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Gluonium Candidates From Hadronic and e^+e^- Interactions*

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1. Introduction: Quarkless Hadrons At Low Masses

In the context of this Topical Seminar on Few- and Many-Quark Systems, it must be of interest to consider the limiting case of few-quark systems: quantum chromodynamics, in its natural reading, implies that the self-coupling of the 8 gauge bosons (gluons) should lead to the existence of strongly bound systems consisting of gluons only. We expect the lowest-mass gluonic systems to consist of two valence gluons; in analogy with bound two-fermion systems, we call these states gluonia (whereas n-gluon bound states, $n > 2$, are commonly called glueballs). Although one might prepare QCD formulations that do not lead to gluonium as hadronic matter, or that relegate valence gluons to a role that adds gluonic degrees of freedom to quark-dominated matter, the simple facts that Feynman's formulation[1)] of the parton model in deeply inelastic lepton-hadron scattering assigns roughly one-half of the target hadron momentum to gluons, and that QCD-inspired evolution equations[2)] for hadronic structure functions treat gluons and quarks almost equally, alert us to the likelihood that quarkless hadrons may be found; a failure to find convincing evidence for this predicted form of matter would therefore have to be seen as a puzzling piece of evidence.

To date, no compelling such evidence for the existence of gluonic hadrons has been forthcoming – surely not for a lack of imaginative and persistent experimental efforts. A number of candidate states have been advanced,[3)] based both on collisions of light-hadron initial states and on decays of heavy-quark bound systems that may favor the formation of pure gluonia. If gluons are the flavor-insensitive gauge bosons of QCD, their bound states should show up in both sets of experiments. A failure to identify candidate states in both will further tend to discredit what evidence there is at this time.

To gain insight into masses and quantum numbers of the lowest-mass gluonia, it is easiest to either assign gluons an effective constituent mass, then form gluonia out of two gluons with a potential model; or, alternatively, to adopt a bag model with bag parameters dictated by successful quark mass fits. The latter has the advantage that the problem is easily solved for the case of two massless (transverse) gluons.

When comparing bag model spectroscopy for quark-based *vs.* gluon-based hadrons, one striking difference lies in the mass ordering of low-mass states: the lowest-mass $q\bar{q}$ states are, for $\ell = 0$,

$$J^{PC}(q\bar{q}) = 0^- \ , \ 1^- \qquad (e.g., \ \ \pi \text{ and } \rho)$$

whereas massless-gluon resonant states start, at low masses, with the TE (transverse electric)–TE states

$$J^{PC}(gg) = 0^+ \ , \ 0^- \ , 2^+ \quad .$$

All calculations[4)] appear to be more or less agreed on the mass values to be expected. Figure 1 gives an indication of where calculations based on solutions of the Maxwell's equations in a spherical bag, on lattice gauge theory, on potential models, or on QCD sum rules lead us to expect the lowest-mass gluonia of given space-time properties. Notice the predictions of scalar[2)] gluon states at about the ρ mass, of pseudoscalars around 1.3 - 1.4 GeV/c^2.

Given these mass expectations, what are the distinguishing marks of the quarkless states? There have been arguments in favor of small widths characteristic of the OZI[5)] forbidden disconnected decay topology, but they are not generally accepted as compelling. Still, the possibility of 20–30 MeV wide low-spin states may yield an indicative criterion for identifying a gg state.

Another distinguishing mark is an *a-priori* expectation of equality of couplings to all quark flavors, motivated by the symmetry properties of the gauge gluons. It has been pointed out[6)] that configuration mixing with available quark-based mesonic states may well obfuscate this tell-tale criterion.

The most convincing trademarks of pure gluonia must therefore come from other quarters: their symmetry properties should reflect their origin. Their composition of two gauge bosons without a rest mass suggest J^{PC} quantum numbers accessible to systems of two massless vectors: $0^{++}, 0^{-+}, 2^{++}, 2^{-+} \ldots$, and the characteristic absence not only of all $C = -1$ states, but also of all vectors and axial vectors. Furthermore, they must be free of all charges, *i.e.*, singlet states of color and flavor SU(3) representations. Lastly, since their quantum numbers are shared by $q\bar{q}$ meson states, they must be supernumeraries in the traditional quark model schematic, which is well known to properly account for most observed mesonic states in the mass range of interest, and to be well saturated by them in the J^{PC} combinations of interest.

We will see in the following that there is no dearth of candidate states – but that none of them yields completely compelling evidence. We would therefore be more inclined to lend credence to individual claims if a last (and maybe most persuasive) criterion – that gluonia are most likely to show up where the density of potentially resonating gluons in a given J^{PC} state is highest, *i.e.*, where normal quark-mediated processes are suppressed – could be supported by independent production and decay processes: Suggestions that we search in a "gluon-rich environment" have therefore been especially followed into channels where a signal might well stand out above experimental backgrounds: the central region of (quasi-diffractive) high-energy hadron-hadron scattering ("Pomeron hadronization") is a candidate *locus* of the search for quarkless hadrons just as the decay of heavy quarkonia ($c\bar{c}, b\bar{b}$) is; the latter has the advantage of a cleanly defined initial $J^{PC}I^G$ state; the former that of higher luminosity.

In the following, we trace evidence for the principal channels of $|gg>$ candidate states. We will do so for the lowest J^{PC} states expected for the $|gg>$ system, making the question of compatibility of suggestive evidence from hadron–hadron scattering with that from quarkonium decay the principal object of this presentation.

2. Experimental Approaches

Before passing review of individual candidate claims, we mention the experimental approaches that appear most promising, and that have been exploited in the search for gluonia.

Highest luminosities, and therefore the best statistical significance, can be expected from hadron-hadron collisions. Here, three methods may be identified:

a) In (quasi-) diffractive processes, our notion of "Pomeron" exchange is realized in QCD as 2- or more gluon exchange. Hadronization in this central rapidity region (cf. Fig. 2a) can therefore be regarded as a promising *locus* for the formation of quarkless matter, since this exchange is a singlet in flavor and color indices. Isolation of the central rapidity region becomes possible at ISR and collider energies.

b) Again in quasi-diffractive processes, leading quarks in the final state may radiate hard gluons, which may then hadronize. This perception has led to searches for gluonia in the non-central region of ISR data.

c) Irrespective of particular production processes, decay signatures may suffice to tell gluonia apart: Claims have been staked on the basis of preferential decays of chargeless neutral mesons into pairs of meson that are known or suspected of having a "gluonic component", such as η, η' (as will be seen in Chapter 3), or that are observed prominently in $\gamma\gamma$ (as in Fig. 5b) collisions. Similarly, final states that can be generated only by an apparent violation of the topological OZI rule[5,8] have served as the basis for claims (See Fig. 2b). Such arguments are possible only in clean experimental channels, and remain controversial in their interpretation.

A large amount of suggestive evidence has been accumulated in the decay of heavy quarkonia:

d) Radiative J/ψ decay proceeds largely through the 2-gluon intermediate state, while a monochromatic tell-tale photon provides a clear experimental signature. Similar searches are possible using other $c\bar{c}$ or $b\bar{b}$ states with $J^{PC} = 1^{--}$.

In the process

$$e^+e^- \to Q\bar{Q} \to \gamma X \quad , \tag{2.1}$$

the $Q\bar{Q}$ system will be in a $J^{PC} = 1^{--}$ state, whereas

$$\begin{aligned} e^+e^- &\to Q\bar{Q}\ \gamma \\ &\quad (Q\bar{Q} \to \text{ hadrons}) \end{aligned} \tag{2.2}$$

leads to a $Q\bar{Q}$ state of, most likely, $J^{PC} = 0^{-+}$. Radiative decays of the J/ψ have yielded the largest amount of information on potential gluonia formed in OZI forbidden decays

$$J/\psi \to \gamma(gg) \ ; \qquad (gg) \to \text{ hadrons} \ . \tag{2.3}$$

The graph shown in Fig. 3a yields the advantages of a clean initial state and low final-state multiplicities.

e) Hadronic decays of $c\bar{c}$ or $b\bar{b}$ quarkonia via two or three gluons, depending on their J^{PC} values, often serve to clarify the picture emerging from *d*) above by providing cross-checks of the quark and gluon content of putative signal states. The presence of hadronic decays

$$J/\psi \to V^0 \ + \text{ hadrons} \qquad (V^0 = \rho, \omega, \phi) \tag{2.4}$$

will then permit quantitative comparisons with process (2.3) by way of the usual vector dominance relations (cf. Figs. 3b and 3c).

