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Progress Toward Identification of Gluonic States *

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Invited talk presented at The Second International Conference on Hadron Spectroscopy, April 16-18, 1987, KEK, Tsukuba, Japan, and to be published in the proceedings.

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Progress Toward Identification of Gluonic States ·

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Abstract

Progress in the last two years toward identification of gluonic states is reviewed. Discovery of additional pseudoscalars tends to confirm the glueball interpretation of $\iota(1460)$. A variety of evidence indicates new physics in the $J = 1$ channel in the E mass region.

1. Introduction

This has been a very interesting, even exciting conference. Much progress has been made since the previous meeting two years ago. Many new states have been added to the list of the "ordinary" $\bar{q}q$ spectrum, increasing our understanding of gluonic candidates such as $\iota(1460)$. Striking new data has been presented that points clearly to new physics in the $J = 1$ channel, possibly due to gluonic states.

An important result is the emergence of the pseudoscalar $\eta(1400)$, seen at KEK^{1,2} and BNL^{3,4}. From the mass and width it cannot be identical with $\iota(1460)$. The excited pseudoscalar nonet can now be filled by $\eta(1280)$ and $\eta(1400)$, leaving $\iota(1460)$ as the "odd man out". Together with its "sticky" production and decay dynamics, ι is essentially confirmed as the first clear glueball. However, there is still much to do. We need to understand the differences in the KEK and BNL data and why the ι in radiative J/ψ decay is not fit by a simple Breit-Wigner^{5,6}. To understand the $I, J^{PC} = 0, 0^{-+}$ channel in this region will take higher statistics studies of $\eta(1280)$, $\eta(1400)$, and $\iota(1460)$, in radiative J/ψ decay, two photon scattering, and hadronic reactions. In particular, the BNL data might hold still more surprises.⁴

It was clear two years ago that $\theta(1730)$ cannot be an ordinary $\bar{q}q$ meson.⁷ LASS Kp scattering data adds further confirmation, with the absence of a θ signal beside a prominent f' signal.⁸ θ is certainly a resonance, since it is clearly seen in three decay channels by three experimental groups, but only in radiative J/ψ decay. It might be a glueball or a $\bar{q}qg$ state. The LASS data suggests that $B(\theta \rightarrow \bar{K}K) \ll 1$ which would imply a large value for $B(\psi \rightarrow \gamma\theta)$, making a glueball interpretation more likely.

A comment about the names for $\bar{q}qg$ states: *meikton*, *hermaphrodite*, and *hybrid*. Though *hybrid* is preferred by the Editorial Board of *Nuclear Physics B*, I prefer *meikton* because it is firmly rooted in the classical Greek tradition of particle names, such as *electron* and *proton*. Pronounced make-ton, it means a "mixed thing" in ancient Greek. But

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for this meeting a more appropriate name is 交配已禾重 (with apologies for terrible calligraphy). Pronounced *ko-hai-shu*, it means "cross bred species", abbreviated in this talk as 交 or *ko*. (In Texas where people ride horses this is sometimes written as 交.)

Now back to physics: there are fascinating signs of new physics in the $J = 1$ channel, once again in the E/ν region! While high statistics experiments disagree^{4,9} on the existence of the $J^{PC} = 1^{++} E(1420)$, the TPC^{10,11} and Mark II^{12,6} groups report an unambiguous $\bar{K}K\pi$ resonance at ~ 1420 in tagged two photon scattering, $\gamma\gamma^* \rightarrow \bar{K}K\pi$. It is not seen in untagged events, $\gamma\gamma \rightarrow \bar{K}K\pi$, which can only be understood if the object $X(1420)$ has $J = 1$, therefore $J^C = 1^+$. The large size of the reported signal and the possible connection with the "E" signal seen by the Mark III¹³ in $\psi \rightarrow \omega \bar{K}K\pi$ suggest that $X(1420)$ might be¹⁴ an exotic $J^{PC} = 1^{-+}$ state, perhaps $(\bar{u}u + \bar{d}d)g$. Compelling evidence for new physics is added by the LASS confirmation⁸ of the $J^{PC} = 1^{++} D'(1530)$ in Kp scattering. With $D'(1530)$, $X(1420)$, and $D(1280)$ there are at least three $J^C = 1^+$ states where the nonrelativistic $\bar{q}q$ spectrum can only accommodate the two isoscalars of the 1^{++} nonet. The hypothesis that $X(1420)$ is a 1^{-+} exotic is consistent with the preliminary evidence¹⁵ presented here of a p-wave $\eta\pi$ resonance in the 1400 MeV region. If $X(1420)$ is an isoscalar 交, an $\eta\pi$ p-wave resonance could be its isovector partner.

$C(1480)$, reported by the Lepton-F collaboration,¹⁶ is a $J^{PC} = 1^{--}$ resonance in the $\phi\pi$ channel. $\phi\pi$ is an interesting decay mode since it is OIZ forbidden for any $\bar{q}q$ meson and could be¹⁸ a "signature" decay mode of 交 states. The hint of a $\phi\omega$ decay of $\xi(2230)$ could have a similar interpretation.¹⁸ (Lipkin will discuss the possibility that $\bar{q}\bar{q}qq$ states could also have such apparently OIZ violating decays.)

The topics introduced above are discussed at greater length in the sections that follow. In the remainder of this section I comment on some objects that there is not time to discuss more fully: $G/f_0(1590)$, $S_1/f_0(991)$, and the three g_T/f_2 states. A common theme is that none is observed in radiative J/ψ decay, with stringent upper limits in each case. Since perturbation theory¹⁹ suggests that the 0^{++} and 2^{++} digluon channels in $\psi \rightarrow \gamma gg$ are as important as the 0^{-+} channel in which the large iota signal is observed, it would be surprising if any of these objects were glueballs.

$G(1590)$ is distinguished principally by its pattern of decays, in the ratios²⁰

$$\eta\eta' : \eta\eta : \bar{K}K : \pi\pi \cong 1 : 3 : (< 1) : (< 0.3). \quad (1.1)$$

Assuming $SU(3)$ symmetry this pattern cannot be explained by any $\bar{q}q$ assignment. The large couplings of η and η' to the two gluon channel that is suggested by radiative ψ decay data (which incidentally can be understood *without* assuming large glueball admixtures in η or η' ²¹) implies a mechanism²² by which $G \rightarrow \eta\eta$ or $\eta\eta'$ could dominate if G were a glueball. But the failure to observe a clear $G \rightarrow \eta\eta$ signal in the θ region, $B(\psi \rightarrow \gamma G) < 10^{-3}$, weighs against the glueball interpretation.²⁰ A more recent hypothesis²³ is that G could be an octet component of a 0^{++} 交 nonet, which would be naturally suppressed in radiative ψ decay and would still have large $\eta\eta'$ and $\eta\eta$ decays.

