Title
MESON SPECTROSCOPY VIEWED FROM J/4 DECAY: GLUONIC STATES AT BEPC

Author
Chancwitz, M.S.

Publication Date
1987-07-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

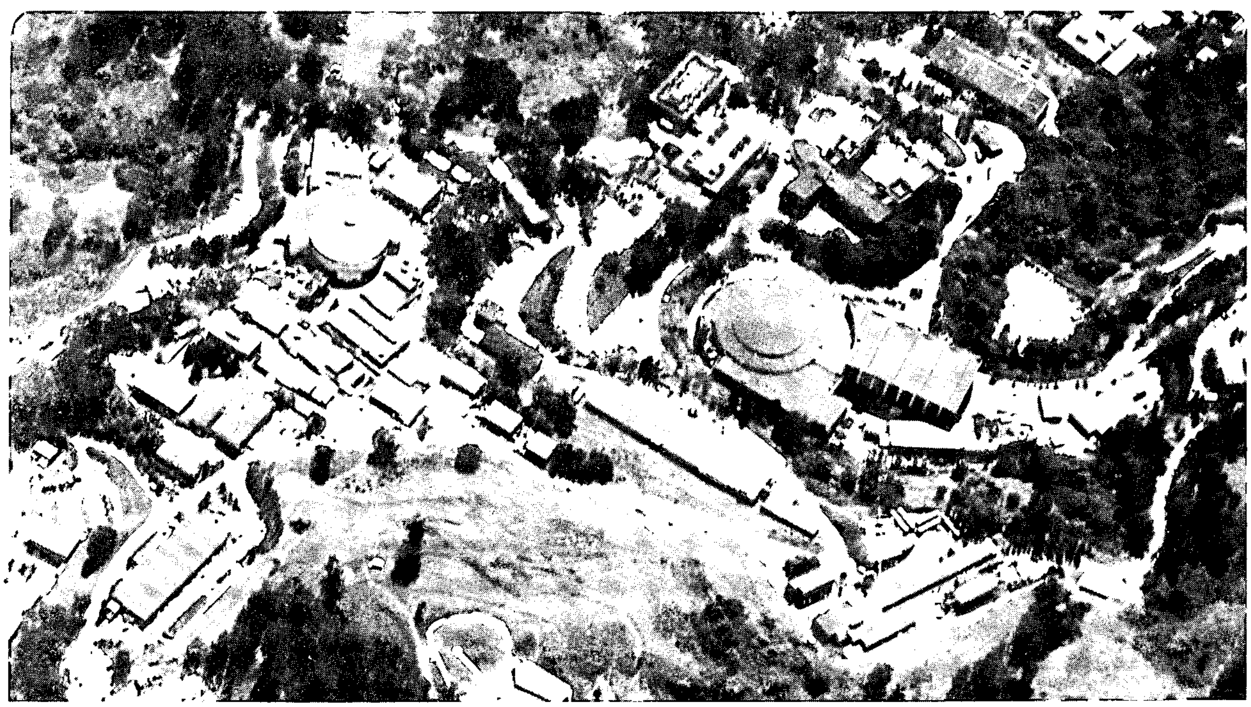
Physics Division

Lectures presented at the Charm Physics Symposium,
Beijing, PRC, June 4–16, 1988, and
to be published in the Proceedings

Meson Spectroscopy Viewed from J/ψ Decay: Gluonic States at BEPC

M.S. Chanowitz

July 1987



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

July, 1987 LBL-24355

MESON SPECTROSCOPY VIEWED FROM J/ψ DECAY: GLUONIC STATES AT BEPC *

Michael S. Chanowitz

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Five lectures presented at the Charm Physics Symposium/Workshop, Institute of High Energy Physics, Beijing, June 4–16, 1987. To be published in the proceedings.

Abstract

The theoretical and experimental status of the search for gluonic states is reviewed. Progress clearly requires much higher statistics studies of J/ψ decay, as will be possible at the Beijing Electron Positron Collider.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

1. INTRODUCTION

QCD and Existence of Gluonic States

Everyone is convinced that QCD is the correct theory of hadrons, chiefly because we can compute the short distance properties and find that they agree with what is observed in high energy experiments. But we still know very little about the properties of QCD at long distances, of order 1 fermi = 10^{-13} cm. or larger. This is the physics that controls the spectrum of hadrons made from the light quarks — u, d, and s. Usually we do not consider a theory to be "solved" until we have understood the spectrum. I am not arguing against the popular conclusion that QCD is correct, but I want to suggest that we cannot say we understand the theory until we at least understand the spectrum qualitatively and understand at least some of the simpler bound states at a quantitative level. This is an ambitious goal that can be accomplished in the next ten to twenty years. It will result from more powerful theoretical calculations that will be possible with the next generations of computers and by future experiments that will go far beyond what has already been accomplished to clarify the complexity of the hadron spectrum. With high luminosity studies of J/ψ decay, BEPC can make critical contributions to this process.

I stressed above that we do not even understand the hadron spectrum in a qualitative way. The principal qualitative novelty of QCD is that it is a nonabelian gauge theory. As such the gauge bosons — gluons — are themselves color–charged and confined. This creates the possibility that there are states in the spectrum that contain gluonic constituents. Some, made only of gluons in first approximation, we call glueballs. Others, mixed states of quarks and gluons, I call *meiktons* from the ancient Greek word for a "mixed object". At this meeting we could call them: 混合, huĕn hé . The most important qualitative question we can ask about the hadron spectrum is whether glueballs or $\bar{q}qg$ states exist.

We must be humble about proposing the answer to this question because we still do not have a deep understanding of the spectrum of ordinary hadrons made from u, d, and s. The nonrelativistic model seems to describe the spectrum qualitatively, but we know these hadrons are actually relativistic systems. In fact it is not even obvious that the static properties of hadrons must be dominated by the valence quarks. The $\pi^+ = |u\bar{d}>$ has other components in its wave functions, such as $|u\bar{d}q\bar{q}>$, $|u\bar{d}q\bar{q}q\bar{q}>$, ... If those higher components were important in leading order, the hadrons need not have been in simple $SU(3)$ flavor representations and quarks might not have been deduced from the spectrum as they were in 1964.[1]

The existence of valence quarks suggests that the concept of valence gluons could also be valid. Then the lightest glueballs would contain two confined valence gluons and there would also be hadrons made of a color octet $\bar{q}q$ and one valence gluon. This is what we expect in the bag model,[2] a relativistic model of hadrons that gives a good description of the ground state hadrons but not yet of the excited states.

I will discuss the question of the existence of gluonic states in more detail in section 3. Here I want to present an argument due to Bjorken[3] that glueballs would be required to exist because of confinement and the short-distance properties of QCD if all quarks were very heavy. Let us imagine that u, d, and s do not exist and that there is only one very heavy quark flavor, Q. Suppose $M_Q = 40$ GeV. Then there will be a $\bar{Q}Q$ vector meson bound state $\psi(\bar{Q}Q)$,

$$m_{\psi(\bar{Q}Q)} < 2M_Q = 80 \text{ GeV} \tag{1.1}$$

$\psi(\bar{Q}Q)$ could be formed in e^+e^- annihilations

$$e^+e^- \to \psi(\bar{Q}Q). \tag{1.2}$$

Since Q is very heavy, ψ is small enough that we can use the known perturbative short distance properties to predict that ψ decays to three gluons,

$$\psi(\bar{Q}Q) \to ggg. \tag{1.3}$$

But in this imaginary experiment what hadrons would appear in the detectors? Pairs of $\bar{Q}Q$ mesons would be too heavy. Since gluons are confined, the only possibility is to form color-singlet glueballs. If we next imagine introducing u, d, and s quarks, we expect the glueball states to remain in the spectrum. But since they might decay to hadrons made of u, d, s, we must understand the dynamics to know whether they would be narrow enough to appear as well-defined resonances.

Difficulties and General Strategy

The study of gluonic states is clearly not easy. Experiments are very difficult and theoretical understanding is poor. Serious experimental study began in 1980, when the iota was discovered in radiative J/ψ decay by the Mark II group.[4] Few definite conclusions have been reached in this period, though progress made during the last two years makes it seem probable that iota is indeed a glueball.[5] But many questions remain. Iota is poorly understood and even less is known about other possible glueballs. It is not known experimentally whether 混合 exist, though there are interesting experimental clues discussed in the following lectures. Because the subject is so very difficult, many fundamental discoveries remain to be made. Third generation experiments such as BES at BEPC are essential to make these discoveries.

BES is in a strategic position to contribute because it can study the most favored process for glueball production, radiative J/ψ decay:

$$\psi \to \gamma G. \tag{1.4}$$

For a very heavy $\bar{Q}Q$ system the inclusive radiative decay width can be calculated,[6] since the bound state radius is small enough to be in the short distance domain of perturbation theory. In lowest order

$$\Gamma(\psi \to \gamma X) = \Gamma(\psi \to \gamma gg). \tag{1.5}$$

In perturbation theory the dominant partial waves are[7] $J^{PC}(gg) = 0^{++}, 0^{-+}, 2^{++}$. Since the two gluons are in a color singlet, we expect $0^{++}, 0^{-+}$, and 2^{++} glueballs to be copiously produced.

The ψ is not heavy enough for eq. (1.5) to be precisely correct but it is valid as a rough approximation. The lowest order prediction is[6]

$$\frac{\Gamma(\psi \to \gamma X)}{\Gamma(\psi \to hadron)_{strong}} = \frac{\Gamma(\psi \to \gamma gg)}{\Gamma(\psi \to ggg)} = \frac{16\alpha}{5\alpha_s} = 0.12 \tag{1.6}$$

The ψ total width is[8]

$$\Gamma_\psi(TOT) = 63 \pm 9 \ keV. \tag{1.7}$$

Of this total

$$\Gamma(\psi \to e^+e^- + \mu^+\mu^-) = 9.4 \pm 0.6 \ keV. \tag{1.8}$$

from which we can estimate the electromagnetic contribution to the hadronic width at

$$\Gamma(\psi \to \gamma^* \to hadrons) = R_{3.1} \cdot \Gamma(\psi \to e^+e^-) \cong 12 \ keV. \tag{1.9}$$

The measured value[9] of the radiative decay width is

$$\Gamma(\psi \to \gamma X) \cong 4 \ keV. \tag{1.10}$$

(obtained by using the theoretical spectrum to extrapolate the measurement at $x > 0.4$ to small x).

Subtracting eqs. (1.8-1.10) from (1.7) we get

$$\Gamma(\psi \to hadrons)_{strong} \cong 38 \ keV. \tag{1.11}$$

Then from eq. (1.10)

$$\frac{\Gamma(\psi \to \gamma X)}{\Gamma(\psi \to hadrons)_{strong}} = 0.11 \tag{1.12}$$

in good agreement with eq. (1.6). (The uncertainties are greater than the difference between (1.6) and (1.12).)

Though the partial width $\Gamma(\psi \to \gamma X)$ agrees roughly with eq. (1.6), we should not expect the shape of the photon energy spectrum to be consistent with perturbation theory because the ψ radiative decays are dominated by the resonance region, $M_X = 1 - 2.5$ GeV. The prediction for the inclusive partial width $\Gamma(\psi \to \gamma X)$ is understood in the "duality" sense familiar from deep inelastic scattering, where the sum over resonances agrees with the inclusive parton model prediction.[10]

The fact that the resonance region dominates is good news. It means that radiative ψ decays are the perfect channel to explore resonances that couple to gluons. We therefore expect prominent decays to 0^{++}, 0^{-+}, and 2^{++} glueballs if they are kinematically allowed. Heavier quarkonia cannot compete with J/ψ because the ψ_{QQ} production cross sections are much smaller and because a smaller fraction of the radiative decays are in the resonance region.

What we do not know about gluonic states is much greater than what we do know. Therefore what we know is very precious and must be used to the greatest possible advantage. What we know best is that gluonic states must be additional states in the spectrum beyond what is predicted in the $\bar{q}q$ spectrum of the nonrelativistic quark model. To use this obvious statement it is necessary to understand the spectrum of ordinary mesons very precisely. This is not easy because the 1-2.5 GeV region is filled with many $\bar{q}q$ nonets, requiring careful partial wave analysis that can only be done with accurate high statistics data.

A year ago it seemed that only three nonets were completely and unambiguously filled: π, ρ and A_2/a_2. (For familiar states I often use the old particle names but in some cases I will use the new system of the Particle Data Group[8], sometimes giving both old and new names as in A_2/a_2.) We can be encouraged that in just the last year, two and perhaps four more nonets have been completed. As discussed in section 2, the $J^{PC} = 1^{+-}$ B/b_1 nonet and the $J^{PC} = 3^{--}$ $\rho_3(1690)$ nonet are unambiguously filled, and there are at least enough states to fill the $J^{PC} = 0^{-+}$ $\pi(1300)$ and $J^{PC} = 1^{++}$ A_1/a_1 nonets. Partial wave analysis of BES data will be of tremendous value, both in the radiative decay channel and for the direct hadronic decays.

Though ψ decay may be the single most valuable channel in searching for gluonic states, data from all experimental channels must eventually be combined to understand the total picture. As will be evident in the following lectures, there have been many important contributions from photon-photon scattering and from hadron scattering experiments with π, K, p, and $\bar{p}$ beams. High statistics experiments with low energy $\bar{p}$ beams at LEAR will provide interesting data in the next few years. PEP, Tristan, SLC and LEP will provide additional photon-photon scattering data. Hadron scattering experiments will continue at the CERN SPS, the KEK proton synchrotron, at Fermilab and Brookhaven.

Theoretical Overview

The theoretical perspective will be discussed more fully in section 3. Now I will just make a few brief remarks. The problem is that we still do not understand QCD at long distances, and that is also why the subject is still interesting. We should be encouraged that this theoretical ignorance is not a permanent condition. Serious quantitative calculations can be expected within the next ten to twenty years that can be tested by and provide guidance for the experimental studies.

For the present the only theoretical guidance comes from models and approximations that are at best very crude. These models can provide suggestions of what to explore and what might be found, but the dominant role must be played by experiment. That is why we need BEPC!

Since gluons are massless it is natural to use a relativistic model to represent their bound states. The bag model is a simple relativistic model of confinement that naturally predicts gluonic states containing valence gluons. In lowest order the glueball ground states are $J^{PC} = 0^{++}$ and 2^{++} two gluon bound states, while $J^{PC} = 0^{-+}$ and 2^{-+} are the first excited states.[11] Including first order corrections from cavity perturbation theory[2] the expected pattern from lowest to highest mass becomes

$$0^{++} < 0^{-+} < 2^{++} < 2^{-+} \tag{1.13}$$

in the range from ~ 1 to 2.5 GeV. Iota (1460) could well be the 0^{-+} state and $\theta(1730)$ might be the 2^{++}. Then the 0^{++} state is expected between 1 and 1.3 GeV, for which there is no experimental support. The 0^{++} mass might be affected by the structure of the vacuum,[12] *i.e.* "vacuum mixing", which would tend to increase the mass.

The bag model also predicts qqg states. The ground state[3] consists of four nonets, in the order

$$0^{-+} < 1^{-+} < 1^{--} < 2^{-+}. \tag{1.14}$$

In the fit to $\iota(1460)$ and $\theta(1730)$ the $I = 1$ members of these nonets range from 1200 to 1800 MeV. The 1^{-+} nonet is especially interesting since it has exotic J^{PC} that cannot occur in the nonrelativistic $\bar{q}q$ spectrum. Excited states[13] are expected in the order

$$0^{++} < 1^{++} < 1^{+-} < 2^{++} \tag{1.15}$$

In the fit to ι and θ the $I = 1$ members fall between 1800 and 2230 MeV.