3. Candidate States

In the following, we summarize presently available evidence on those states that have been claimed as possible gluonia. Proceeding in order of lowest-mass expectation, we categorize only in terms of definitive (or putative) J^{PC} assignments. For an overview, see Table I; for detailed arguments, we refer to the literature as cited.

3.1 SCALAR GLUONIUM CANDIDATES

The prediction of the scalar gluonium as the lowest-mass quarkless hadron sets its mass below that of scalar $q\bar{q}$ states (which cannot be $\ell = 0$); consequently, the identification of a $J^{PC} = 0^{++}$ state in one of the promising channels would be a major bonus. Two cautionary remarks are in order: Theoretical prejudice has it that instanton effects make the width of the scalar gluonium such as to render the state unidentifiable for practical purposes;[9)] experimentally, a rest mass of about 0.7 GeV/c^2 would make $0^{++} \rightarrow \pi\pi$ the likeliest decay mode; but $\pi\pi$ signals will be hard to unravel from backgrounds, unless additional information is available.

$\underline{\sigma(750)}$

Such additional information can come in the form of known polarization parameters. Analysis of available data[10)] of the reaction

$$\pi^{\pm} N_{pol} \rightarrow \pi^{+}\pi^{-} N$$

leads Sveč[11)] to claim evidence for a scalar state that could well be the lowest-mass gluonium. The data involve scattering off transversely polarized proton targets, permitting an isolation of S-wave $\pi^{+}\pi^{-}$ systems without further assumptions. The resulting transversity amplitudes display a persistent structure at all incident π energies (from 6 to 17 GeV); they are most easily interpreted as evidence for a state of mass 750 MeV/c^2 and width $\lesssim$ 100 MeV/c^2. This is illustrated in Fig. 4:

two different solutions give almost the same resonance parameters, but differ in the decay width of $\sigma(750) \to \pi^+\pi^-$.

The claim that the postulated state is a candidate for the scalar gluonium is based mainly on its suggestive mass. No particular dynamical mechanism is inferred. Given the notorious difficulties in dealing with dipion analysis in multipion production, we join Sveč in decrying a lack of confirming evidence (which, for the sake of the present argument, should include recoil polarization information). Radiative J/ψ decay data have not been analyzed fully to investigate Sveč's claim.

$\underline{G(1590)}$

At considerably higher mass, an analysis of the $\eta\eta$ mass spectrum in reactions initiated by 40 GeV/c pions,

$$\pi^- p \to \eta\eta\, n \quad ,$$

as published by a CERN–IHEP collaboration,[12] gives an indication of structure observed in the $\eta\eta$ spectrum in both the 4γ and 8γ final-state modes, when analyzed in terms of different angular momenta: Figure 5a is interpreted as evidence for a $J^{PC} = 0^{++}$ state with mass 1580 ± 30 MeV/c^2, $\Gamma = 280$ MeV/c^2, named $G(1590)$. Note that the same experiment (based on shower detection in the GAMS spectrometer) does not observe decays of the same state into the $\pi^0\pi^0$ final state (quoted limit: $\Gamma(\pi^0\pi^0)/\Gamma(\eta\eta) < 0.3$), nor does this state show up in $K^0\bar{K}^0$. A preference for the decay mode $\eta\eta$ (or $\eta\eta'$) is interpreted by Gershtein *et al.*,[13] as motivated by the "gluonium nature" of η and η', favoring a decay diagram of the type shown in Fig. 5b. While the observation of $G \to \eta\eta'$ is reported by the same group at a strength 2.7 times that of the $\eta\eta$ mode, we note that recent data on the quark and gluon content of η, η'[14] may make η a poor candidate for this line of reasoning (whereas η' could be).

3.2 Pseudoscalar Gluonium Candidates

$\eta(560)$, $\eta'(958)$

It has long been known that the pseudoscalar nonet displays an anomaly when confronted with the linear or quadratic mass formulae. This fact, together with the plentiful observation of these states in radiative J/ψ decays, has led to analyses that permit an admixture of $|gg\rangle$ to their $|q\bar{q}\rangle$ basis. In a scheme[15] that makes the ansatz

$$
\begin{aligned}
|\eta\rangle &= X_\eta \ |q\bar{q}\rangle + Y_\eta \ |s\bar{s}\rangle + Z_\eta \, |gg\rangle \\
|\eta'\rangle &= X_{\eta'} \, |q\bar{q}\rangle + Y_{\eta'} \ |s\bar{s}\rangle + Z_{\eta'} \, |gg\rangle \\
&\quad \text{with } \ q\bar{q} = 2^{-1/2} \ (u\bar{u} \ + d\bar{d}) \quad ,
\end{aligned}
$$

any deviation from $X^2 + Y^2 = 1$ will indicate a possible $|gg\rangle$ admixture to the wave function. In an analysis of all its data on $J/\psi \rightarrow$ vector + pseudoscalar, the MARK III collaboration[16] finds indications that the η wave function is well saturated by u, d, s quarks, whereas η' has a fair amount of room for a gg admixture to the configuration:

$$
\begin{aligned}
X_\eta^2 + Y_\eta^2 &= 1.1 \ \pm \ 0.2 \\
X_{\eta'}^2 + Y_{\eta'}^2 &= 0.63 \ \pm \ 0.18 \quad .
\end{aligned}
$$

Other analyses of their data[17] differ insofar as they assign an important component beyond X, Y also to they η (a feature which would be welcome news to proponents of the gluonium "trademark" decay into $\eta\eta$[13] (see section 3.1). We conclude this section by stating that old suspicions of the pseudoscalar nonet can be allayed somewhat by postulating a mixing of a new component into some of its $q\bar{q}$ wave functions.

$\iota(1460)$ $(\stackrel{?}{=} E(1420))$

Data from the MARK II,[18] Crystal Ball,[19] and MARK III[20] collaborations have firmly established the pseudoscalar state $\iota(1460)$ as the single-largest contributor to the tell-tale radiative J/ψ decay:

$$J/\psi \to \gamma + X \quad ,$$

with a combined branching ratio of $BR^2(J/\psi \to \gamma\iota)\ (\iota \to K\bar{K}\pi) \approx 0.5\%$. This abundance in the preferred gg decay channel, in combination with its mass and quantum numbers (just as predicted in Fig. 1) have made it a prime suspect in the gluonium search game. Arguments that have been advanced to the contrary are based on the observations that, although seen in three charge modes of the decay

$$\iota \to K\bar{K}\pi\ (K^+K^-\pi^\circ\ ,\ K^\pm K_S\pi^\mp\ ,\ K_SK_S\ \pi^\circ)\ ,$$

where the $K\bar{K}$ system prefers to be in a $\delta(980)$ state,[19] there is no signal for the decay

$$\iota \to \delta^\pm\pi^\mp\ \ (\delta^\pm \to \eta\pi^\pm)\ .$$

The quoted branching fraction

$$BR^3(J/\psi \to \gamma\iota)\ (\iota \to \delta^\pm\pi^\mp)\ (\delta^\pm \to \eta\ \pi^\pm)\ <\ 3.9 \times 10^{-4} \quad (90\%\ CL)$$

is well below what flavor-independent decay would permit. Moreover, a signal in the $m(\gamma\rho)$ spectrum[21] of the radiative decay mode (Fig. 6)

$$J/\psi \to \gamma(\gamma\rho)$$

may well have to be ascribed to a non-negligible decay $\iota \to \gamma\rho$:

$$BR^2(J/\psi \to \gamma\iota)\ (\iota \to \gamma\rho^0) = (1.1 \pm\ 0.24\ \pm\ 0.25)\ \times 10^{-4}\ ;$$

this may not be easy to accommodate for a gluonium state without charged subcomponents.[22]

Observations of these signals in other channels could therefore be of great importance. Unfortunately, the evidence on hadronic production is entirely unclear: the state $E(1420)$ observed originally by Baillon *et al.*,[23] has been confirmed to be a pseudoscalar by recent reanalysis.[24] New evidence on structure in the $K\bar{K}\pi$ system of the production processes

$$\pi^- p \to K^+ \, K_S \, \pi^- \; + \; \ldots$$
$$\bar{p}p \to K^+ \, K_S \, \pi^- \; + \; \ldots$$

at the Brookhaven MPS[25,26] agree with a $J^{PC} = 0^{-+}$ assignment for the E, with mass 1420 MeV/c^2 and width 60 MeV/c^2, based on Dalitz plot studies of some 600 events each. On the other hand, C. Dionisi *et al.*,[27] show a marked preference for a $J^{PC} = 1^{++}$ assignment. So does the WA76 experiment using the Omega Spectrometer at CERN for an investigation of the $K_S K^{\pm}\pi^{\mp}$ system in the reactions[28] (at 85 GeV)

$$\pi^+ p \to \; \pi^+(K_S K^{\pm}\pi^{\mp}) \; p$$
$$p \; p \to \; p(K_S K^{\pm}\pi^{\mp}) \; p \quad .$$

The clean mass peak (Fig. 7a) containing some 1000 events in the central rapidity region clearly prefers $J^{PC} = 1^{++}$ for the E signal; the decays proceed largely via $E \to \bar{K}^{*\mp} K^{\pm} \to K_S \; K^{\pm}\pi^{\mp}$.