A partial wave analysis²⁴ of the $0^{++}\pi\pi$ and $\bar{K}K$ channels near 1 GeV provides evi-

dence for three isoscalar resonances. I am not competent to judge the model-independence of the conclusions or whether uncertainties in the data might effect the qualitative conclusions. One of these resonances, $S_1(991)$, has approximately flavor independent couplings to $\pi\pi$ and $\bar{K}K$, and is therefore suggested as a possible glueball. This motivation is counter to an observation²⁵ made shortly after the discovery of iota in radiative J/ψ decay that $J = 0$ glueballs may decay preferentially to K mesons, because in perturbation theory

$$\mathcal{M}(gg \rightarrow \bar{q}q)_{J=0} \propto m_q \quad (1.2)$$

so that $\bar{s}s$ dominates. The physics of eq. (1.2) is familiar to everyone: it is why $\Gamma(\pi \rightarrow \mu\nu) \gg \Gamma(\pi \rightarrow e\nu)$. (The amplitude $gg \rightarrow \bar{q}q\bar{q}q$ occurs in the same order but is suppressed at low mass by phase space.) Furthermore, the rate for $\psi \rightarrow \gamma\pi\pi$ in this mass region is extremely small. The upper limit¹³ $B(\psi \rightarrow \gamma S^* \rightarrow \gamma\pi\pi) < 0.7 \cdot 10^{-4}$ also applies to S_1 and is two orders of magnitude less than $B(\psi \rightarrow \gamma\mu)$. Nor does S_1 have a larger double pomeron coupling than the other two states, though the conjecture that double pomeron exchange might favor glueball production is one of the motivations of such a search. I wonder whether the three states could instead be explained in terms of "cryptoexotic" $\bar{q}\bar{q}qq$ states expected²⁶ in this region and p-wave $\bar{q}q$ states?

According to the OZI rule a resonance in $\pi\pi \rightarrow g_T \rightarrow \phi\phi$ could not be a $\bar{q}q$ meson but might be a glueball or an $\bar{s}sg$ \bar{X} . I repeat the apology that I am not competent to have an opinion on the sophisticated partial wave analysis needed to see the three g_T states.²⁷ Both Mark III and DM2 data imply stringent upper limits⁶ on $\psi \rightarrow \gamma g_T$. For the entire 2.1–2.4 GeV region, the rate according to the Mark III is

$$B(\psi \rightarrow \gamma\phi\phi) \cong 3 \cdot 10^{-4}. \quad (1.3)$$

There is a peak at 2200 but with $J^P = 0^-$ according to DM2. Furthermore, there is no $\psi \rightarrow \gamma\phi\phi$ signal at the mass corresponding to $g_T(2010)$, the most prominent state in the $\pi\pi \rightarrow \phi\phi$ analysis.

The contents of the remaining sections are as follows:

- Section 2: a brief sketch of the status of the "ordinary" $\bar{q}q$ spectrum.
- Section 3: iota.
- Section 4: theta.
- Section 5: comments on production and decays of gluonic states, with discussions of $C(1480)$ and $\xi(2230)$.
- Section 6: new physics in the $J = 1$ channel.
- Section 7: conclusion.

2. "Ordinary" Mesons

The spectrum and dynamical properties of the "ordinary" mesons is interesting physics, that must be understood in detail to find and identify gluonic states. The success of the simple $\bar{q}q$ classification is itself a puzzle, since the light mesons are *not* nonrelativistic systems. We are lucky that spectroscopic properties are dominated by the valence quarks. If $\bar{q}q$, $\bar{q}q\bar{q}q$, $\bar{q}q\bar{q}q\bar{q}q$... wave function components were important spectroscopically, then there would not be simple $SU(3)_{\text{flavor}}$ representations and it would have been much harder to discover quarks and QCD. The spectroscopic dominance of the valence quarks is one reason to hope that a simple-minded view of gluonic states in terms of valence gluons may be qualitatively correct.

Table 2.1 is a nonauthoritative, noncomprehensive, personal view of the status of the spectrum. As the key shows, the four sides of a box denote the $I = 1$, $I = 1/2$, and two $I = 0$ members of a nonet. Solid lines are established, dashed lines require confirmation and crooked lines have ambiguous assignment (e.g., excited $J^P = 1^-$ could be radially or orbitally excited). One year ago my chart only had three complete nonets - π, ρ, a_2 - astonishingly meager for thirty years of hard work, the lesson being that mesons spectroscopy is very difficult. It is encouraging that one year later we can add two and perhaps four more nonets. The b_1 and ρ_3 nonets have been completed, and the a_1 and π' (radial) nonets seem to have a least enough (if not too many!) states.

Progress in the radially excited π' nonet concerns the two isoscalars. In $\pi p \rightarrow \eta\pi\pi n$ a KEK experiment finds two 0^- resonances in the $\delta\pi$ channel.^{1,2} Observation of $\eta(1280)$ confirms a previous observation at Argonne.²⁸ The mass and width are 1279 ± 5 and 32 ± 10 , where the width is not corrected for the 20 MeV mass resolution. The second state was originally reported at 1420 ± 5 with $\Gamma = 31 \pm 7$ (uncorrected for 25 MeV resolution), and a more recent data sample gives a mass of 1390 ± 10 . I will refer to this state as $\eta(1400)$. It is certainly not identical with ι , $M = 1461 \pm 5 \pm 5$ and $\Gamma = 101 \pm 10 \pm 10$.¹³

A BNL experiment in $\pi p \rightarrow \bar{K}K\pi n$ also finds evidence for pseudoscalars in the mass region.^{3,4} The $0^{-+}\delta\pi$ intensity has a peak at 1280 that seems compatible with $\eta(1280)$ seen at KEK in $\delta\pi \rightarrow \eta\pi\pi$. In $0^{-+}\delta\pi$ at 1400 MeV there is an enhancement that might be consistent with $\eta(1400)$ in $\delta\pi \rightarrow \eta\pi\pi$ but is marginal statistically (depending on how the background is drawn). The dominant 0^{-+} structure is in K^*K . It peaks at ~ 1420 MeV with $\Gamma \sim 60$ MeV, apparently too broad to be simply identified with $\eta(1400)$ at KEK.

Since KEK and BNL are perhaps not confirming one another at 1400 MeV, pessimists could argue that we still have not found the states that fill the nonet. They might be right. But both experiments see structure in the 0^{-+} channel at 1400-1420 MeV that cannot be identical to ι , so that there seem to be at least enough pseudoscalars to fill the nonet. Furthermore, the Mark III group observes an $\eta\pi\pi$ enhancement in $\psi \rightarrow \gamma\eta\pi\pi$ at 1390 MeV that could be $\eta(1400)$.¹³ If analysis shows this state to have $J^{PC} = 0^{-+}$, it would confirm the existence of $\eta(1400)$.

$N = 1$ $S = 0$ $S = 1$ $L = 0$ $\boxed{0^{--}}$ $\boxed{1^{--}}$ $L = 1$ $\boxed{1^{+-}}$ $(\boxed{0}, \boxed{1}, \boxed{2})^{++}$ $L = 2$ $|2^{--}\rangle$ $(\{\underline{1}\}, 2, \underline{3})^{--}$ $L = 3$ $3^{+-}\rangle$ $(\underline{2}, \underline{3}, \underline{4})^{++}$ $L = 4$ $4^{--}\rangle$ $(\underline{3}, \underline{4}, \underline{5})^{--}$ \vdots $N = 2$ $L = 0$ $\boxed{0^{--}}$ $\boxed{1^{--}}$ $L + 1$ 1^{+-} $(0, \underline{1}, \underline{2})^{++}$

KEY:

$$1 \begin{array}{c} \bar{s}s \\ \boxed{I} \\ \bar{u}u + \bar{d}d \end{array} \frac{1}{2}$$

Established

Possible

Ambiguous

 ~

Table 1. A non-authoritative summary of the meson spectrum.

If there are too many pseudoscalars in the region for one nonet and a glueball, it will not be hard to make use of the extra states. If the speculations about 1^{-+} ~~\bar{K}~~ in section 6 and $C(1480)$ in section 5 are verified, then the bag model^{17,29,30} would predict a pseudoscalar ~~\bar{K}~~ nonet in this mass region. In the bag model the $J^{PC} = 0^{-+}$ nonet is predicted to be the lightest of the four ground state nonets, 1^{--} and $(0, 1, 2)^{-+}$.

