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GLUONIA*

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ABSTRACT

The postulated existence of hadrons with no quark content, implied by the non-Abelian nature of quantum chromodynamics, has been the object of much experimental activity. Recent data from radiative ψ decay permit a confrontation of available evidence with the most simple-minded criteria for their appearance. In the absence of compellingly positive evidence we give a rating of the relative merits of several possible candidates.

1. INTRODUCTION

It has been only in the past 12 years that we have had a credible candidate theory for the strong interaction of hadronic matter. It is possibly due to a general sense of relief at its appearance that quantum chromodynamics (QCD) has quickly been accepted as virtually a creed, notwithstanding the fact that not only some of its key tenets remain unproven, but also that some of its predictions have been hard put when confronted with experimental evidence. For the phenomenology of hadrons, the most striking QCD prediction has been the observation originally proffered by Fritzsch and Gell-Mann[1)] that the presence of the color index a in the gluon field operator $A_{a\mu}$ implies a term in the Lagrangian which leads to the existence of bound gluonic states. Formation and decay of hadrons that have no quark content, but instead consist of neutral gauge bosons coupling to the quarks' color only, irrespective of flavor, clearly may be subject to rules spectacularly different from those governing formation and decay of quark-based hadronic states.

Looking for gluonic matter (vulgo glueballs or, for 2-gluon states, gluonia) has therefore developed into a favorite sport for experimentalists studying hadron spectroscopy; and for theorists whose apologetic faculties have been taxed by the elusiveness of clear, "smoking-gun"-quality signals produced by their experimental colleagues. Still, there is no dearth of claims of evidence on both sides.

It is not the purpose of the present lecture to join in the fray and produce yet another set of claims or disclaimers. Rather, I will take a minimal, simplistic approach to the phenomenology of gluonia and

first, set up a set of criteria that would permit us to identify gluonia if they were produced at low masses and without being hopelessly mixed with quark-based mesons;

second, review the principal candidate states in the light of recently produced data from radiative ψ decays, mostly by the MARK III Collaboration at SPEAR;

third, provide a rating system for the likelihood that any of these states constitute evidence for the existence of gluonia by virtue of the very simplistic criteria adopted above.

The usefulness of such a restrictive approach lies not so much in a claim that it provide information with any degree of finality; rather, we claim that if we are not lucky enough to locate gluonium candidates that do in fact fulfill our criteria to a considerable extent, it may be very difficult to come up with any definitive statement as to the existence of this QCD-inspired form of matter. Conversely, we believe that preparing even one state clearly responding to our all-points bulletin, would constitute a spectacular strengthening of the credibility of our favorite theory of hadronic interactions.

2. GLUONIUM PROPERTIES FOR LUCKY RESEARCHERS

The non-Abelian nature of the QCD vector potential $A_{a\mu}$ [2] leads to the existence, in the Lagrangian, of terms proportional to

$$\partial_\mu(A^a_\nu A^{\mu b} A^{\nu c}) \quad \text{and} \quad A^b_\mu A^c_\nu A^{\mu b'} A^{\nu c'} ,$$

the physical motivation of which is the self-coupling of the gauge bosons. Taken at face value, these terms then imply the occurrence of hadronic states built up out of two (or more) gluons. To remain as specific as possible, I will deal today only with two-gluon states, or gluonia. Our known hadron spectrum has been categorized according to mass, width, space-time symmetry properties, various charges, as well as production and decay properties. What distinctive criteria can we expect for gluonia? Proceeding in order of compellingness, they are:

a) Unitary Symmetry properties: $|gg\rangle$ states will be singlet states in both color SU_3 and flavor SU_n. This implies the absence of all hadronic flavor, electric charge, baryon or lepton number. It also implies that neither in formation nor in decays will there be any preferential coupling to particular quark flavors or charges.

