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Invited talk presented at the VII International Workshop on Photon-Photon Collisions, Shoresh, Jerusalem Hills, Israel, April 24–28, 1988, and to be published in the Proceedings

Resonances in Photon-Photon Scattering

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Abstract

Selected topics in meson spectroscopy are reviewed as they are illuminated by photon-photon collisions. Subjects include the S^*/f_0 (975) and δ/a_0 (980) as $\overline{q}\overline{q}qq$ candidates, the ι/η (1460) and θ/f_2 (1700) as glueball candidates, and the spin 1 $X(1420)$ seen in tagged events which represents new physics whether its parity is positive, $J^{PC} = 1^{++}$, or negative with exotic $J^{PC} = 1^{-+}$.

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1. Who Cares?

In this time of The Bomb, T.O.E.'s, and superstrings, why are particle physicists still interested in an old-fashioned subject like the two photon couplings of hadronic resonances? Certainly many colleagues have happily declared victory over hadronic physics and moved on to the next battleground. I do not question that they are brave warriors but I believe the declaration of victory is premature. As those fighting in two and ten dimensional worlds are the first to acknowledge, the traditional test of any theory is its spectrum. To "solve" a theory is to find its spectrum. By that measure we are far from understanding QCD and hadron physics. Today there are only five complete unambiguous meson nonets, with $J^{PC} = 0^{-+}, 1^{--}, 2^{++}, 3^{--}$, and 1^{+-}, of which the last two were only completed in the last year or two thanks to high statistics experiments such as the 140,000,000 Kp scattering events of LASS at SLAC and the two Brookhaven experiments with several tens of millions of events.[1] There are many painful gaps that are crucial to our understanding of new physics, among which are the $\bar{q}q$ p-wave 0^{++} and 1^{++} nonets and the radially excited 0^{-+} nonet. These three nonets have positive charge conjugation and can be investigated in $\gamma\gamma$ collisions.

Our ignorance is not only quantitative. Apart from confinement itself, we have not tested the principal *qualitative* feature of the QCD spectrum: the existence of states with gluon constituents. These include the glueball states that are purely gluonic in "zero'th order" and the $\bar{q}qg$ meiktons (pronounced MAKE-TON — beware of Tennessee accents with mispronunciations such as *maahktahn*). Though there is at least one very compelling glueball candidate,[2] progress has been slow, for easily understandable reasons. Theory is not yet able to overcome the intractability of physics in the strong coupling domain. Experiment faces a complex overlapping spectrum of states above 1 GeV that requires painstaking spin-parity analysis to understand.

The tremendous growth of computational power suggests that by the 1990's there will be reliable calculations of the spectrum and, eventually, even of low energy dynamics, using the lattice approximation and, hopefully, other techniques yet to be developed. Today we are forced by our ignorance to follow a strategy that relies on *qualitative* features of gluonic states:

- Gluonic states are "extra", *i.e.*, they exist in addition to the "ordinary" $\bar{q}q$ spectrum. Of course gluonic and $\bar{q}q$ states may mix (depending on dynamics that we do not now understand well) but the number of states is still increased. The prediction of extra states is very reliable, but to use it requires thorough mastery of the "ordinary" spectrum.

- Some gluonic states should carry exotic J^{PC}, which cannot mix with or be confused with the $\bar{q}q$ spectrum.

- Gluonic states may in some cases have unusual production and/or decay characteristics — this is the most uncertain feature and must be exercised "judiciously", where "judicious" is defined by whoever happens to be speaking at the moment. For instance, some glueballs should be prominent in radiative J/ψ decay which proceeds by $\psi \to \gamma gg$ but have small $\gamma\gamma$ couplings since gluons are electrically neutral. Therefore glueballs should be very sticky, where stickiness is defined up to an arbitrary normalization by[3)]

$$S_X = \frac{\Gamma(\psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)} \cdot \frac{\text{LIPS } (X \to \gamma\gamma)}{\text{LIPS } (\psi \to \gamma X)} \tag{1.1}$$

  and LIPS stands for Lorentz invariant phase space.

This qualitative strategy means that for now experiment must lead. Bump hunting is not good enough because there are too many states with similar masses and widths. Partial wave analysis is essential, which means in most cases that progress requires experiments with vastly increased statistics.

In this talk I will restrict myself to just a few of the questions illuminated by $\gamma\gamma$ physics: the $\delta - S^*$ puzzle in section 2, a glueball update in section 3, and in section 4 the very amusing new physics that has been discovered in tagged $\gamma\gamma$ scattering in the $J^C = 1^+$ channel. Section 5 is a brief conclusion.

2. The $\delta/a_0(980)$ $- S^*/f_0(975)$ Puzzle

Two photon physics has recently contributed to the long standing $\delta - S^*$ puzzle, which provides the best clue to $\overline{q}\overline{q}qq$ states while teaching us at the same time that δ and S^* may be the only recognizeable resonances that can be so interpreted. Sad to say, as is often the case, incomplete understanding of the ordinary $\bar{q}q$ spectrum prevents our drawing a definite conclusion from the new data.

δ and S^* are degenerate to within 1%, suggesting, as for the vector mesons, ideal mixing so that $S^* = (\bar{u}u + \bar{d}d)/\sqrt{2}$. However S^* (and δ) has a very strong $\overline{K}K$

coupling as if it were an $\bar{s}s$ state. Three classes of solutions have been proposed to this puzzle:

1) Conventional $\bar{q}q$: mixing effects invert the $(\bar{u}u + \bar{d}d)/\sqrt{2}$ and $\bar{s}s$ states, so that S^* is indeed the $\bar{s}s$ member of the p-wave 0^{++} $\bar{q}q$ nonet.[4)]

2) Cryptoexotic $\overline{qq}qq$: single gluon exchange in the bag model projects out a low lying scalar "nonet", *i.e.*, nine states with the net quantum numbers of a $\bar{q}q$ nonet but each containing an extra hidden $\bar{q}q$ pair.[5)] Among the nine states, shown in figure 1, are a degenerate isotriplet and isoscalar containing hidden $\bar{s}s$ pairs (C^S states in the notation of the figure) that can be interpreted as δ and S^*, *e.g.*,

$$S^* = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)\bar{s}s \tag{2.1}$$

$$\delta^0 = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d)\bar{s}s \tag{2.2}$$

thus explaining both the degeneracy and the strong $\overline{K}K$ couplings. It was eventually realized[6)] that the other five members of this "nonet" should not appear as resonances, since they can fall apart into two $\bar{q}q$ mesons. Since it is below $\overline{K}K$ threshold the S^* is stabilized by the OIZ rule, explaining its small width to $\pi\pi$. The δ is an intermediate case as discussed below.

3) $\overline{K}K$ molecules: in a potential model $I = 0$ and $I = 1$ $\overline{K}K$ weakly bound states are expected just below $\overline{K}K$ threshold, interpreted as S^* and δ.[7)] This approach shares the same ordering of states as the bag model calculation, since in both calculations the hyperfine splitting due to color octet exchange determines the spectrum according to the Casimir operators of $SU(6)_{\text{Color-Spin}} \times SU(3)_{\text{Flavor}}$. The dynamics is however different and the molecule picture has the advantage of explaining why δ and S^* occur just below the $\overline{K}K$ threshold.

Both $\bar{q}q$ states and $\overline{qq}qq$ states near $\overline{K}K$ threshold would be expected to acquire $\overline{K}K$ wave function components by mixing, which tends to obscure the difference between bag and molecule. The question I wish to focus on is not the strength of those components but whether δ and S^* are extra states in the spectrum.