Neither KEK nor BNL have yet provided estimates of the production cross sections for their pseudoscalar signals. Since both experiments have the same $E_\pi = 8$ GeV beam energy, the ratio of cross sections for a given state is the ratio of the partial widths. This would be very helpful for understanding the nonet structure and possible mixing.

LASS has presented data⁸ from $Kp \rightarrow K\bar{K}\pi\Lambda$ that might complete both the 1P_1 and 3P_1 nonets, $J^{PC} = 1^{+-}$ and 1^{++} respectively. The $1^+\bar{K}K\pi$ channel is dominated by a peak at ~ 1500 MeV with an asymmetry in \bar{K}^*K and $K^*\bar{K}$ understood as interference of the $1^{+-}H'(1400)$ and the $1^{++}D'(1530)$. The H' , with $\Gamma < 150$ MeV, is seen for the first time in this experiment and completes the b_1 nonet. (I am mixing old and new nomenclature so the reader will be as confused as I am!) The mixing of this nonet remains to be understood. It is correlated with the 1^{++} nonet because the mass eigenstates Q_1 and Q_2 are presumably mixtures of the $SU(3)$ states Q_A and Q_B . Previous analyses by LASS³¹ and ACCMOR³² suggested 45° mixing, implying

$$m_{Q_A} = m_{Q_B} = \frac{1}{2}(m_{Q_1} + m_{Q_2}) = 1340 \text{ MeV}. \quad (2.1)$$

The confirmation of the $1^{++}D'(1530)$ by LASS adds weight to its assignment as the $\bar{3}_s$ member of the a_1 nonet since it is produced in K scattering where $E(1420)$ is conspicuously absent. This would leave the puzzle of understanding the $1^{++}E$, seen most convincingly in a ~ 1000 event signal in central production by WA76 at the SPS.⁹ It also leaves the problem of understanding the $J^C = 1^+$ signal in $\gamma\gamma^* \rightarrow \bar{K}K\pi$ at the E mass, discussed in section 6. As for the excited pseudoscalars, we seem to have at least enough states for the nonet. Maybe I have been thinking about the E for too long and should take up superstrings, but I am still too confused to be confident the a_1 nonet is finally understood.

The filled nonet of highest spin is the leading $L = 2$ 3D_3 ρ_3 nonet with $J^{PC} = 3^{--}$. To the previously known $\rho_3(1690)$, $\omega_3(1670)$, and $K_3^*(1780)$, LASS⁸ now adds the $\phi_3(1857)$. This makes a textbook ideal nonet with the relations

$$m_\rho = m_\omega \quad (2.2)$$

$$m_\rho + m_\phi = 2m_K \quad (2.3)$$

beautifully fulfilled.

3. $\iota(1460)$, $\eta(1420)$ and all that ...

The glueball interpretation of $\iota(1460)$ is summarized by (1) too many $I = 0$ pseudoscalars and (2) sticky production and decay properties. Point (1) was discussed in section 2: there are now at least enough $I = 0$ pseudoscalars to fill the radially excited 0^{-+} nonet without the $\iota(1460)$. The $\eta(1280)$ has been seen by three experiments in $\pi p \rightarrow \eta(1280)n$, in two decaying to $\eta\pi\pi$ and in one to $\bar{K}K\pi$. The $\eta(1400)$ with $\Gamma \sim 30$ MeV is seen in $\pi p \rightarrow \eta\pi\pi n$ in the $\delta\pi$ channel, perhaps in $\pi p \rightarrow \bar{K}K\pi n$ (also in $\delta\pi$), and corresponds nicely in mass and width to a signal in $\psi \rightarrow \gamma\eta\pi\pi$ that still requires spin-parity analysis. In addition there is a strong 0^{-} signal seen in $\pi p \rightarrow K^*K n$, though with possibly larger mass, ~ 1420 MeV, and width, ~ 60 MeV.

The second point is the striking stickiness of iota as seen in $\psi \rightarrow \gamma\iota$ and (not) $\iota \rightarrow \gamma\gamma$. The rate

$$B(\psi \rightarrow \gamma\iota) > (5 - 7) \cdot 10^{-3} \quad (3.1)$$

is the largest of any meson and is a large fraction ($\sim 5 - 10\%$) of all $\psi \rightarrow \gamma X$. The $\bar{K}K\pi$ mode accounts for $\sim 5 \cdot 10^{-3}$ and $\rho\rho$ and $\omega\omega$ might account³³ for another $\sim 2 \cdot 10^{-3}$. Since there could be other decay modes ($\eta'\pi\pi$ might be large), eq. (3.1) is a lower bound. Iota is not seen in the $\gamma\gamma$ channel, with the strongest limit from the TPC,³⁴

$$\Gamma(\iota \rightarrow \gamma\gamma)B(\iota \rightarrow \bar{K}K\pi) < 1.6 \text{ keV (95\%CL)} \quad (3.2)$$

Since $\psi \rightarrow \gamma X$ proceeds perturbatively³⁵ by $\psi \rightarrow \gamma gg$, the partial width $\Gamma(\psi \rightarrow \gamma\iota)$ measures the gg coupling as $\iota \rightarrow \gamma\gamma$ measures the $\gamma\gamma$ coupling. This oversimplifies since $\psi \rightarrow \gamma\iota$ has contributions from off-shell gluons. Nonetheless, the stickiness³⁶ is roughly a measure of the ratio of color to electric charges, defined to remove the effect of phase space:

$$S_X = \frac{\Gamma(\psi \rightarrow \gamma X) \text{LIPS}(X \rightarrow \gamma\gamma)}{\Gamma(X \rightarrow \gamma\gamma) \text{LIPS}(\psi \rightarrow \gamma X)} \quad (3.3)$$

where LIPS = Lorentz Invariant Phase Space. S_X is a nice variable theoretically because wave function properties tend to cancel and experimentally because unknown branching ratios (such as $B(\iota \rightarrow \bar{K}K\pi)$) cancel. From (3.1) and (3.2) we find

$$S_\iota : S_\gamma : S_\eta = (> 65) : 4 : 1 \quad (3.4)$$

where $S_\eta = 1$ by convention.

As discussed in section 1, the prominence of $\iota \rightarrow \bar{K}K\pi$ is not evidence against a glueball interpretation since iota has spin zero so that²⁵ eq. (1.2) applies, i.e., $gg \rightarrow \bar{s}s$ dominance for $J = 0$. This suggests another possibility: could iota be a radially excited $\bar{s}s$ state? It would then have a naturally small $\gamma\gamma$ coupling and would be produced more copiously in radiative J/ψ decay than its $\bar{u}u + \bar{d}d$ partner because of eq. (1.2). This model fails however to explain the relative rates for $\psi \rightarrow \gamma + \eta/\eta'/\iota$. Furthermore such a model could not explain the proliferation of pseudoscalars. However, it might account for the lower component of iota in the two resonance fit described by Wisniewski.⁵

To really understand the pseudoscalars in this region and how they may be mixed, there is much more to do. The structures in the hadronic experiments need more study, including the Kp data which is apparently very different from πp . The $\gamma\gamma$ channel must be studied with more sensitivity; surprisingly neither $\eta(1280)$ nor $\eta(1400)$ have yet been observed despite a search by the Crystal Ball in the $\eta\pi\pi$ channel at the 0.3 keV level.³⁷ Higher statistics J/ψ studies are needed to see $\eta(1280)$ and $\eta(1400)$ in radiative and hadronic J/ψ decay and to understand why θ is not fit by a simple Breit-Wigner. These studies will also clarify whether there are even too many pseudoscalars for one nonet and a glueball. As discussed in section 2, a second pseudoscalar nonet is expected in this mass region if the wild speculations of sections 5 and 6 are correct.