$\bar{q}qg$ states are also expected in the flux-tube model,[14] though a few hundred MeV heavier than the bag model estimates quoted above. I am not certain that these flux-tube excitations should be identified with the valence gluon states of the bag model. They may instead correspond to collective excitations, that is, string modes in a string model or cavity excitations in the bag. This is an example of a qualitative (and controversial) theoretical question that is really not understood.

QCD sum rules have also been used to estimate the masses of gluonic states. The $I = 1$ exotic $J^{PC} = 1^{-+}$ $\bar{q}qg$ is found to lie between 1.3 and 1.7 GeV.[15] Glueball masses have also been studied. One recent calculation[16] predicts 0^{++} glueball masses below 1 GeV, possibly very narrow. A light scalar glueball might have avoided detection in scattering data if it were very narrow[17] but I do not think it would have escaped detection in $\psi \to \gamma\pi\pi$. An estimate for the 2^{++} glueball is consistent with the $\theta(1730)$ mass.[18] A 0^{-+} glueball is estimated at 1700 MeV, with an uncertainty that includes the iota mass.[18]

For the future the most serious approach is certainly the lattice approximation. Since I am no expert and since there has just been a workshop in Beijing with many experts, I will only make a few comments. The present calculations typically give results for glueball masses in the same 1-2 GeV range as the models mentioned above. A recent review of lattice QCD was given by Iwasaki at the KEK Hadron '87 conference[19]. Present computations cannot reach large enough lattice sizes with enough statistics to be quantitatively reliable. Mixing with the $\bar{q}q$ sector is not yet included. But eventually future generations of supercomputers and special-purpose dedicated computers will provide reliable results.

Further discussion of the theoretical expectations are given in section 3.

Phenomenological Overview

Here I want to give a very quick impression of the status of the phenomenology. More complete discussions are given in sections 4 and 5.

In the last two years more evidence has accumulated in favor of the glueball

interpretation of iota, ι (1460). The upper limit on $\iota \to \gamma\gamma$ has become very strong. Two pseudoscalar mesons have been observed, $\eta(1280)$ and η (1400), that could fill the radially excited pseudoscalar nonet, leaving no room for iota as a $\bar{q}q$ state. However there is still much that is not understood. Iota itself is not well described by a single Breit–Wigner.[4] The evidence for $\eta(1400)$ is not complete, and it is possible the data will require more pseudoscalars. I have already mentioned that bag model estimates place a 混合 nonet in this mass region. As discussed in section 4, high statistics studies in radiative and hadronic ψ decay are crucial to clarify what could be an interesting and complicated system.

There are many other possible gluonic states to consider. They include the following:

$\theta(1730)$ is a 2^{++} resonance seen in radiative J/ψ decay. It cannot be understood as a $\bar{q}q$ meson. It might be a glueball, though the evidence is less clear than for iota. The failure to observe it in Kp scattering[21] suggests that it has large missing decay modes, which would in turn make the glueball assignment very strong. High statistics studies of radiative J/ψ decay are needed to search for the missing modes.

$C(1480)$ is a $J^{PC} = 1^{--}$ $\phi\pi$ resonance discovered in pion scattering.[20] $C \to \phi\pi$ is OIZ forbidden for any $\bar{q}q$ meson but could result from decay of a $\bar{q}qg$ state. If it is a $\bar{q}qg$ state it should be produced in hadronic J/ψ decay, such as $\psi \to C\pi$.

$\xi(2230)$ has recently been observed in Kp scattering.[21] This and the observation[4] that $J > 0$ contradicts the Higgs boson interpretation considered previously. Other possibilities are that it is a 4^{++} $\bar{s}s$ state[22] or a $(\bar{u}u + \bar{d}d)g$ 2^{++} state.[13] As discussed at the 1984 BEPC workshop by Gao *et al.*,[33] $\gtrsim 25{,}000{,}000$ J/ψ decays are probably needed to do a J^P determination of ξ.

Several different sets of data indicate very interesting physics in the $J = 1$ channel in the E region, around 1400 MeV. Tagged two photon scattering studies[24,25] find a narrow $\bar{K}K\pi$ resonance at the E mass that must have $J^C = 1^+$. Confirmation of the $J^{PC} = 1^{++}$ $D'(1530)$ in Kp scattering then implies that there are too many $J^C = 1^+$ states for the $\bar{q}q$ spectrum. A signal in $\psi \to \omega\bar{K}K\pi$ is seen with mass and width consistent with E, but it is not seen in $\psi \to \phi\bar{K}K\pi$, contrary to what is expected if E were an $\bar{s}s$ state as previously supposed.[26] One hypothesis is that the resonance seen in these experiments at 1420 MeV is a $J^{PC} = 1^{-+}$ $\bar{q}qg$ state, a J^{PC} exotic that cannot be a $\bar{q}q$ state in the nonrelativistic spectrum.[37] High statistics studies of $\psi \to \omega K \bar{K} \pi$ could test this hypothesis. It is consistent with a preliminary report[20] that a $J^{PC} = 1^{-+}$ $\eta\pi$ resonance may have been observed in the 1400 MeV region in πp scattering.

Other developments will be reviewed in less detail, including the 2^{++} g_T $\phi\phi$ structures,[29] the 0^{++} $G(1590)$ observed[30] decaying to $\eta\eta$ and $\eta\eta'$ and three 0^{++} resonances found near $\bar{K}K$ threshold in a recent partial wave analysis.[31]

The above topics are discussed in more detail in sections 4 and 5.

Prospects for BEPC

The study of gluonic states is just beginning. Though there have been many interesting developments in the last two years, most of the work remains to be done. Previous experiments have often lacked the statistical power to reach definitive conclusions. J/ψ decay is the most favorable channel for the study of gluonic states. The largest data samples are the $\sim 6,000,000$ events of the Mark III and $\sim 8,000,000$ of $DM2$. They define the interesting statistical level for future experiments as 50 to 100 million events. At that level it should be possible to answer many of the questions discussed in these lectures and to find new phenomena that nobody today has anticipated. The work will rely heavily on the techniques of partial wave analysis.

This is clearly a difficult and ambitious program. The greatest difficulties are probably not in producing a sufficient number of J/ψ's but in detecting and recording the decays and in the off-line analysis.

The theoretical peak cross section for $e^+e^- \to \psi$ is

$$\sigma_\psi = \frac{12\pi}{M_\psi^2} B(\psi \to e^+e^-) = (1.05 \pm 0.14) \cdot 10^{-28} cm^2. \tag{1.16}$$

Smearing with the energy spread of the beam (done incorrectly by me at the 1984 workshop as pointed out by Tao Huang), the observed cross section is

$$\bar{\sigma}_\psi = \frac{\Gamma_\psi(TOT)}{\sqrt{2}\Delta E_{beam}} \sigma_\psi = (7.4 \pm 1.0) \cdot 10^{-30} cm^2. \tag{1.17}$$

Here I assume $\Delta E_{beam}/E_{beam} = 4.1 \cdot 10^{-4}$ at $E_{beam} = M_\psi/2$, the RMS value extracted from the BEPC design parameters of 1984. Below the optimization energy the luminosity scales like E^2, so a peak luminosity of $1.7 \cdot 10^{31} cm^{-2} sec^{-1}$ at $E_{beam} = 2.8$ GeV corresponds to a luminosity at the J/ψ of

$$\mathcal{L}_\psi = 5 \cdot 10^{30} cm^{-2} sec^{-1}. \tag{1.18}$$

Assuming an average luminosity of $\bar{\mathcal{L}}_\psi = \frac{1}{4}\mathcal{L}_\psi$ to take account of fill time and time to accelerate the beam, we then find for a run of 10^7 sec $\cong \frac{1}{3}$ year by the clock that

$$N_\psi = \bar{\sigma}_\psi \bar{\mathcal{L}}_\psi T \cong 9 \cdot 10^7 \tag{1.19}$$

50,000,000 J/ψ's is therefore a realistic possibility if performance near the design parameters can eventually be achieved.

The problem of detecting, recording, and analyzing this volume of events was examined at the 1984 workshop and will be reexamined at this workshop. It is critical to determine if the planned computing capability will be sufficient. Here we can profit from the recent experience of high statistics fixed target experiments.

For example the LASS group has begun to report[32,33] many important results, several to be quoted in these lectures, which are based on a data sample of 140,000,000 recorded Kp events. Since the average multiplicity of their events is ~ 5, similar to J/ψ decay, the computing requirement is similar to what is needed for 100,000,000 J/ψ decays. LASS did the analysis using the SLAC mainframe to distribute events to a parallel microprocessor farm, while collaborators in Nagoya used a mainframe for the analysis.

BES might profit from the experience at LASS both in off-line computing and also perhaps in acquiring the essential techniques of partial wave analysis. The analysis of the LASS data is continuing and will provide more interesting results in the next few years.

In his lectures Mike Witherell will describe parallel processing systems being used by other fixed target experiments for high statistics studies that were inconceivable a few years ago.

2. "ORDINARY" MESONS

The spectrum of the "ordinary" mesons is itself interesting physics, that must be understood in detail to find and identify gluonic states. For example, the success of the simple $\bar{q}q$ classification is a puzzle, since the light mesons are not nonrelativistic systems. We are lucky that spectroscopic properties are dominated by the valence quarks. If the $\bar{q}\bar{q}qq$, $\bar{q}\bar{q}\bar{q}qqq, \ldots$ wave function components were important spectroscopically, then there would not be simple $SU(3)$ 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.

If our theoretical understanding were more advanced, it would be less important to understand the $\bar{q}q$ spectrum in such detail. But at present the only sure property of a gluonic state is that it is not (though it may mix with) a $\bar{q}q$ state. We need to understand the $\bar{q}q$ spectrum very precisely in order to identify the particles which do not belong to it.

Overview of the spectrum

The presently known mesons have J^{PC} quantum numbers that correspond to the hydrogen-like spectrum of the nonrelativistic quark model. The total angular momentum J is the sum

$$J = L + S \tag{2.1}$$

of orbital angular momentum and spin where

$$S = s_q + s_{\bar{q}}. \tag{2.2}$$

$S = 0$ for the antisymmetric spin singlet

$$S = 0: \quad \frac{1}{\sqrt{2}}(\uparrow\downarrow - \uparrow\downarrow) \tag{2.3}$$

and

$$S = 1: \quad \uparrow\uparrow, \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow), \downarrow\downarrow \tag{2.4}$$

for the symmetric triplet. Since q have $\bar{q}$ have opposite phases under P and C the parity and change conjugation of the $\bar{q}q$ states are

$$P = (-1)^{L+1} \tag{2.5}$$

$$C = (-1)^{L+1}(-1)^{S+1} = (-1)^{L+S}. \tag{2.6}$$

Therefore the ground state with $L = 0$ has $J = S$, or $J^{PC} = 0^{-+}$ for the spin singlet and $J^{PC} = 1^{--}$ for the triplet. The orbitally excited states with $L = 1$ are then the singlet with $J = L = 1$ or $J^{PC} = 1^{+-}$ and the triplet with $J = 1 + 1 = 0, 1, 2$ and $J^{PC} = (0, 1, 2)^{++}$. The $L = 2$ states are the singlet with $J^{PC} = 2^{-+}$ and the triplet with $J^{PC} = (1, 2, 3)^{--}$. Notice that this spectrum contains no state with $J^{PC} = 1^{-+}$. This is an example of exotic quantum numbers. If we find such a state, it must represent some form of new physics, perhaps 混合 .

There are also radial excitations corresponding to large values of the principal quantum numbers $N = 1, 2, \ldots$. The $N = 2$ states duplicate the $N = 1$ states at a larger mass. For instance, the $N = 2$, $L = S = 0$, $J^{PC} = 0^{-+}$ nonet is very important for our understanding of the glueball candidate iota.

Though the J^{PC} values of the observed mesons correspond to this nonrelativistic spectrum, the light mesons are certainly not nonrelativistic systems. The nonrelativistic model assumes $v << c$ and an instantaneous potential. But for a typical meson radius

$$r \sim 0.8\ fm = 8 \cdot 10^{-14}\ cm \tag{2.7}$$

the uncertainty principle tells us that

$$p \sim \frac{1}{r} \sim 250\ MeV \tag{2.8}$$

which implies

$$v \sim O(c) \tag{2.9}$$

for $m_q \lesssim 300$ MeV. Since the quarks move at nearly the speed of light, the approximation of an instantaneous potential must eventually fail. There may be collective modes, for instance, string modes in a string model or cavity excitations in a model based on the bag, that are not found in the nonrelativistic model. It is a controversial and deep dynamical question whether these states are identical to gluonic states made from valence gluons. My intuition, based on the bag model, is that they are not identical, but many theorists (especially the lattice theorists who start from the coarse-grained, strong coupling limit of the lattice) would disagree. Experiment and/or much more powerful theory will eventually decide.

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 $I = 1$, $I = \frac{1}{2}$ and two $I = 0$ members of a nonet. Solid lines are established, dashed lines require confirmation and crooked lines have ambiguous assignments (e.g., excited $J^P = 1^-$ could be radially or orbitally excited). One year ago my chart had only three complete nonets — π, ρ, a_2, — astonishingly meager for thirty years of hard work, the lesson being that meson 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 at least enough (if not too many!) states.

Notice that I am mixing the old and new meson name systems, just to be sure you will be as confused as I am. For example, the $J^{PC} = 2^{++}$ $I = 1$ resonance that

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

KEY:

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

Established	——
Possible	- - -
Ambiguous	~~~

Table 2.1 A Non-authoritative summary of the meson spectrum.

used to be $A_2(1320)$ is by the new system called $a_2(1320)$. Sometimes I will write this as $A_2/a_2(1320)$. The 1987 Particle Data Group book[8] gives both old and new names to help us through the transition.

<u>Groundstates: mixing and the OIZ rule</u>

Now we discuss the relationship between "ideal" mixing and the OIZ (Okubo–Iizuka-Zweig) rule. For three flavors u, d, s, there are nine $\bar{q}q$ combinations, a flavor "nonet" corresponding to one $SU(3)$ singlet and one $SU(3)$ octet. The octet contains two strange isodoublets, $(u\bar{s}, d\bar{s})$ and $(\bar{d}s, \bar{u}s)$, the isotriplet $(u\bar{d}, \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}), d\bar{u})$ and an isoscalar

$$X_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}). \tag{2.10}$$

The ninth member is the $SU(3)$ singlet,

$$X_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}). \tag{2.11}$$

However, there is no reason to expect the $I = 0$ physical eigenstates to correspond to X_1 and X_8 since nothing forbids them to mix. I want to show that their flavor content is related to the OIZ rule. When the OIZ rule works well, then instead of X_1 and X_8 we expect ideal mixing for the eigenstates,

$$X_0 = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d) \tag{2.12}$$

$$X_0' = \bar{s}s. \tag{2.13}$$

When there are large OIZ violating forces in the flavor-singlet channel (as we would expect in QCD since gluons are flavor singlet) then the eigenstates will be nonideal and will approximate X_1 and X_8. In general the mixing may be intermediate between these extremes.