If δ and S^* are "extra" then we should look for the scalar $\bar{q}q$ nonet above ~ 1200 MeV. This is not implausible considering the masses of the other p-wave $\bar{q}q$ nonets whose $I = 1$ members are the $a_2(1310)$, $a_1(1270)$, and $b_1(1235)$. A candidate nonet might be assembled from the $\epsilon/f_0(1300) \to \pi\pi$, the $\kappa/K_0(1350) \to K\pi$, the $S^{*\prime}/f_0(1730) \to \overline{K}K$ (perhaps mixed with $G/f_0(1590)$), and the $\delta'/a_0(1300) \to \overline{K}K$. Of these the $f_0(1300)$ and $K_0(1350)$ are the best established, though broad and poorly understood. The weakest link is the $\delta'/a_0(1300)$ seen in one partial wave analysis[8] of $\pi^- p \to K^- K^0 p$ and consistent with another.[9] There are claims for two additional $I = J = 0$ resonances associated with S^* and ϵ, from a partial wave analysis driven by data for $\pi\pi$ central production (double Pomeron region).[10],[11] Since the $I = 0$ spectrum could be complicated by old-fashioned flavor mixing and by new physics, the cleanest signals for the nonet may be found in the $I = 1/2$ and $I = 1$ channels. In particular, verification of $\delta'(1300)$ would support the interpretation of δ as a $\overline{q}\overline{q}qq$ state. There is relevant data (unreported and perhaps not yet analyzed) from LASS and from Chung *et al.* in $\overline{K}K$ final states and from GAMS in the $\eta\pi$ channel.[1]

The $\gamma\gamma$ widths of these states are an important clue to their underlying structure, with smaller widths, of order a few tenths of a keV, expected for $\overline{q}\overline{q}qq$ states[12] or $\overline{K}K$ molecules.[13] For the $\bar{q}q$ states the naive nonrelativistic quark model suggests partial widths at least an order of magnitude larger. For a given $\bar{q}q$ flavor composition the ratio of scalar and tensor $\gamma\gamma$ widths is

$$0^{++} : 2^{++} = 15 : 4 \left(\frac{m_2}{m_0}\right)^n \qquad (2.3)$$

where $n = +3$ for a Coulomb potential and $n = -1/3$ for a linear potential. Since the linear potential seems most reasonable and because $n = 0$ best fits the ratio of the e^+e^- partial widths of ρ, ω, and ϕ, I will use equation (2.3) with $n = 0$. Then the experimental values for a_2, f, and f' (~ 1 keV, ~ 3 keV, and ~ 0.1 keV respectively) imply for the isovector and the "ω" and "ϕ" like isoscalars partial widths of order ~ 4 keV, ~ 10 keV, and ~ 0.4 keV respectively. For comparison we have [14] the measurements of $\Gamma(\delta \to \gamma\gamma)B(\eta\pi) \cong 0.19 \pm 0.07^{+0.10}_{-0.07}$ keV or $0.29 \pm 0.05 \pm 0.14$ keV from the Crystal Ball and Jade respectively and the new Mark II measurement $\Gamma(S^* \to \gamma\gamma)B(\pi\pi) = 0.19 \pm 0.05 \pm 0.12$ keV.

These results seem to indicate a decisive victory for the $\overline{q}\overline{q}qq$ or $\overline{K}K$ molecule interpretations. But a declaration of victory would be premature before we have found the $\bar{q}q$ scalars with $\gamma\gamma$ partial widths in the expected few to several keV range. The moral is familiar: we do not understand the "ordinary" well enough to be certain of the extraordinary.

Where could the $\epsilon(1300) \to \gamma\gamma$ and $\delta'(1300) \to \gamma\gamma$ signals be hiding? Could $\gamma\gamma \to \epsilon(1300) \to \pi\pi$ and $\gamma\gamma \to \delta'(1300) \to \eta\pi$ be part of what have been presumed to be exclusively the tensor meson signals of $\gamma\gamma \rightarrow f_2(1270) \rightarrow \pi\pi$ and $\gamma\gamma \rightarrow a_2(1320) \rightarrow \eta\pi$ respectively? Clearly this possibility should be examined with great care. In particular the incomplete solid angle coverage and variable efficiency as a function of angle mean that fits should allow for the possibility of interfering helicity zero scalar and tensor amplitudes, with the potential for larger effects than would appear in incoherent fits. The question is not just what is the best fit but what are the 90% or 95% confidence level upper limits for $\Gamma(\epsilon \rightarrow \gamma\gamma)B(\pi\pi)$ and $\Gamma(\delta' \rightarrow \gamma\gamma)B(\eta\pi)$ if ϵ and δ' are degenerate with f and a_2. As an incentive to the search (and to provide guidance toward the right answer) I am announcing a prize: a free lunch to the experimenter who proves (Chez Panisse in Berkeley) or disproves (Weizmann Institute cafeteria of the winner's [*sic*] choice) that $\geq$ 50% of the "f" $\pi\pi$ or "a_2" $\eta\pi$ signals are really due to ϵ and δ'.

It has also been suggested that the large expected $\epsilon \rightarrow \gamma\gamma$ signal may not have been seen because of the possibility that $\epsilon(1300)$ is extremely broad, perhaps even as broad as 1 GeV. However the beautiful measurements of $\gamma\gamma \rightarrow \pi^0\pi^0$ by Jade[15)] and the Crystal Ball[15)] seem to leave little room for this possibility (see also the comment of H. Marsiske in the discussion following this talk in the proceedings). The Crystal Ball spectrum has very little room for a broad background under the $f_2(1270)$. We are told that the towering peak at 1270 corresponds to $\Gamma(f_2 \rightarrow \gamma\gamma)B(\pi\pi) \cong 3$ keV. If it is completely attributed to $f_2(1270)$, it is hard for my untutored eye to see how a $\sim$ 10 keV signal could be hiding in the low lands below that peak, though reportedly[17)] more sophisticated analysts do not exclude such a possibility. To me a several keV $\gamma\gamma$ width for $\epsilon(1300)$ only seems likely if $B(\epsilon \rightarrow \pi\pi) \ll 1$ which would require that we see large signals in $\gamma\gamma \rightarrow \epsilon \rightarrow \overline{K}K$ or $\eta\eta$. This also seems unlikely though I cannot cite data to rule it out. Though I would have expected a big $\epsilon \rightarrow \gamma\gamma$ signal I do not see where it can be hiding. Perhaps the nonrelativistic quark model is not reliable here (see Rosner's remark in the discussion following this talk) and the $\bar{q}q$ scalars do not have large $\gamma\gamma$ widths, but then the $\gamma\gamma$ measurements of δ and S^* cannot be used to support the $\overline{qq}qq$ assignment. In the words of the poet, "We got a real situation here."[18)]

I conclude this section with two comments. Though the apparent total width of $\delta(980)$ as seen in $\delta \rightarrow \eta\pi$ is[19)] 54 ± 7 MeV, it was immediately shown by Flatté[20)] (an experimenter and therefore above suspicion) in a companion paper to the original experimental paper[21)] on $\delta(980)$ that the true width could be much broader, say $\sim$ 300 MeV, with the narrower structure in the $\eta\pi$ channel understood as a "cusp" effect due to the $\overline{K}K$ threshold. This suggestion predates the bag model discussion, and is just what is required if the bag model is correct. That is, unlike $S^* = (\bar{u}u + \bar{d}d)\bar{s}s/\sqrt{2}$ which has no OIZ allowed fall-apart decay channels, the $\delta = (\bar{u}u - \bar{d})\bar{s}s/\sqrt{2}$ has a $\sim$ 25% probability to fall apart to $\eta\pi$ which should imply a few hundred MeV width if the explanation[6]) of the inobservability as resonances of the $\overline{qq}qq$ $\epsilon(650)$ and $\kappa(900)$ is correct. To test this hypothesis we need a high statistics study of $\delta \rightarrow \overline{K}K$, which would show a broad threshold enhancement in the bag model but not in the potential model of the $\overline{K}K$ molecule. In fitting $\delta \rightarrow \overline{K}K$ in other processes, such as $D/f_1(1270)$ or $\iota/\eta(1460) \rightarrow \overline{K}K\pi$, we should be mindful of the possibility that δ might be very broad.

The second comment is that both the bag model and molecule approaches were in agreement that δ and S^* should be the only $\overline{qq}qq$ states narrow enough to observe as resonances. All others are expected to lie above their fall apart thresholds in the bag model or to be unbound in the potential model, a conclusion based on the $SU(6)_{\text{Color Spin}} \times SU(3)_{\text{Flavor}}$ ordering common to both models. This is an elegant solution to the question of whether $\overline{qq}qq$ states exist and why if they do exist we have not been flooded with them. It also explains the viability of the $\bar{q}q$ model of the ordinary mesons, since mixing with a multitude of low-lying $\overline{qq}qq$ states would wipe out many of its successes including $SU(3)_{\text{Flavor}}$ predictions.[22]) The prediction that there are two and only two directly observable $\overline{qq}qq$ states would be an elegant solution and should not be casually abandoned. Remember the baryonium fiasco. Beware of revisionists and recidivists.