4. $\theta/f_2(1720)$

Since θ has been observed by three different groups in three decay modes, with spin $J = 2$ determined in two of the modes, there is no question it is a genuine resonance. All this evidence comes from radiative J/ψ decay. There is no firm evidence of θ production from any other source. There are bumps at the right mass in hadronic J/ψ decay with no spin determinations; they are discussed in section 5.

θ has been observed decaying to $\eta\eta, \bar{K}K$ and $\pi\pi$, with $J = 2$ determined in the first two. The $\bar{K}K$ channel is most prominent and gives¹³

$$M, \Gamma = 1720 \pm 10 \pm 10, 130 \pm 20 \quad (4.1)$$

consistent with the more difficult measurement in the $\eta\eta$ channel

$$M, \Gamma = 1670 \pm 50, 160 \pm 80. \quad (4.2)$$

Adding all three channels,

$$B(\psi \rightarrow \gamma\theta) \geq 1.6 \cdot 10^{-3} \quad (4.3)$$

The right side of (4.3) is comparable to $B(\psi \rightarrow \gamma f)$ and an order of magnitude bigger than $B(\psi \rightarrow \gamma f')$.

The upper limit on $\theta \rightarrow \gamma\gamma$ has become rather tight, with the best limit from the TPC³⁸

$$\Gamma(\theta \rightarrow \gamma\gamma)B(\theta \rightarrow \bar{K}K) < 0.2 \text{ keV (95\% CL)} \quad (4.4)$$

The right hand side is an order of magnitude smaller than $\Gamma(f \rightarrow \gamma\gamma) \cong 2\frac{1}{2}$ keV and a factor two bigger than $\Gamma(f' \rightarrow \gamma\gamma) \cong 0.1$ keV. Assuming the s-wave amplitudes dominate over the d-wave we can compute the stickiness ratio

$$S_\theta : S_{f'} : S_f = (> 20) : 3 : 1 \quad (4.5)$$

This is impressive though less striking than eq. (3.4) for θ .

A possible θ signal is seen by WA76³⁹ in central production, $\pi^+p \rightarrow \pi^+(K^+K^-)p$, with $M = 1742 \pm 10$ and $\Gamma = 127 \pm 30$. However, the signal is rather small and the evidence for $J = 2$ is not definitive. No θ enhancement is evident in the Y_4^0 moment.

Though LASS sees f' clearly in $K^-p \rightarrow K_S K_S \Lambda$, no θ signal is observed.⁸ This suggests θ is a very different object than f' but it also suggests a problem.^{40,41} Since $\theta \rightarrow \bar{K}K$ is the most prominent of the observed decay modes and since θ is broad, the absence of θ in Kp scattering requires either that single K exchange is suppressed or that there are still many missing decay modes so that $B(\theta \rightarrow \bar{K}K) \ll 1$. Concerning the latter possibility, Longacre's global fit⁴⁰ to $\pi\pi \rightarrow \pi\pi/\eta\eta/\bar{K}K$ and $\psi \rightarrow \gamma\pi\pi/\eta\eta/\bar{K}K$ results in $B(\theta \rightarrow \bar{K}K) = .38_{-0.19}^{+0.09}$ and $B(\theta \rightarrow \pi\pi) < .04$. This does not incorporate the latest LASS data which will cause $B(\theta \rightarrow \bar{K}K)$ to decrease further.⁴² Given the uncertainties the possibility of many missing modes cannot be ruled out. If there were large missing modes, $\Gamma(\psi \rightarrow \gamma\theta)$ would be of the order of $\Gamma(\psi \rightarrow \gamma\iota)$ and a glueball interpretation would be more compelling.

It seems clear that θ is not a $\bar{q}q$ state. If it were it would be a radial excitation of f and f' . The low mass would suggest predominant $\bar{u}u + \bar{d}d$ content, but then the prominence of the $\bar{K}K$ mode and the tight $\gamma\gamma$ limit, eq. (4.4), are difficult to understand. If on the other hand we assume θ is predominantly $\bar{s}s$, there are many problems:

- $m_\theta - m_{f'}$ is too small.
- $\Gamma(\psi \rightarrow \gamma\theta)/\Gamma(\psi \rightarrow \gamma f')$ is too large.
- $\sigma(Kp \rightarrow \theta\Lambda)/\sigma(Kp \rightarrow f'\Lambda)$ is too small.
- There should be a lighter $\bar{u}u + \bar{d}d$ partner.

In fact the BNL $\pi\pi \rightarrow \bar{K}K$ analysis⁴⁰ suggests a broad 2^{++} $\bar{u}u + \bar{d}d$ excitation at 1858 MeV. We would then expect the $\bar{s}s$ partner at ~ 2100 MeV.

With what is known now we should consider both glueball and $\bar{\chi}$ hypotheses as possibilities. The lack of $SU(3)$ symmetry in the small $\pi\pi : \bar{K}K \cong 1 : 4$ ratio does not rule out the glueball hypothesis. As argued elsewhere⁴³ in more detail, this could be due to kinematics. For instance, in a model with $\theta \rightarrow \bar{u}u + \bar{d}d + \bar{s}s$ that is $SU(3)$ symmetric at the quark level, the greater phase space of the multibody channels available to the $\bar{u}u + \bar{d}d$ component would cause a smaller fraction of $\bar{u}u + \bar{d}d$ to hadronize to $\pi\pi$ than $\bar{s}s$ to $\bar{K}K$. This is essentially equivalent to Liu's discussion⁴⁴ of a form factor effect.

5. Comments on Production and Decay: $\iota(1460)$, $\theta(1700)$, $C(1480)$, and $\xi(2230)$.

Consider the naive perturbative estimates for radiative J/ψ decay to glueballs $G = |gg\rangle$, ko-hai-shu $\bar{\chi} = |\bar{q}qg\rangle$, and ordinary mesons $M = |\bar{q}q\rangle$. In lowest order $\psi \rightarrow \gamma X$ proceeds by $\psi \rightarrow \gamma gg$, and counting powers of α_S we find

$$\Gamma(\psi \rightarrow \gamma G) \sim O(\alpha_S^2) \quad (5.1)$$

$$\Gamma(\psi \rightarrow \gamma \bar{\chi}) \sim O(\alpha_S^3) \quad (5.2)$$

$$\Gamma(\psi \rightarrow \gamma M) \sim O(\alpha_S^4) \quad (5.3)$$

implying a hierarchy of production rates

$$\Gamma(\psi \rightarrow \gamma G) > \Gamma(\psi \rightarrow \gamma \bar{\chi}) > \Gamma(\psi \rightarrow \gamma M) \quad (5.4)$$

Equation (5.4) explains why iota was immediately regarded²⁵ as a possible glueball: confused with the obscure $1^{++}E$, it appeared in $\psi \rightarrow \gamma "E"$ with the largest branching ratio of any radiative J/ψ decay. Since there is no reason to expect a 0^{-+} glueball to be produced in $\psi \rightarrow \gamma G$ much more copiously than a 2^{++} glueball, $\theta(1700)$ would be a more convincing glueball candidate if it were observed with a larger branching ratio $B(\psi \rightarrow \gamma\theta)$ (as the LASS data indirectly suggests). In the presently observed modes it occurs at a rate that is only 1/4 of that observed so far for iota.

