – by an order of magnitude.

For a versatile detector like the Mark III with good photon and charged particle detection capability, 10^7 ψ's is a desireable benchmark. This is a factor four increase over the present sample. With good SPEAR running as occured last Spring, this many events could be logged in ~ 20 weeks. This would be enough events to begin to find the states which can only be seen by partial wave analysis. We could profit not only by the discovery of new candidate glue states but also by finding at lower yields new states in the $\bar{q}q$ spectrum, such as ζ and ζ' which should appear at smaller rates than $\psi \to \gamma\iota$ if the glueball interpretation of ι is correct.

Appendix: A Postscript

For completeness I include some comments on two interesting new results presented at the SLAC[33] and Cornell[34] meetings shortly after the preceding talk was given. These are the observation of a $\rho\gamma$ signal in the iota region from the Mark III and Crystal Ball, an apparently inconsistent upper limit on $\iota \to \rho\gamma$ from DCI, and the discovery by the Mark III of a new state, the $\xi(2220)$, seen in $\psi \to \gamma\xi \to \gamma\bar{K}K$.

The $\rho\gamma$ signal seen by Mark III and Crystal Ball is extremely large if attributed to a single state. The Mark III result is $B(\psi \to \gamma + \rho\gamma) = (1.3 \pm 0.9) \cdot 10^{-4}$ with $M = 1420 \pm 20$ MeV and $\Gamma = 200 \pm 100$ MeV. Similar results are obtained with the Crystal Ball. If we attribute the entire signal to ι and use $\Gamma_\iota = 97 \pm 25$ MeV (the Mark III fit to $\iota \to \bar{K}K\pi$) and the Mark III result $B(\psi \to \gamma\iota \to \bar{K}K\pi) = (5.3 \pm .6 \pm 1.9) \cdot 10^{-3}$, then we find $\Gamma(\iota \to \rho\gamma) \simeq 2.4$ MeV $\times$ $B(\iota \to \bar{K}K\pi)$ with big errors. For comparison $\eta' \to \rho\gamma$ scaled by phase space to m = 1440 MeV would be 2.9 MeV. Assuming ι and η' are both approximate SU(3) flavor singlets and using vector meson dominance we would then expect $\Gamma(\iota \to \gamma\gamma)/B(\iota \to \bar{K}K\pi)$ to be about as large as $\Gamma(\eta' \to \gamma\gamma)$ scaled by phase space or ~ 19 KeV.[F1] Since $B(\iota \to \bar{K}K\pi)$ is apparently very large ($\geq 2/3$?) this implies a large value for $\Gamma(\iota \to \gamma\gamma)$, larger then I would expect for a glueball, a meikton, or an $\bar{s}s$ radial excitation. It is also at the edge of inconsistency with the TASSO limit from $\gamma\gamma$ scattering, $\Gamma(\iota \to \gamma\gamma) < 7$ KeV$/B(\iota \to \bar{K}K\pi)$. To reconcile this limit with $\Gamma(\iota \to \gamma\gamma) \simeq 19$ KeV $\cdot B(\iota \to \bar{K}K\pi)$ we need $B(\iota \to \bar{K}K\pi) < 2/3$ implying substantial signals in $\iota \to 4\pi$ and/or $\iota \to \eta\pi\pi$ which have yet to be seen.

Of course the central value that this exercise was based on $B(\psi \to \gamma\,``\iota" \to \gamma\gamma\rho) \simeq 1.3 \cdot 10^{-4}$, come with large errors, $\pm\, 0.9 \cdot 10^{-4}$, and could be several times smaller. In addition, there are two clues that more than one state contributes to this $\rho\gamma$ signal. First, the reported width of the $\rho\gamma$ signal, 200 ± 100 MeV, is ~ 4 times the value of Γ_ι(TOT) obtained by the Mark II and Crystal Ball from $\bar{K}K\pi$ and twice the value obtained by the Mark III from $\bar{K}K\pi$. Second, DCI finds an upper limit for $\iota \to \rho\gamma$ about

2 1/2 times smaller than the signal reported by the Mark III and Crystal Ball.[34] The DCI analysis required Γ_ι(TOT) $\simeq$ 50 MeV and so would exclude additional states which might contribute to the Mark III and Crystal Ball signals (I am grateful to D. Hitlin for this information about the DCI analysis.)