3. Glueball Update

This section contains a brief discussion of the two strongest glueball candidates, $\iota/\eta(1460)$ and $\theta/f_2(1720)$, emphasizing in the case of the iota questions posed by $\gamma\gamma$ scattering. I will not discuss such objects as the putative second scalar in the S^* region,[11]) the $G(1590)$, the tensor $\phi\phi$ resonances, and the $\xi(2230)$, since their feeble production in radiative ψ decay (one or two or more orders of magnitude below $\psi \rightarrow \gamma\iota$) make them unlikely glueball candidates in my view.[2])

3.1 Iota $\iota/\eta(1460)$

Iota is impressively sticky. The upper limit from the TPC

$$\Gamma(\iota \rightarrow \gamma\gamma)B(\overline{K}K\pi) < 1.6 \text{ keV } (95\% \text{ CL}) \tag{3.1}$$

and the observed rate for $\Gamma(\psi \to \gamma\iota)B(\overline{K}K\pi)$ implies

$$S_\iota : S_{\eta'} : S_\eta = (>65) : 4 : 1. \tag{3.2}$$

Iota is so sticky because $\Gamma(\psi \to \gamma\iota)$ is big and $\Gamma(\iota \to \gamma\gamma)$ is small. I do not know of a viable explanation of these facts in terms of a $\bar{q}q$ state, though I have tried to construct one.[23]

Following the discussion of section 1 the remaining question is whether iota is "extra". A candidate radially excited nonet exists, consisting of $\pi(1300)$, $\kappa(1460)$, $\eta(1275)$ and $\eta(1390)$. If confirmed this would leave iota as the "odd man out". The first three states are well established, with $\eta(1275)$ seen convincingly by two experiments[24),25] in $\eta\pi\pi$ and by one[26] in $\overline{K}K\pi$. $\eta(1390)$ requires confirmation, being seen[27] in $\eta\pi\pi$ with $m = 1390 \pm 10$ MeV and $\Gamma = 31 \pm 7$ MeV (uncorrected for the $\Delta m = 25$ MeV mass resolution) and perhaps also[26] in $\overline{K}K\pi$, though with a larger mass, ~ 1420 MeV, and width, ~ 60 MeV. Mark III and DM2 data for $\psi \to \gamma\eta\pi\pi$ have bumps with m and Γ nicely matched to $\eta(1275)$ and $\eta(1390)$. Their spin and parity has not yet been measured, and they are sometimes assumed[28] to be the D/f_1 and E/f_1 states. I will be surprised if this is correct: just as for the old prediction[29] that the $\psi \to \gamma$"E", "E" $\to \overline{K}K\pi$ would prove to be $J^P = 0^-$ rather than 1^+, the Landau-Yang theorem suggests that 1^+ production should be suppressed in radiative ψ decay. This expectation is consistent with the result of a perturbative calculation[30] resulting in the estimate $B(\psi \to \gamma D) \cong 6 \cdot 10^{-5}$. It is very important to do the J^P analysis of the $\psi \to \gamma\eta\pi\pi$ bump at 1390, since a finding of $J^P = 0^-$ would verify completion of the $\pi(1300)$ nonet.

That would not however be the end of the story, because two-photon physics is making trouble. The problem is the strong upper limit from the Crystal Ball[31]

$$\Gamma(\eta(1275/1390) \to \gamma\gamma)B(\eta\pi\pi) < 0.3 \text{ keV (90\% CL)} \tag{3.3}$$

which applies to states below 1500 MeV with widths less than 50 MeV. Since the total widths of $\eta(1275)$ and $\eta(1390)$ as seen at KEK[25] may be ~ 25 MeV, the 90% confidence level bound for them is actually 0.15 keV.

For a crude estimate of what might have been expected I will assume that $\eta(1390)$ has the flavor content of $\eta'(958)$. Taking guidance from $\rho' \to e^+e^-$ and $\psi' \to e^+e^-$ I guess that the square of the amplitude for the radial excitation is about half that of the ground state. Then including p-wave phase space I would expect

$$\Gamma(\eta(1390) \to \gamma\gamma) \sim \frac{1}{2}\left(\frac{1390}{958}\right)^3 \cdot 4 \text{ keV}$$
$$\sim 6 \text{ keV}, \qquad (3.4)$$

a factor 40 larger than the upper bound for $\Gamma(\gamma\gamma)B(\eta\pi\pi)$. Once again we got a real situation here.

If the radially excited pseudoscalars were heavier, say $\sim$ 1500-1600 MeV and $\sim$ 1700-1800 MeV like ρ' and ϕ', then they might also be appreciably broader (200 MeV or more) and their branching ratios to $\eta\pi\pi$ would be smaller because of the opening of other channels. Then the Crystal Ball upper limit is much weaker and is not in conflict with the naive expectation. To confirm this story we would have to find the heavier pseudoscalars. We would still be left with a question: what are $\eta(1275)$ and $\eta(1390)$? I will present a possible answer in section 4 that is suggested by one interpretation of the new physics in the $J^C = 1^+$ channel.

3.2 Theta $\theta/f_2(1720)$

The upper limit[14)] from the TPC and Pluto

$$\Gamma(\theta \to \gamma\gamma)B(\overline{K}K) < 0.2 \text{ keV } (95\% \text{ CL}) \qquad (3.5)$$

implies that θ is at least six times stickier than the f' which is already very sticky because of its very small $\gamma\gamma$ coupling:

$$S_\theta : S_{f'} : S_f = (> 25) : 4 : 1. \qquad (3.6)$$

It also seems clear that θ is an extra state: the small value of $\Gamma(\theta \to \gamma\gamma)$ and the predominance of $\theta \to \overline{K}K$ among the observed decays ($\overline{K}K, \eta\eta, \pi\pi$) both suggest an $\bar{s}s$ state, but then $m_\theta - m_{f'}$ is much too small, $\Gamma(\psi \to \gamma\theta)/\Gamma(\psi \to \gamma f') > 10$ is much too big,[32)] and $\sigma(Kp \to \theta\Lambda)/\sigma(Kp \to f'\Lambda)$ is much too small.[33)]

It therefore seems clear that θ is some kind of new physics. However the relatively modest rate observed *so far* for $\Gamma(\psi \to \gamma\theta \to \gamma + \overline{K}K/\eta\eta/\pi\pi) \sim \Gamma(\psi \to \gamma f(1270) \lesssim \frac{1}{4}\Gamma(\psi \to \gamma\iota)$ is smaller than what perturbation theory suggests for a $J^P = 2^+$ glueball (*cf.* Billoire *et al.*, ref. 30). Though Liu[34)] has reported a lattice calculation for $\psi \to \gamma +$ tensor glueball that is consistent with the rate observed so far for θ, I am skeptical that such dynamical properties are reliably calculable given the present state of the art in lattice computations.

Another possibility is suggested by the dramatic absence of a θ signal in Kp scattering.[33] Since $\Gamma_{TOT}(\theta) \cong 130$ MeV, if $\overline{K}K, \eta\eta$, and $\pi\pi$ were the principal decay modes we would have $\Gamma(\theta \to \overline{K}K) \sim 100$ MeV implying a strong $\theta\overline{K}K$ coupling and it would be difficult to understand the absence of a large $Kp \to \theta\Lambda$ signal from K exchange. A dynamical explanation involving a form factor effect has been proposed by Liu.[34] Another possibility is that the LASS data is telling us that $B(\theta \to \overline{K}K) \ll 1$, so that θ has important undiscovered decay modes and $\Gamma(\psi \to \gamma\theta) \gtrsim \Gamma(\psi \to \gamma\iota)$ as naively expected for a glueball. The missing decays of θ could then be in three body or quasi two body channels that would easily have escaped detection in previous experiments.[23] An updating of Longacre's coupled channel analysis[35] that would incorporate the LASS data is needed to make this suggestion quantitative.

4. New Physics in $J^C = 1^+$

In the past several years the axial $E/f_1(1420)$ meson with $J^{PC} = 1^{++}$ has served chiefly as a confusing "old physics" background to the new physics of the ι/η (1460) in the $J^{PC} = 0^{-+}$ channel. Now the "E" again refuses to leave us in peace. The tagged $\gamma\gamma^* \to \overline{K}K\pi$ signal discovered by the TPC collaboration[36] together with Kp scattering data from the LASS collaboration[33] establish that there *must* also be new physics in the $J^C = 1^+$ channel.