Next consider hadronic J/ψ decays, $\psi \rightarrow M + (G \text{ or } \mathfrak{X} \text{ or } M')$ where M is a meson of known flavor content, e.g., ω or ϕ . Such decays have been studied systematically by the Mark III^{5,16,13} and DM2.^{45,46} Direct hadronic J/ψ decay occurs in lowest order⁴⁷ by $\Gamma(\psi \rightarrow ggg) \sim O(\alpha_s^3)$. From the lowest order diagrams beginning from the three gluon intermediate state we obtain

$$\Gamma(\psi \rightarrow M \mathfrak{X}) \sim O(\alpha_s^5) \quad (5.5)$$

$$\Gamma(\psi \rightarrow MG) \sim O(\alpha_s^6) \quad (5.6)$$

$$\Gamma(\psi \rightarrow MM') \sim O(\alpha_s^6) \quad (5.7)$$

The estimates (5.5) and (5.7) are reduced by α_s^2 for flavor configurations that are DOZI⁴⁸ (double OZI suppressed), such as $\psi \rightarrow \phi f$ or $\psi \rightarrow \omega f'$. Provided the $M \mathfrak{X}$ final state is not DOZI suppressed, the hierarchy is

$$\Gamma(\psi \rightarrow M \mathfrak{X}) > \Gamma(\psi \rightarrow MG) \sim \Gamma(\psi \rightarrow MM') \quad (5.8)$$

In $\psi \rightarrow \omega \bar{K} K \pi$ a significant $\bar{K} K \pi$ enhancement is seen in the E region, $M = 1444 \pm 5_{-20}^{+10}$ and $\Gamma = 40_{-13}^{+17} \pm 10$.¹³ The spin is not yet well-determined. No similar enhancement is seen in $\psi \rightarrow \phi \bar{K} K \pi$, so it is unlikely to be $E(1420)$ interpreted as the $\bar{3}_s$ member of the A_1 nonet (more about this in section 6!). There is no evidence for $\psi \rightarrow M \iota$.

Enhancements^{13,46,47} in $\psi \rightarrow \omega K^+ K^-$ and $\psi \rightarrow \phi K^+ K^-$ might be due to $\theta(1730)$ though such an identification would be premature in the absence of a J^P determination. The enhancement in $\phi K^+ K^-$ is 50–60 MeV lower than the nominal θ mass and could easily be due to another state.

If \mathfrak{X} with valence gluons do indeed exist, we can use the bag model to get a qualitative understanding of their likely properties. The bag⁴⁹ is a relativistic model of confined bound states which accounts well for mesons and baryons containing unexcited quarks, though it stumbles in an essential way when excited quarks are required. For gluonic states, it naturally puts valence gluons on an equal footing with valence quarks and therefore predicts that \mathfrak{X} should exist.^{17,29,30} The ground state valence gluon is the TE (transverse electric) mode with axial (!) spin-parity $J^P = 1^+$, obtained by solving Maxwell's equation in a spherical cavity (just as the quark modes are obtained from the free Dirac equation solved in a spherical cavity). Excited TM (transverse magnetic) modes also occur with the naively expected $J^P = 1^-$. If we trust cavity perturbation theory further than we perhaps should, then the TE modes couple in an approximately flavor symmetric way to $\bar{q}q$ while the TM modes favor $\bar{3}_s$, which could lead to dominantly strange final states for $\bar{q}qg_{TM}$ decays.¹⁸

The ground state $\bar{\mathfrak{X}}$ then consist of four $\bar{q}qg_{TE}$ nonets, a $\bar{q}q$ spin singlet with $J^{PC} = 1^{--}$ and the triplet $(0,1,2)^{-+}$. The 1^{-+} nonet is of particular interest since it is a $\bar{q}q$ exotic. The $\bar{q}qg_{TM}$ nonets have the same J^{PC} as the p-wave $\bar{q}q$ nonets of the nonrelativistic model: 1^{+-} and $(0,1,2)^{++}$.

I want to make two comments on the decay modes. The first concerns the flavor structure of the final state for $\bar{\ell}\ell'g$ states where ℓ, ℓ' can be u or d . Consider decays that proceed by $g \rightarrow \bar{s}s$. The first step is

$$(\bar{\ell}\ell')_8g \rightarrow (\bar{\ell}\ell')_8(\bar{s}s)_8 \quad (5.9)$$

where the subscript 8 denotes *color octet*. We can then form a final state of two hadrons either by rearrangement

$$(\bar{\ell}s)_1(\bar{s}\ell')_1 \quad (5.10)$$

or by soft gluon exchange

$$(\bar{\ell}\ell')_1(\bar{s}s)_1 \quad (5.11)$$

with the subscript 1 denoting *color singlet*. Equation (5.10) should usually dominate but (5.11) might occur an appreciable fraction of the time. If (5.11) does occur, it may be the signature^{17,18} of a $\bar{\mathfrak{X}}$ decay, since such final states are OIZ forbidden decays of all $\bar{q}q$ mesons. The decay $C(1480) \rightarrow \phi\pi$ and the possible decay $\xi(2230) \rightarrow \phi\omega$ are discussed below.

The second comment¹⁷ concerns two body decays of the ground state $\bar{\mathfrak{X}}$ $\bar{q}qg_{TE}$'s. The first step of the decay

$$(\bar{q}q)_8^{\ell=0}g_{TE} \rightarrow (\bar{q}q)_8^{\ell=0}(\bar{q}'q')_8^{\ell=1} \quad (5.12)$$

leads to two color octet $\bar{q}q$ pairs, one in the $J^{PC} = 0^{-+}$ or 1^{--} state of an $\ell = 0$ $\bar{q}q$ pair, the other with the $J^{PC} = 1^{++}$ of the TE gluon. In the bag model, one member of the 1^{++} $\bar{q}q$ pair is in an excited cavity mode, $j^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$ ($j-j$ coupling). After rearrangement to make color singlets, as in eq. (5.10), the naive expectation is to have one ground state meson, $J^{PC} = 0^{-+}$ or 1^{--} , and one excited meson incorporating the excited quark, $J^{PC} = 1^{+-}$ or $(0,1,2)^{++}$ depending on the particular initial state in question. This is also the expectation of the flux tube model.⁵⁰ However, the dynamics of bag fission is not at all understood, and another possibility is that the excited quark "loses" its angular momentum to the orbital angular momentum of one of the two newly formed bags, resulting in two ground state mesons which are in a p-wave with respect to one another. For example, the $I = 1, J^{PC} = 1^{-+}$ exotic $\bar{\mathfrak{X}}$ could decay to $(\pi b_1)_{\ell=0}$ by the first mechanism or to $(\pi\eta)_{\ell=1}$ by the second. Depending on the $\bar{\mathfrak{X}}$ masses, phase space might sometimes favor or even require the second mechanism. The bottom line is this: *all models are guilty until proven innocent*. Until our understanding is much greater than it is now, we should search in all the kinematically allowed channels. The two body $\ell = 1$ decays are experimentally easier than the $\ell = 0$ decays which are quasi two body.

Now I turn to two examples. A very interesting object is reported¹⁶ by the Lepton-F collaboration at Serpukhov in $\pi^-p \rightarrow \phi\pi^0n$. A $\phi\pi$ resonance is seen with $M = 1480 \pm 40$

and $\Gamma = 130 \pm 60$, denoted $C(1480)$. The spin-parity is determined to be $J^P = 1^-$ from the t -dependence, implying single pion exchange, and from the angular distribution, favoring 1^- over 3^- or higher J . Since the decay mode is of the type of eq. (5.11) it immediately sets off the \mathfrak{A} alarm:

$$\begin{aligned} C^+ &\stackrel{?}{=} (\bar{u}d)_8^1 S_0 g_{TE} \rightarrow (\bar{u}d)_8^1 S_0 (\bar{s}s)_8^3 P_1 \\ &\rightarrow \phi\pi^+ \\ &\text{gluon exch.} \end{aligned} \quad (5.13)$$

This is a decay to two ground state mesons in a relative p -wave, as discussed in the previous paragraph. Other such modes are $\omega\pi, \eta\rho, \pi\pi$, and $\bar{K}K$. If C is a $\bar{q}qg_{TE}$ \mathfrak{A} then the TE gluon probably couples to $\bar{u}u$ and $\bar{d}d$ as often as to $\bar{s}s$, so I would expect

$$B(C \rightarrow \omega\pi) \gtrsim B(C \rightarrow \phi\pi) \quad (5.14)$$

whereas if it is a $\bar{q}q\bar{q}q$ state containing an $\bar{s}s$ pair I would expect

$$B(C \rightarrow \omega\pi) \ll B(C \rightarrow \phi\pi). \quad (5.15)$$

Examples of s -wave decays to a ground state meson plus an excited meson are $a_1\pi$ and $b_1\pi$, both with small Q -values.