To understand these ideas we begin with a very simple model that I would like to call the Idiot's Quark Model in which there are no forces at all! Then besides the kinetic energy terms which are flavor symmetric and which I do not bother to write, the free Hamiltonian contains just the quark mass terms

$$\mathcal{H}_{Free} = m(\bar{u}u + \bar{d}d) + m_s\bar{s}s.$$

Since there are no interactions, we have a trivial OIZ rule

$$< \frac{\bar{u}u + \bar{d}d}{\sqrt{2}} |\mathcal{H}_{Free}| \bar{s}s > = 0. \tag{2.14}$$

Then the eigenstates are just determined by the quark masses and of course we have ideal mixing with eigenstates X_0 and X_0'. The masses of the $\bar{q}q$ pairs are just the sum of their constituent masses, so of course

$$\begin{aligned} m_{I=1} &= 2m \\ m_{I=1/2} &= m + m_s \\ m_{X_0} &= 2m \\ m_{X_0'} &= 2m_s \end{aligned} \tag{2.15}$$

From eq. (2.15) we can deduce two relations,

$$m_{I=1} = m_{X_0} \tag{2.16}$$

and

$$2m_{I=1/2} = m_{X_0} + m_{X_0'}. \tag{2.17}$$

This may all seem very boring but I will now explain why it is interesting. The last two relations are valid not just for a free theory but for the interacting theory providing the OIZ rule and $SU(3)$ symmetry are approximately valid. When those two conditions are satisfied we expected ideal mixing as in (2.12) and (2.13) and we expect the relations (2.16) and (2.17) to be correct to a good approximation!

To show this we now introduce the interaction Hamiltonian $\mathcal{H}'$. Then the total Hamiltonian is $\mathcal{H} = \mathcal{H}_{free} + \mathcal{H}'$. If the OIZ rule is valid then

$$< \bar{s}s|\mathcal{H}'|\frac{\bar{u}u + \bar{d}d}{\sqrt{2}} > \cong 0 \tag{2.17}$$

as for the idiot quark model (2.14). Then the ideal mixtures X_0 and X_0' diagonalize the Hamiltonian and we have ideal mixing, (2.12) and (2.13).

The next step is to prove a little "theorem".

"*Theorem*": $SU(3)_{Flavor}$ symmetry and the OIZ rule imply equal singlet and octet interaction energies (so-called "nonet symmetry" for the interaction energies).

Proof. From (2.10), (2.11), (2.12), and (2.13),

$$X_0 = \sqrt{\frac{1}{3}}X_8 + \sqrt{\frac{2}{3}}X_1 \tag{2.18}$$

$$X_0' = -\sqrt{\frac{2}{3}}X_8 + \sqrt{\frac{1}{3}}X_1. \tag{2.19}$$

Then the OIZ rule implies

$$\begin{aligned} 0 &= \langle X_0'|\mathcal{H}'|X_0\rangle \\ &= \frac{\sqrt{2}}{3}(\mathcal{H}'_{11} - \mathcal{H}'_{88} + \frac{1}{\sqrt{2}}\mathcal{H}'_{18} - \sqrt{2}\mathcal{H}'_{81}) \end{aligned} \tag{2.20}$$

where $\mathcal{H}'_{11} =< X_1|\mathcal{H}'|X_1 >$ and so forth. From flavor $SU(3)$ symmetry of the interactions,

$$\mathcal{H}'_{18} = \mathcal{H}'_{81} = 0 \tag{2.21}$$

so that (2.20) implies

$$\mathcal{H}'_{11} = \mathcal{H}'_{88}. \tag{2.22}$$

This is just the result we wanted to prove.

Because of (2.22) the interactions do not violate the idiot relations (2.16) and (2.17). So we have shown that $SU(3)$ symmetry and the OIZ rule imply ideal mixing, (2.12) and (2.13), and the mass relations

$$m_{I=1} = m_{X_0} \tag{2.23}$$

$$2m_{I=\frac{1}{2}} = m_{X_0} + m_{X_0'}. \tag{2.24}$$

Now consider some examples. The ideal ideal nonet is the ground state $J^{PC} = 1^{--}$ ρ nonet, consisting of $\rho(770), K^*(892), \omega(783)$, and $\phi(1020)$. In fact, it was this nonet that led comrades O, I, and Z to formulate the OIZ rule. Ideal mixing

$$\begin{aligned} \omega &\sim \frac{\bar{u}u + \bar{d}d}{\sqrt{2}} \\ \phi &\sim \bar{s}s \end{aligned}$$

and the OIZ rule are indicated by the suppression of $\phi \to \rho\pi$ compared to $\phi \to \bar{K}K$ by two orders of magnitude in the square of the amplitudes (*i.e.*, after removing the effect of phase space). The mass relations hold to about 2%:

$$770 \sim 788$$

and

$$2(892) \sim 783 + 1020$$

The highest spin complete nonet, $J^{PC} = 3^{--}$, consists of $\rho_3(1690)$, $K_3^*(1780)$, $\omega_3(1670)$ and $\phi_3(1850)$. This is an $L = 2$ spin triplet state in the nonrelativistic classification. ϕ_3 is produced in K scattering and decays to $\bar{K}K$ and K^*K while ω_3 is produced in

π scattering and decays to 3π and 5π, both suggesting ideal mixing and the OIZ rule. The mass relations are valid to 1%!

The clearest example of nonideal mixing is provided by the π, K, η, η' nonet. The mass relations are terrible: $140 \neq 549$ and $2(494) \neq 549+958$. Instead the $SU(3)$ mass formula for the octet component

$$m_{\eta_8}^2 = \frac{4}{3}m_K^2 - \frac{1}{3}m_\pi^2 = (565)^2 \cong m_\eta^2 \tag{2.25}$$

gives a very good approximation to the η mass. Equation (2.25) follows from $SU(3)$ and the assumption that the $SU(3)$ breaking Hamiltonian is in the octet representation, as is true in QCD where $SU(3)$ breaking is due to quark masses (the Gell Mann-Nishijima formula). I use the quadratic formula because current algebra implies it for near-Goldstone bosons associated with spontaneous breaking of chiral symmetry. Equation (2.25) shows the mixing is nearer to singlet-octet than to ideal:

$$\eta \cong \eta_8 = \frac{1}{\sqrt{6}}(\bar{u}u + \bar{d}d - 2\bar{s}s) \tag{2.26}$$

$$\eta' \cong \eta_1 = \frac{1}{\sqrt{3}}(\bar{u}u + \bar{d}d + \bar{s}s). \tag{2.27}$$

Singlet-octet mixing with the singlet much heavier than the octet, $m_1^2 >> m_8^2$, can be understood if the singlet interaction energy is much bigger than the octet,

$$\mathcal{H}'_{11} >> \mathcal{H}'_{88}. \tag{2.28}$$

From eq. (2.20) we see that this requires a large OIZ violating force. In QCD a large flavor singlet OIZ violating force could arise from multigluon exchange. We expect it to be stronger in the $J = 0$ channel than $J = 1$ since in perturbation theory $J = 0$ but not $J = 1$ states can couple to two real gluons (so that the two gluon mixing amplitude cannot have an imaginary part in the $J = 1$ channel and is suppressed). The problem of understanding $\eta - \eta'$ mixing is sometimes referred to as the "$U(1)$ problem". Plausible qualitative explanations have been given but it is still not understood quantitatively.

Let's consider a simple model that contains the essential physics.[34] We neglect the u and d masses (the chiral $SU(2)$ limit), so that $m_u = m_d = m_\pi = 0$, and we assume

$$\mathcal{H}'_{11} >> \mathcal{H}'_{88} \cong 0.$$

Then in the 8-1 basis the mass matrix (squared) is

$$M = \begin{pmatrix} \frac{4}{3}m_K^2 & -\frac{2\sqrt{2}}{3}m_K^2 \\ -\frac{2\sqrt{2}}{3}m_K^2 & \frac{2}{3}m_K^2 + \mathcal{H}'_{11} \end{pmatrix} \tag{2.29}$$

Diagonalizing, the eigenvalues are

$$m_\eta^2, m_\eta^{2\prime} = \frac{1}{2}\left(\mathcal{H}'_{11} + 2m_K^2 \pm \sqrt{9\mathcal{H}'^2_{11} - 4\mathcal{H}'_{11}m_K^2 + 4m_K^4}\right) \tag{2.30}$$

Summing the two roots we determine the free parameter $\mathcal{H}'_{11}$

$$\mathcal{H}'_{11} = m_\eta^2 + m_{\eta'}^2 - 2m_K^2 = (0.85GeV)^2 \tag{2.31}$$

From

$$\tan 2\theta = -\frac{4\sqrt{2}m_K^2}{3\mathcal{H}'_{11} - 2m_K^2} \tag{2.32}$$

we then find

$$\theta = -19^0 \tag{2.33}$$

$$m_\eta = 490\ MeV \tag{2.34}$$

$$m_{\eta'} = 990\ MeV. \tag{2.35}$$

These three results came from one free parameter. As expected, (2.31) shows that $m_{\eta'}$ is dominated by the large singlet OIZ violating interactions.

The usual quark model angle $\theta = -11^0$ is obtained by assuming two free parameters, M_{11} and M_{18}, and fitting to m_η and $m_{\eta'}$. A recent analysis[35] of many experiments favors $\theta \cong -20^0$. For example, if $\psi \to \gamma + \eta/\eta'$ is proportional to the η_1 components of η and η', as we would naively expect from $SU(3)$ symmetry, then[36]

$$\frac{\Gamma(\psi \to \gamma\eta)}{\Gamma(\psi \to \gamma\eta)')} = \left(\frac{k_\eta}{k_{\eta'}}\right)^3 \tan^2\theta \tag{2.36}$$

Experimentally the left side is 4.8 ± 0.2 which gives $\theta \cong -22^0$.

The important lesson of this analysis is that when ideal mixing fails it is dangerous to assume "nonet symmetry". The analysis[37] of hadronic ψ decays to pseudoscalar plus vector meson which suggested a glueball component in η' could more conservatively have been interpreted as a violation of "nonet symmetry". That analysis was abandoned because it predicted a too large $\gamma\gamma$ width for iota interpreted as the mixed glueball. A more recent analysis[38] that includes DOZI (double OZI suppressed) interactions is equivalent to including "nonet symmetry" breaking terms.

Before leaving this subject I want to comment on a related misconception. It is sometimes said that the large η' mass can be understood if the η' mixes with a heavy glueball. It is true that if a rabbit eats an elephant the rabbit will get fatter. But if a rabbit and an elephant mix quantum mechanically, then the rabbit will get lighter and the elephant heavier. The "levels repel" according to the old rule for two body mixing. Mixing with a heavier glueball does not help explain the η' mass.

A Tour of Some Excited States

The 2^{++} nonet, along with the ground state 0^{-+} and 1^{--}, is one of the best established $\bar{q}q$ nonets, consisting of $A_2(1320)$, $K_2^*(1430)$, $f(1275)$ and $f'(1525)$. It is approximately ideal since the mass relations are good to a few percent and the f' is prominently produced in K scattering and decays chiefly to $\bar{K}K$ as expected for an $\bar{s}s$ state. With the conventional analysis we define the mass matrix

$$M = \begin{pmatrix} m_8 & \delta \\ \delta & m_1 \end{pmatrix}, \tag{2.37}$$

δ and m_1 are free parameters while m_8 is fixed by the Gell Mann-Nishijima formula

$$m_8 = \frac{4}{3} m_{K^*} - \frac{1}{3} m_{A_2}. \tag{2.38}$$

Diagonalizing and fitting the parameters to the f and f' masses, we find the angle θ in the ideal basis

$$\begin{aligned} f &= \cos\theta \, \frac{\bar{u}u + \bar{d}d}{\sqrt{2}} + \sin\theta \, \bar{s}s \\ f' &= -\sin\theta \, \frac{\bar{u}u + \bar{d}d}{\sqrt{2}} + \cos\theta \, \bar{s}s \end{aligned} \tag{2.39}$$

to be $\theta = -6^0$, very nearly ideal. This understanding of the A_2 nonet helps us to recognize that $\theta(1730)$ must be new physics, as discussed in section 4.

The 0^{++} nonet wins the prize for the most confusing nonet. There is an established isovector δ/a_0 (980) which decays to $\eta\pi$ and $\bar{K}K$, even though it is just below $\bar{K}K$ threshold. This is very puzzling since a $\bar{q}q$ isovector does not contain $\bar{s}s$ quarks. The nearly degenerate $I = 0$ S^*/f_0 (975) decays to $\pi\pi$ and also to $\bar{K}K$! Two other established isoscalars are $\epsilon/f(1300)$ (decays predominantly to $\pi\pi$) and G/f_0 (1590) which decays most strongly to $\eta\eta'$ and $\eta\eta$. Two other possible states are f_0 (1240) and f_0 (1730). The κ/K^* (1350), seen as a $K\pi$ resonance, is an established 0^{++} isodoublet.

It is hard to make a nonet of these. $m_{S^*} \cong m_\delta$ suggests ideal mixing but the strong couplings to $\bar{K}K$ are then not understandable. It may be that δ and S^* are cryptoexotic four quark states,[39]

$$\begin{aligned} S^* &\stackrel{?}{=} (\bar{u}u + \bar{d}d)\bar{s}s \\ \delta^+ &\stackrel{?}{=} u\bar{d}s\bar{s} \end{aligned}$$

which could explain the strong $\bar{K}K$ coupling and their degeneracy. Then f_0 (1300), f_0 (1730) and K_0^* (1350) could be 6/9 of the $L = 1$ $\bar{q}q$ nonet, leaving the isovector still to be found. The $J = 0$ states between 1 and 2 GeV may be the most difficult to discover, since low partial waves have flat angular distributions that are most difficult to see above the background. Therefore high statistics data of very high quality is required. This may explain why there is still no clear indication of a scalar glueball in radiative J/ψ decay.

The radially excited pseudoscalars are crucial for the interpretation of ι (1460). There may be a complete nonet consisting of π (1300), K (1460), η (1275), and η (1400). π (1300) is seen by five experiments. It is very broad though there is some disagreement about the width, with estimates ranging from 200 to 500 MeV — another example of the difficulty of measuring low partial waves. $K(1460)$ is seen by two high statistics experiments, LASS and ACCMOR, as a $K\pi\pi$ resonance with $\Gamma \sim 250$ MeV. The isoscalars will be discussed with $\iota(1460)$ in section 4. There is still some question about the existence and properties of $\eta(1400)$ that must be resolved in order to understand iota.

The $J^{PC} = 1^{++}$ and 1^{+-} nonets are of great interest in connection with the indications of new physics in the $J = 1$ channel, to be discussed in section 5. Both are only recently added to my list of complete nonets because of new results obtained by LASS from their 140,000,000 event sample of Kp scattering data.[21,33] LASS has discovered the $\bar{s}s$ isoscalar H'/h_1 (1400) to complete the B/b_1 nonet, consisting also of $b_1(1235)$, Q_b, and h_1 (1190). The h_1 (1400) is also evident in BNL data reported at Hadron '87 though the analysis is not completed.[40] LASS also confirms the D'/f_1 (1530) which is an excellent candidate for the $\bar{s}s$ state needed to complete the 1^{++} nonet consisting in addition of A_1/a_1 (1270), Q_a, and D/f_1 (1285).

However there are still major questions about the A_1 nonet. As reviewed by Gilman[41], data from $\tau \to \pi\pi\pi\nu$ suggest a smaller A_1 mass, though some experiments find ~ 1200 MeV, approaching the larger hadronic values ranging from 1240 to 1280 MeV. The uncertainty about the mass could be related to the large width, estimated between 300 and 500 MeV. The second major controversy concerns $E(1420)$, previously regarded as the $\bar{s}s$ member of the nonet. There is controversy as to whether a 1^{++} E exists at all (see section 5), and there is no evidence for 1^{++} E production in Kp scattering. $D(1285)$, $E(1420)$, and $D'(1530)$ would be too many $I = 0$, $J^{PC} = 1^{++}$ states for the $\bar{q}q$ spectrum.