Everyone, except perhaps Renard,[37] was surprised by the discovery of a beautiful peak in tagged events at 1420 MeV, $\gamma\gamma^* \to \overline{K}K\pi$, where nothing was seen in untagged events, equation (3.1). Using the Landau-Yang theorem, but in the opposite direction from its use in the analysis of the E/ι puzzle in $\psi \to \gamma\overline{K}K\pi$, we learn that the state seen in $\gamma\gamma^* \to \overline{K}K\pi$, which I will call the $X(1420)$ in order not to prejudge its interpretation, must be a spin 1 meson with positive charge conjugation, $J^C = 1^+$.

Brodsky[38] has suggested that $X(1420)$ might be a C-negative state, $J^{PC} = 1^{--}$, due to the $0(\alpha^2)$ amplitude arising from t-channel photon exchange with bremstrahlung of a virtual photon that gives rise to the X meson. This possibility should be carefully studied — for example, by looking for analogous production of the known vector mesons — but seems to me unlikely, since I would guess that very large $X(1420)$ signals would then have already been seen in photoproduction and in e^+e^- annihilation at $\sqrt{s} = m_X$. For the remainder of this talk I will assume X is produced by $\gamma\gamma^*$ scattering with $J^C(X) = 1^+$.

For reasons explained below I am fond of the (at this conference) unpopular hypothesis that X is a negative parity state,[39] in which case it is a $J^{PC} = 1^{-+}$ exotic representing new physics beyond the nonrelativistic $\bar{q}q$ spectrum. However even if $P(X) = +$ so that $J^{PC}(X)$ has the nonexotic 1^{++} value and whether X has $I = 0$ or $I = 1$ (the isospin of $X(1420)$ is not yet measured in $\gamma\gamma^*$ scattering), it is likely that $X(1420)$ still represents physics beyond the ordinary $\bar{q}q$ spectrum. If X is a 1^{++} isoscalar we could identify it with the putative $E/f_1(1420)$, sometimes regarded as the predominantly $\bar{s}s$ isoscalar of the $A_1/a_1(1270)$ nonet, together with the predominantly $(\bar{u}u + \bar{d}d)/\sqrt{2}$ $D/f_1(1285)$. This interpretation is consistent with the ratios $\tilde{\Gamma}(D \to \gamma\gamma^*)/\tilde{\Gamma}(X \to \gamma\gamma^*)$ reported at this meeting,[14] which can be accommodated by a modest deviation from ideal mixing of order $\sim 10°$. However the $E(1420)$ has never been observed in Kp scattering (with $J^{PC} = 1^{++}$ confirmed), and the LASS collaboration's confirmation[33] of the previously observed[40] $D'/f_1(1530)$ in $Kp \to D'\Lambda$ suggests that D' is a better candidate to be the $\bar{s}s$ member of the nonet. On the other hand $X(1420)$ can also not be a conventional isovector 1^{++} $\bar{q}q$ state since at 1420 MeV it is much too light to be the radial excitation of the $a_1/A_1(1270)$ for which a more plausible candidate may exist at 1700 MeV.[41]

Apart from $\gamma\gamma^*$ scattering the best evidence for a 1^{++} $E(1420)$ comes from the central production data of the WA-76 collaboration,[42] $\pi p \to \pi(\overline{K}K\pi)p$ at $E_\pi = 85$ GeV. A signal of about 1000 "E"'s is observed with K^*K the dominant decay mode. No partial wave analysis has been reported but a Dalitz plot analysis is reported to prefer $J^{PC} = 1^{++}$. The mass and width are given as 1425 ± 2 MeV and 62 ± 5 MeV. The latter is somewhat broader than the widths reported in the two photon experiments, the most serious discrepancy being with the upper limit of the MARK II collaboration, $\Gamma(X) < 40$ MeV at the 90% confidence level.[43] This is an indication that it is not safe to identify uncritically $X(1420)$ with the $E(1420)$ of WA-76. Higher statistics $\gamma\gamma^*$ data will be needed to see if the discrepancy in the width is real and, most importantly, to perform a definitive, model independent determination of the parity.

I am intrigued by a possibly related anomaly in hadronic J/ψ decay observed both by the Mark III and DM2 collaborations, reviewed at this meeting by Augustin.[44] A signal with mass and width consistent with "E"/X (*e.g.*, 1445 $\pm 5^{+10}_{-20}$ MeV and $40^{+17}_{-13} \pm 10$ MeV are reported by the Mark III group[45]) is seen in $\psi \to \omega\overline{K}K\pi$ but not in $\psi \to \phi\overline{K}K\pi$. Like the Kp scattering data this is also contrary to expectation if "E" is an $\bar{s}s$ state. The Mark III branching ratios are

$$B(\psi \to \omega\text{"}E\text{"})B(\text{"}E\text{"} \to \overline{K}K\pi) = (6.8 \pm 2.4) \cdot 10^4 \tag{4.1}$$

$$B(\psi \to \phi\text{“}E\text{”})B(\text{“}E\text{”} \to \overline{K}K\pi) < 1.1 \cdot 10^{-4} \quad (90\% \text{ CL}) \tag{4.2}$$

and there is a preliminary finding that the signal seen recoiling against ω has spin greater than zero .

It is tempting to identify this “E” produced in $\psi \to \omega$“E” with the $X(1420)$ seen in $\gamma\gamma^*$ scattering, since both signals suggest $\bar{u}u+\bar{d}d$ content rather than $\bar{s}s$. However, this identification poses another puzzle due to the absence of a $\gamma\gamma^* \to X(1420) \to \eta\pi\pi$ signal, so far quantified only by the Mark II collaboration as[43]

$$\frac{B(X \to \eta\pi\pi)}{B(X \to \overline{K}K\pi)} < 0.6. \tag{4.3}$$

Equation (4.3) suggests that X has predominant strangeonium content while equations (4.1) and (4.2) suggest the opposite. One of the reasons I am holding out for the negative parity hypothesis is that it allows a simple explanation of this puzzle[39] which the positive parity alternative does not.

Since a conventional $\bar{q}q$ interpretation seems difficult I will consider some unconventional alternatives, discussing both the positive and negative parity cases.

4.1 Unconventional: $P = +$

We will consider both $J^{PC} = 1^{++}$ $\bar{q}qg$ meiktons and $\overline{q}\overline{q}qq$ cryptoexotics. Neither possibility seems very plausible, another reason that I am keeping my shekels on negative parity.

4.1.1 A 1^{++} meikton? Though the bag model is a crude model of confinement, it has the virtue of being a *relativistic* model and provides a good description of the ground state mesons and baryons. Since the lowest gluon cavity mode has $J^{PC} = 1^{+-}$ (transverse electric), the meikton ground states consist of a spin triplet $(0,1,2)^{-+}$ and a 1^{--} spin singlet. Including hyperfine splitting from gluon exchange, the order of masses is found to be[46]

$$0^{-+} < 1^{-+} < 1^{--} < 2^{-+} \tag{4.4}$$

with isovector masses ranging from $\sim$ 1200 to $\sim$ 1800 MeV. (For the work of Chanowitz and Sharpe, reference 46, we refer here to the fit with $C_{TE}/C_{TM} = 1/2$, which is implied by the glueball interpretation of ι and θ.) The 1^{++} meikton contains an excited (transverse magnetic) gluon, $J^{PC} = 1^{--}$, so that the $\bar{q}qg_{\text{TM}}$ $(0,1,2)^{++}$ triplet and 1^{+-} singlet are expected a few hundred MeV above the $\bar{q}qg_{\text{TE}}$ ground states, with the ordering from hyperfine splitting given by[47]

$$0^{++} < 1^{++} < 1^{+-} < 2^{++}. \tag{4.5}$$

Illustrative estimates of the masses are shown in table 1. The assignment of $X(1420)$ to the 1^{++} meikton is unlikely not just because of the $\gtrsim 600$ MeV discrepancy with the predicted mass, but because we would then expect several other lighter meikton nonets including the exotic 1^{-+} nonet.

Considering the penalty required to create the valence gluon, the O(keV) $\tilde{\Gamma}(\gamma\gamma^*)$ width would suggest a predominantly $(\bar{u}u + \bar{d}d)g$ flavor composition. This would explain equations (4.1) and (4.2) but not equation (4.3). As three body decays, $\eta\pi\pi$ and $\overline{K}K\pi$ would both require one unit of angular momentum with $\eta\pi\pi$ having the smaller Q-value. The quasi two body decay $X \to K^*K$ would be s-wave while $X \to \delta\pi$ would be p-wave, but the former has a much smaller Q-value (~ 35 MeV) than the latter (~ 300 MeV) and a larger p-wave barrier does not prevent the lighter $D/f_1(1285)$ from decaying strongly by $D \to \delta\pi \to \eta\pi\pi$ (with only half the Q value of $X \to \delta\pi$). In contrast we will see in section 4.2.1 below that a $J^{PC} = 1^{-+}$ X would have strong kinematical barriers against $\eta\pi\pi$.