The second example is $\xi(2230)$, seen by the Mark III¹³ in $\psi \rightarrow \gamma K^+ K^-, \gamma K_S K_S$ with a modest rate, $B(\psi \rightarrow \gamma\xi \rightarrow \gamma\bar{K}K) \sim (6-8) \cdot 10^{-5}$, that does not set off the glueball alarm. The Mark III reports $J \geq 2$. DM2 does not observe the ξ but the disagreement is not serious since their upper limit⁴⁶ is consistent with the Mark III if $\Gamma_\xi \geq 30$ MeV or for any width if $B(\psi \rightarrow \gamma\xi \rightarrow K^+ K^-) \sim 2 \cdot 10^{-5}$, the latter being a 1.5σ fluctuation on the Mark III measurement of $(4.2_{-1.4}^{+1.7} \pm 1.8) \cdot 10^{-5}$.

The $\xi(2230)$ has been seen by LASS⁸ in $K^- p \rightarrow (K^+ K^- + K_S K_S) \Lambda$ with $J \geq 2$ clearly established and a suggestion of $J \geq 4$ from an enhancement at the ξ mass in the Y_8^0 moment. If $J = 4$ were confirmed, it would verify a suggestion⁵¹ that ξ is the 4^{++} $\bar{s}s$ state, partner to the $f_4(2030)$.

GAMS reports^{20,2} an $\eta\eta'$ enhancement in $\pi^- p \rightarrow \eta'\eta n$ with $M = 2220 \pm 10$, $\Gamma < 60$, and $J \geq 2$, which could be due to the ξ . If it is ξ and if it is identified with a similar signal seen by MIS-IHEP in $\pi p \rightarrow K_S K_S n$, then $B(\eta\eta') > 2B(\bar{K}K)$, which would be inconsistent with an $\bar{s}s$ interpretation.

Sharpe and I suggested that ξ might be a $(\bar{u}u + \bar{d}d)g_{TM}$ \mathfrak{A} which would decay to $\bar{K}K$ because of the enhanced $g_{TM}\bar{s}s$ coupling mentioned above.¹⁸ Under this hypothesis it could have $J^{PC} = 0^{++}$ or 2^{++} . We suggested a search for $\xi \rightarrow \phi\omega$ since by the gluon exchange mechanism the decay would proceed by

$$\begin{aligned} (\bar{u}u + \bar{d}d)_8^3 S_1 g_{TM} &\rightarrow (\bar{u}u + \bar{d}d)_8^3 S_1 (\bar{s}s)_8^3 S_1 \\ &\sim \omega_8 \phi_8 \\ &\rightarrow \omega\phi \\ &\text{gluon exch.} \end{aligned} \quad (5.16)$$

The second line emphasizes that after $g_{TM} \rightarrow \bar{s}s$ the four quarks are essentially an ω and a ϕ in color octets, which can become $\omega\phi$ by soft gluon exchange. The Mark III reports a 90% upper limit $B(\phi \rightarrow \gamma\xi)B(\xi \rightarrow \phi\omega) < 6 \cdot 10^{-5}$ based on the data in figure (5.1). It is intriguing that 6 of the ~ 50 events on the plot fall in the ξ bin, the largest bin on the plot. If these six events were attributed to ξ , they would correspond to a branching ratio of $B(\phi \rightarrow \gamma\xi)B(\xi \rightarrow \omega\phi) \sim 3 \cdot 10^{-5}$, which is as large as the signals in K^+K^- or $K_S K_S$. Clearly we want to see more statistics. If ξ is the 2^{++} $\bar{\mathfrak{X}}$ then its dominant decay would be to $\bar{K}^* K^*$.

Finally a word about $\bar{\mathfrak{X}}$ mass estimates in the bag model. In refs. (17) and (18) the $\bar{q}qg_{TE}$ and $\bar{q}qg_{TM}$ ground state masses are computed with second order perturbation theory. After fitting to the iota mass there is one free parameter, C_{TE}/C_{TM} , the ratio of the TE and TM self energies. References (29) and (30) consider only the $\bar{q}qg_{TE}$ states, also through second order, the former with no self energy contributions and the latter with self energy contributions fixed by a dynamical model. If in ref. (17), C_{TE}/C_{TM} is set to $\sim 1/2$ to fit θ as the 2^{++} glueball, then the $I = 1$ $1^{--}\bar{q}qg_{TE}$ is expected at ~ 1600 (cf. $C(1480)$) and the $I = 0$ $2^{++}(\bar{u}u + \bar{d}d)g_{TM}$ is expected near ~ 2300 (cf. $\xi(2230)$).¹⁸ We then also expect the $1^{-+}(\bar{u}u + \bar{d}d)g_{TE}$ near 1400 MeV (see section 6). With this value of C_{TE}/C_{TM} , the $\bar{q}qg_{TE}$ masses from ref. (18) are in agreement with those of refs.(29) and (30). In the flux tube model,⁵² the 1^{-+} $\bar{\mathfrak{X}}$ are expected to be a few hundred MeV heavier.

6. $E(1420)$ and all that ... again ($J = 1$ version).

In the study of $\iota(1460)$ the $J = 1$ $\bar{K}K\pi$ channel in the E/ι mass region was regarded as background to the new physics emerging in the $J = 0$ channel. Now that we are close to understanding the new physics of the $J = 0$ channel (see Section 3), we begin to find signs of new physics in the $J = 1$ channel. It seems that the E/ι region does not want to go away!

I will begin with a capsule summary of the developments from 1966 to the present. In 1966 a $J^{PC} = 0^{-+}\bar{K}K\pi$ resonance was observed⁵³ in $\bar{p}p$ annihilation at rest with the CERN hydrogen bubble chamber. Named E for Europe, the parameters were $M = 1425 \pm 7$ and $\Gamma = 80 \pm 10$. The statistical level was high for the time, 600 total events in the signal over virtually no background, and the 0^{-+} determination was made by two methods. In the years until 1980 the spin-parity was not confirmed, though there were also no experiments that matched the original one in statistical power.

In 1980 at the CERN PS the channel $\pi^-p \rightarrow \bar{K}K\pi n$ was studied⁵⁴ with a 4 GeV π beam. With 100 events over comparable background, the analysis indicated that the E is a $J^{PC} = 1^{++}$ state, confirming a previous experiment⁵⁵ at the LBL Bevatron. This result was widely accepted at the time; the Particle Data Group⁵⁶ incorporated the E into the meson table as an established 1^{++} resonance. Together with other developments in the 1^{++} nonet, the E was plausibly the $\bar{s}s$ member of the nonet.