To add to the confusion, WA76 does not observe a corresponding signal in the $E \to \eta\pi^+\pi^-$ channel; on the other hand, the CERN–IHEP collaboration, at somewhat lower energies, does observe structure in the all-neutral channel $E \to \eta^0\pi^0\pi^0$.[12] Their mass peak in the $\eta\pi^0\pi^0$ distribution (Fig. 7b) does, however, not permit a clear J^{PC} determination.

The easiest way out of this conflicting evidence would be the presence of a mixing of a radial excitation of $\eta'(958)$ with a gluonium in the $J^{PC} = 0^{-+}$ channel, thus making up two closely spaced states, and relegating the $J^{PC} = 1^{++}$ signal (if further confirmed) to the $q\bar{q}$ sector. Unfortunately, the 1^{++} signal from

WA76 is observed in the central rapidity region of a quasi-diffractive process, just where the common lore expects gluonia to emerge.

A viable explanation may need inclusion of a reported enhancement at 1280 MeV/c^2 in the $\eta\pi\pi$ system[29] in the phenomenology.[30] The situation remains fluid for the time being.

<u>$X \to \rho\rho,\ \omega\omega$</u>

The MARK III collaboration shows convincing evidence of structure in the vector-vector channels of radiative J/ψ decay[31,32]

$$J/\psi \to \gamma\rho^0\rho^0\ ,\ \gamma\rho^+\rho^-\ ,\ \gamma\omega\omega$$

in the mass region 1500–1800 MeV/c^2 (Fig. 8). A spin-parity analysis finds a preponderance of $J^{PC} = 0^{-+}$. While no clean resonance fit has been proposed, a recent coupled-channel analysis[33] includes this signal in the ι phenomenology. Figure 9 illustrates the fits that have been obtained: at the expense of introducing one new state at 1800 MeV/c^2, phase space effects added to the ι signal may be able to account for most of the observed signal, with ι coupling to $K\bar{K}\pi$, $\gamma\rho$, $\omega\omega, \rho\rho$.

The most important implication of this analysis is to be seen in the large branching fraction the inclusion of the vector-vector signal implies for the radiative J/ψ decay channel into $\gamma\iota$:

$$BR(J/\psi \to \iota\gamma) \gtrsim\ .7 \times 10^{-2}\ .$$

This large fraction ($\sim$ 8%) of the tell-tale channel can in itself not be ignored in any gluonium search.

<u>$J^{PC} = 2^{++}$ Candidates</u>

There are two features that make the "tensor meson" channel with $J^{PC} = 2^{++}$ stand out in the gluonium search. First, perturbative QCD calculations of radiative J/ψ decay[34] indicate that by far the greatest fraction of $|gg\rangle$ states will hadronize in the 2^{++} channel. Second, of the helicity amplitudes mediating the hadronization, it is reasonable to give special attention to the one that corresponds to a diffractive hadronization of two spin-1 objects in an $\ell = 0$ state: among the three independent helicity amplitudes (A_0, A_1, A_2) for $\ell = 0$, we expect a gluonium to choose one that corresponds most closely to this premise (*i.e.*, $J^P = 2^+$).

$f(1268)$, $f'(1525)$

These isoscalars in the tensor nonet are well known to show up prominently when coupled to $\gamma\gamma$ or gg initial states. The mass mixing in the nonet, however, is so close to ideal that early speculations concerning their possible gluonic nature should be laid to rest. In the context of the present study, this is a loss: Mesons prominently observed in both hadronic interactions and radiative $Q\bar{Q}$ decay can yield considerable insight, as the study of η and η' shows.[35]

$\theta(1720)$

This state has been well observed in all relevant J/ψ radiative decay studies.[36] Its branching fractions add up to a sizeable total:

$$\begin{aligned} BR^2(J/\psi \to \gamma\theta)(\theta \to \eta\eta) &= (3.8 \pm 1.1 \pm 0.8)\ 10^{-4}\ , \\ (\theta \to K^+K^-) &= (4.8 \pm 0.6 \pm 0.9)\ 10^{-4} \\ (\theta \to \pi^+\pi^-) &= (1.6 \pm 0.4 \pm 0.3)\ 10^{-4}\ , \\ (\theta \to \rho\rho) &< 4 \qquad\qquad 10^{-4}\ . \end{aligned}$$

The observation in several channels containing strange and non-strange quarks hints at possibly flavor-independent decay features typical of basic gluonium notions. Maybe most importantly, the helicity amplitudes active in its formation, in the process $J/\psi \to \gamma\theta$, show as much helicity-2 as helicity-1, whereas the certified $q\bar{q}$ states f, f' have almost no helicity-2 contribution. Numerically, MARK III studies show a comparison as in Table 2. Clearly, only the θ appears to favor a production mechanism that could correspond to gluonium formation from two aligned helicity-1 gluons. Is θ then a good gluonium candidate, also to be observed in tell-tale hadron-initiated interactions?

The CERN–IHEP collaboration[12)] did not find a distinctive signal in the 2^{++} channel at $m(\theta)$, although its sensitivity to the $\eta\eta$ ($\rightarrow 4\gamma, 8\gamma$) decays makes it a selective detector for what Gershtein *et al.*,[13)] consider an indicative decay mode (see Fig. 10). Neither the WA76 collaboration nor other hadron-initiated experiments confirm the existence of the $\theta(1720)$. This is clearly a let-down for an otherwise attractive gluonium candidate.[51)]

$\xi(2220)$

Let us then follow the di-pseudoscalar invariant-mass plot to higher masses. While MARK III data[37)] on exclusive decays

$$J/\psi \rightarrow \gamma\pi^+\pi^- \ (K^+K^-)$$

have the f, f', θ structures in common, Figs. 11 and 12 show the higher-mass regions to be quite dissimilar: the most suggestive feature is seen in the K^+K^- channel, and is confirmed by studies of the decay

$$J/\psi \rightarrow \gamma \ K_S K_S \ .$$

There is a narrow structure with the parameters

$$m(\xi) = (2230 \pm 15 \pm 20) \ MeV/c^2$$
$$\Gamma(\xi) = (30 \pm 15 \pm 20) \ MeV/c^2$$
$$BR^2(J/\psi \rightarrow \gamma\xi)(\xi \rightarrow K^+K^-) = (4.2 \pm 2 \pm 1) \times 10^{-5}$$

This structure, observed, with comparable parameters for mass and width, in the K_SK_S mode, was seen in independent data sets by the MARK III collaboration;[38)] it was not confirmed by the comparable experiment of the DM2 collaboration at Orsay, which sets 95% C.L. limits of 1.2 and 2.0 $\times$ 10^{-5}, respectively on the branching fractions in the two charge modes. The statistical sample collected by the MARK III group is not sufficient for a definitive J^{PC} assignment.[38)] Both $J^{PC} = 0^{++}$ and 2^{++} remain possible at this time. This discrepancy may not be statistically overwhelming, and may well be due largely to experimental sensitivities. Still, the unusually narrow width makes $\xi(2230)$ sufficiently intriguing as a possible gluonium so that we would love to see it confirmed in additional decay channels, and by production through appropriate hadron-induced reactions.

The upper limits established for further 2-body decays (Table 3) are not stringent enough to constrain the flavor-independence argument, but there is no further confirmation. In hadronic interactions, only one claim for a narrow enhancement involving strange quarks exists in the ξ mass region: A Fermilab experiment[40)] analyzing 400 GeV $p - N$ interactions reports production of an object M (Fig. 13) which decays into ϕK^+K^- and $\phi\pi^+\pi^-$,

$$m(M) = (2.145 \pm 0.004 \pm 0.010)\, GeV/c^2 \ ,$$
$$\Gamma(M) = 0.04\, GeV/c^2 \ .$$

The branching fraction ratio for ϕK^+K^- *vs.* $\phi\pi^+\pi^-$

$$\frac{BR\ (M \to \phi K^+K^-)}{BR\ (M \to \phi\ \pi^+\pi^-)} = 0.49 \pm 0.16 \ .$$

makes it a good candidate for a non-$q\bar{q}$ state. Whether the difference in masses makes it compatible with ξ, will remain to be seen.