The tantalizing questions raised by the $\rho\gamma$ signal might be answered with further analysis or they might require more statistics. However for the interpretation of $\iota(1440)$ the $\rho\gamma$ chanel is chiefly of interest as a window to the $\gamma\gamma$ decay. $\Gamma(\iota \to \gamma\gamma)$ can be bounded by bounding $\Gamma(\iota \to \gamma\gamma) \cdot B(\iota \to KK\pi)$ from above in $\gamma\gamma$ scattering and $B(\iota \to KK\pi)$ from below in radiative ψ decay (which means bounding $B(\iota \to 4\pi)$ and $B(\iota \to \eta\pi\pi)$ from above). Interesting scales are set by the $\gamma\gamma$ widths we might anticipate for ζ and ζ', the putative I = 0, $J^{PC} = 0^{-+}$ radial excitations. If for instance I assume ideal mixing, $\zeta(1270) = 1/\sqrt{2}\,(uu + dd)$ and $\iota = \zeta' = ss$, then I estimate

$$\Gamma(\zeta \to \gamma\gamma) \simeq 13 \text{ KeV}$$

$$\Gamma(\zeta' \to \gamma\gamma) \simeq 3 \text{ KeV}$$

The estimates are based on $\Gamma(\eta' \to \gamma\gamma)$ rescaled by phase space, by the effective quark charges of the different states,[F2] and divided by 2 for the radial excitation as suggested by $\psi' \to e^+e^-$ and $\rho' \to e^+e^-$. Similarly for 1-8 mixing, $\zeta = 1/\sqrt{6}\,(uu + dd - 2ss)$ and $\zeta' = 1/\sqrt{3}\,(uu + dd + ss)$ I find

$$\Gamma(\zeta \to \gamma\gamma) \simeq 5 \text{ KeV}$$

$$\Gamma(\zeta' \to \gamma\gamma) \simeq 12 \text{ KeV}$$

If ι is identified with ζ' than these estimates give a crude idea of the likely scale of $\Gamma(\zeta' \to \gamma\gamma)$ depending on the assumed $\zeta - \zeta'$ mixing. I have argued in Section III that no choice of $\zeta - \zeta'$ mixing allows $\iota = \zeta'$ to be consistent with already established experimental facts. The reader may wish to consult Section III to decide what $\zeta - \zeta'$ mixing seems least unpalatable.

I will conclude with a comment on $\xi(2220)$, seen with $B(\psi \to \gamma\xi \to \gamma K^+K^-) = (8.0 \pm 2.0 \pm 1.6) \cdot 10^{-5}$, $m_\xi = 2.22 \pm .02$ GeV, and $\Gamma_\xi(\mathrm{TOT}) = 30 \pm 10 \pm 20$ meV. The width could be "zero" (i.e., weak or semi-weak), in which case ξ is not likely to be a hadron. ξ cannot be the Higgs boson of the standard model because $\Gamma(\psi \to \gamma\xi \to \gamma K^+K^- + \gamma K^0K^0)$ is already bigger by 5 than $\Gamma(\psi \to \gamma H(2200))$.[35] It could be a nonstandard Higgs boson, say in a model with more than one Higgs doublet, but this hypothesis pulls the rug out from under our initial motivation since such a Higgs boson need not decay preferentially to $s\bar{s}$ quarks.