Just as order seemed to emerge from chaos, chaos struck again with the discovery of a large "E" signal by the Mark II⁵⁷ in $\psi \rightarrow \gamma\bar{K}K\pi$. For several reasons — including the

Landau–Yang theorem⁵⁸ which suggests that a 1^{++} state should not be copiously produced in the two gluon $\psi \rightarrow \gamma X$ channel — Ishikawa and I suggested²⁵ that the object seen by the Mark II was a pseudoscalar and probably a glueball. The pseudoscalar hypothesis was confirmed by the Crystal Ball⁵⁹ in 1982, and it seemed that both 1^{++} and $0^{-+} \bar{K} K \pi$ resonances had been established.

This moment of apparent clarity would also not last long. The existence of the $1^{++} E$ was called into question by the high statistics $\pi p \rightarrow \bar{K} K \pi n$ BNL experiment with an 8 GeV π^- beam which observed $\eta(1420)$ in the 0^{-+} partial wave but no clear resonant structure in the 1^{++} wave.^{3,4} Partial wave analysis of K beam data failed to confirm the $1^{++} E(1420)$ though a $1^{++} \bar{K} K \pi$ isobar was seen⁶⁰ at 1530, labeled $D'/f_1(1530)$. But the $1^{++} E(1420)$ was also not without support: WA76 observing central $\bar{K} K \pi$ production with high energy π and p beams at the SPS⁹ finds a high statistics $1^{++} K^* K$ signal at $M = 1425 \pm 2$ and $\Gamma = 62 \pm 5$. At this point we could only cry out for help!

In 1986 help arrived (or so it seemed at first) from the TPC collaboration. In untagged $\gamma\gamma \rightarrow \bar{K} K \pi$ scattering they obtained the upper bound on $\iota \rightarrow \gamma\gamma$ utilized in Section 3, but in tagged events $\gamma\gamma^* \rightarrow \bar{K} K \pi$ they discovered an unmistakable “E” signal,¹¹ confirmed by the Mark II.¹² The Landau–Yang theorem now enters the story for the second time (now read in the other direction): since a $J = 1$ particle cannot couple to two massless gauge bosons, the data requires — as shown quantitatively by fits to the q^2 dependence — that the $\gamma\gamma^*$ signal be $J = 1$. Apparently then we have strong confirmation of a $1^{++} E$.

Well, maybe The data suggested two or three problems. First, the initial TPC signal¹¹ was too much of a good thing. In the Renard⁶¹ convention (a factor 2 larger than that used by the TPC), which corresponds to the physical partial width for real decays such as $1^{++} \rightarrow \gamma e^+ e^-$, the TPC result was

$$\frac{m_E^2}{Q^2} \Gamma(E \rightarrow \gamma\gamma^*) \cdot B(E \rightarrow \bar{K} K \pi) = 12 \pm 4 \pm 4 \text{ keV} \quad (6.1)$$

Correcting an error in the prescient paper of Renard, we can use the nonrelativistic quark model for a crude estimate of the D and E partial widths in terms of the known $\gamma\gamma$ widths of other p-wave mesons. Assuming D and E to be the ideally mixed 1^{++} states, we find comparing to $\Gamma(f \rightarrow \gamma\gamma)$ that

$$\frac{Q^2}{M_E^2} \Gamma(E \rightarrow \gamma\gamma^*) \sim 0.4 \text{ keV} \quad (6.2)$$

$$\frac{Q^2}{M_D^2} \Gamma(D \rightarrow \gamma\gamma^*) \sim 4 \frac{1}{2} \text{ keV}. \quad (6.3)$$

Equations (6.1) and (6.2) differ by at least an order of magnitude. It seemed very difficult to understand the data in terms of an $\bar{3}_s$ state.

A second problem, with a similar message, emerges from the Mark III study of hadronic J/ψ decays.¹³ As noted in Section 3, an “E” signal is seen in $\psi \rightarrow \omega$ “E” but

not in $\psi \rightarrow \phi$ "E":

$$B(\phi \rightarrow \omega \text{ "E"})B(\text{ "E"} \rightarrow \bar{K}K\pi) = (6.8 \pm 2.4) \cdot 10^{-4} \quad (6.4)$$

$$B(\psi \rightarrow \phi \text{ "E"})B(\text{ "E"} \rightarrow \bar{K}K\pi) < 1.1 \cdot 10^{-4} (90\%CL) \quad (6.5)$$

Again we have data that cannot be understood in terms of an $\bar{s}s$ state.

Motivated by these two problems I proposed¹⁴ a radical solution: that the state seen in $\gamma\gamma^* \rightarrow \bar{K}K\pi$ and $\psi \rightarrow \omega\bar{K}K\pi$ is an isoscalar exotic with $J^{PC} = 1^{-+}$ that could be interpreted as a $(\bar{u}u + \bar{d}d)g_{TE}$ ground state $\bar{\chi}$. The most attractive feature of the exotic hypothesis is that if it is confirmed, it points unmistakably to new physics. We would not need to repeat the kind of analysis needed in the 0^{-+} channel to decide whether ι represents new physics. But we would still need to decide whether a $1^{-+}X(1420)$ is a $\bar{\chi}$ or something else.

I argued¹⁴ that a substantial $\gamma\gamma^*$ width, say of the order of magnitude estimated for the $D(1280)$ in eq. (6.3), might be expected for a $(\bar{u}u + \bar{d}d)g$ exotic since the suppression for creating the gluon could be compensated by the fact that the $\bar{u}u + \bar{d}d$ $\bar{\chi}$ is in a relative s-wave compared to p-wave for $D(1280)$. The principal decay modes would be K^*K (consistent with what is observed¹²) and $A_1\pi$. The $\delta\pi$ and $\rho\rho$ decay modes would be forbidden while $\eta\pi\pi, \rho\pi\pi$, and " ϵ " " ϵ " would be suppressed. ($\eta\pi\pi$ is suppressed because definite J for the dipion requires four units of angular momentum for the $\eta\pi\pi$ system. Definite J^P for $\eta\pi$ favors $\eta\pi$ in the exotic $J^{PC} = 1^{-+}$ channel and would only be important if X could decay by single pion emission to its $I = 1$ partner, unlikely because ΔE is probably too small — I thank J. Rosner for bringing the latter possibility to my attention).

A 1^{-+} at ~ 1400 MeV would be consistent with the bag model mass estimates discussed at the end of Section 5. The other members of the 1^{-+} nonet could appear in the following decay modes:

$$X_\rho \rightarrow \pi\eta, \pi\eta', \pi\rho, \pi B, \pi D, K^*K \quad (6.6)$$

$$X_\phi \rightarrow \eta\eta', K^*K \quad (6.7)$$

$$X_{K^0} \rightarrow \pi K, \eta K, \pi Q, \phi K \quad (6.8)$$

The $\pi\eta, \pi\eta'$, and $\eta\eta'$ modes are attractive experimentally since in a p-wave they are uniquely $J^{PC} = 1^{-+}$.

Other developments reported at this meeting are encouraging. LASS has confirmed the $1^{++} D'(1530)$ in Kp scattering,⁸ as one would expect for the $\bar{s}s$ member of the A_1 nonet. This means there must be new physics in the $J = 1$ channel, since we now have evidence for at least three states with $J^C = 1^+$ between 1280 and 1530 MeV, whether we accept the hadronic data for a $J^{PC} = 1^{++}E$ or not. If $D(1280)$ and $D'(1530)$ are the $I = 0$ members of the A_1 nonet, then the $\gamma\gamma^*$ signal at 1420 MeV must be new physics. If $D(1280)$ and $E(1420)$ are the $1^{++}\bar{q}q$ states then $D'(1530)$ must be something new, since it could not be the $\bar{s}s$ radial excitation at such a low mass. Considering the evidence from WA76 I am not yet prepared to write off a $1^{++}E(1420)$. Though I cannot imagine

a theoretical explanation, it is conceivable that there are 1^{++} states at 1280, 1420, and 1530 as well as an exotic 1^{-+} state near 1420.