Confirmation from other e^+e^- experimentation is equally problematic. The CLEO group at Cornell[41)] was unable to identify $\xi(2230)$ in Υ or Υ' as well as B decays, but with limits that are none too constraining. The DM-2 group does[42)] observe a possibly narrow signal in the decay channel

$$J/\psi \to \gamma\phi\phi$$

at a mass close to $m(\xi)$ (Fig. 14); but the statistics do not permit any claim either way.

g_T (2,050; 2,300; 2,350)

A Brookhaven–CCNY collaboration[43] has investigated the OZI forbidden channel

$$\pi^- p \rightarrow \phi\phi\, n$$

(the production diagram for this resembles Fig. 2b closely) in a search for gluonic states. The plentiful $\phi\phi$ production observed above threshold (*cf.* Fig. 15a) has been seen by a number of other collaborations: in the CERN Omega Spectrometer[44] (85 GeV $\pi^- Be \rightarrow \phi\phi X$), at the FNAL Multiparticle Spectrometer[45] (400 GeV pN) most recently. Etkin *et al.*,[43] performed a partial wave analysis on the (experimentally well-defined) $\phi\phi$ system; their data are best described by a three-Breit-Wigner fit involving three $\phi\phi$ resonances, all in the $J^{PC} = 2^{++}$ channel (Fig. 15b); although parameters change somewhat in the publications of the group,[46] all are in the 2000 to 2300 MeV/c^2 range, and all are 150–300 MeV wide. The only supporting evidence for resonance structure in $\phi\phi$ comes from Omega at CERN,[44] where (Fig. 16) two enhancements emerge in the mass plot, but without a J^{PC} determination.

There has been a vivid discussion[47] *re* the applicability of the OZI rule as a unique selection criterion for the g_T states, and indeed the compellingness of telling the dominant S-wave resonance from a threshold effect such as observed in other vector-vector production experiments.[48]

Unfortunately, there is no confirmation of the existence of the g_T states from other quarters: neither from hadronic interactions with decay, say, into $\omega\omega$ or $\eta\eta$, nor from radiative quarkonium decay. Whereas the experimental sensitivity in the g_T mass range is poor for the Mark III detector[49] (which presents beautiful evidence for the decay $\eta_c \rightarrow \phi\phi$ at higher masses),[50] the DM2 detector has yielded a respectable $\phi\phi$ mass plot in the region of interest. Figure 14 certainly gives no indication for a corresponding structure, but unfortunately lacks the statistical significance for a full spin-parity analysis. The Crystal Ball experiment that discovered the $\theta(1700)$ in its $\eta\eta$ decay[36] would have been fully efficient for a decay $g_T \rightarrow \eta\eta$ – and there is no easy argument that will suppress the $\eta\eta$ decay w.r.t. $\phi\phi$ in a gluonium. There is a clear need for additional data that may help us to understand the g_T states.

4. Conclusions

It is rather anticlimatic to compile, after the large amount of suggestive data that have been collected in the past few years, the evidence that may summarize our understanding of where gluonia stand today. Table I attempts to supply some relevant information at a brief glance; we conclude that:

1) There is no gold-plated gluonium candidate at this time.
2) There is an almost total lack of coincident information on the top candidates from hadron-induced vs. $Q\bar{Q}$ decay-product gluonium candidates.
3) Evidence that η', ι, θ, and ξ contain new degrees of freedom is impressive.
4) There is an urgent need to clarify the low-mass $\pi^+\pi^-$ spectrum for possible evidence of the scalar gluonium.
5) An unraveling of the complex phenomenology in the $K\bar{K}\pi$ and $\eta\pi\pi$ channels may do much to shed light on the gluonium question.
6) Only high-statistics, systematically optimized experiments are likely to improve the presently unsatisfactory evidence.

The stakes are certainly high enough to warrant major efforts: only the hard-scattering aspects of QCD have met with full experimental confirmation – here is a crucial place where QCD applied to "soft" phenomena can prove its mettle.

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51. Note, however, that signals that may be identified with $\theta(1720)$ have been tentatively advanced both by the Axial Field Spectrometer Collaboration (T. Akesson *et al.*,Ref. 11) at ISR energies, and by an Omega Spectrometer collaboration, T. Armstrong *et al.*,CERN-EP/85-179 (1985)).

Table 1: Overview of Gluonium Candidates

J^{PC}	State [Mass] (MeV/c^2)	Width (MeV/c^2)	Produced in: Hadron–Hadron Collisions	Produced in: Radiative J/ψ Decay	Decay Modes Observed
0^{++}	$\sigma(750)$	100	√	--	$\pi^+\pi^-$
	$G(1590)$	290	√	--	$\eta\eta,\ \eta\eta'$
0^{-+}	$\eta'(958)$	~ 0	√	√	$\eta\pi^+\pi^-,\ \eta\pi^0\pi^0$ $\rho\gamma,\ \omega\gamma, \gamma\gamma$
	$E(1420)$	50	√	--	$K\bar{K}\pi, \delta\pi$
	$\iota(1460)$	100	--	√	$K\bar{K}\pi$ (3 modes) $\gamma\rho$
	$X(1600$–$1900)$	300	--	√	$\rho^0\rho^0,\ \rho^+\rho^-,\ \omega\omega$
[1^{++}	$E(1420)$	50	√	--	$K\bar{K}\pi,\ \eta\pi\pi$]
2^{++}	$\theta(1700)$	130	--	√	$K^+K^-,\ K_SK_S,$ $\eta\eta,\ \pi^+\pi^-$
	$g_T(2050$–$2300)$ (3 states)	150-250	√	--	$\phi\phi$
	$\xi(2230)$	< 30	--	√	$K^+K^-,\ K_SK_S$

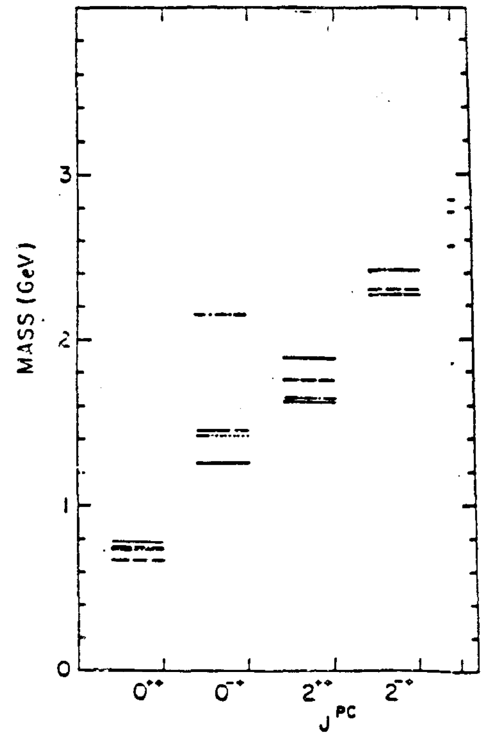
Mass and width values quoted are approximate. Note that we have entries for $E(1420)$ with $J^{PC} = 0^-$ and 1^+, the latter of which cannot be formed by two massless gluons. $E(1420)$ may or may not be related to $\iota(1460)$. Note also that only $\eta'(958)$ is clearly seen in both production categories, and that this state is *not* a candidate for a pure gluonium.

Table 2: Helicity amplitudes for tensor meson production in radiative J/ψ decay.