I did not quote masses for Q_a and Q_b in the discussion above because they are not directly observed. The observed mass eigenstates, Q_1/K_1 (1280) and Q_2/K_1 (1400), are not $\mathcal{G}$ parity eigenstates ($\mathcal{G}$ being the $SU(3)$ generalization of the $SU(2)$ G-parity, $G=(-1)^I C$) and do not correspond to Q_a and Q_b. Expressed in the G parity basis the mass matrix is not diagonal,

$$M = \begin{pmatrix} m(Q_a) & \epsilon \\ \epsilon & m(Q_b) \end{pmatrix}. \tag{2.40}$$

Q_1 (1280) and Q_2 (1400) are the eigenstates that diagonalize (2.40). We can define a mixing angle θ:

$$\begin{aligned} Q_1 &= \cos\theta\, Q_a + \sin\theta\, Q_b \\ Q_2 &= -\sin\theta\, Q_a + \cos\theta\, Q_b \end{aligned} \tag{2.41}$$

Because $\Gamma(Q \to \rho K) >> \Gamma(Q_1 \to K^*\pi)$, while $\Gamma(Q_2 \to K^*\pi) >> \Gamma(Q_2 \to \rho K)$, LASS[42] and ACCMOR[43] found by using $SU(3)$ symmetry that $\theta \cong 45^0$, which implies

$$m(Q_a) \sim m(Q_b) \sim \frac{1}{2}(m(Q_1) + m(Q_2)) \sim 1340 MeV. \tag{2.42}$$

This satisfies the mass relation for an ideal 1^{++} nonet quite well if $E(1420) = \bar{s}s$ but not for $D'(1530)$. The analysis should be reconsidered in light of the recent data.

3. PROPERTIES OF GLUONIC STATES

In this section I summarize some of the theoretical ideas about gluonic states. I will discuss their production in radiative and hadronic J/ψ decay, the spectrum according to the bag model, and some features of their decays. Nothing I say should be accepted uncritically, since as I have stressed repeatedly the state of the theory is very poor. The slogan for this section should be: ALL THEORISTS GUILTY UNTIL PROVEN INNOCENT.

Consider the naive perturbative estimates for radiative J/ψ decay to glueballs $G = |gg>$, 混合 $= |\bar{q}qg>$, and ordinary meson $M = |\bar{q}q>$. In lowest order $\psi \to \gamma X$ proceeds by $\psi \to \gamma gg$, and counting powers of α_s we find

$$\begin{aligned} \Gamma(\psi \to \gamma G) &\sim O(\alpha\alpha_s^2) && (3.1) \\ \Gamma(\psi \to \gamma \text{ 混合}) &\sim O(\alpha\alpha_s^3) && (3.2) \\ \Gamma(\psi \to \gamma M) &\sim O(\alpha\alpha_s^4) && (3.3) \end{aligned}$$

implying a hierarchy of production rates

$$\Gamma(\psi \to \gamma G) > \Gamma(\psi \to \gamma \text{ 混合}) > \Gamma(\psi \to \gamma M) \tag{3.4}$$

Equation (3.4) explains why iota was immediately regarded[44] as a possible glueball: confused with the obscure 1^{++} E, it appeared in $\psi \to \gamma$ "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 $\psi \to \gamma G$ 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 $B(\psi \to \gamma\theta)$ (as the LASS data indirectly suggest). In the presently observed modes it occurs at a rate that is only 1/4 of what is observed so far for iota.

Next consider hadronic J/ψ decays, $\psi \to M + (G$ or 混合 or $M')$ where M is a meson of known flavor content, e.g., ω or ϕ. Such decays have been studied systematically[4] by the Mark III and DM2. Direct hadronic J/ψ decay occurs in lowest order by $\Gamma(\psi \to ggg) \sim 0(\alpha_s^3)$. From the lowest order diagrams beginning from the three gluon intermediate state we obtain

$$\begin{aligned} \Gamma(\psi \to M \text{ 混合}) &\sim O(\alpha_s^5) && (3.5) \\ \Gamma(\psi \to MG) &\sim O(\alpha_s^6) && (3.6) \\ \Gamma(\psi \to MM') &\sim O(\alpha_s^6). && (3.7) \end{aligned}$$

The estimates (3.5) and (3.7) are suppressed by an additional α_s^2 for flavor configurations that are DOZI[38] (double OZI suppressed) such as $\psi \to \phi f$ or $\psi \to \omega f'$. Provided the M final state is not DOZI suppressed, the hierarchy is

$$\Gamma(\psi \to M \text{ 混合}) > \Gamma(\psi \to MG) \sim \Gamma(\psi \to MM') \tag{3.8}$$

Equation (3.8) suggests that $\bar{q}qg$ states may be favored in hadronic J/ψ decay.

<u>Spectrum of Gluonic States</u>

Next we briefly review the spectrum of gluonic states expected in the bag model. The lowest gluon cavity mode is g_{TE} or "transverse electric" and has $J^{PC} = 1^{+-}$ (like the b_1 nonet). The higher energy transverse magnetic mode g_{TM} has more familiar vector quantum numbers $J^{PC} = 1^{--}$. The ground state glueballs contain $g_{TE}g_{TE}$ with $J^{PC} = 0^{++}, 2^{++}$ (since $J=1$ is forbidden by Bose statistics). Excited glueball states made of $g_{TE}g_{TE}$ have $J^{PC} = 0^{-+}$ and 2^{-+}. (The 1^{-+} state that also naively arises by combining $1^{+-} \oplus 1^{--}$ is "spurious", being interpreted as the $L=1$ motion of the 0^{++} ground state with respect to the artificially fixed frame of the bag.

	0^{-+}	1^{-+}	1^{--}	2^{-+}
ρ	1200	1410	1640	1790
ω	1300	1510	1650	1890
K	1410	1590	1800	1940
ϕ	1630	1800	1980	2100

Table 3.1: bag model estimates of $\bar{q}qg_{TE}$ masses (MeV) from ref. 46, with $C_{TE}/C_{TM} = \frac{1}{2}$ in order to fit ι and θ.

However, as mentioned in section 2, such states might actually exist with large masses as the result of cavity mode excitations.) The degeneracy of the $0^{++} - 2^{++}$ and $0^{-+} - 2^{-+}$ pairs is lifted by the order α_s gluon exchange corrections. Using cavity perturbation theory as systematically developed by Lee,[45] three groups[46,47,48] have found the mass hierarchy

$$0^{++} < 0^{-+} < 2^{++} < 2^{-+}. \tag{3.9}$$

In the calculation of ref. 46, which includes gluon self energies as parameters, the 0^{++} and 2^{-+} glueballs are estimated at 1-1.3 GeV and 2.3 GeV respectively if $\iota(1460)$ and $\theta(1730)$ are assumed to be the 0^{-+} and 2^{++} glueballs.

The $\bar{q}qg_{TE}$ ground state consists of four nonets, the spin singlet $0^{-+} \oplus 1^{+-} = 1^{--}$ and the triplet $1^{--} \oplus 1^{+-} = (0,1,2)^{-+}$. The 1^{-+} $\bar{q}qg_{TE}$ nonet is exotic and cannot be confused with ordinary $\bar{q}q$ states. The excited $\bar{q}qg_{TM}$ states include the singlet $0^{-+} \oplus 1^{--} = 1^{+-}$ and the triplet $1^{--} \oplus 1^{--} = (0,1,2)^{++}$, the same quantum numbers as the $L = 1$ $\bar{q}q$ states. The gluon exchange corrections imply[2]

$$0^{-+} < 1^{-+} < 1^{--} < 2^{--} \tag{3.10}$$

for the $\bar{q}qg_{TE}$ nonets and [13]

$$0^{++} < 1^{++} < 1^{+-} < 2^{++} \tag{3.11}$$

for $\bar{q}qg_{TM}$. The mass estimates based on refs. 46 and 13 respectively are shown in tables 3.1 and 3.2, again assuming $\iota(1460)$ and θ (1730) are the 0^{-+} and 2^{++} glueballs.

Notice in table 3.1 the 0^{-+} nonet is in the same mass region that we expect the radially excited 0^{-+} $\bar{q}q$ nonet. Perhaps the $\pi(1300)$ nonet discussed in sections 2 and

	0^{++}	1^{++}	1^{+-}	2^{++}
ρ	1800	1940	2130	2230
ω	1900	2040	2130	2320
K	1980	2110	2260	2350
ϕ	2220	2310	2400	2510

Table 3.2: Bag model estimates of $\bar{q}qg_{TM}$ masses (MeV) from ref. 13 with $C_{TE}/C_{TM} = \frac{1}{2}$ in order to fit ι and θ.

4 are $\bar{q}qg$ states or mixtures of $\bar{q}qg$ and $\bar{q}q$. This hypothesis is supported by the strong upper limits on $\eta(1280) \to \gamma\gamma$ and $\eta(1400) \to \gamma\gamma$ discussed in section 4, which are more easily understood for $\bar{q}qg$ states than for $\bar{q}q$. Further discussion of this possibility is given in section 4.

Also in table 3.1 we see that the exotic $1^{-+}\rho$ and ω are in the mass region corresponding to the new physics in the $J^C = 1^+$ channel discussed in section 5. Notice also that the $\bar{q}qg$ states in table 3.1 are the third possible source of 1^- excitations around $1.5 - 2$ GeV, along with the $N = 1$, $L = 2$ and $N = 2$, $L = 0$ $\bar{q}q$ excitations discussed in section 2. Nobody promised that life would be easy! It is only relatively easy in the exotic channels like 1^{-+} which cannot be confused with "ordinary" physics.

Decays of Glueballs and Meiktons

Glueballs are $SU(3)$ flavor singlets but it is dangerous to use this as a criterion for identifying them because large $SU(3)$ breaking may effect their decays. For example, in lowest order perturbation theory

$$\mathcal{M}(gg \to \bar{q}q)_{J=0} \propto m_q \tag{3.12}$$

so that decays to $\bar{s}s$ are much larger than to $\bar{u}u + \bar{d}d$ for the 0^{++} and 0^{-+} glueballs. Equation (3.12) is a familiar consequence of "helicity conservation", the same reason $\Gamma(\pi \to \mu\nu >> \Gamma(\pi \to e\nu)$. (The decay $gg \to \bar{q}q\bar{q}q$ occurs in the same order in α_s but with smaller phase space.) This might explain why $\iota \to \bar{K}K\pi$ is dominant.

A second possible source of large $SU(3)$ breaking emerges in cavity perturbation theory:[13] the $g_{TM}\bar{s}s$ coupling is much larger than $g_{TM}(\bar{u}u + \bar{d}d)$. Since $\iota = g_{TM}g_{TE}$ in the bag model even the $gg \to \bar{q}q\bar{q}q$ decays may be dominated by $(\bar{s}s)_8(\bar{u}u + \bar{d}d)_8$ ("8" = color octet) that hadronize to $\bar{K}K\pi$.

Kinematic or form factor effects can also cause large $SU(3)$ breaking. For instance, θ decays to $\bar{K}K$ and $\pi\pi$ in the ratio 4:1, a big $SU(3)$ violation. As argued elsewhere[49] this could be due to kinematics: in a model with $\theta \to \bar{u}u + \bar{d}d + \bar{s}s$ that is $SU(3)$ symmetric at the quark level, the bigger phase space for multibody decays open to $\bar{u}u + \bar{d}d$ 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 equivalent to the observation that the pion form factor may fall off more rapidly than the K.[50]

Another source of $SU(3)$ violation is the gluon "discoloration" mechanism[51] by which a second gg pair is created by vacuum polarization. The four gluon system may then couple pair-wise to η or η', which appear in radiative J/ψ decay to have large gg couplings. This might explain $\theta \to \eta\eta$ and suggests a search for $\theta \to \eta\eta'$ and more generally a study of $\psi \to \gamma\eta\eta'$ or $\gamma\eta'\eta'$.

The safest conclusion of this discussion is that there are no reliable predictions about the $SU(3)$ symmetry properties of glueball decays.

A seemingly safe prediction, discussed in section 1, is that glueballs should have smaller couplings than $\bar{q}q$ mesons. In perturbation theory, $M(gg \to \gamma\gamma) \sim \alpha\alpha_s$ proceeds by a $\bar{q}q$ loop while $M(\bar{q}q \to \gamma\gamma) \sim \alpha$ goes directly. However for light $J = 0$ glueballs this seemingly obvious result may be wrong![52] Because of the chiral and trace anomalies light $G = 0$ glueballs could couple to $\gamma\gamma$ in order α with no power of α_s. This strange result is reviewed in refs. 53 and 54.

A second related conclusion[55,53,54] is that the large coupling of the $\eta'(958)$ to gg indicated by the large value of $\Gamma(\psi \to \gamma\eta')$ can be understood qualitatively by the chiral anomaly and approximate chiral symmetry, with no need to assume a big glueball component in η'. For simplicity neglect the $\eta - \eta'$ mixing and assume that $\eta' \cong \eta_1$. Consider the chiral $SU(3)$ limit, $m_u = m_d = m_s = 0$. Then the QCD chiral anomaly for the singlet axial current is

$$\partial A_1 = \frac{\sqrt{3}\alpha_s}{2\sqrt{2}\pi} G\tilde{G} \tag{3.13}$$

where $G\tilde{G} = \epsilon_{\mu\nu\alpha\beta}G^{\mu\nu}G^{\alpha\beta}$ and $G^{\mu\nu}$ is the gluon field strength tensor. The singlet PCAC constant F_1 is defined by

$$< 0|A_1^\mu|\eta' >= ik^\mu F_1. \tag{3.14}$$

Taking the divergence and using (3.13) we find

$$< 0|\frac{\sqrt{3}\alpha_s}{2\sqrt{2}\pi} G\tilde{G}|\eta' >= m_{\eta'}^2 F_1. \tag{3.15}$$

Equation (3.15) tells us that the $\eta' gg$ coupling is $O(\alpha_s^{-1})$ times a typical coupling of a meson to a quark bilinear current, without the suppression factor we would have expected from a $\bar{q}q$ loop! Together with the remark in section 2 about $\eta'-$ glueball mixing and the η' mass, I conclude that there is no compelling reason to assume the η' has a large glueball component.

Finally I want to make two comments about 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 $g \to \bar{s}s$. The first step in

$$(\bar{\ell}\ell')_8 g \to (\bar{\ell}\ell')_8(\bar{s}s)_8 \tag{3.16}$$

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

$$(\bar{\ell}s)_1(\bar{s}\ell')_1 \tag{3.17}$$

or by soft gluon exchange

$$(\bar{\ell}\ell')_1(\bar{s}s)_1 \tag{3.18}$$

with the subscript 1 denoting *color singlet*. Mechanism (3.17) should usually dominate but (3.18) might occur an appreciable fraction of the time. If (3.18) does occur, it may be the signature of a decay, since such final states are OIZ forbidden decays of all $\bar{q}q$ mesons. The decay $C(1480) \to \phi\pi$ and the possible decay $\xi(2230) \to \phi\omega$ are examples discussed below.

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

$$(\bar{q}q)_8^{L=0} g_{TE} \to (\bar{q}q)_8^{L=0}(\bar{q}'q')_8^{L=1} \tag{3.19}$$

leads to two other color octet $\bar{q}q$ pairs, one in the $J^{PC} = 0^{-+}$ or 1^{--} state of an $L = 0$ $\bar{q}q$ 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. (3.17), the naive expectation is to have one ground state meson, $J^{PC} = 0^{-+}$ of 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.[14] However, 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 混合 could decay to $(\pi b_1)_{L=0}$ by the first mechanism or to $(\pi\eta)_{L=1}$ by the second. Depending on the 混合 (huĕn-hé) masses, phase space might favor or even require the second mechanism. The bottom line is this: like the theorists, all models are guilty until proven innocent. Until our understanding is much greater than it is now, we should search in all kinematically allowed channels. The two body $L = 1$ decays are experimentally easier to observe than the $L = 0$ decays which are quasi two body.