4.1.2 A 1^{++} cryptoexotic? This possibility has been suggested by Dave Caldwell.[48] If $X(1420)$ has positive parity it seems as good an explanation as any other. However, coming from me this is damning with faint praise, since I believe the 1^{++} cryptoexotic hypothesis has serious difficulties as discussed below — another reason to hold out for negative parity.

To describe the $\overline{q}\overline{q}qq$ states we can use Jaffe's $SU(6)_{\text{Color-Spin}} \times SU(3)_{\text{Flavor}}$ classification of the hyperfine splitting which applies to both the bag[5] and molecular[7] models. Then an s-wave 1^{++} $\overline{q}\overline{q}qq$ candidate occurs in the 18 dimensional multiplet shown in figure 2. Of these the six states shown on the right are cryptoexotics with hidden $\bar{s}s$ pairs (C^S states), like δ and S^* as discussed in Section 2. The twelve states on the left are either flavor exotics (E states) or cryptoexotics (C states) with hidden nonstrange quarks. Where quantum numbers permit the C states on the left and the C^S on the right can mix. The isoscalar $C^S = (\bar{u}u + \bar{d}d)\bar{s}s/\sqrt{2}$ is then a possible interpretation of $X(1420)$, *i.e.*, the same flavor content as proposed for the S^* in Section 2.

We note immediately that we would then expect $\psi \to \omega X(1420)$ and $\psi \to \phi X(1420)$ to occur with comparable rates (equal in the $SU(3)$ limit), contrary to equations (4.1) and (4.2). Therefore we cannot identify X with the "E" seen in hadronic ψ decay under this hypothesis. It is unsatisfying that the hypothesis leaves the $\psi \to \omega$"E" signal unexplained.

Another very serious class of problems concerns the many other light $\overline{qq}qq$ states we would expect to see if $X(1420)$ is identified with C^S, recapitulating the kinds of problems that arose during the baryonium days. The message is that we cannot lightly abandon the solution[5),6),7)] reviewed in section 2, according to which only δ and S^* are expected to emerge as resonant $\overline{qq}qq$ states. In particular, using the $SU(6)_{\text{Color-Spin}}$ results[49)] with the 1^+ C^S normalized to 1400 MeV, we would expect the following dramatic effects to occur:

1) The $\underline{18}$ would contain an $I = 3/2$ exotic at $\sim$ 1200 MeV, the $E_{\pi K}(1200)$, with a doubly charged member decaying to $K^{*+}\pi^+$. The Q-value, $\sim$ 170 MeV, is only five times that of $X \rightarrow K^*K$, so we would expect an observable enhancement with a width of order a few hundred MeV.

2) More seriously, the $\underline{18}$ would contain an $S = -2$ exotic degenerate with the $C^S = X(1400)$ in the color-spin classification, the $E_{\overline{KK}}(1400)$. It is a neutral isoscalar that decays to $\bar{K}^0\bar{K}^{*0}$. Since the recoupling coefficient is $\sqrt{2}$ times larger than the C^SK^*K coupling and the Q-values are identical, we would expect $\Gamma_{E_{KK}} \sim 2\Gamma_X$ so that the $E_{\overline{KK}}(1400)$ would easily be narrow enough to observe as a resonance. Its exotic nature would be masked in the decay (since $S = +1$ or -1 could not be fixed for the $\overline{K}^0$ detected as a K_S), but it could be determined from the formation reaction.

3) Equally serious, we would expect a cryptoexotic $J^{PC} = 1^{+-}$ nonet about fifty MeV below the putative $\underline{18}$ containing $X(1420)$. This 1^{+-} nonet, in the vicinity of the B/b_1 nonet, would include $C^0(950) \rightarrow \rho\pi$ and $C_K(1150) \rightarrow K^*\pi$, states that might be narrow enough to observe as resonances. The $C_\pi^S(1350) \rightarrow \phi\pi$ could give rise to a specacular s-wave OIZ violating enhancement; none is seen though a 1^{--} $\phi\pi$ enhancement has been observed[50)] at $\sim$ 1480 MeV. Most dangerous is the expected $C^S(1350)$ isoscalar, completely analogous to $S^*(980)$ interpreted as the 0^{++} C^S state. Like a 0^{++} $C^S(980)$, a 1^{+-} $C^S(1350)$ would lie below its nominal fall apart K^*K threshold. It could decay by OIZ rule violation to $\rho\pi$ or to K^*K by virtue of the K^* width. Comparing with $X(1420)$, which has a positive Q-value for the decay to K^*K, we expect this $C^S(1350)$ to be quite narrow, leading to the unlikely prediction of a second well-defined 1^{+-} $\rho\pi$ resonance in the well-studied region of the $h(1190)$.

The central point is that the $\overline{qq}qq$ interpretation of $X(1420)$ comes with a great deal of additional heavy baggage that cannot be ignored. Either we observe the predicted additional states (which include dramatic flavor exotics) **OR**, as for the $\delta - S^*$ hypothesis reviewed in section 2, we have a good understanding of why the other states are not observed, **OR**, following Occam, we should discard the $\overline{q}\overline{q}qq$ interpretation as introducing more puzzles than it explains.

4.2 Unconventional: $P = -$

As for the positive parity case we consider both meikton and cryptoexotic interpretations of a $J^{PC} = 1^{-+}$ $X(1420)$.

4.2.1 A 1^{-+} meikton? As described in section 4.1.1, the ground state meikton nonets are ordered in the bag model by $0^{-+} < 1^{-+} < 1^{--} < 2^{-+}$. Both the O(keV) $\gamma\gamma^*$ width and the hypothesis that X be identified with the $\psi \rightarrow \omega$"E" signal suggest that we take X to be predominantly the "ω"-like isoscalar, *i.e.*,

$$X \cong \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)g. \tag{4.6}$$

Production in hadronic ψ decay is then very natural[23] and the relative suppression of $\psi \rightarrow \phi$"E", equation (4.2), is readily understood. It is less obvious why $X \rightarrow K^*K$ dominates $X \rightarrow \eta\pi\pi$ as reported in equation (4.3). But there is a simple explanation, which is essentially kinematical.[39]

Unlike a 1^{++} state which can decay to $\delta\pi \rightarrow \eta\pi\pi$ or η"ϵ" $\rightarrow \eta\pi\pi$ in a p-wave, the $\delta\pi$ and η"ϵ" channels are strictly forbidden for a 1^{-+} state. Next consider the three body $\eta\pi\pi$ final state. Either the $\pi\pi$ pair or an $\eta\pi$ pair can have definite angular momentum. It is elementary to show that if the dipion is in an angular momentum eigenstate, then the smallest angular barrier has four units of angular momentum: $(\eta + (\pi\pi)_{L=2})_{L=2}$, that is, the dipion is in a d-wave which then is in turn in a d-wave with respect to the η. Since the dipion d-wave has negligible intensity for $m_{\pi\pi} < 1$ GeV and $m_\eta + 1$ GeV $> m_X$, there is a stupendous kinematical suppression. The other possibility[51] is that an $\eta\pi$ pair be in an angular momentum eigenstate. Then angular momentum conservation and Bose statistics also suppress the decay (at least four units of angular momentum are needed) unless there is an enhancement in the $(\eta\pi)_{L=1}$ channel, *i.e.*, an isovector $J^{PC} = 1^{-+}$ exotic resonance, which removes the Bose symmetry constraint. Referring to this 1^{-+} isovector as X_1 (since it could be the $I = 1$ partner of the $X(1420)$), we could then have the p-wave decay $X \rightarrow X_1\pi \rightarrow \eta\pi\pi$. In fact an $\eta\pi$ p-wave resonance, the $M(1400)$, has recently been discovered[52),44] which according to the 1^{-+} meikton hypothesis is the expected isovector partner of

$X(1420)$. But then the decay $X \to M\pi$ has a negative Q-value and cannot occur. Thus kinematics alone implies that a predominantly nonstrange 1^{-+} state would have a strongly suppressed $\eta\pi\pi$ decay. This is a compelling feature of the negative parity meikton hypothesis.