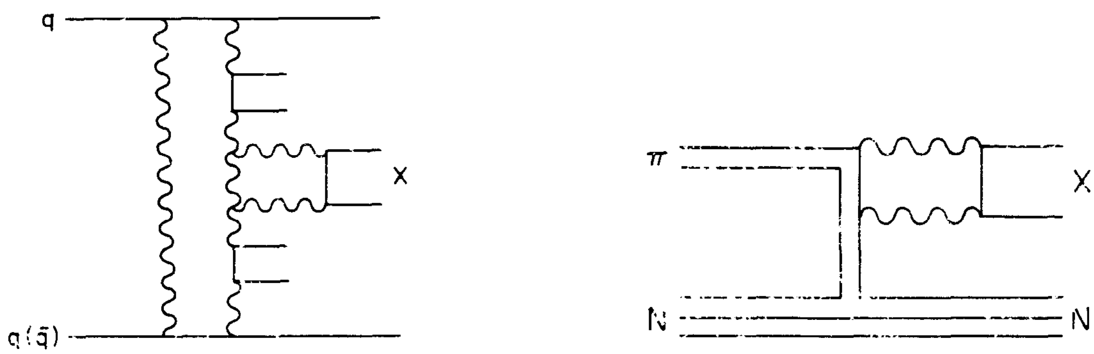
Amp/State	f	f'	θ
$x = A_1/A_0$	0.96 ± 0.12	0.63 ± 0.10	-1.14 ± 0.20
$y = A_2/A_0$	0.06 ± 0.13	0.17 ± 0.20	-1.28 ± 0.20

Table 3: Upper-limit branching fractions (90% C.L.) for various 2-body final states in $\xi(2230)$ decay.

Decay Mode	$BR^2(J/\psi \to \gamma\xi)(\xi \to \ldots)$
$\xi \to \mu^+\mu^-$	$< 7.3 \times 10^{-6}$
$\to \pi\pi$	$< 2 \times 10^{-5}$
$\to K^*K$	$< 2.5 \times 10^{-4}$
$\to K^*\bar{K}^*$	$< 3 \times 10^{-4}$
$\to \eta\eta$	$< 7 \times 10^{-5}$
$\to p\bar{p}$	$< 2 \times 10^{-5}$



1. Mass predictions for lowest-lying gluonium states from various model calculations (from Ref. 4).



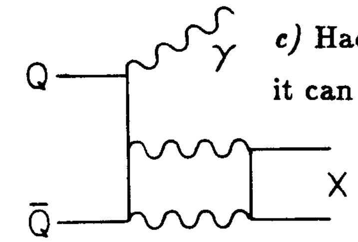
2. *a)* Lowest-order graph for gluonium production in the central rapidity region of quasi-diffractive scattering.

b) Possible gluonium production graph in disconnected topology.

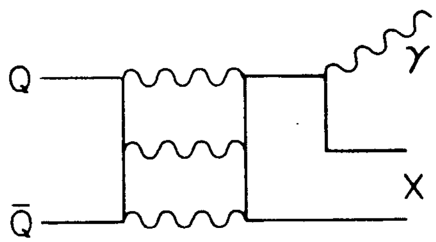
3. *a)* Radiative quarkonium decay via two-gluon exchange produces flavor-singlet hadrons.

   b) Radiative quarkonium decay via three-gluon exchange may produce flavor-octet hadrons.

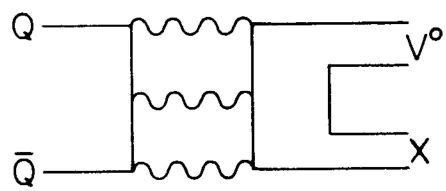
   c) Hadronic quarkonium decay analogous to Fig. 3b; for V^0X final state, it can be linked to Fig. 3b amplitudes by vector-dominance relations.



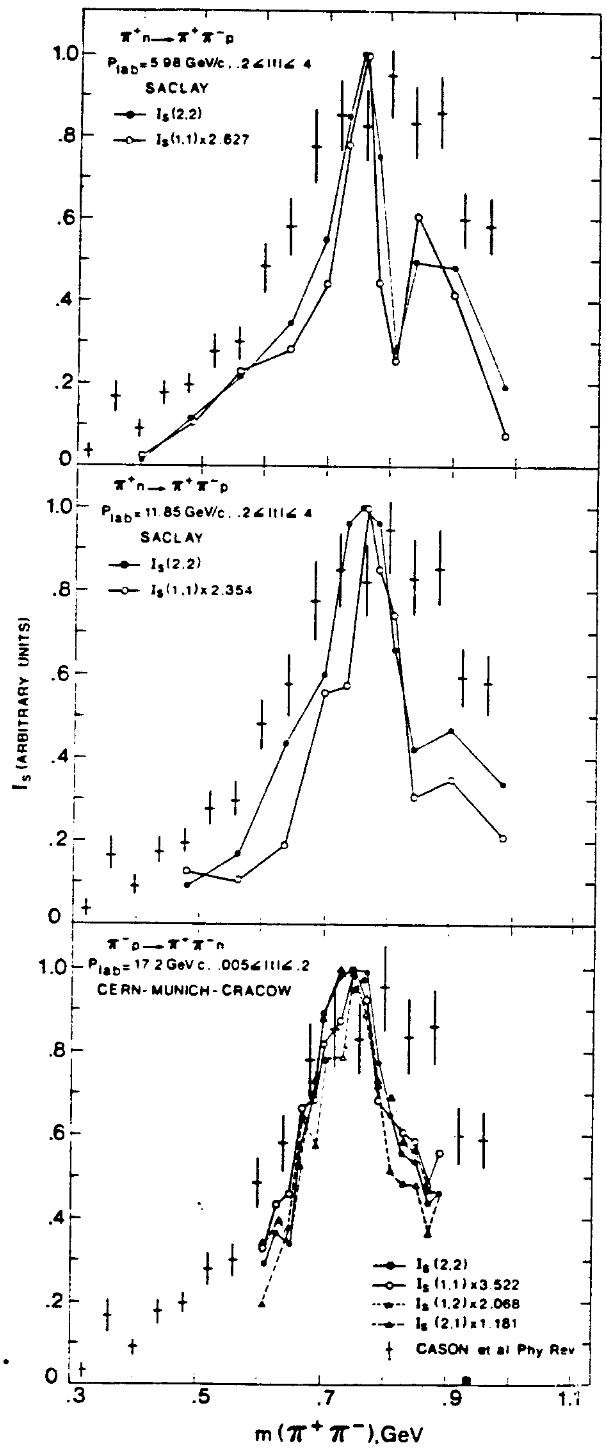
(a)



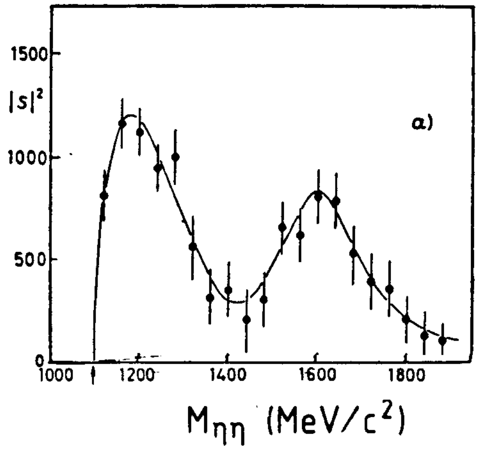
(b)

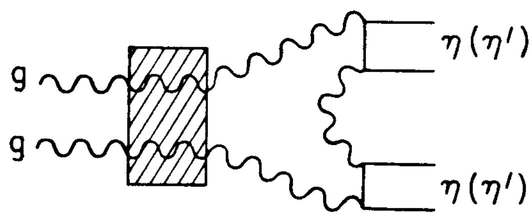


(c)



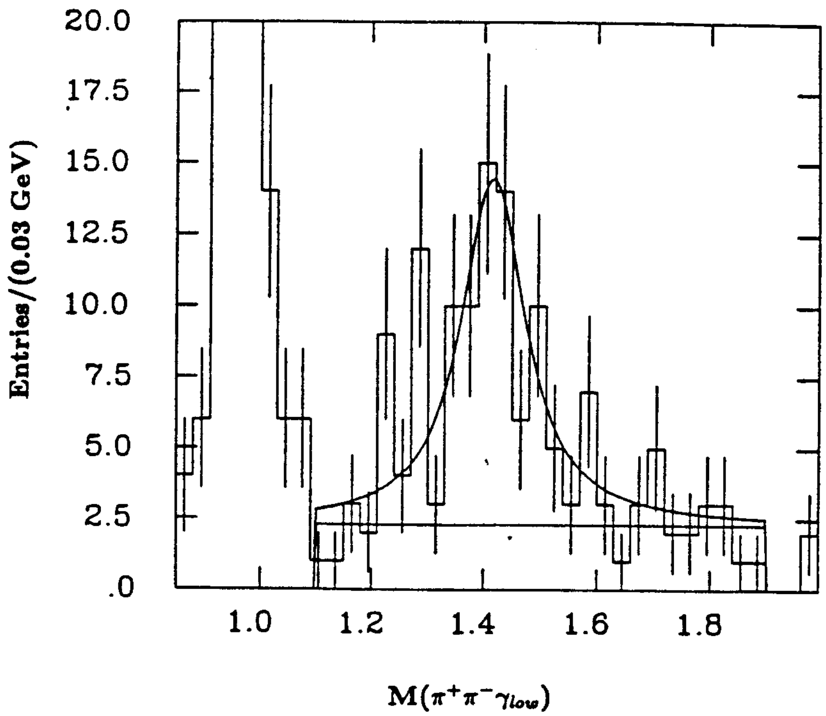
4. Transversity amplitudes for S-wave $\pi^+\pi^-$ from Ref. 11. At all energies, structure emerges at energy $\sim$ 750 MeV/c^2.