A second encouraging development is the preliminary evidence¹⁵ for a p-wave $\pi\eta$ resonance in the 1400 MeV region. This could be the $I = 1$ $J^{PC} = 1^{-+}$ \bar{X} decaying per eq. (6.6).

New results in the $\gamma\gamma^*$ channel were presented for the first time at this meeting. Bauer presented a new TPC result⁸ that supercedes eq. (6.1), quoted here in the Renard convention (which I follow throughout this talk),

$$\frac{m_E^2}{Q^2} \Gamma(E \rightarrow \gamma\gamma^*) B(E \rightarrow K^*K) = (7.0 \pm 2 \pm 1.4) \text{ keV}. \quad (6.9)$$

Equation (6.9) assumes a ρ form factor fit to the q^2 dependence of the γ^* . Smaller values are reported by the Mark II,^{12,6}

$$\frac{m_E^2}{Q^2} \Gamma(E \rightarrow \gamma\gamma^*) B(E \rightarrow \bar{K}K\pi) = \begin{cases} 2.7 \pm 1.2 \pm 1.5 \text{ keV} & \rho \\ 1.7 \pm .8 \pm .3 \text{ keV} & \phi \end{cases} \quad (6.10)$$

where the smaller value (with a ϕ form factor fit) would be appropriate for an $\bar{s}s$ state. The Mark II also reports a measurement of $\gamma\gamma^* \rightarrow D(1280) \rightarrow \eta\pi\pi$. Using $B(D \rightarrow \eta\pi\pi)$ from the PDG⁶² it implies

$$\frac{m_D^2}{Q^2} \Gamma(D \rightarrow \gamma\gamma^*) = 8.2 \pm 2.2 \pm 1.5 \text{ keV} \quad (6.11)$$

If we assume that $E(1420)$ and $D(1285)$ are the $I = 0$ members of the A_1 nonet, then (6.11) and (6.9) require mixing far from ideal whereas (6.11) and (6.10) can be accommodated by a small, negative mixing angle not far from ideal.

Seiden, Sadrozinski, and Haber⁴⁸ have considered the decay widths suggested by the Mark III data for $\psi \rightarrow (\omega \text{ or } \phi) + (D \text{ or } E)$. I use the work "suggested" because the "D" signals have not been partial-wave analyzed and the "E" J^P determination is not decisive as discussed above. They find that if a fairly small deviation from ideal mixing is assumed for the $E - D$ system, then large DOZI effects (or, equivalently, "nonet symmetry" breaking) are needed to understand the ψ decay. This is a puzzling result, because deviations from ideal mixing and from "nonet symmetry" should be correlated and of similar magnitude since they arise from the same underlying physics.⁶³ Substantial nonet symmetry breaking would be natural in the 0^{-+} nonet but not in an ideal 1^{++} nonet. Previous fits⁶⁴ to the pseudo scalar-vector channel seemed unnatural because they neglected nonet symmetry breaking (included now in the more recent study⁴⁸) although $\eta - \eta'$ mixing is far from ideal.

Another method for investigating mixing in the 1^{++} nonet is suggested by the report¹⁶ here from the Lepton-F collaboration of the branching ratio

$$B(D(1280) \rightarrow \phi\gamma) = (9 \pm 2 \pm 4) \cdot 10^{-4} \quad (6.12)$$

Clearly we would like to know the radiative widths of D , E , and D' to ρ , ω , and ϕ . The upper limit from lepton F for $E \rightarrow \phi\gamma$ is interpreted¹⁶ as suggesting that D and E are not in the same nonet.

Of course the best test of the 1^{-+} hypothesis for $\gamma^*\gamma \rightarrow X(1420)$ is to measure the parity. The TPC has presented data here favoring $P = +$ but stating that $P = -$ is not excluded. New data^{12,6} from the Mark II establishes $P = +$ for $\gamma\gamma^* \rightarrow D(1280) \rightarrow \eta\pi\pi$ but is inconclusive for the parity of $\gamma\gamma^* \rightarrow X(1420) \rightarrow \bar{K}K\pi$. The Mark II angular distributions are shown in figs. (6.1) and (6.2); solid lines represent the prediction for $P = +$ and dashed lines for $P = -$. Beside the obvious problem of marginal statistics, more than one amplitude may contribute (dominance by a single amplitude is assumed in the results quoted above) and there might even be more than one state (if 1^{++} and 1^{-+} states at 1420 both exist). At low q^2 a single amplitude should dominate⁶⁵ but then the cross section is also smallest. At least an order of magnitude more statistics is needed for a decisive parity measurement.

7. Conclusion

There is growing evidence in support of the glueball interpretation of $\iota(1460)$. Two decisive developments are (1) the evidence for $\eta(1400)$ which together with $\eta(1280)$ could fill the $I = 0$ positions in the radially excited pseudoscalar nonet and (2) the much improved upper limits on $\iota \rightarrow \gamma\gamma$. Together with the large rate for $\psi \rightarrow \gamma\iota$ these developments point decisively to the glueball interpretation. However, much remains to be done to understand the extent of possible mixing, requiring more complete data both on ι and on the properties of $\eta(1420)$ and $\eta(1280)$. Present data hints at the possibility that there could even be too many isoscalar pseudoscalars for one $\bar{q}q$ nonet plus a glueball.

The principal new evidence bearing on $\theta(1730)$ is the Kp data, showing clearly that θ is not produced, despite a clear signal for $f'(1515)$. This could be understood if $B(\theta \rightarrow \bar{K}K) \ll 1$, implying a much larger value for $B(\psi \rightarrow \gamma\theta)$ than presently seen. This would in turn strengthen a glueball interpretation of θ . To verify this hypothesis, the missing θ decay modes must be found in radiative ψ decay.

Much progress has been made in finding and analyzing the $\bar{q}q$ spectrum. In the last two years the number of fully understood nonets on my list has doubled, from three to six. This is the kind of progress that is absolutely essential if we hope to find the gluonic states that exist among and possibly mix with the rich and complicated $\bar{q}q$ spectrum.

It is puzzling that there is no clear evidence for a 0^{++} glueball candidate in radiative J/ψ decay. There seems to be no possibility below ~ 1200 MeV for a large scalar signal in the $\psi \rightarrow \gamma X$ data. On the other hand a large, broad scalar signal above ~ 1500 MeV might be very difficult to find. Reliable theoretical calculations would be a great help. Perhaps they will come with the next generation of computers.

Several exciting hints of new physics have been discussed at the meeting. $C(1480) \rightarrow \phi\pi$ and (if it really occurs) $\xi(2230) \rightarrow \phi\omega$ could indicate $\bar{\chi}$. Confirmation of $D'(1530)$ together with the 1420 MeV signal in $\gamma\gamma^* \rightarrow \bar{K}K\pi$ imply unambiguously that there is new physics somewhere in the $J^C = 1^+$ channel. This new physics could be a $J^{PC} = 1^{-+}$

exotic at 1420; perhaps the bag model ground state $\bar{\chi}$. In this connection we look forward to hearing more about the evidence for a p-wave $\pi\eta$ resonance in the 1400 MeV region, which would uniquely have $J^{PC} = 1^{-+}$. If the various hints of χ at $\gtrsim 1\frac{1}{2}$ GeV are correct, then the fun has only just begun. Nonexotic channels could be so complex that discovery and study of the 1^{-+} exotic states may be the essential first step to establish the existence of $\bar{\chi}$.

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