Suppose instead that $\Gamma_\xi(\mathrm{TOT})$ really is of order 30 MeV or so. It has natural spin-parity, probably $J_P = 0^{++}$ or 2^{++}. Then a possible asignment is one of the ω-like $\bar{q}qg_{TM}$ meiktons discussed in Section IV. As shown in Table 3 for $C_{TE}/C_{TM} = 1/2$ (corresponding to θ being the 2^{++} TE^2 glueball) the estimated masses are 1900 MeV for "ω" (0^{++}) and 2300 MeV for "ω" (2^{++}). The signature decays of Table 4 include "ω" $(0^{++}) \to \bar{K}K$ while "ω" (2^{++}) does not decay to $\bar{K}K$ in lowest order but can by single gluon exchange (a kind of color M-1 transistion, $\bar{K}_8{}^*K_8{}^* \to \bar{K}_1K_1$, where the subscripts denote color representations). For either spin we also expect $\xi \to \bar{K}^*K^*$, not a very striking prediction. However we also expect in Table 4 the very peculiar decay $\zeta \to \phi\omega$. This assumes, beyond the lowest order decay mechanism in which $\bar{g}qq \to \bar{q}q\bar{q}q$ which "falls apart", that the ϕ forms either by final state interaction or by soft gluon exchange, $\phi_8\omega_8 \to \phi_1\omega_1$. The decay $\xi \to \phi\omega$ would be an OIZ suppressed decay if ξ were a $\bar{q}q$ state, since both $u\bar{u} + d\bar{d} \to \phi\omega$ and $s\bar{s} \to \phi\omega$ are OIZ suppressed. A rough estimate,[7] based on cavity perturbation theory, of the widths of $\bar{q}qg_{TM}$ meiktons is consistent with the observed value of $\Gamma_\xi(\mathrm{TOT})$.

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Footnotes

F1. In fact vector meson dominance (ρ, ω, ϕ plus SU(3) symmetry) overestimates $\Gamma(\eta' \to \gamma\gamma)/\Gamma(\eta' \to \rho\gamma)$ by a factor ~ 2 and would give $\Gamma(\iota \to \gamma\gamma) \simeq 35$ KeV $\cdot$ B($\iota \to \bar{K}K\pi$) using $\Gamma(\iota \to \rho\gamma) = 2\ 1/2$ MeV $\cdot$ B($\iota \to \bar{K}K\,\pi$) as input.

F2. I assume the usual -11^0 η-η' mixing angle.

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Table 1. The meikton spectrum from Ref. 3 for C_{TE}/C_{TM} = 1/2, 1, 2. . Particles are labeled by analogy with the vector mesons. All masses are in GeV. and all radii in GeV.$^{-1}$.

J^{PC}	TYPE	$C_{TE}/C_{TM}=1/2$ Mass	$C_{TE}/C_{TM}=1/2$ Radius	$C_{TE}/C_{TM}=1$ Mass	$C_{TE}/C_{TM}=1$ Radius	$C_{TE}/C_{TM}=2$ Mass	$C_{TE}/C_{TM}=2$ Radius
	ρ/ω	1.64	6.10	1.83	6.35	2.02	6.56
1^{--}	K*	1.80	6.03	1.99	6.29	2.18	6.50
	ϕ	1.96	5.95	2.16	6.22	2.35	6.44
	ρ/ω	1.20	5.50	1.41	5.81	1.61	6.05
0^{-+}	K*	1.41	5.42	1.62	5.74	1.82	5.98
	ϕ	1.61	5.34	1.82	5.67	2.03	5.91
	ρ/ω	1.41	5.80	1.61	6.05	1.80	6.31
1^{-+}	K*	1.59	5.73	1.80	5.98	1.99	6.25
	ϕ	1.78	5.66	1.99	5.90	2.18	6.18
	ρ/ω	1.79	6.30	1.97	6.51	2.15	6.70
2^{-+}	K*	1.94	6.24	2.13	6.45	2.13	6.65
	ϕ	2.09	6.17	2.28	6.39	2.47	6.59

Table 2. Predicted glueball masses from Ref. (3), for gluon self energy ratios C_{TE}/C_{TM} = 1/2, 1, 2 and for two different fits (I and II) to the mesons and baryons. Masses are in GeV. The 1.44 mass is an input parameter.

FIT	C_{TE}/C_{TM}	0^{++}	2^{++}	0^{-+}	2^{-+}
	1/2	0.67	1.75		
I	1	1.14	2.12	<u>1.44</u>	2.30
	2	1.56	2.47		
	1/2	0.65	1.74		
II	1	1.21	2.18	<u>1.44</u>	2.30
	2	1.70	2.59		

Table 3. Masses of TM^2 glueballs and $\bar{q}_s q_s$ TM meiktons at $O(\alpha_s)$ using fit I of Reference. 3. All masses are in GeV. The radii of the states are $\sim$ 5-6 GeV^{-1}.