4. CANDIDATE GLUONIC STATES

In this section I will discuss the status of the search for gluonic states based on what is now known experimentally. I will indicate which experimental studies will be needed for future progress. Many require high statistics measurements of J/ψ decays.

The particular states discussed are $\iota(1460), \theta(1730), C(1480), \xi(2230)$ and, briefly, several other possible resonances that do not appear strongly in J/ψ decay. Of these, iota is best established as a glueball: the only remaining uncertainty concerns $\eta(1400)$. If $\eta(1400)$ were confirmed by a J^{PC} analysis of $\psi \to \gamma\eta\pi\pi$, the last doubts about iota as a glueball would be removed. I will also discuss the possibility that the data indicates 0^{-+} $\bar{q}qg$ states in the iota mass region.

The most interesting new result about $\theta(1730)$ is that LASS did *not* observe it in their 140,000,000 event Kp scattering data. As I will explain, this probably means that θ has many unobserved decay modes, that $\Gamma(\psi \to \gamma\theta)$ is much bigger than the present lower limit, and that θ is indeed the 2^{++} glueball! To prove this we must find the missing θ decay modes. Again high statistics analysis of radiative J/ψ decay is essential.

$C(1480)$ is a $J^{PC} = 1^{--}$ $\phi\pi$ resonance, an example of the $\bar{q}qg$ "signature" decay modes discussed in section 3, which are OIZ forbidden for $\bar{q}q$ mesons. It may then occur in hadronic J/ψ decay. Similarly there is an unconfirmed possibility that $\xi(2230)$ decays to $\phi\omega$, another huĕn hé "signature" mode. Again more statistics are needed to measure the spin of ξ and to confirm or deny the $\phi\omega$ decay, in order to decide between the 2^{++} $(\bar{u}u + \bar{d}d)g_{TM}$ hypothesis[13] or the 4^{++} $\bar{s}s$ hypothesis.[22]

Iota (1460) and 0^{-+} $\bar{q}qg$

First a quick summary of the properties of iota. Measured in $\psi \to \gamma K^+K^-\pi^0$ by the Mark III the mass and width are

$$M = 1461 \pm 5 \pm 5\ MeV$$

$$\Gamma = 101 \pm 10 \pm 10\ MeV. \tag{4.1}$$

Spin-parity[4] is $J^{PC} = 0^{-+}$ and the production rate in radiative J/ψ decay is

$$B(\psi \to \gamma\iota)B(\iota \to \bar{K}K\pi) = (5.0 \pm 0.3 \pm 0.8) \cdot 10^{-3}. \tag{4.2}$$

A coupled-channel analysis suggests (but should not be regarded as establishing) that ι may also decay to $\rho\rho$ and $\omega\omega$ with

$$B(\psi \to \gamma\iota)B(\iota \to \rho\rho) = (1.5 \pm 0.2) \cdot 10^{-3} \tag{4.3}$$

$$B(\psi \to \gamma\iota)B(\iota \to \omega\omega) = (0.3 \pm 0.1) \cdot 10^{-3} \tag{4.4}$$

Iota may have other undiscovered decays, an interesting possibility being $\eta'\pi\pi$.

From (4.2) - (4.4) we can conclude that $B(\psi \to \gamma\iota)$ is very big, $\gtrsim (5-7) \cdot 10^{-3}$, depending on whether $\rho\rho$ and $\omega\omega$ are included. It is the most prominent state seen in $\psi \to \gamma X$, the second being η' with $B(\psi \to \gamma\eta') = (4.2 \pm 0.5)10^{-3}$. It is also a large fraction of all $\psi \to \gamma X$. Comparing with eq. (1.10),

$$\frac{B(\psi \to \gamma\iota)}{B(\psi \to \gamma X)_{inclusive}} \gtrsim 7 - 10\% \tag{4.5}$$

The upper limit on $\iota \to \gamma\gamma$ is much improved since 1984. Today the best upper limit is[56]

$$\Gamma(\iota \to \gamma\gamma)B(\iota \to \bar{K}K\pi) < 1.6 \text{ keV } (95\% CL). \tag{4.6}$$

As noted in section 2, this improved limit contradicted $\eta - \eta' - \iota$ mixing models[37] that assumed "nonet symmetry" and predicted much bigger values for $\iota \to \gamma\gamma$. The discussion of the unsuppressed $\gamma\gamma$ coupling of a light 0^{-+} glueball only applies if it is the lightest $SU(3)$ singlet pseudoscalar particle and therefore does not apply to iota since η' is lighter. (In fact, applied to the η' the analysis mentioned in section 3 leads[53,54] to the usual prediction for $\eta' \to \gamma\gamma$). The improved limit (4.6) is encouraging for the glueball interpretation.

Because of the improved $\iota \to \gamma\gamma$ upper limit, the lower limit on the stickiness of iota is also dramatically improved. Normalizing to $S_\eta = 1$ we now find

$$S_\iota : S_{\eta'} : S_\eta := (> 65) : 4 : 1 \tag{4.7}$$

a very striking result. Together with the evidence that there are enough pseudoscalars to fill a radially excited $\bar{q}q$ nonet, I would assess the confidence level for the glueball interpretation at about 95%. (This is a preliminary value since I have not yet run the full-scale Monte Carlo.)

Because of eq. (4.7) it is very unlikely that iota is a $\bar{q}q$ meson. We could be even more confident if the radially excited 0^{-+} nonet were completely filled. The $\pi(1300)$ and $K(1460)$ were discussed in section 2. Here we discuss the two isoscalars. One, $\eta(1275)$, seems well established,[57] seen at Argonne and KEK in $\pi p \rightarrow \eta\pi\pi n$ and also at BNL[40] in $\pi p \rightarrow \bar{K}K\pi n$, in both cases in the $\delta\pi$ channel.

The second isoscalar is less well established. KEK[57] sees it in their latest data sample at $M = 1390 \pm 10$ MeV with $\Gamma = 45 \pm 16$ MeV, previously reported[57a] by the same collaboration as 1420 ± 3 MeV and 31 ± 7 MeV. BNL[40] observes a $\bar{K}K\pi$ 0^{-+} state at 1421 ± 3 MeV and $\Gamma \sim 60$ MeV, in better agreement with the older KEK result. Comparing with eq. (4.1) we see that neither the KEK nor BNL states correspond well to iota. Therefore if either the KEK or BNL states are confirmed, there are too many $I = 0$, $J^{PC} = 0^{-+}$ states for just a $\bar{q}q$ nonet, as expected if iota is a glueball. If both the KEK and BNL states are confirmed *and* if they are different, then there are too many states for even a glueball plus a $\bar{q}q$ nonet. In that case we begin to consider the possibility of a second nonet in the region, consisting of $\bar{q}qg$ states as in Table 3.1!

In fact a $\bar{q}qg$ interpretation of $\eta(1275)$ and $\eta(1400)$ is suggested by the strong upper limit[58] $\gamma\gamma \rightarrow \eta$ $(1275)/\eta(1400) \rightarrow \eta\pi\pi$ of less that 0.3 keV for either state. At least one of the $\bar{q}q$ isoscalars would be expected to appear at a larger rate. This result could be explained if $\eta(1275)$ or $\eta(1400)$ are $\bar{q}qg$ states which therefore have somewhat suppressed $\gamma\gamma$ couplings. The $I = 0$ $\bar{q}q$ states could be broader and at larger masses ($\gtrsim 1450$ MeV), for which the $\gamma\gamma \rightarrow \eta\pi\pi$ upper limits are much weaker.

A similar remark applies to the $J^P = 0^- \rho\rho$ and $\omega\omega$ structures seen by the Mark III in radiative ψ decay.[4,59] If they are not attributed to iota then they represent additional 0^{-+} isoscalars. If $\eta(1275)$ and $\eta(1400)$ are in a $\bar{q}qg$ nonet, then the $\rho\rho$ and $\omega\omega$ resonance could belong to the radially excited $\bar{q}q$ nonet. This would remove the conflict with the $\gamma\gamma \rightarrow \eta\pi\pi$ upper limits.

The $\psi \rightarrow \gamma\bar{K}K\pi$ signal for iota is not well described by a single Breit-Wigner.[4] The Mark III group has considered two explanations: a coupled-channel fit assuming $\delta\pi$ and K^*K or a two resonance fit in which the largest signal goes to the heavier resonance. In the second case, the heavier resonance would be dominantly a glueball and the lighter could be the $\eta(1400)$ seen at KEK and/or BNL. A decisive conclusion may require more data.

It is very important to establish the existence of $\eta(1400)$. In $\psi \rightarrow \gamma\eta\pi\pi$ there are enhancements at 1280 and 1400 which could be due to $\eta(1275)$ and $\eta(1400)$. It is essential to measure the spin-parity. The one at 1280 has been interpreted by the $DM2$ group as $D(1285)$, but without measuring J^P the conclusion is uncertain.

To summarize, the very large stickiness of iota and the growing evidence for (at least) a complete $\bar{q}q$ nonet in additon imply that iota is a glueball at the 95% confidence level. To raise the confidence level to 99.9% we need to establish the existence of $\eta(1400)$. This could be done in $\psi \rightarrow \gamma\eta\pi\pi$ by determining the spin-parity of the $\eta\pi\pi$ enhancement seen at 1400 MeV. Further pseudoscalars could also emerge in the complex structure of the iota peak and in the $\rho\rho$ and $\omega\omega$ channels. If in addition to $\eta(1275)$, $\eta(1400)$, and $\iota(1460)$ a fourth $I = 0$, $J^{PC} = 0^{-+}$ state were found, we would suspect the presence of two nonets ($\bar{q}q$ and $\bar{q}qg$) and a glueball!

<u>Theta (1730): missing decays?</u>

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. As discussed below, the most interesting new result is that θ is not observed in Kp scattering.

θ has ben 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 gives[26]

$$\begin{aligned} M &= 1720 \pm 10 \pm 10\ MeV \\ \Gamma &= 130 \pm 20\ MeV \end{aligned} \tag{4.8}$$

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

$$\begin{aligned} M &= 1670 \pm 50\ MeV \\ \Gamma &= 160 \pm 80\ MeV. \end{aligned} \tag{4.9}$$

The observed branching ratios are

$$\Gamma(\psi \rightarrow \gamma\theta)B(\theta \rightarrow \bar{K}K) = (9.6 \pm 1.2 \pm 1.8) \cdot 10^{-4} \tag{4.10a}$$

$$\Gamma(\psi \rightarrow \gamma\theta)B(\theta \rightarrow \eta\eta) = (3.8 \pm 1.6) \cdot 10^{-4} \tag{4.10b}$$

$$\Gamma(\psi \rightarrow \gamma\theta)B(\theta \rightarrow \pi\pi) = (2.4 \pm 1.6 \pm 1.5) \cdot 10^{-4}. \tag{4.10c}$$

Adding all three channels,

$$B(\psi \rightarrow \gamma\theta) \gtrsim 1.6 \cdot 10^{-3}. \tag{4.10d}$$

The right side of (4.10) is comparable to $B(\psi \to \gamma f)$ and an order of magnitude bigger than $B(\psi \to \gamma f')$.

The upper limit on $\theta \to \gamma\gamma$ has become rather tight, with the best limit from the TPC[61]

$$\Gamma(\theta \to \gamma\gamma)B(\theta \to \bar{K}K) > 0.2\,\mathrm{keV}\,(95\% CL). \tag{4.11}$$

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

$$S_\theta : S_{f'} : S_f = (>20) : 3 : 1. \tag{4.12}$$

This is impressive though less striking than eq. (4.7) for iota.

A possible θ signal is seen by WA76[62] in central production, $\pi^+ p \to \pi^+(K^+K^-)p$, with $M = 1742 \pm 10$ MeV and $\Gamma = 127 \pm 30$ MeV. 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 the high statistics LASS experiment[32,33] sees $f'/f_2(1525)$ very clearly in $K^- p \to \bar{K}K\Lambda$, no θ signal is observed. This is an extremely interesting result. The observation of f' establishes K exchange as expected, with the production mechanism

$$\bar{K}K \to f' \to \bar{K}K$$

where one of the initial K's is the virtual exchange meson. On the other hand θ is quite broad, $\Gamma \sim 130$ MeV, and 2/3 of the *known* decay modes are to $\bar{K}K$. Therefore *if* the known decays ($\bar{K}K$, $\eta\eta$, and $\pi\pi$) are actually predominant, then we would have $\Gamma(\theta \to \bar{K}K) \sim 90$ MeV indicating a large $g_{\theta \bar{K}K}$ coupling, and we would expect a large cross section for $Kp \to \theta\Lambda \to \bar{K}K\Lambda$, contrary to what is observed.

To be crudely quantitative, the $f' \to \bar{K}K$ partial width satisfies

$$\Gamma(f' \to \bar{K}K) \lesssim \Gamma_{TOTAL}(f') = 70 \text{ MeV}.$$

Taking account of d-wave phase space we would conclude that if $\Gamma(\theta \to \bar{K}K) \sim 90$ MeV then $g_{\theta\bar{K}K} \sim g_{f'\bar{K}K}$ and that $\sigma(Kp \to f'\Lambda \to \bar{K}K\Lambda)$ and $\sigma(Kp \to \theta\Lambda \to \bar{K}K\Lambda)$ should be roughly comparable. Instead there is a strong f' signal, of order 1000 events in K^+K^- and K_SK_S each, and no θ signal at all! Apparently we should conclude that $\Gamma(\theta \to \bar{K}K) << 90$ MeV or that

$$B(\theta \to \bar{K}K) << 1 \tag{4.13}$$

which means from eq. (4.10) that

$$B(\psi \to \gamma\theta) >> 1 \cdot 10^{3}. \tag{4.14}$$

This is a very exciting possibility. It means that θ, like $\iota(1460)$, may have the large production rate expected for a 2^{++} glueball in radiative J/ψ decay! To verify this hypothesis we must find the missing decays of θ in $\psi \to \gamma\theta$. As discussed below, this will probably require the high statistics studies that could be done at BEPC.

To be more precise about eqs. (4.13) and (4.14) we await a quantitative upper limit from LASS for $Kp \to \theta\Lambda \to \bar{K}K\Lambda$, which could be used in a coupled-channel analysis to estimate $B(\theta \to \bar{K}K)$. An earlier analysis, not including the latest LASS data, has been done by Longacre.[60] He considered the channels $\psi \to \gamma + \bar{K}K/\eta\eta/\pi\pi$ and $\pi\pi \to \bar{K}K/\eta\eta/\pi\pi$, with the results $B(\theta \to \bar{K}K) = 0.38^{+.09}_{-.19}$ and $B(\theta \to \pi\pi) < 0.04$. When the LASS data is included it is likely that $B(\theta \to \bar{K}K)$ will be at most 20%. This would imply $B(\psi \to \gamma\theta \gtrsim 5 \cdot 10^{-3}$ and that at least 70% of all θ decays are still unobserved!

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. (4.11), 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.
- $\Gamma(\psi \to \gamma\theta)/\Gamma(\psi \to \gamma f')$ is too large.
- $\sigma(Kp \to \theta\Lambda)/\sigma(Kp \to f'\Lambda)$ is too small.
- There should be a lighter $\bar{u}u + \bar{d}d$ partner.

In fact the BNL $\pi\pi \to \bar{K}K$ analysis[60] 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. It is therefore very probable that θ is some kind of new physics.