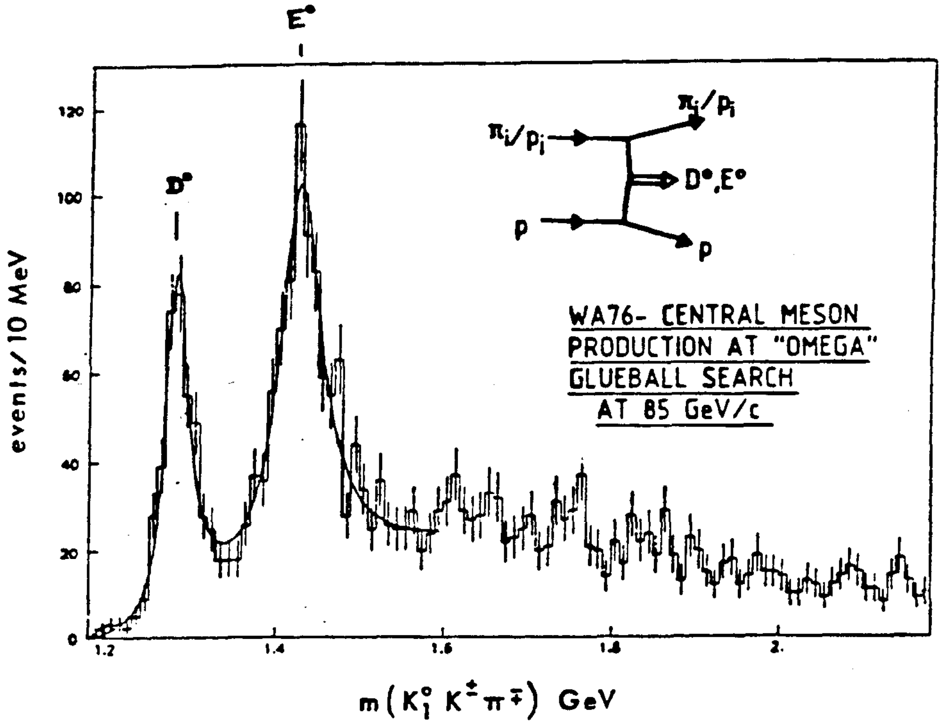


5. *a)* Invariant-mass spectrum for the $\eta\eta$ system produced in 40 GeV/c πp interactions, in the S wave: structure is evident at 1590 MeV/c^2. (From Ref. 12)

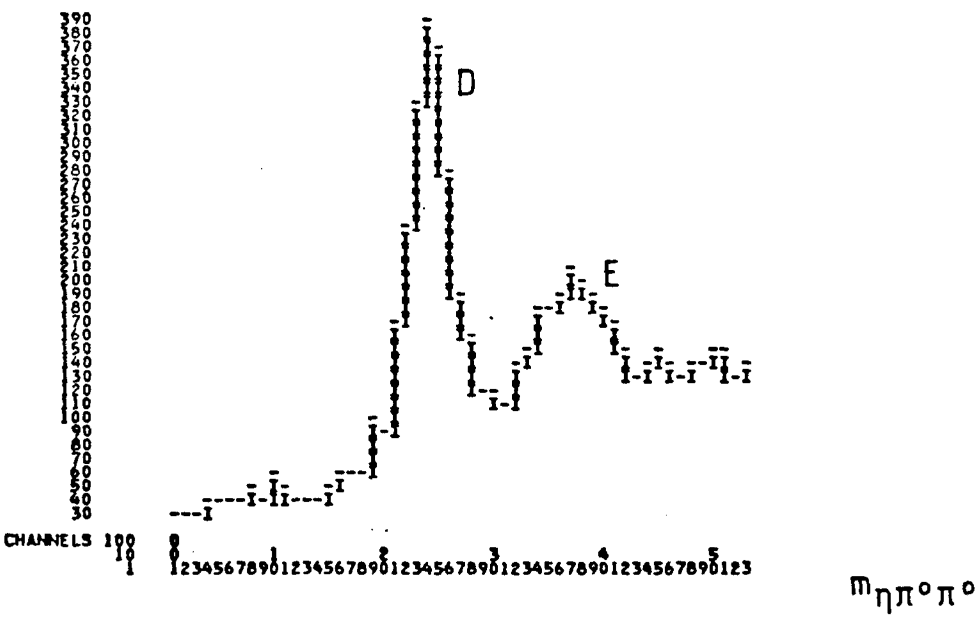
   b) Diagram suggested by Gershtein *et al.*, (Ref. 13) for gluonium decay into mesons with "gluonium affinity".



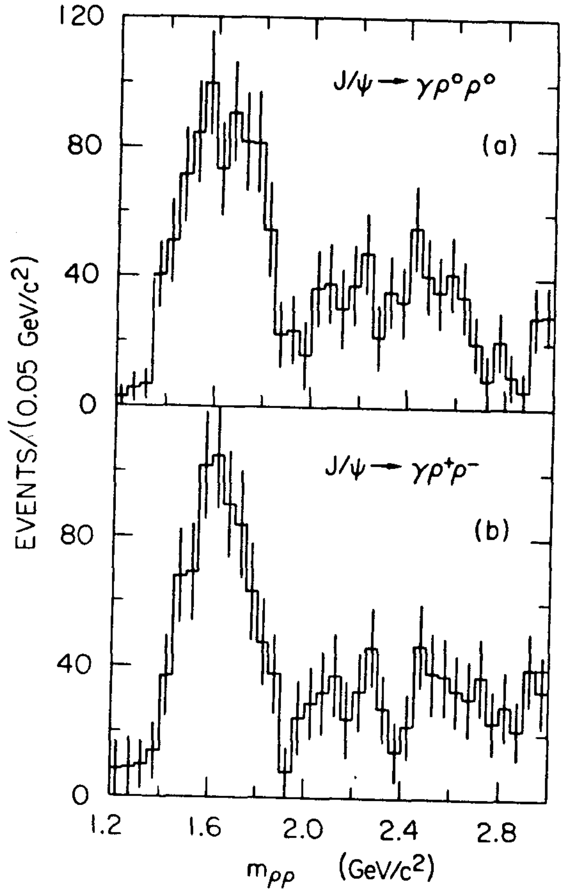
6. Mark III signal for $\gamma\rho^0$ mass enhancement in the radiative decay $J/\psi \rightarrow \gamma(\gamma\rho)$. Mass and width and $J^{PC} = 0^{-+}$ assignment make an identification with ι suggestive. (From Ref. 20).

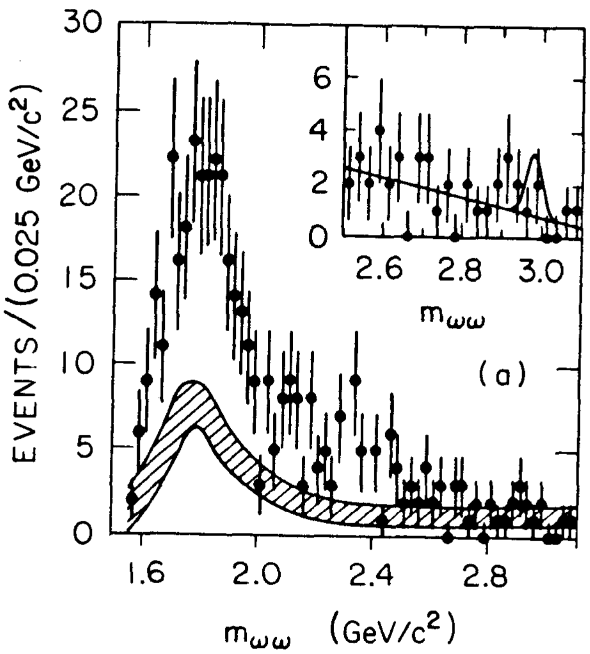


7. *a)* Invariant-mass distribution for the $K_S K^{\pm}\pi^{\mp}$ system centrally produced by π, p beams in WA76 (from Ref. 28).