Like the $\overline{q}\overline{q}qq$ interpretations discussed in sections 4.1.2 and 4.2.2, a 1^{-+} $\overline{q}qg$ interpretation of $X(1420)$ implies the existence of companion states in the same mass region as suggested in table 1. It is amusing that experimental indications exist for several of these states. As discussed in section 3.1 the strong upper limits in $\gamma\gamma \to \eta\pi\pi$ for $\eta(1275)$ and $\eta(1390)$ are highly unexpected for radially excited $\bar{q}q$ pseudoscalars. They would be more readily understood if $\eta(1275)$ and $\eta(1390)$ were the $\overline{q}qg$ ground states expected in roughly that mass region. As argued in section 3.1, if the radially excited isoscalar pseudoscalars were above 1500 MeV they could coexist with the weaker bounds in that region. The $J^{PC} = 1^{--}$ $C(1480) \to \phi\pi$ state[50] could be the 1^{--} "ρ" $\overline{q}qg$ state, since it has the characteristic OIZ violating final state that could be characteristic of meikton states.[53),2),23)] The ACCMOR collaboration[41)] has observed a possible second bump at $\sim$ 1800 MeV in the $I = 1$ $J^{PC} = 2^{-+}$ channel of the $A_3/\pi_2(1680)$. It would be far too light at 1800 MeV to be the radial excitation of $A_3/\pi_2(1680)$ but would fit nicely with the expected "ρ" $\overline{q}qg$ 2^{-+} state. Finally the $M(1400)$ $\eta\pi$ p-wave resonance[52)] could be the isovector partner of $X(1420)$. Though it may be difficult to assess the full partial wave analysis of reference 52, the existence of the $M(1400)$ seems very likely just on the strength of the observed front-back asymmetry. The asymmetry implies an odd partial wave, which is necessarily exotic in the $\eta\pi$ channel. If it is not 1^{-+} then it must be an even more peculiar $3^{-+}, 5^{-+}, \ldots$

.

For the 1^{-+} $\overline{q}qg$ nonet of table 1, the expected two body decay modes are[53),2),23)]

$$
\begin{aligned}
``\rho"(1410) &\to \pi\eta, \pi\eta', \pi\rho, \pi b_1, \pi D, K^*K \\
``\omega"(1510) &\to \rho\rho, K^*K \\
``\phi"(1700) &\to \eta\eta', K^*K \\
``K"(1500) &\to \pi K, \eta K, \phi I, \pi Q
\end{aligned}
\tag{4.7}
$$

The "ρ"(1410) corresponds to $M(1400)$ and the "ω"(1510) to $X(1420)$. The decay $X(1420) \to \rho\rho$ could still occur by virtue of the ρ width. (In reference 39 it is incorrectly stated that $1^{-+} \to \rho\rho$ is forbidden in a narrow width approximation for the rho meson — I am grateful to Frank Close for pointing out the error.) The question of whether decays to an s-wave plus a p-wave state (*e.g.*, πb_1 or πD) are greatly enhanced[54] relative to decays to two s-wave states (*e.g.*, $\pi\eta, \pi\eta'$, or $\pi\rho$) is in my opinion[2),23)] an uncertain dynamical issue.

The 1^{-+} "ρ" $\stackrel{?}{=} M(1400)$ and "ϕ" states would also be formed in $\gamma\gamma^*$ scattering. For ideal mixing and neglecting mass corrections we would expect the usual quark model ratio

$$\text{“}\rho\text{”} : \text{“}\omega\text{”} : \text{“}\phi\text{”} \cong 9 : 25 : 2. \tag{4.8}$$

Thus a second smaller peak is expected above the $X(1420)$ in $\gamma\gamma^* \to \overline{K}K\pi$ (smaller by no more than an order of magnitude), and it would be interesting to look for and place bounds on $\gamma\gamma^* \to M(1400) \to \pi\eta$. The 1^{-+} nonet may also show up in hadronic J/ψ decay, in the channels

$$\psi \to \begin{cases} (\rho \text{ or } b_1) & + \quad \text{“}\rho\text{”} \\ (\omega \text{ or } h) & + \quad \text{“}\omega\text{”} \\ (\phi \text{ or } h') & + \quad \text{“}\phi\text{”} \\ (K^* \text{ or } Q) & + \quad \text{“}K\text{”} \end{cases} \tag{4.9}$$

The second of these would correspond to the observed $\psi \to \omega$"E" decay discussed above, which could then be used to estimate the expected signals in the ρ"ρ", ϕ"ϕ", and K^*"K" channels.

4.2.2 A 1^{-+} cryptoexotic? Close and Lipkin[55] (of U. Tenn. and U. Wis.) have proposed that $M(1400)$ and $C(1480)$ might be interpreted as $\overline{qq}qq$ cryptoexotic states, resulting from mixing of 18 and 18* multiplets (see figure 1 for the content of the 18). The same explanation could be offered for a 1^{-+} $X(1420)$. $J^{PC} = 1^{-+}$ and 1^{--} $\overline{qq}qq$ states do not appear in the s-wave ground state; they must have at least one unit of orbital angular momentum, $L = 1$. The subsequent centrifugal barrier would then help stabilize them, though this effect could typically be offset by the correspondingly greater masses. Close and Lipkin argue that the ratio $\Gamma(M \to \eta\pi)/\Gamma(M \to \eta'\pi) \cong O(1)$ if $M(1400)$ is a meikton and $\gg 1$ if it is a cryptoexotic state. Lipkin[56] has also invoked the OIZ rule to deduce that $M \to \eta\pi$ cannot proceed by the octet component of the η, though I believe the conclusion is vitiated by the fact that we know (from the $\eta - \eta'$ mixing and the associated "$U(1)$ problem") that the OIZ rule is strongly violated for the light pseudoscalars.

This proposal has many uncertainties and potential problems. Neither the flavor mixing nor the 18 - 18* mixing are predicted. And it is not known which of the multitude of possible $L = 1$ (or lighter $L = 0$) states are narrow enough to observe as resonances. However, just as was discussed in section 4.1.2 for the case of an s-wave 1^{++} cryptoexotic, we would also expect narrow, neutral $S = 2$ E_{KK} exotics to appear in the p-wave K^*K decay channel at $\sim$ 1400 MeV. The color-spin analysis would also predict a much lighter $L = 1$ 1^{-+} cryptoexotic nonet, which would be just the $L = 1$ excitation of the ground state 0^{++} cryptoexotic nonet discussed in section 2 (see figure 1). Extrapolating from the mass difference of the 0^+ $C^S(9)$ and the 1^+ $C^S(18)$ given in reference 5, this lighter 1^{-+} nonet would lie 500 MeV below the 1400-1500 MeV scale of the $M(1400)$ and $C(1480)$, a clearly implausible proposition.

The s-wave 1^+ C^S state discussed in section 4.1.2 would at 1420 MeV be about $\sim$ 100 MeV lighter than the color-spin calculation would predict if the overall scale is normalized to the 0^+ nonet with S^* and δ interpreted as C^S and C^S_π. That discrepancy is certainly acceptable given the large theoretical uncertainty. But the $L = 1$ $18 + 18^*$ 1^+ C^S and C^S_π states would then have been expected to be still $\sim$ 1/2 GeV heavier, say $m_{A_2} - m_\rho \cong 550$ MeV. This is a much more serious discrepancy. Conversely if we interpret $M(1400)$ and $C(1480)$ as $L = 1$ cryptoexotics then we would expect the 18 $L = 0$ axial vector states discussed in section 4.1 to be about 500 MeV lighter. The 18 would include a very light $S = 2$ E_{KK} exotic that would lie near or even below KK threshold, an astounding prospect. The $J^{PC} = 1^{+-}$ cryptoexotic nonet discussed in section 4.2.1 would be even lighter. The C^S and C^S_π states would be stabilized by the OIZ rule and could not have avoided detection.

5. Conclusion

Despite the impressive and beautiful data reported at this meeting, there are still major gaps in our knowledge of the two photon widths of the ordinary $\bar{q}q$ mesons. These gaps impede our ability to confirm the possible existence of new phenomena beyond the $\bar{q}q$ spectrum. In particular, the absence of the expected few keV signals for the p-wave $\bar{q}q$ scalars and the radially excited $\bar{q}q$ pseudoscalars prevents our drawing final conclusions as to the nature of δ and S^* in the first case and $\iota(1460)$, $\eta(1275)$, and $\eta(1390)$ in the second.