State		C_{TE}/C_{TM} = 1/2 (C_{TM} = 2.16)	C_{TE}/C_{TM} = 1 (C_{TM} = 1.62)	C_{TE}/C_{TM} = 2 (C_{TM} = 1.08)
TM^2	0^{++}	1.93	1.55	1.13
	2^{++}	2.64	2.30	1.94
1^{+-}	ρ/ω	2.13	1.95	1.76
	K^*	2.26	2.08	1.89
	ϕ	2.40	2.21	2.02
0^{++}	ρ	1.80	1.61	1.41
	ω	1.90	1.71	1.51
	K^*	1.98	1.79	1.59
	ϕ	2.20	2.01	1.81
1^{++}	ρ	1.94	1.76	1.56
	ω	2.04	1.86	1.67
	K^*	2.11	1.92	1.72
	ϕ	2.31	2.12	1.93
2^{++}	ρ	2.23	2.05	1.87
	ω	2.32	2.14	1.96
	K^*	2.35	2.17	1.99
	ϕ	2.51	2.33	2.15

Table 4. "Signature" decays of the $\bar{q}_s q_s$ TM meiktons into two $L = 0$ mesons in a relative s-wave, as expected from the decay mechanism discussed in the text.

	1^{+-}	0^{++}	1^{++}	2^{++}
"ρ"	$\phi\pi, K^*\bar{K}^*$, $K\bar{K}^*, K^*\bar{K}$	$\phi\rho, K\bar{K}, K^*\bar{K}^*$	$\phi\rho, K\bar{K}^*, K^*\bar{K}$	$\phi\rho, K^*\bar{K}^*$
"ω"	$\phi\eta, \phi\eta', K^*\bar{K}^*$, $K\bar{K}^*, K^*\bar{K}$	$\phi\omega, K\bar{K}, K^*\bar{K}^*$	$\phi\omega, K\bar{K}^*, K^*\bar{K}$	$\phi\omega, K^*\bar{K}^*$
"K^*"	$\phi K, \phi K^*$	ϕK^*	$\phi K, \phi K^*$	ϕK^*
"ϕ"	$\phi\eta, \phi\eta'$	$\phi\phi, \phi\omega^{\S}$	$\phi\omega^{\S}$	$\phi\phi, \phi\omega^{\S}$

§These decays may be suppressed relative to the others in the table since they involve the TM gluon coupling to $\bar{u}u$ and $\bar{d}d$, but they are included because they are not OZI suppressed for meikton decays unlike the corresponding decays of their ordinary meson counterparts.

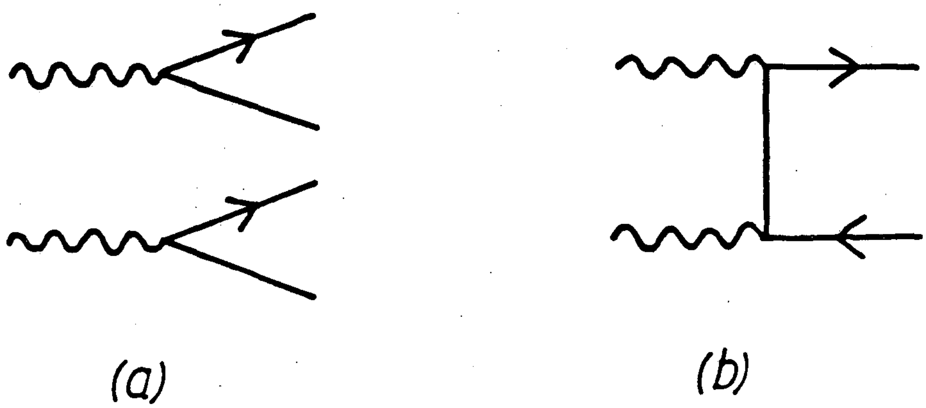

Figure 1

Lowest order glueball decay mechanisms.

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