Practically speaking, this means that flavor-independent couplings make us expect gluonia to decay equally into, say, $u\bar{u}$ and $s\bar{s}$ pairs (for given space-time and phase space conditions)-- clearly a spectacular signature that we have not observed in any hadron. (To come up with easy-to-follow selection criteria, we will not heed the usual caveat which says: a resonating gg state, when looking at available phase space while wanting to decay into a $q\bar{q}$ configuration, may well find overlapping with normal $q\bar{q}$ states available close-by in the appropriate J^P channel the easiest way. If, say, a gg state of mass 1.6 GeV looked around in this way, it might well find (Fig. 1) the comparative density of close-by $s\bar{s}$ states to be a motivation for what will appear as "preferential decay" into $K\bar{K}$ modes).

b) The simple quark-parton model has been successful in accommodating observed hadrons in its SU_6 multiplet structure. gg states may have exotic quantum numbers that do not fit into this model. It may also be that all candidate multiplets for a newly observed state are credibly filled with $q\bar{q}$ configurations, leaving a gg candidate state without multiplet partners. Table 1 shows which J^{PC} states are accessible to gg composites.

Table 1: J^{PC} Values Accessible to $|gg\rangle$, $|q\bar{q}\rangle$, $J \leq 2$.

J^{PC}	$\|q\bar{q}\rangle$	$\|gg\rangle$
0^{++}		
0^{+-}	x	x
0^{-+}		
0^{--}	x	x
1^{++}		
1^{+-}		x
1^{-+}	x	
1^{--}		x
2^{++}		
2^{+-}	x	x
2^{-+}		
2^{--}		x

States not accessible to $|q\bar{q}\rangle$ or $|gg\rangle$ are crossed. Note that $C(X) = -1$ is excluded in radiative decays $\psi \to \gamma X$. We also do not expect to see any 1^- or 1^+ state formed by two massless identical bosons: 2 gluons in a color singlet state therefore are not likely to yield the low-mass exotic J^{PC} signature 1^{-+}, nor indeed the pseudovector 1^{++}.

c) Production mechanisms will favor gg state formation if they involve gluons prominently. This would indicate central production in Pomeron-exchange dominated hadronic reactions as an interesting locus for $|gg\rangle$ searches. Even more promising are reactions with s-channel gluonic intermediate states: the decay of quarkonia at masses below threshold for two-meson decay without flavor change must be prime candidates, as will be reactions heavily suppressed by the topological OZI rule[3].

d) Masses may or may not be characteristic: They are likely to overlap with the most populated quark-hadron mass range, but <u>may</u> well be distinct[4]. Calculations based on heuristic potential models[5], on lattice[6] or bag model[7] calculations, or on the QCD sum rules[8] appear to gravitate toward a compatible set of predictions summarized in Fig. 2. A string model approach[9] presented at this Institute comes up with distinctively higher values. Given that instanton effects make the determination of most scalar parameters suspect, the 0^-, 2^+, 2^- channels may present the best hopes for gg identification in the mass ranges indicated in Fig. 2.

e) Widths of gluonia may well turn out to be particularly useful parameters in searches. This would follow from the empirical argument qualitatively illustrated in Fig. 3, taking a lead from the OZI-suppressed decay of a heavy quarkonium ($\Gamma \leq$ a few MeV) as in Fig. 3a; the decay of a resonant gg state can be postulated to couple to $q\bar{q}$ with a width (Fig. 3b) intermediate between η_c decay and, say, ρ decay (Fig. 3c). A gluonium decay width of some 20-30 MeV/c^2 would be a natural consequence. (Again, there are several <u>caveats</u> that may vitiate the argument. Lipkin[10] has long pointed out that, e.g., the OZI forbidden $\phi \to \rho\pi$ decay can proceed, without suppression, through $K\bar{K}$ intermediate states. In general, configuration mixing will furnish every excuse if $|gg\rangle$ states are found to have normal hadronic widths.

f) Any state not containing charged constituents is not expected to have a prominent decay mode into radiative final states. Photons do not couple to gluons and should not be prominent in the decay of gg states.

We can formulate, out of the above, a simplistic set of rules for the gluonium researcher. While we are in no way limited by them, they will help search out clear-cut cases. They will figure in our final assignment of gluonic merit to candidate states.