The power of two photon physics is clearly illustrated by the studies of the spin 1 $\overline{K}K\pi$ resonance, "$X(1420)$", seen in tagged events. With ten or twenty such events the TPC decisively ended the twenty year debate over whether there is a $J = 1$ $\overline{K}K\pi$ resonance at 1420 MeV, a question that had remained unclear despite many hadron scattering experiments, some with two orders of magnitude greater statistics. The interesting question that still remains unanswered today is whether the X is a J^{PC}

exotic, *i.e.*, whether it has positive or negative parity. To answer it we must *measure* $\sigma_{\rm LT}/\sigma_{\rm TT}$ or we must restrict the analysis to $Q^2 \gg M_X^2$ where it is safe to assume that $\sigma_{\rm LT}$ dominates. In either case much higher statistics experiments are needed than we have today.

The experimental studies presented at this meeting[14] were based on a model[57] of $\sigma_{\rm LT}/\sigma_{\rm TT}$ that applies to nonrelativistic $\bar{q}q$ mesons. The light hadrons, made of u, d, and s quarks, are certainly *relativistic* bound states, so it is not surprising that the nonrelativistic model of the light hadrons has a mixed history of success and failure. In fact, at first sight the successes are more surprising than the failures. In any event it is clear that any new application of the model cannot be blindly trusted but needs to be tested directly. The studies of the $D/f_1(1280)$ provide some indirect confirmation but fall short of a systematic measurement of $\sigma_{\rm LT}/\sigma_{\rm TT}$. Furthermore, no one has produced a model of $\sigma_{\rm LT}/\sigma_{\rm TT}$ for a 1^{-+} $\overline{q}qg$ state, nor is a reliable model likely in the near future. A model-dependent analysis that is consistent with positive parity would not exclude negative parity. We really need a model-independent analysis. Nothing less should be trusted to answer such a fundamental question.

To give a (pre)judicious summary, the hypothesis that $X(1420)$ is a $J^{PC} = 1^{-+}$ $\overline{q}qg$ exotic is able to explain the paradox of the X's flavor content — that both the $\gamma\gamma^*$ and ψ decay data suggest $\bar{u}u + \bar{d}d$ while the dominance of $X \to \overline{K}K\pi$ over $\eta\pi\pi$ suggests $\bar{s}s$. The simple, essentially kinematical explanation is given in section 4.2.1. It does not apply to a $J^{PC} = 1^{++}$ state.

There are other problems associated with the 1^{++} hypothesis. Since the 1^{++} nonet is nicely filled by the $D'/f_1(1530)$, a 1^{++} state would not fit into the $\bar{q}q$ spectrum. Then the only possibility seems to be a narrow $\overline{q}\overline{q}qq$ state, which would open a Pandora's box of many, many new states including $S = 2$ and $I = 3/2$ flavor exotics at low mass, $\lesssim 1400$ MeV, as discussed in section 4.1.1. Either we should find these flavor exotics or have a very good reason for why we have not. Because of the range of undetermined possibilities, a world of $\overline{q}\overline{q}qq$ states could drive a person to drink or even to superstrings. Indeed superstring and $\overline{q}\overline{q}qq$ models have similar predictive power for the meson spectrum below 2 GeV.

Since I have now alienated most of my friends I will conclude by saying that the study of two photon physics is more exciting than ever. It is at the center of the effort to study gluonic states, along with J/ψ decay and hadron scattering experiments. To go farther we badly need a higher luminosity facility. PEP could begin to answer this need by providing another order of magnitude in statistics. However it is clear that a two order of magnitude increase could be profitably used, as would be provided by an e^+e^- collider operating at a luminosity of 10^{33} cm.$^{-2}$ sec.$^{-1}$ Two photon physics then provides another motivation for some of the high luminosity B factory proposals under consideration.

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References

1. Proceedings of the Second International Conference on Hadron Spectroscopy, eds. Y. Oyanagi, K. Takamatsu, and T. Tsuru, April 16-18, 1987, KEK report 87-7 (Tsukuba, July, 1987).
2. M. Chanowitz, ref. 1, p. 269.
3. M. Chanowitz, p. 95, Proc. VI Intl. Workshop on Photon-Photon Collisions, ed. R. Lander (World Scientific, Singapore, 1984).
4. N. Tornqvist, *Phys. Rev. Lett.* **49**, 624 (1982).
5. R. Jaffe, *Phys. Rev.* **D15**, 267 (1977).
6. R. Jaffe and F. Low, *Phys. Rev.* **D19**, 2105 (1979).
7. J. Weinstein and N. Isgur, *Phys. Rev. Lett.* **48**, 659 (1982); *Phys. Rev.* **D27**, 588 (1983).
8. A. Martin *et al.*, *Phys. Lett.* **74B**, 417 (1978).
9. A. Etkin *et al.*, *Phys. Rev.* **D25**, 2446 (1982).
10. K. Au, D. Morgan, and M. Pennington, *Phys. Lett.* **167B**, 229 (1986); *Phys. Rev.* **D35**, 1633 (1987).
11. M. Pennington, these proceedings.
12. N. Achasov *et al.*, *Zeit. für Physik* **C16**, 55 (1982).
13. T. Barnes, *Phys. Lett.* **165B**, 434 (1985); p. 25, Proc. VII Intl. Workshop on Photon-Photon Collisions, eds. A. Courau and P. Kessler (World Scientifc, Singapore, 1986).
14. G. Gidal, these proceedings, and references cited therein.
15. J. Olsson, these proceedings.
16. H. Marsiske, these proceedings. *Cf.* also ref. 14.
17. According to a private communication from a camel merchant at the Ber Sheva market on Thursday morning April 28, the possibility of extracting a large

$\epsilon \to \gamma\gamma$ signal from the data was discussed that morning at the Shoresh meeting and should appear in reference 11.
18. W. Allen, private communication to M. Farrow, c. 1984.
19. Particle Data Group, *Phys. Lett.* **170B**, 1 (1986).
20. S. Flatté, *Phys. Lett.* **63B**, 224 (1976).
21. J. Gay *et al.*, *Phys. Lett.* **63B**, 220 (1976).
22. H. Harari, private communication.
23. M. Chanowitz, LBL-24355, to be published in Proc. of the Charm Physics Symposium/Workshop, I.H.E.P., Beijing, June, 1987.
24. N. Stanton *et al.*, *Phys. Rev. Lett.* **42**, 346 (1979).
25. A. Ando *et al.*, *Phys. Rev. Lett.* **57**, 1296 (1986); T. Tsuru, p. 233, reference 1.
26. S. Chung *et al.*, *Phys. Rev. Lett.* **55**, 779 (1985).
27. T. Tsuru, p. 233, reference 1.
28. B. Jean-Marie, p. 652, Proc. XXXIII Intl. Conf. on H.E.P., Berkeley, July, 1986, ed. S. Loken (World Scientific, Singapore, 1987); A. Seiden, H. Sadrozinski, and H. Haber, SCIPP-88/08, 1988.
29. K. Ishikawa, *Phys. Rev. Lett.* **46**, 978 (1981); M. Chanowitz, *Phys. Rev. Lett.* **46**, 981 (1981).
30. J. Korner and M. Krammer, *Zeit. für Physik* **C16**, 279 (1983).
31. S. Cooper, reference 1.
32. L. Köpke, p. 692, Proc. XXXIII Intl. Conf. on H.E.P., *op cit.*
33. S. Suzuki, p. 64, reference 1.
34. K. Liu, these proceedings.
35. R. Longacre *et al.*, p. 729, Proc. XXXIII Intl. Conf. on H.E.P., *op cit.*
36. H. Aihara *et al.*, *Phys. Rev. Lett.* **57**, 2500 (1986); S. Yellin, these proceedings.
37. F. Renard, *Nuovo Cim.* **A80**, 1 (1984).
38. S. Brodsky, these proceedings.
39. M. Chanowitz, *Phys. Lett.* **B187**, 409 (1987).
40. P. Gavillet *et al.*, *Zeit. für Physik* **C16**, 119 (1982).
41. C. Daum *et al.*, *Nucl. Phys.* **B182**, 269 (1982).
42. T. Armstrong *et al.*, *Phys. Lett.* **167B**, 133 (1986).
43. G. Gidal, private communication.
44. J. Augustin, these proceedings.
45. See reference 32.