Both the Mark III and $DM2$ have observed $\bar{K}K$ enhancements[64] in hadronic J/ψ decay that have been attributed to θ. In $\psi \to \omega K^+K^-$ the Mark III observes a K^+K^- enhancement at 1731 $\pm 10 \pm 10$ MeV (or 1750 ± 17 MeV from DM2) with $\Gamma = 110^{+45}_{-35} \pm 15$ MeV with a branching ratio from the ψ of $(4.5^{+1.2}_{-1.1} \pm 1.0) \cdot 10^{-4}$. In $\psi \to \phi K^+K^-$ the signal is at a significantly lower mass, $1671^{+15}_{-17} \pm 10$ MeV (or 1686 ± 14 MeV for $DM2$) with $\Gamma = 126^{+60}_{-40} \pm 15$ MeV and a branching ratio of $(3.4^{+1.0}_{-0.8} \pm 0.9) \cdot 10^{-4}$. The low mass of the signal seen with ϕ suggests that it may be something other than θ. The spin of these two enhancements is not yet measured. Since there are many mesons in this mass region, we should not conclude that either is θ until the spin is established.

Before the Kp scattering data was presented by LASS it seemed that θ must be something new, perhaps a glueball or perhaps a . But because $B(\psi \to \gamma\theta)$ might not be very big, eq. (4.10d), it was not clear that a glueball interpretation should be preferred. If eqs. (4.13) and (4.14) are the correct interpretation of the LASS data, then $B(\psi \to \gamma\theta)$ is very, very big and the glueball interpretation is very strong. To prove this it is essential to find the missing θ decay modes. Some possible decay channels are

$$\begin{aligned} &(\eta\eta')_{L=2} \\ &(a_2\pi)_{L=1,3} \to \rho\pi\pi, \eta\pi\pi \\ &(a_1\pi)_{L=1,3} \to \rho\pi\pi \\ &(f_2\eta)_{L=1,3} \to \pi\pi\eta \\ &(K^*K)_{L=1,3} \to \bar{K}K\pi \end{aligned}$$

The nominal Q-value for $\theta \to f_2\eta$ is negative $(1730) - 1270 - 549 < 0)$, but since θ and f_2 are both rather broad the decay may still occur. All the above decays will be experimentally very challenging. To discover them will require partial wave analysis of high quality, high statistics data from radiative J/ψ decay. The $\eta\eta'$ mode would also require good photon and/or π^0 detection. Two other possible decay modes are already known to be small: the Mark III has obtained the upper limits.[59]

$$\begin{aligned} B(\psi \to \gamma\theta)B(\theta \to \rho\rho) &< 5 \cdot 10^{-4} \\ B(\psi \to \gamma\theta)B(\theta \to \omega\omega) &< 2.4 \cdot 10^{-4} \end{aligned}$$

$C(1480)$, a $\phi\pi$ resonance

An isovector $\phi\pi$ resonance is reported[64] by the Lepton F collaboration at Serpukhov in $\pi p \to \phi\pi^0 n$. The mass is 1480 ± 40 MeV and the width is 130 ± 60 MeV. $J^{PC} = 1^{--}$ is established by first determining that the angular distribution is consistent with pion exchange. This means that C couplies to $\pi\pi$, implying natural $J^{PC} = 0^{++}, 1^{--}, 2^{++}, 3^{--}, \cdots$. Since it also couples to $\phi\pi^0$ it must have negative charge conjugation, reducing the possibilities to $J^{PC} = 1^{--}, 3^{--} \cdots$. Finally a fit to the $\phi\pi$ angular distribution establishes $J^{PC} = 1^{--}$. An upper limit

$$\Gamma(C \to \omega\pi^0) < 2\Gamma(C \to \phi\pi^0) \tag{4.15}$$

is also reported.

The decay $C \to \phi\pi$ is a nice example of the "signature" decays discussed in section 3 which can occur by soft gluon exchange eq. (3.18) but are OIZ suppressed decays for any $\bar{q}q$ meson. It is then natural to speculate that $C(1480)$ could be the $I = 1$ $\bar{q}qg_{TE}$ state, expected in table 3.1 at ~ 1640 MeV. It would then decay to $\phi\pi$ by the sequence

$$C^+ \stackrel{?}{=} (u\bar{d})_8^{0^{-+}} g_{TE} \to (u\bar{d})_8^{0^{-+}} (s\bar{s})_8^{1^{+-}} \longrightarrow \phi\pi^+ \tag{4.16}$$

where the last step occurs by gluon exchange.

Some other possible decay modes[46] are

$$\begin{aligned} &(h\pi)_{L=0} \to \rho\pi\pi \\ &(a_1\pi)_{L=0} \to \rho\pi\pi \\ &(\omega\pi)_{L=1} \to \pi\pi\pi\pi \\ &(\rho\eta)_{L=1} \to \pi\pi\eta \\ &(K^*K)_{L=1} \to \bar{K}K\pi \\ &(K^+K)^-_{L=1} \\ &(K_SK_L)_{L=1} \\ &(\pi\pi)_{L=1} \\ &(\rho\rho)_{L=1} \end{aligned} \tag{4.17}$$

The first two $L = 0$ decays are of the type (see section 3) in which the angularly excited quark from $g_{TE} \to \bar{q}q$ keeps its angular excitation in the final state h or a_1, while the remaining $L = 1$ decays are of the type in which the quark "loses" its angular excitation to the relative orbital angular momentum of the two newly formed bags. The first two modes may be difficult to study experimentally because of the large widths of h and a_1.

Since there is no reason to expect $g_{TE} \to u\bar{u} + d\bar{d}$ to be suppressed relative to $g_{TE} \to s\bar{s}$, the same mechanism that causes $C \to \phi\pi$ should also cause $C \to \omega\pi$ at least at a comparable level. If $C = \bar{q}qg_{TE}$, we therefore expect

$$\Gamma(C \to \omega\pi) \gtrsim \Gamma(C \to \phi\pi) \tag{4.18}$$

which is not yet incompatible with the experimental bound (4.15). In contrast, if C were a four quark state, eg., $C^+ = u\bar{d}s\bar{s}$, then by the OIZ rule we would expect

$$\Gamma(C \to \omega\pi) << \Gamma(C \to \phi\pi) \tag{4.19}$$

It is therefore interesting to push the study of $G \to \omega\pi$ as far as possible. I do not understand how a $\bar{q}q\bar{s}s$ hypothesis can explain the 130 MeV width of $G(1480)$, since such a state will "fall apart" into two color singlet hadrons with a very large width,[39] perhaps so large that it would not be recognizable as a resonance.

$\xi(2230)$: 4^{++} $\bar{s}s$ or 2^{++} ?

$\xi(2230)$ has been an object of much interest since its discovery by the Mark III in radiative J/ψ decay.[4] It is seen in $\psi \to \gamma K^+K^-$ with $M = 2230 \pm 16 \pm 14$ MeV and $\Gamma = 26^{+20}_{-16} \pm 17$ MeV and with

$$B(\psi \to \gamma\xi)B(\xi \to K^+K^-) = (4.2^{+1.7}_{-1.4} \pm 1.8)\cdot 10^{-5} \qquad (4.20)$$

and in the more background-free K_SK_S channel at $2232 \pm 7 \pm 7$ MeV with $\Gamma = 18^{+23}_{-15} \pm 10$ MeV with

$$B(\psi \to \gamma\xi)B(\xi \to K_SK_S) = (3.1^{+1.6}_{-1.3} \pm 1.7)\cdot 10^{-5}. \qquad (4.21)$$

Since the width is consistent with zero, there was originally speculation that ξ might be a Higgs boson in a two doublet model. This is now ruled out, both by a report from Mark III that $J > 0$ and because ξ is produced in Kp scattering[21] (where a Higgs boson would have too small a coupling to be produced) also with $J > 0$. However the spin of ξ is still not known.

The rather small rate $B(\psi \to \gamma\xi \to \gamma\bar{K}K)$ does not set off the glueball alarm. DM2 does not observe the ξ but the disagreement is not serious since their upper limit[65] is consistent with the Mark III if $\Gamma_\xi \leq 30$ MeV or for any width if $B(\psi \to \gamma\xi \to K^+K^-) \sim 2\cdot 10^{-5}$, the latter being a 1σ fluctuation on the Mark III measurement of $(4.2^{+1.7}_{-1.4} \pm 1.8)\cdot 10^{-5}$.

The $\xi(2230)$ has been seen by LASS[21] in $K^-p \to (K^+K^- + K_SK_S)\Lambda$ with $J \geq 2$ clearly established and a suggestion of $J \geq 4$ from an enhancement at the ξ mass in the Y^0_8 moment. If $J = 4$ were confirmed, it would verify a suggestion[22] that ξ is the 4^{++} $\bar{s}s$ state, partner to the $f(2030)$.

GAMS reports[66,57] an $\eta\eta'$ enhancement[4] in $\pi^-p \to \eta'\eta n$ with $M = 2220 \pm 10$ MeV, $\Gamma < 60$ MeV, 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 $\pi p \to K_SK_Sn$, 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 $(\bar{u}u + \bar{d}d)g_{TM}$ which would decay to $\bar{K}K$ because of the enhanced $g_{TM}\bar{s}s$ coupling mentioned above.[13] Under this hypothesis it could have $J^{PC} = 0^{++}$ or 2^{++}. We suggested a search for $\xi \to \phi\omega$ since by the gluon exchange mechanism the decay would proceed by

$$\begin{aligned}(\bar{u}u + \bar{d}d)^{3S1}_8 g_{TM} &\to (\bar{u}u + \bar{d}d)^{3S1}_8 (\bar{s}s)^{3S1}_8 \\ &\sim \omega_8\phi_8 \\ &\to \omega\phi \ \text{(gluon exchange)}. \end{aligned} \qquad (4.22)$$

The second line emphasizes that after $g_{TM} \to \bar{s}s$ 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 $B(\phi \to \gamma\xi)B(\xi \to \phi\omega) < 6\cdot 10^{-5}$ based on the data shown in ref. 4. 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 are attributed to ξ, they correspond to a branching ratio of $B(\phi \to \gamma\xi)B(\xi \to \omega\phi) \sim 3\cdot 10^{-5}$, which is as large as the signals in K^+K^- or K_SK_S. Clearly we want to see more statistics. If ξ is the 2^{++} then its dominant decay would be to $\bar{K}^*K^*$. Under the $\bar{q}qg_{TM}$ hypothesis $\xi(2230)$ is the state at 2320 MeV in table 3.2.

It is crucial to measure the spin of the ξ. Gao estimated at the 1984 BEPC workshop that at least 25,000,000 J/ψ decays will be needed. This estimate is supported by the fact that with 6,000,000 decays the Mark III group has been unable to determine the ξ spin.

Other gluonic candidates, not seen in J/ψ decay

Finally I will discuss very briefly some other objects that have been mentioned as gluonic candidates. These include the $\phi\phi$ 2^{++} channel at $2 - 2.3$ GeV, the $0^{++}\pi\pi$ channel around 1 GeV, and two $\eta\eta$ resonances at 1590 and 1750. A common theme is that none is observed in radiative J/ψ decay, with stringent upper limits in each case. Since perturbation theory[7] suggests that the 0^{++} and 2^{++} digluon channels in $\psi \to \gamma gg$ 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 ratios[66]

$$\eta\eta' : \eta\eta : \bar{K}K : \pi\pi \cong 3 : 1 : (<1) : (<0.3). \qquad (4.23)$$

Assuming $SU(3)$ symmetry this pattern is not readily understood with 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 implies a mechanism[67] discussed in section 3 by which $G \to \eta\eta$ or $\eta\eta'$ could dominate if G were a glueball. But the failure to observe $G \to \eta\eta$ in the θ region, probably $B(\psi \to \gamma G) < 10^{-4}$, weighs against the glueball interpretation. A more recent hypothesis[68] is that G could be an octet component of a 0^{++} nonet, which would be naturally suppressed in radiative ψ decay and would still have large $\eta\eta'$ and $\eta\eta$ decays. A similar limit must apply to a second recently announced $\eta\eta$ resonance, $X(1750)$, seen in a high statistics study of $\pi p \to \eta\eta n \to \gamma\gamma\gamma\gamma n$ at Serpukhov by the GAMS collaboration.[64] The mass is 1755 ± 8 MeV and the width is bounded by $\Gamma < 50$ MeV. $J^{PC} = 0^{++}$ is preferred but 2^{++} is possible. The X mass is in the θ region but the width is significantly smaller.

A partial wave analysis[31] of the $0^{++}\pi\pi$ and $\bar{K}K$ channels near 1 GeV suggests the possibility of 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, $S(991)$, has approximately flavor independent couplings to $\pi\pi$ and $\bar{K}K$, and was therefore considered as a possible glueball. This motivation is contrary to the discussion in section 3 that $J = 0$ glueballs may decay preferentially to K mesons, because in perturbation theory

$$M(gg \to \bar{q}q)_{J=0} \propto m_q \tag{4.24}$$

so that $\bar{s}s$ dominates. Furthermore, the rate for $\psi \to \gamma\pi\pi$ in this mass region is extremely small. The upper limit[26] $B(\psi \to \gamma S^* \to \gamma\pi\pi) < 0.7 \cdot 10^{-4}$ also applies to S_1 and is two orders of magnitude less than $B(\psi \to \gamma\iota)$. 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 the analysis. If they all exist I wonder whether the three states could instead be explained in terms of "cryptoexotic" $\bar{q}\bar{q}qq$ states expected[39] in this region and p-wave $\bar{q}q$ states?

According to the OIZ rule a resonance in $\pi\pi \to g_T \to \phi\phi$ could not be a $\bar{q}q$ meson but might be a glueball or an $\bar{s}sg$. I am again not competent to judge the sophisticated partial wave analysis needed to see the three g_T states.[69] Both Mark III and DM2 data imply stringent upper limits on $\psi \to \gamma g_T$. For the entire 2.1-2.4 GeV region, the rate according to the Mark III is

$$B(\psi \to \gamma\phi\phi) \cong 3 \cdot 10^{-4}. \tag{4.25}$$

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

5. $E(1420)$ AND ALL THAT ... AGAIN: NEW PHYSICS IN THE $J^C = 1^+$ CHANNEL

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 4), 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 observed[70] in $\bar{p}p$ annihilation at rest with the CERN hydrogen bubble chamber. Named E for Europe, the parameters were $M = 1425 \pm 7$ MeV and $\Gamma = 80 \pm 10$ MeV. The statistical level was high for the time, 800 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 $\pi^- p \to \bar{K}K\pi n$ was studied[71] with a 4 GeV π beam. With 100 events over a comparable background, the analysis indicated that the E is a $J^{PC} = 1^{++}$ state, confirming a previous experiment[72]. The Particle Data Group[73] then 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 II[74] in $\psi \to \gamma\bar{K}K\pi$. For several reasons — including the Landau-Yang theorem[75] which suggests that a 1^{++} state should not be copiously produced in the two gluon $\psi \to \gamma X$ channel — Ishikawa and I suggested[44] that the object seen by the Mark II was a pseudoscalar and probably a glueball. The pseudoscalar hypothesis was confirmed by the Crystal Ball[76] in 1982, and it seemed that both 1^{++} and 0^{-+} $\bar{K}K\pi$ resonances had been established.

As discussed at the end of section 2, the $E(1420)$ seemed a good candidate for the $\bar{s}s$ state to complete the 1^{++} nonet, assuming the LASS-ACCMOR analysis for the "unmixing" of Q_1/K_1 (1280) and $Q_2/K_1(1400)$ which implies Q_A and Q_B masses both at 1340 MeV. The 1^{++} nonet would then consist of $A_1(1270)$, $D(1285)$, $Q_A(1340)$ and $E(1420)$. The dominance of $E \to K^*K$ and the small branching ratio $B(D \to KK^*) \cong 0.1$ are both as expected for ideal mixing and the OIZ rule. The mass relations expected for ideal mixing also work very well,

$$1270 \cong 1285 \tag{5.1}$$

$$2 \cdot 1340 \cong 1285 + 1420, \tag{5.2}$$

good to 1%!