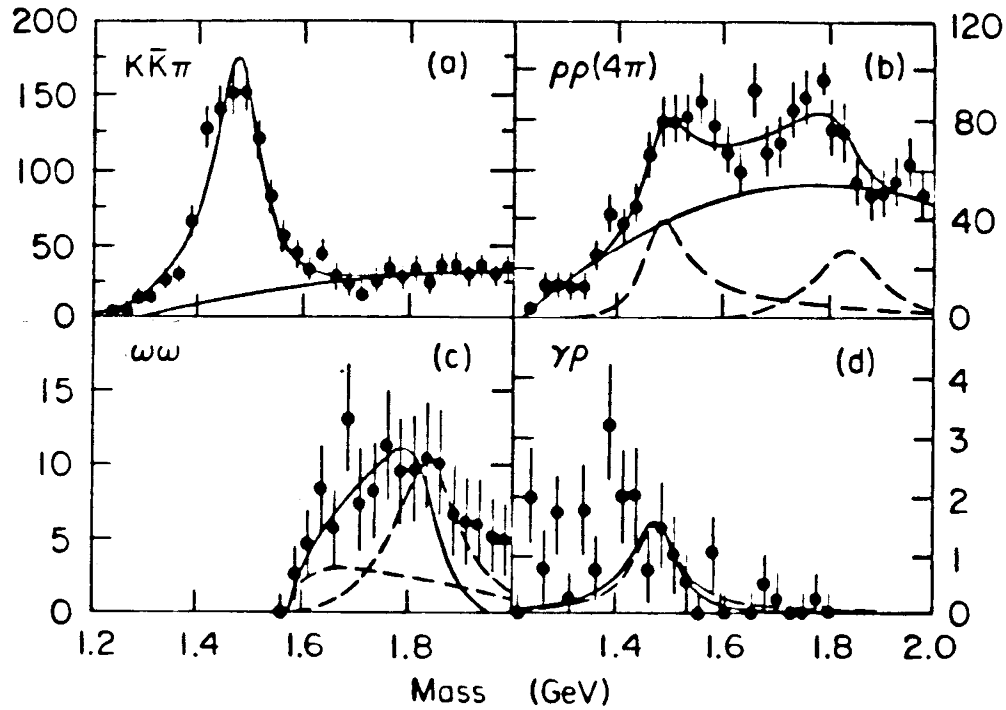


7. *b)* Invariant-mass distribution for the $\eta\pi^0\pi^0$ system from the CERN-IHEP Collaboration (from Ref. 12).

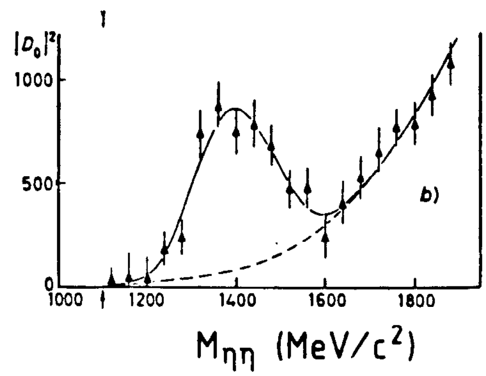




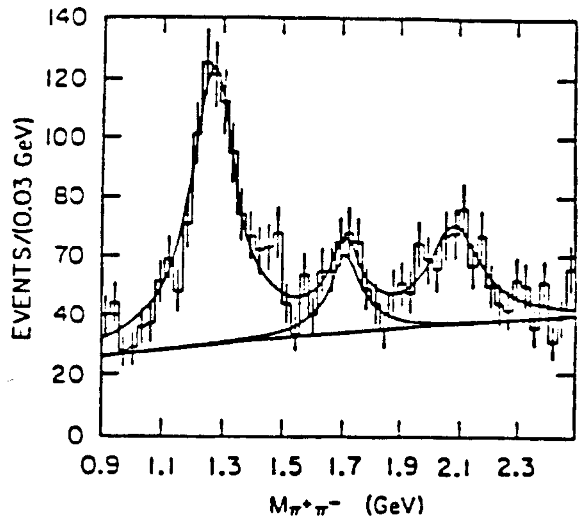
8. Mark III signals for $\rho\rho$, $\omega\omega$ enhancements in radiative J/ψ decay (from Refs. 31, 32).



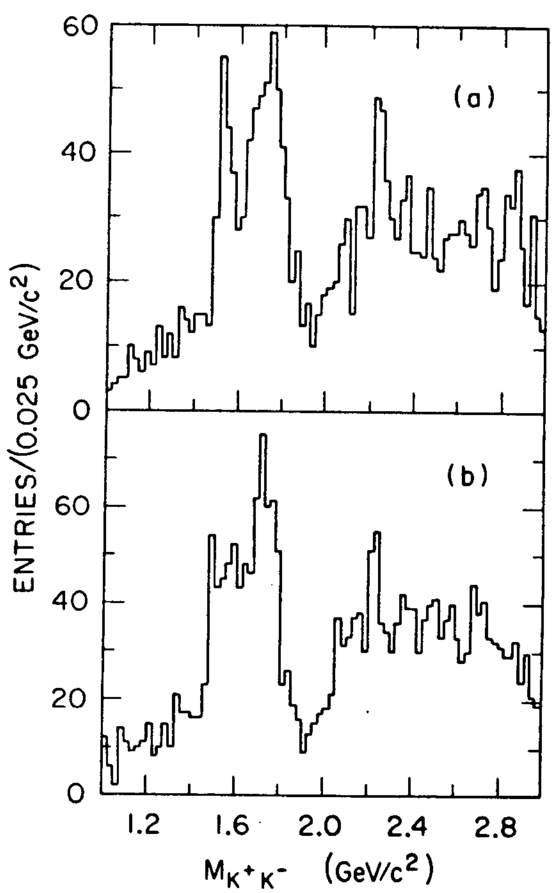
9. A coupled-channel analysis by the Mark III Collaboration provides a possible link between ι and the V^0V^0 enhancements in the $J^{PC} = 0^{-+}$ channel of radiative J/ψ decay. Note the need for a new 0^{-+} state at $\sim$ 1800 MeV/c^2. (See Ref. 33.)



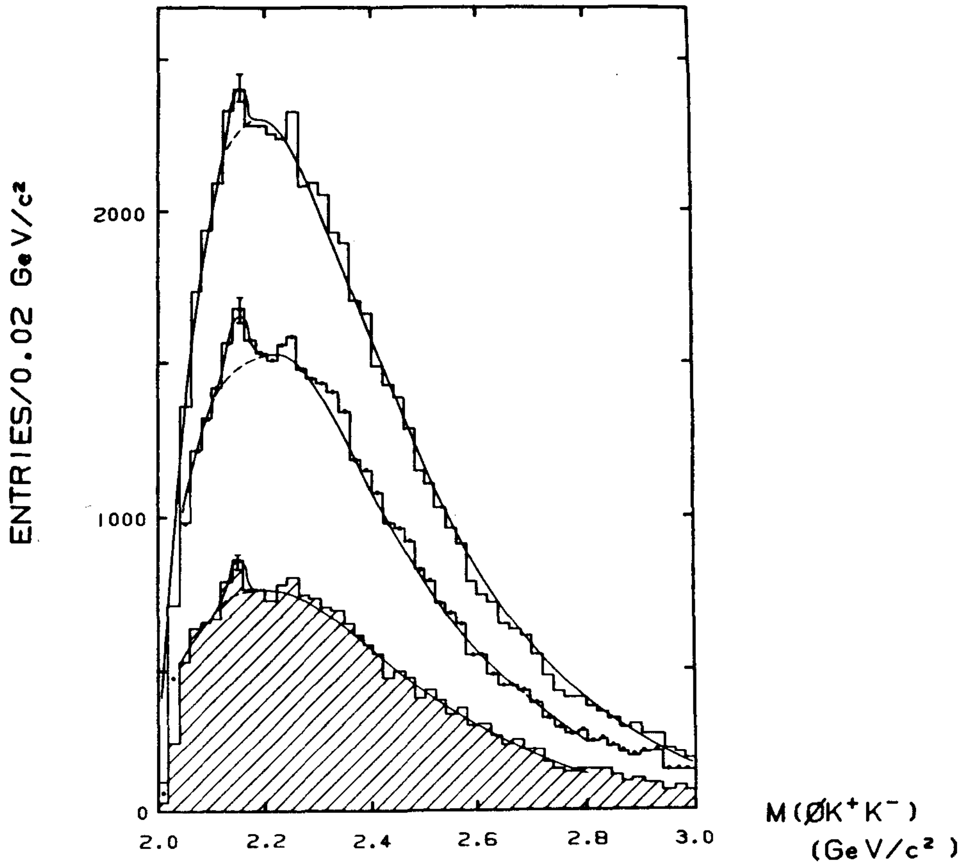
10. D wave projection of $\eta\eta$ production in 40 GeV πN interactions (from Ref. 12).