46. M. Chanowitz and S. Sharpe, *Nucl. Phys.* **B222**, 211 (1983); T. Barnes, F. Close, and F. de Viron, *Nucl. Phys.* **B224**, 241 (1983); M. Flensburg, C. Peterson, and L. Sköld, *Zeit. für Physik* C22, 293 (1984).
47. M. Chanowitz and S. Sharpe, *Phys. Lett.* **132B**, 413 (1983).
48. D. Caldwell, *Mod. Phys. Lett.* **A2**, 771 (1986); and these proceedings.
49. See reference 5.
50. D. Alde *et al.*, *Nucl. Phys.* **B269**, 485 (1986); *Yad. Fiz.* **44**, 120 (1986).
51. I wish to thank J. Rosner for calling this possibility to my attention and B. Ioffe for pointing out the role of Bose statistics.
52. D. Alde *et al.*, CERN-EP/88-15.
53. M. Chanowitz and S. Sharpe, reference 46.
54. N. Isgur and J. Paton, *Phys. Lett.* **124B**, 247 (1983).
55. F. Close and H. Lipkin, RAL-87-046.
56. H. Lipkin, p. 363, reference 1.
57. R. Cahn, *Phys. Rev.* **D35**, 3342 (1987); *Phys. Rev.* **D37**, 833 (1988).

	0^{-+}	1^{-+}	1^{--}	2^{-+}	0^{++}	1^{++}	1^{+-}	2^{++}
ρ	1200	1410	1640	1790	1800	1940	2130	2230
ω	1300	1510	1650	1890	1900	2040	2130	2320
K	1410	1590	1800	1940	1980	2110	2260	2350
ϕ	1630	1800	1980	2100	2220	2310	2400	2510

Table 1. Ground state meikton masses in MeV from Chanowitz and Sharpe, references 46 and 47, for the choice $C_{TE}/C_{TM} = 1/2$ as implied by glueball assignments for $\iota(1460)$ and $\theta(1720)$.

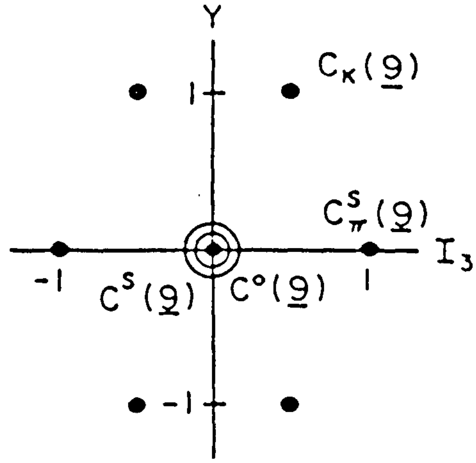

Figure 1. The cryptoexotic $\overline{q}\overline{q}qq$ nonet from reference 5.

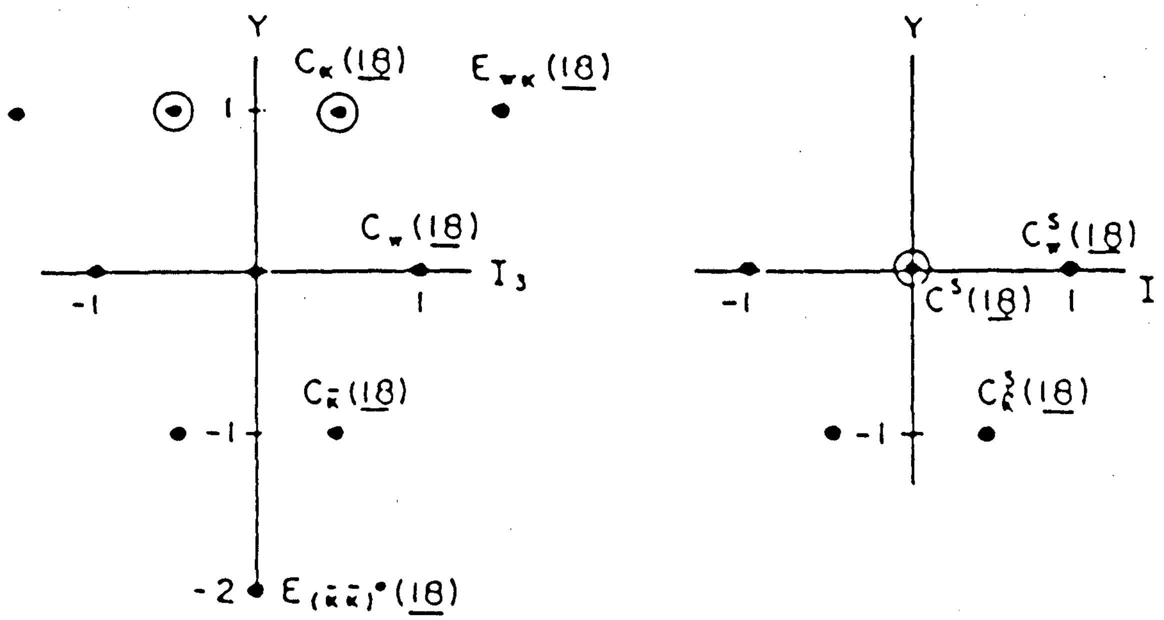

Figure 2. The 18 dimensional $\overline{q}\overline{q}qq$ multiplet from reference 5. The six states with hidden $\bar{s}s$ pairs are displayed on the right.

Questions and Discussion

<u>H. Marsiske (DESY)</u>

Comment on the scalar state underneath the $f_2(1270)$: Using the channel $\gamma\gamma \to \pi^0\pi^0$ Crystal Ball has put an upper limit on $\Gamma_{\gamma\gamma}(f0(1300))$ of less than 1.8 keV at 90% CL assuming $\Gamma_{TOT}(f0) = 300$ MeV. This limit does not account for the interference effects. However, the recent Mark II analysis of $\gamma\gamma \to \pi^+\pi^-$ suggests $\Gamma_{\gamma\gamma}(f0)$ less than about 1 keV including these effects. So the existence of a $\Gamma_{\gamma\gamma} \approx 10$ KeV object in the $f_2(1270)$ region is highly unlikely.

<u>H. Lipkin (WIS – Wisconsin)</u>

The $\delta - S^*$ puzzle might be illuminated by a consistent high-statistics investigation of $\gamma\gamma \to K\bar{K}$ and $\gamma\gamma \to \eta\pi$ near $K\bar{K}$ threshold and using an updated Flatté analysis.

<u>M. Chanowitz (LBL – Ljublana)</u>

Absolutely!

<u>J. Rosner (U. Chicago)</u>

Not all $q\bar{q}$ models for the 0^+ nonet give large $\gamma\gamma$ widths. If one considers the transitions $0^+ \to 1^-\gamma$ (and relates the $\gamma\gamma$ widths to them by vector dominance) there are <u>two</u> possible E1 contributions, the naive one and another which arises only in relativistic order. This second E1 contribution is quite important, for example, in photoproduction of negative-parity baryon resonances. The same cancellation is also responsible for the prediction of a dominant $\lambda = 2$ in $f_2 \to \gamma\gamma$ [See J. Babcock and J. Rosner, *Phys. Rev.* **D14**, 1286 (1976)].

<u>M. Chanowitz</u>

That is an interesting possibility. If true it would illustrate the danger of relying blindly on the nonrelativistic quark model for the light hadrons.

<u>S. Brodsky (SLAC)</u>

In a relativistic theory one expects mixing between Foch states such as $|q\bar{q}g\rangle$, $|q\bar{q}q\bar{q}\rangle$, $|gg\rangle$, $|ggg\rangle$ etc., as long as quantum numbers match. Shouldn't we expect this type of mixing in the spectra you are analyzing?

<u>M. Chanowitz</u>

We should indeed. How much mixing there is needs to be considered case by case. Of course the nice thing about J^{PC} exotics is that they will not mix with $\bar{q}q$. I would add that while higher Foch states are important in short distance hadron dynamics (*e.g.*, in deep inelastic scattering), it is remarkable how little impact has been demonstrated on spectroscopy. Instead static properties seem to be dominated by the valence quanta (to an even greater extent than one might have guessed). For instance, good old $SU(3)$ flavor symmetry — where the subject began — would not apply if the valence $\bar{q}q$ and qqq Foch states didn't dominate meson and baryon static properties. This is not to say that flavor octet mesons don't contain higher Foch states but rather that the extent to which those Foch states are also in the octet reflects the importance of the valence component.

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