However there are also serious problems. E has never been observed in Kp scattering, as would be expected for an $\bar{s}s$ state. The A_1 mass is controversial, with data from $\tau \to \pi\pi\pi\nu$ favoring lower values as discussed in section 2. Also discussed in section 2, the determination of the Q_A mass is indirect and requires theoretical assumptions. The existence and/or interpretation of $E(1420)$ was also challenged in 1982 by the observation[77] of $D'(1530)$ as a 1^{++} resonance in $Kp \to K^*K\Lambda$, as expected for the $\bar{s}s$ member of the nonet.

The existence of the 1^{++} $E(1420)$ was called into question again in 1985 by the high statistics $\pi p \to \bar{K}K\pi n$ BNL experiment that observed the $\eta(1420) \to K^*K$ in the $J^{PC} = 0^{-+}$ partial wave but no 1^{++} resonance at the E mass. However another high statistics experiment, WA76 at CERN,[79] studying central production of $\bar{K}K\pi$ at high energy with π and p beams, *did* report a 1^{++} E in the K^*K channel (1000 events)! They measured $M = 1425 \pm 2$ MeV and $\Gamma = 62 \pm 5$ MeV. 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 $\gamma\gamma \to \bar{K}K\pi$ scattering they obtained the upper bound on $\iota \to \gamma\gamma$ discussed in section 4, but in tagged events, $\gamma\gamma^* \to \bar{K}K\pi$, they discovered an unmistakeable "E" signal,[24] confirmed by the Mark II.[25] The Landau-Yang theorem[75] here 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 $J = 1$. The signal was observed by the TPC at $M = 1425^{+10}_{-18}$ MeV and by the Mark II at 1423 $\pm$ 4 MeV, in good agreement with the 1^{++} K^*K signal of WA76 at 1425 $\pm$ 2 MeV. This seemed to be very strong confirmation of a 1^{++} E.

Well, maybe .... The data suggested two or three problems. First, the initial TPC signal[24] was too much of a good thing. In the Renard[80] convention (a factor 2 larger than that used by the TPC), which corresponds to the physical partial width for real decays such as $1^{++} \to e^+e^-\gamma$ the TPC result was

$$\frac{m_E^2}{Q^2}\Gamma(E \to \gamma\gamma^*) \cdot B(E \to K\bar{K}\pi) = 12 \pm 4 \pm 4 \text{ keV}. \tag{5.3}$$

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 $\Gamma(f \to \gamma\gamma)$ that

$$\frac{Q^2}{M_E^2}\Gamma(E \to \gamma\gamma^*) \sim 0.4 \text{ keV} \tag{5.4}$$

$$\frac{Q^2}{m_D^2}\Gamma(D \to \gamma\gamma^*) \sim 4\frac{1}{2} \text{ keV}. \tag{5.5}$$

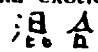
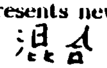
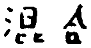
Equations (5.3) and (5.4) differ by at least an order of magnitude. It seemed very difficult to understand the data in terms of an $\bar{s}s$ state.

A second problem, with a similar message, emerges from the Mark III study of hadronic J/ψ decays.[4,26] An "E" signal is seen in $\psi \to \omega$ "E" but not in $\psi \to \phi$ "E":

$$B(\phi \to \omega\ \text{"E"})\, B(\text{"E"} \to K\bar{K}\pi) = (6.8 \pm 2.4) \cdot 10^{-4} \tag{5.6}$$

$$B(\psi \to \phi\text{"}E\text{"})B(\text{"}E\text{"} \to \bar{K}K\pi) < 1.1 \cdot 10^{-4}\ (90\%CL). \tag{5.7}$$

Again we have data that cannot be understood in terms of an $\bar{s}s$ state. The J^P of the "E" in (5.6) is not known.

Motivated by these two problems I proposed[27] a radical solution: that the state seen in $\gamma\gamma \to \bar{K}K\pi$ and $\psi \to \omega\bar{K}K\pi$ is an isoscalar exotic with $J^{PC} = 1^{-+}$ that could be interpreted as a $(\bar{u}u + \bar{d}d)g_{TE}$ ground state . The most attractive feature of the exotic hypothesis is that if it is confirmed it points unmistakeably to new physics. We would not need to repeat the kind of analysis needed in the 0^{-+} channel to decide whether iota represents new physics. But we would still need to decide whether a 1^{-+} $X(1420)$ is a  or something else. According to the  hypothesis $X(1420)$ would be the state predicted in table 3.1 at ~ 1500 MeV.

Most recently, new results were presented at the HADRON '87 meeting by the TPC, Mark II, and LASS. The TPC quoted a somewhat smaller $\gamma\gamma^*$ width than eq. (5.3),

$$\frac{m_E^2}{Q^2}\Gamma(E \to \gamma\gamma^*)B(E \to K^*K) = (7.0 \pm 2 \pm 1.4) \text{ keV}. \tag{5.8}$$

Equation (5.8) assumes a ρ form factor fit to the q^2 dependence of the γ^*. Smaller values were reported by the Mark II[25],

$$\frac{m_E^2}{Q^2}\Gamma(E \to \gamma\gamma^*)B(E \to K\bar{K}\pi) = \begin{cases} 2.7 \pm 1.2 \pm 1.5 \text{ keV} & \rho \text{ fit} \\ 1.7 \pm 0.8 \pm 0.3 \text{ keV} & \phi \text{ fit} \end{cases} \tag{5.9}$$

where the smaller value (with a ϕ form factor fit) would be appropriate for an $s\bar{s}$ state. The Mark II also reports a measurement of $\gamma\gamma^* \to D(1280) \to \eta\pi\pi$. Using $B(D \to \eta\pi\pi)$ from the PDG[8] it implies

$$\frac{m_D^2}{Q^2}\Gamma(D \to \gamma\gamma^*) = 8.2 \pm 2.2 \pm 1.5\ \text{keV}. \tag{5.10}$$

If we assume that $E(1420)$ and $D(1285)$ are the $I = 0$ members of the A_1 nonet, then (5.10) and (5.8) require mixing far from ideal whereas (5.10) and (5.9) can be accommodated by a small, negative mixing angle not far from ideal.

As discussed in section 2, LASS presented results[32] at HADRON '87 confirming the existence of the $1^{++}D'(1530)$, observed in $K\bar{p} \to D'\Lambda \to K^*\bar{K}\Lambda$. In addition the BNL experiment which previously reported[78] the absence of a 1^{++} E signal presented new data[40] which seems to have an enhancement in the 1^{++} $K^*\bar{K}$ intensity at the E mass in the small t region, $|t| < 0.2$ GeV.^{2} (Phase motion was not displayed for this data.)

All together this makes a very confusing picture. However one point is clear: *there are too many $J^C = 1^+$ states for the $\bar{q}q$ model.* Both $D(1285)$ and $D'(1530)$ are now established $J^{PC} = 1^{++}$ states, and the $\gamma\gamma^*$ data clearly establishes a $J^C = 1^+$ state at 1420 MeV. Whether we accept the evidence from hadron scattering for a $1^{++}E$ or not, there is convincing evidence for *three* $J^C = 1^+$ states where the $\bar{q}q$ model can only accommodate the two isoscalars of the 1^{++} nonet.

Since it is possible that a $1^{++}E$ (1420) exists but is not the $J^C = 1^+$ state seen in $\gamma\gamma^* \to \bar{K}K\pi$, I will refer to the $\gamma\gamma^* \to \bar{K}K\pi$ state as $X(1420)$. There are then two critical questions:

1. Does a $1^{++}E(1420)$ exist?

2. If so are $X(1420)$ and $E(1420)$ identical, or could $X(1420)$ be a $P = -$ state?

The critical tests are to determine the parity of the $\gamma\gamma^* \to \bar{K}K\pi$ resonance and to measure the spin and parity of the $\bar{K}K\pi$ signal in $\psi \to \omega\bar{K}K\pi$ at the E/X mass.

At HADRON '87 the TPC announced[81] a parity measurement for X favoring $P = +$ but stated that $P = -$ could not be excluded. The Mark II presented data[25] verifying $P = +$ for the D signal in $\gamma\gamma^* \to \eta\pi\pi$ but stated that no conclusion was possible for the parity of $\gamma\gamma^* \to X \to \bar{K}K\pi$. The TPC parity determination is not definitive because of very low statistics and because it assumes that only one of the

possible amplitudes dominates. This assumption would be justified[82] for $q^2 << M_X$ but the data sample used is dominated by larger q^2 values. Much higher statistics (one or more orders of magnitude) would be needed to have a large enough sample of events with $q^2 << M_X^2$.

The E/X signal in $\psi \to \omega\bar{K}K\pi$, eq. (5.6), is at $M = 1444 \pm 5^{+10}_{-20}$ MeV with $\Gamma = 40^{+17}_{-13} \pm 10$ MeV. An E/X signal is also seen in $\eta\pi\pi$,

$$B(\psi \to \omega\text{“}E\text{”})B(\text{“}E\text{”} \to \eta\pi\pi) = (9.2 \pm 2.4 \pm 2.8)\cdot 10^{-4} \tag{5.11}$$

with $M = 1421 \pm 8 \pm 10$ MeV and $\Gamma = 45^{+32}_{-23} \pm 15$ MeV. The J^P of both signals, (5.6) and (5.11), is not known. However, the Mark II reports an upper limit[25] from $\gamma\gamma^* \to X \to \eta\pi\pi$,

$$\frac{B(X \to \eta\pi\pi)}{B(X \to \bar{K}K\pi)} < 0.56^{+0.44}_{-0.18}\ (90\% CL) \tag{5.12}$$

which is inconsistent with the nominal ratio of eq. (5.11) to eq. (5.6). If $\psi \to \omega\text{“}E\text{”} \to \omega\bar{K}K\pi$ is due to X, then $\psi \to \omega\text{“}E\text{”} \to \omega\eta\pi\pi$ is probably not X but is perhaps $\eta(1400)$. To understand these signals we require J^P analysis of both the two $\psi \to \omega\text{“}E\text{”}$ signals ($\eta\pi\pi$ and $\bar{K}K\pi$) and of the corresponding signals in the $D(1285)/\eta(1275)$ region.

If $X = (\bar{u}u + \bar{d}d)g$, then why is $B(X \to \bar{K}K\pi) > B(X \to \eta\pi\pi)$ as in (5.12)? Naively we would expect the opposite inequality. The answer[27] may be found in the quantum numbers of X in the [illegible] hypothesis: $I = 0$ and $J^{PC} = 1^{-+}$. They imply that if the dipion is in a J eigenstate, then the lowest partial wave is

$$X \to [(\pi\pi)_{L=2} + \eta]_{L=2} \tag{5.13}$$

which is strongly suppressed since the d-wave dipion is negligible below 1 GeV. On the other hand,[83] if $\eta\pi$ is in a J eigenstate the decay proceeds by

$$X \to [(\eta\pi)_{L=1} + \pi]_{L=0}\,. \tag{5.14}$$

But $(\eta\pi)_{L=1}$ corresponds precisely to the $I = 1$, $J^{PC} = 1^{-+}$ exotic expected in table 3.1 at ~ 1400 MeV and possibly seen[28] in that mass region. This decay is also suppressed if the splitting between X and its $I = 1$ partner is less than m_π.

The $\rho\pi\pi$ mode with $\pi\pi$ in a J eigenstate is also suppressed, since the lowest such partial wave is

$$[\rho + (\pi\pi)_{L=1}]_{L=1}\,. \tag{5.15}$$

The $L = 1$ dipion is usually dominated by the ρ which is however forbidden in (5.15) by Bose statistics. Similarly $X \to \rho\rho$ is forbidden by Bose statistics in the narrow width approximation for the ρ and is therefore suppressed in general. $X \to \delta\pi \to \bar{K}K\pi$ or $\eta\pi\pi$ is strictly forbidden by conservation of J and P.

What decays are allowed? According to the qqg_{TE} hypothesis the dominant decays of X are expected to be

$$X \to K^*K \quad L=1, \; Q = 30 \text{ MeV}$$
$$X \to A_1\pi \quad L=0, \; Q = 15 \text{ MeV}.$$

The preliminary experimental evidence is that the $\gamma\gamma^* \to X \to \bar{K}K\pi$ signal[25] is indeed dominated by K^*K.

If we normalize the masses of the 1^{-+} nonet in table 3.1 downward by 90 MeV to fit $X(1420)$ to the "ω" $= (\bar{u}u+\bar{d}d)g$, then we expect the other members of the nonet to be $X_\rho(1320)$, $X_\phi(1700)$, and $X_K(1500)$. Some possible decay modes are

$$X_\rho \to (\pi\eta, \pi\eta', \pi\rho, K^*K)_{L=1}, \; (\pi b, \pi D)_{L=0}$$
$$X_\phi \to (\eta\eta', K^*K)_{L=1}$$
$$X_K \to (\pi K, \eta K, \phi K)_{L=1}, \; (\pi Q_1)_{L=0}$$

Of these $(\pi\eta)_{L=1}, (\pi\eta')_{L=1}$, and $(\eta\eta')_{L=1}$ are especially interesting since they uniquely imply $J^{PC} = 1^{-+}$. As discussed in section 3, hadronic J/ψ decay is a very good place to look for these states, either in

$$\psi \to (\omega X, \phi X_\phi, \rho X_\rho, K^* X_K)_{L=1}$$

or

$$\psi \to (hX, h'X_\phi, b_1 X_\rho, Q_1 X_K)_{L=0}.$$

The preliminary report[28] of a p-wave $\eta\pi$ resonance in the 1300–1400 MeV region is encouraging. The natural channel to seek this object is

$$\psi \to \rho X_\rho \to \rho\pi\eta.$$

To summarize, if 混合 exist at $m \gtrsim 1200$ MeV as in table 3.1, then the spectrum is even more complicated than previously imagined. In this case there could be as many as five $I=0$, $J^{PC} = 0^{-+}$ states between 1200 and 1500 MeV: two $\bar{q}q$ mesons, two $\bar{q}qg$ meiktons and one glueball. They could overlap with one another and mix. In the face of such complexity, the best chance to established the existence of 混合 is to find the $J^{PC} = 1^{-+}$ nonet which cannot be confused with ordinary $\bar{q}q$ physics.

6. SUMMARY AND CONCLUSIONS

The long distance properties of QCD are not understood quantitatively or qualitatively. One of the most fundamental qualitative questions is whether the hadronic spectrum contains states with gluon constituents, glueballs and $\bar{q}qg$ mixed states, 混合. If so, are they characterized by valence gluons as the bag model naively suggests? Are there also excitations of the $\bar{q}q$ spectrum involving collective modes of the soft confining quanta which are different from gluonic states made of valence gluons? There are opinions about these questions but no real answers.

It is interesting to think hard about how well QCD is really understood. The evidence in its favor is convincing but there are no precise tests, like those for QED, which challenge the theory at a deep quantitative level. Therefore despite the "conventional wisdom" in favor of QCD, we should be open to the possibility of fundamental surprises. Such surprises could emerge from careful study of the hadron spectrum, since the spectrum is the central consequence of any theory.

I have stessed that only crude theoretical models are available today. As was discussed extensively at the workshop which preceded us in Beijing in May, in the 1990's we can look forward to serious lattice calculations of the spectrum from future generations of computers — mainframe and special-purpose. These results would be well synchronized with high statistics data from BEPC. Theory will be in a better position to guide experiment, to interpret the data and to suggest important questions. Precise, high statistics experiments will be needed to guide the theory, to test the improved calculations, and to learn which approximations are adequate. This could be the best kind of physics, which does not happen often in a physics lifetime: strong theory and strong experiment working effectively together.