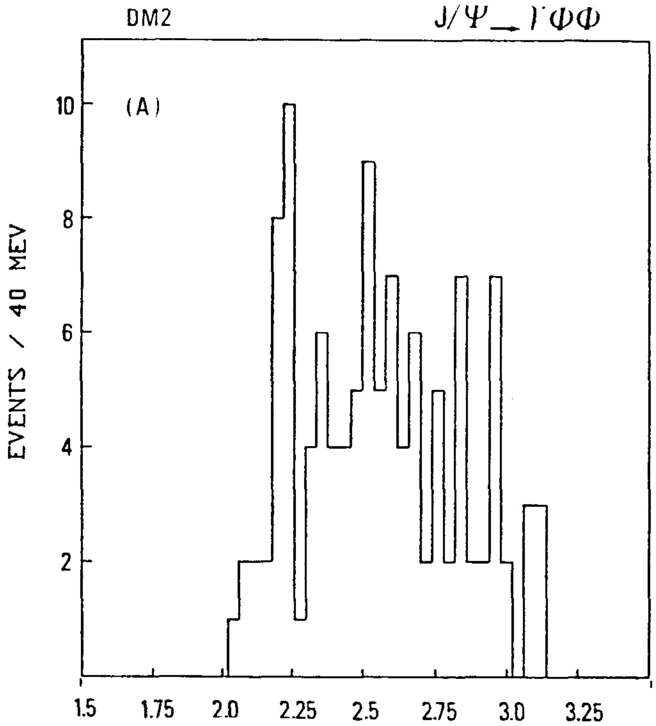
11. Invariant-mass spectrum for $\pi^+\pi^-$ system in exclusive radiative J/ψ decay. Note the clean θ signal. There is no present interpretation for the higher-mass peak, which may be connected with the h meson (from Ref. 36 (Mark III)).



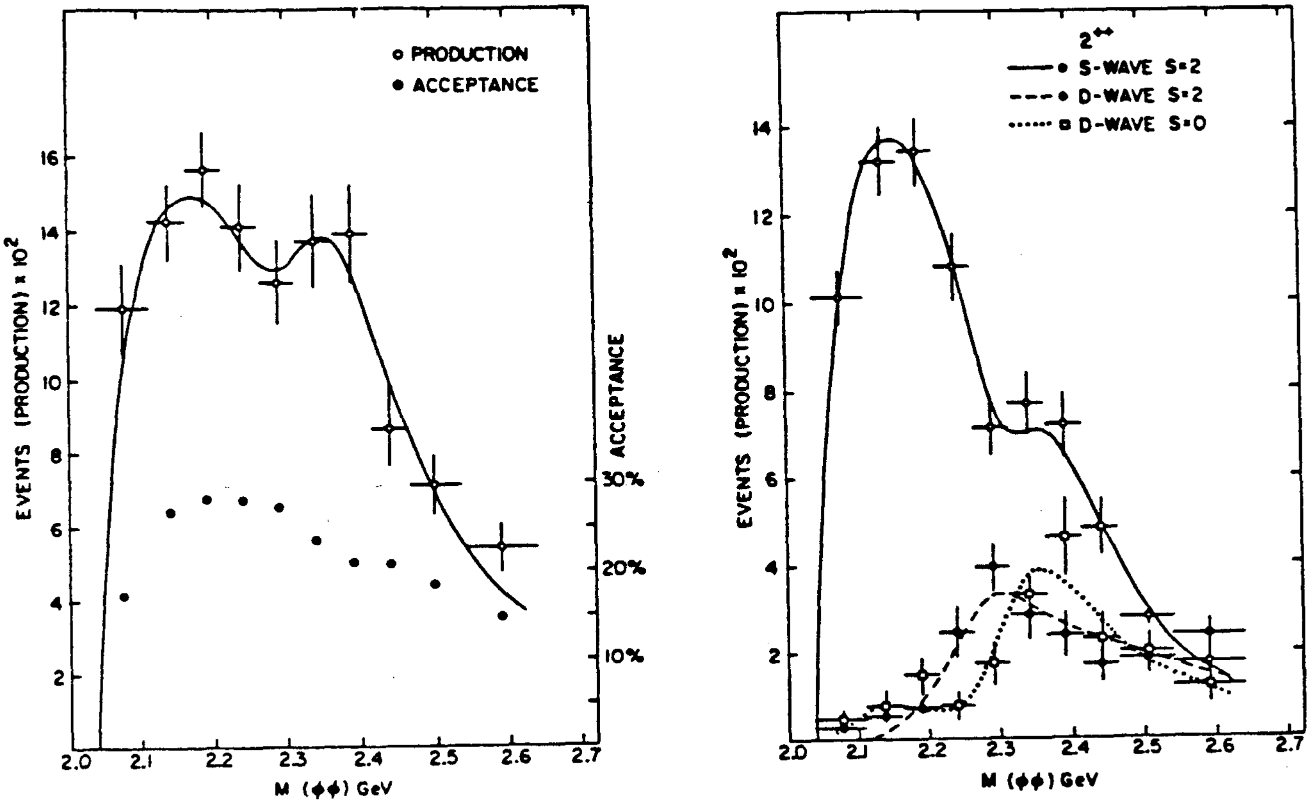
12. Invariant-mass spectrum for K^+K^- system in exclusive radiative J/ψ decay. The narrow ξ state at 2,230 MeV/c^2 is also seen in the K_SK_S system, not shown here (from Ref. 38 (Mark III).



13. Invariant-mass spectrum of hadronically produced ϕK^+K^- system shows indications of a narrow enhancement at 2,145 MeV/c^2 (from Ref. 40).



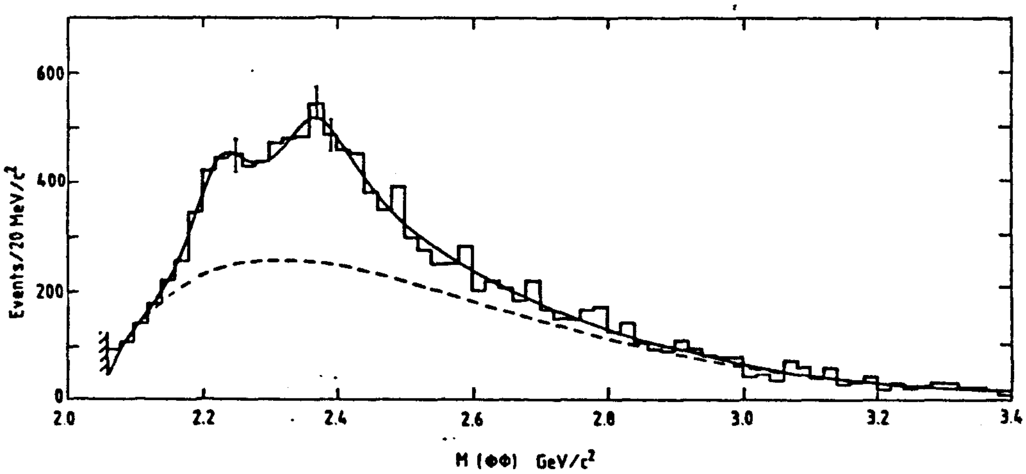
14. Invariant-mass spectrum of $\phi\phi$ system from exclusive radiative J/ψ decay shows possible narrow structure at a mass one bin below $m(\xi)$. From Ref. 39 (DM2).



15. Hadronically produced $\phi\phi$ signal seen by the BNL-CCNY Collaboration in $\pi^- p \rightarrow \phi\phi n$.

a) Invariant-mass spectrum of $\phi\phi$ system.

b) Results of partial-wave analysis for one resonant S-, two resonant D-waves in the 2^{++} channel (from Refs. 43, 46).



16. Invariant-mass spectrum for the $\phi\phi$ system produced in 85 GeV $\pi^- Be$ interactions using the Omega Spectrometer at CERN (from Ref. 44).