While theory today cannot provide reliable quantitative predictions, we are still not operating completely in the dark. We have a very successful theory of the hadrons in QCD, and we do understand its short distance properties and the qualitative features of the spectrum of "ordinary" mesons and baryons. We therefore have good chances to find and recognize examples of gluonic states. Each case must be analyzed individually, but some possible guidelines include the following:

1.) Glueballs and 混合 are not $\bar{q}q$ mesons, that is, they are *extra* states from the viewpoint of the nonrelativistic $\bar{q}q$ spectrum. This is the most reliable prediction (it could be deduced by the philosophy department without building an accelerator) but it is also the most difficult to put into practice, since it requires a detailed understanding of the "ordinary" qq spectrum. Physicists interested in gluonic states must understand what is already known about the $\bar{q}q$ spectrum and what important questions still need answers.

2. Sticky dynamics can help identify glueballs: small $\gamma\gamma$ widths and large gg couplings suggested by large $\Gamma(\psi \to \gamma G)$ partial widths. Stickiness (see section 1) is the ratio of the square of these couplings with phase space factors removed.

3. [illegible] might give rise to apparent OIZ rule violations of a kind that are strongly suppressed for $\bar{q}q$ mesons, as discussed in section 3. The reliability of this suggestion needs to be tested by experience. Some examples from recent data were discussed in section 4.

4. Exotic quantum numbers are an unambiguous sign of new physics. In section 5 I discussed clues that there may be $J^{PC} = 1^{-+}$ states in the mass region predicted by the bag model for [illegible] .

All these remarks were illustrated in the discussion of sections 4 and 5. Our knowledge of QCD at short distances suggests that $J^{PC} = 0^{++}, 0^{-+}$, and 2^{++} glueballs should be produced prominently in radiative J/ψ decay. With improved upper limits on their $\gamma\gamma$ decay widths, both the 0^{-+} $\iota(1460)$ and the 2^{++} $\theta(1730)$ are quite sticky,

$$\iota : \eta' : \eta \sim (>65) : 4 : 1$$

and

$$\theta : f' : f \sim (>20) : 3 : 1.$$

Since $\eta(1275)$ is established, the question of whether iota is "extra" depends on whether $\eta(1400)$ exists: it is seen by two experiments but with discrepancies that could leave a skeptic unconvinced. It might be verified by establishing $J^P = 0^-$ for the clear enhancement that is seen in $\psi \to \gamma\eta\pi\pi$ with the same mass and width as $\eta(1400)$. According to my Monte Carlo, verification of $\eta(1400)$ would establish $\iota(1460)$ as a glueball at the 99% confidence level. As discussed in section 4 and also by Toki,[4] the structure and mixing of iota will require careful study even if the glueball interpretation is confirmed.

In addition to its stickiness, the failure to observe θ in the high statistics Kp scattering experiment of LASS implies (see section 4) $B(\theta \to K\bar{K}) << 1$ which in turn implies $B(\psi \to \gamma\theta) >> 1 \cdot 10^{-3}$. Since it has long been clear that θ is "extra", the large rate for $\psi \to \gamma\theta$ would confirm the glueball interpretation. The challenge

is to find the missing decay modes of θ ($\gtrsim$70%) in radiative ψ decay and therefore confirm the large value of $\Gamma(\psi \to \gamma\theta)$ directly. High statistics partial wave analysis in quasi two body decay channels is required.

It is probable from the absence of signals in $\psi \to \gamma(\pi\pi, \bar{K}K, \eta\eta)$ that theoretical estimates of a light scalar glueball mass, < 1300 MeV, cannot be correct. However, if the 0^{++} glueball is heavier, it is not surprising that it has not been discovered since low partial waves with flat angular distributions are the most difficult to observe over the typically flat background. Precise, high statistics partial wave analysis is again essential.

The experimental search for [illegible] is less advanced but several clues exist that correspond roughly to the mass regions of tables 3.1 and 3.2. If $\eta(1390)$ seen at KEK and $\eta(1420)$ at BNL are both real and different from each other and if the $0^{-+}\rho\rho$ enhancement seen by the Mark III at 1530 is not due to iota, then there are too many states for even a glueball plus a $\bar{q}q$ nonet. We might then need a 0^{-+} $\bar{q}qg$ nonet in addition. The $J^{PC} = 1^{--}$ $C(1480) \to \phi\pi$ decay might be an example of an apparently OIZ violating [illegible] decay. The same explanation could apply to the possible $\xi(2230) \to \phi\omega$ decay; to confirm it and measure the spin of ξ will require at least 25,000,000 J/ψ decays. Finally there are hints of $I = 0$ and $I = 1$ $J^{PC} = 1^{-+}$ exotic [illegible] in the mass region expected in table 3.1: the $\gamma\gamma^* \to \bar{K}K\pi$ and $\psi \to \gamma\bar{K}K\pi$ enhancements at 1420 MeV and the passible p-wave $\pi\eta$ resonance at $\sim$ 1400 MeV which would necessarily have $J^{PC} = 1^{-+}$. If these are the 1^{-+} exotic [illegible] they should also be produced in hadronic J/ψ decay.

Because the search for gluonic states is so difficult, the prospects are excellent that BEPC will be able to make important contributions in the early 1990's. The goal is to improve on present data samples by an order of magnitude, meaning 50,000,000 to 100,000,000 J/ψ decays. this is certainly an ambitious goal. To accomplish it, several major challenges must be met. BEPC must run at or near the design parameters in luminosity nd beam spread. BES must obtain high quality data and be able to handle instantaneous data acquisition rates much greater than 10 Herz. And the off line analysis may require a parallel processor farm, as discussed in Witherell's lectures.

While data from many different experiments are necessary, J/ψ decay is expecially important for the discovery and analysis of gluonic states. BEPC will therefore be one of the most important world facilities for this physics, arguably *the* most important.

Acknowledgments: I wish to thank Professor Ye Ming Han and the members of the Institute of High Energy Physics for their magnificent hospitality. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

References

1. M. Gell Mann, *Phys. Lett.* **8**, 214 (1964); G. Zweig, CERN-8419/TH 412, 1964 (unpublished).
2. M. Chanowitz and S. Sharpe, *Nucl. Phys.* **B222**, 211 (1983); T. Barnes, F. Close, and F. deViron, *Nucl. Phys.* **B224**, 241 (1983); M. Flensburg, C. Peterson, and L. Sköld, *Zeit. fur Physik* **C22**, 293 (1984).
3. J.D. Bjorken, Proc. SLAC Summer Inst. (ed. A. Mosher), 1979.
4. W. Toki, these proceedings.
5. M. Chanowitz, p. 269, Proc. of the Second Intl. Conf. on Hadron Spectroscopy, KEK Report 87-7, eds. Y. Oyanagi et al., April 16-18, 1987, KEK (and LBL-23437).
6. M. Chanowitz, *Phys. Rev.* **D12**, 918 (1975); L. Okun and M. Voloshin, ITEP-95, 1976 (unpublished). Also, with a factor 3 error: T. Appelquist *et al.*, *Phys. Rev. Lett.* **34**, 365 (1975).
7. A. Billoire *et al.*, *Phys. Lett.* **80B**, 381 (1979).
8. Particle Data Group, *Phys. Lett.* **170B**, 1 (1986).
9. D. Scharre *et al.*, *Phys. Rev.* **D23**, 43 (1981).
10. E. Bloom and F. Gilman, *Phys. Rev.* **D4**, 2901 (1970).
11. R. Jaffe and K. Johnson, *Phys. Lett.* **60B**, 201 (1976); J. Donoghue, K. Johnson, and B.A. Li, *Phys. Lett.* **99B**, 416 (1981).
12. K. Johnson, *Phys. Scr.* **23**, 997 (1981); T.H. Hansson, K. Johnson, *Phys. Rev.* **D26**, 2069 (1982).
13. M. Chanowitz and S. Sharpe, *Phys. Lett.* **132B**, 413 (1983).

14. N. Isgur and J. Paton, *Phys. Lett.* **124B**, 247 (1983)
15. I. Balitski et al., *Phys. Lett.* **112B**, 71 (1982); J. Govaerts *et al.*, *Nucl. Phys.* **B248**, 1 (1984); A.J. Latorre *et al.*, *Phys. Lett.* **147B**, 169 (1984).
16. C. Dominguez, N. Paver, *Zeit. fur Physik* **C31**, 591 (1986).
17. S. Sharpe, R. Jaffe, and M. Pennington, *Phys. Rev.* **D30**, 1013 (1984).
18. S. Narison, Proc. XXIII Intl. Conf. on High Energy Physics, page 709, ed. S. Loken, Berkeley, July 1986 (World Scientific, Singapore, 1986).
19. Y. Iwasaki, Proc. II Intl. Conf. on Hadron Spectroscopy, p. 345, *op cit.*
20. Y. Prokoshkin, p. 28, *ibid.*
21. S. Suzuki, p. 64, *ibid.*
22. S. Godfrey, R. Kokoski, and J. Paton, *Phys. Lett.* **54B**, 869 (1985).
23. C. S. Gao *et al.*, Proc. of the Workshop on Colliding Beam Physics, eds. W. Chen *et al.*, Beijing, June 12–21, 1984.
24. H. Aihara *et al.*, *Phys. Rev. Lett.* **57**, 2500 (1986).
25. G. Gidal *et al.*, LBL-22690, 1987 and Proc XXIII Intl. Conf. on H.E.P., p. 1220, *op cit.*
26. L. Köpke *et al.*, Proc. XXIII Intl. Conf. on H.E.P., p. 692, *op cit.*
27. M. Chanowitz, *Phys. Lett.* **187B**, 409 (1987).
28. F. Binon, Proc. II Intl. Conf. on Hadron Spectroscopy, p. 19, *op cit.*
29. R. Longacre, p. 46, *ibid.*
30. For a recent summary, see V. Obraztsov, Proc. XXIII Intl. Conf. on H.E.P., p. 703, *op cit.*
31. K. Au, D. Morgan, and M. Pennington, *Phys. Rev.* **D35**, 1633 (1987).
32. S. Suzuki, Proc. II Intl. conf. on Hadron Spectroscopy, p. 64, *op. cit.*
33. D. Aston, *et al.*, Proc. XXIII Intl. conf. on H.E.P., p. 718, *op cit.*

34. M. Chanowitz, Proc SLAC Summer Inst., p. 41, ed. A. Mosher, (SLAC-245), 1981.

35. F. Gilman and R. Kauffman, *Phys. Rev.* **D36**, 2761 (1987).

36. R. Cahn and M. Chanowitz, *Phys. Lett.* **59B**, 277 (1975).

37. H. Haber and J. Perrier, *Phys. Rev.* **D32**, 2961 (1985).

38. A. Seiden, H. Sadrozinski, and H. Haber, SCIPP-87/73.

39. R. Jaffe, *Phys. Rev.* **D15**, 267 (1977).

40. S. Protopopescu, Proc. II Intl. Conf. on Hadron spectroscopy, p. 56, *op cit.*

41. F. Gilman, these proceedings.

42. R. Carnegie *et al.*, *Phys. Lett.* **68B**, 287 (1977).

43. M. Mazzucato, *Nucl. Phys.* **B156**, 532 (1979).

44. K. Ishikwa, *Phys. Rev. Lett.* **46**, 978 (1981); M. Chanowitz, *Phys. Rev. Lett.* **46**, 981 (1981).

45. T.D. Lee, *Phys. Rev.* **D19**, 1802 (1979).

46. M. Chanowitz and S. Sharpe, ref. 2.

47. T. Barnes, F. Close, and S. Monaghan, *Nucl. Phys.* **B198**, 380 (1982).

48. C. Carlson, T. Hansson, and C. Peterson, *Nucl. Phys.* **B198**, 380 (1982).

49. M. Chanowitz, Proc. XIV Intl. Symposium on Multiparticle Dynamics, p. 716, Tahoe 1983, eds. P. Yager and J. Gunion (World Sceintific, Singapore, 1983).

50. K. Liu, submitted to II Intl. Conf. on Hadron Sepectroscopy.

51. G. Gershtein, A. Likhoded, and Y. Prokoshkin, *Zeit. fur Physik* **C24**, 305 (1984).

52. V. Novikov *et al.*, *Nucl. Phys.* **B191**, 301 (1981).

53. S. Sharpe, Proc. Symposium on High Energy e^+e^- Interactions, Vanderbilt Univ., Nashville, 1984.

54. M. Chanowitz, Proc. VI Intl. Workshop on Photon-Photon Collisons, p. 45, ed. R. Lander, Tahoe, 1984 (World Scientific, Singapore, 1984).

55. V. Novikov *et al.*, *Nucl. Phys.* **B165**, 55 (1980).

56. H. Aihara, *et al.*, *Phys. Rev. Lett.* **57**, 51 (1986).

57. K. Tsuru, Proc. II Intl. Conf. on Hadron Spectropscopy, p. 233, *op cit.*

57a. A. Ando *et al.*, *Phys. Rev. Lett.* **57**, 1296 (1986).

58. S. Cooper, p. 98, *ibid.*

59. N. Wermes, Physics in Collision, 1985, Proc 6'th Intl. Conf. Autun, eds. B. Aurbert and L. Montanet, p. 221 and SLAC-PUB-3730, 1985.

60. R. Longacre, Proc. XXIII Intl. Conf. on H.E.P., p. 729, *op cit.*

61. H. Aihara *et al.*, *Phys. Rev. Lett.* **57**, 404 (1986).

62. T. Armstrong *et al.*, *Phys. Lett.* **167B**, 133 (1986).

63. R. Longacre, private communication.

64. Y. Prokoshkin, Proc. II Intl. Conf. on Hadron Spectropscopy, p. 20, *op cit.*

65. B. J. Marie, Proc. XXIII Intl. conf. on H.E.P., p. 689, *op cit.*

66. V. Obraztsov, p. 703, *ibid.*

67. C. Edwards *et al.*, *Phys. Rev. Lett.* **48**, 458 (1982).

68. S. Gerstein, submitted to XXIII Intl. Conf. on H.E.P., Berkeley, 1986.

69. R. Longacre, Proc. II Intl. Conf. on Hadron Spectroscopy, p. 46, *op cit.*

70. P. Baillon *et al.*, *Nuovo Cim.* **A50**, 393 (1967).

71. C. Dionisi, *et al.*, *Nucl. Phys.* **B169**, 1 (1980).

72. O. Dahl, *et al.*, *Phys. Rev.* **163**, 1377 (1967).

73. Particle Data Group, *Rev. Mod. Phys.* **53**, No. 2, part 1, 51 (1980).

74. D. Scharre, G. Trilling *et al.*, *Phys. Lett.* **97B**, 329 (1980).

75. C.N. Yang, *Phys. Rev.* **77**, 243 (1950).

76. C. Edwards, *Phys. Rev. Lett.* **49**, 259 (1982).

77. P. Gavillet *et al.*, *Zeit. fur Physik* **C16**, 119 (1982).

78. S. Chung *et al.*, *Phys. Rev. Lett.* **55**, 779 (1985).

79. T. Armstrong *et al.*, *Phys. Lett.* **146B**, 273 (1984).

80. F. Renard, *Nuovo Cim.* **80A**, 1 (1984).

81. D. Bauer, Proc. II Intl. Conf. on Hadron Spectroscopy, p. 107, *op cit.*

82. R. Cahn, *Phys. Rev.* **D35**, 3342 (1987).

83. J. Rosner, private communication.