1. Search in "gluon-rich channels". Any state clearly identified here, but not in other reactions, is promising.

2. Determine J^{PC} of candidate states in the appropriate mass ranges. If they do not fit into (unpopulated but accessible) quark model multiplets, but are accessible to the gg system, press on.

3. Determine the width: Is it noticeably below normal hadronic widths? If yes, rejoice. If not, beware but don't despair.

4. Study as many decay modes as possible: if a mode containing real photons is prominent, desist. If flavor independence looks like a good approximation, the state may become a compelling candidate.

The lucky experimentalist may find (or show the non-existence of) gluonia in the mass range under investigation by following these rules. Nature may not be kind enough to give us a clear-cut case. That may well prevent us from an unambiguous identification of gg states in the foreseeable future.

3. CANDIDATE STATES -- PRESENT STATUS

3.1 g_T (2200) states from hadronic interactions.

Let us follow the above criteria to look at the states which have been in evidence recently. Among "gluon-rich environments", first examine the only one that has claimed positive evidence from hadronic interactions. The BNL-CCNY experiment[11)] that studied the channel

$$\pi^- p \to \phi\phi n$$

showed convincing evidence for a copious $\phi\phi$ signal just above threshold, since confirmed by other groups[12)]; a phase shift analysis performed on the $\phi\phi$ sample[13)] convinced the Brookhaven group that they are dealing with three resonant vector-vector states, all in the $J^{PC} = 2^{++}$ channel. They are closely spaced in mass around 2,100 to 2,400 MeV/c^2; all have widths in the 150-300 MeV/c^2 range. The group states that the non-resonant background is negligible; the observed total cross-section signal is fitted in the manner indicated in Fig. 4.

If we follow our rules as stated at the end of the previous section, rules 1 and 2 appear to mark these signals as promising. Rule 3 (small width?) appears maximally violated. Rule 4 has not been investigated in hadronic interactions: it is only in the experimentally very distinctive $\phi\phi$ channel that the signal has been identified. If these resonant $\phi\phi$ states were identified as gg states, there is no selection rule that would preclude their decay into $\eta\eta$ (or $\eta'\eta'$). The Crystal Ball Collaboration has made a definitive search of the $\eta\eta$ channel through the decay $\psi \to 5\gamma$[14)], and finds no evidence for a state at the mass of the $\phi\phi$ enhancements. More information on these channels will be forthcoming from the MARK III Collaboration[15)].

Note that the |gg> candidacy of these enhancements is entirely based on their identification as resonant states, and the resultant OZI suppression involved as a "gluonium filter" (Fig. 5). If the observed $\phi\phi$ production were non-resonant, an interpretation would be much more difficult (and less interesting), as in other vector-vector enhancements above threshold (see, e.g., Section 3.2.2 below).

3.2 Candidates from radiative ψ decay.

Rule 2 leads us compellingly to investigate the process[16)]

$$\psi \to \gamma X. \quad (X = \text{hadrons}).$$

ψ decay is mediated by three vector gauge bosons, either ggg for hadronic decays or γgg for radiative decays. The latter channel is illustrated in Fig. 6. In the framework of the OZI suppression of ψ decay, replacing one gluon by a (real) photon penalizes us only by the ratio[16)]

$$\frac{\Gamma(\psi \to \gamma X)}{\Gamma(\psi \to \text{hadrons})} \approx \frac{16}{5} \frac{\alpha}{\alpha_S} .$$

Radiative ψ decay has a number of promising features, not the least of which is a plentiful and almost background-free supply of data of hadronic systems X originating from gg hadronization. ψ formation in the $e^+e^- \to \psi$ channel is thus an abundant source of interesting hadronic final states X. The final-state photon shares the quantum numbers $J^{PC} = 1^{--}$ of the ψ (with the possible exception of isospin). The system X therefore has a restricted set of possible quantum numbers, further depressing potential backgrounds:

$$J^{PC}(X) = 0^{++},\ 0^{-+},\ 2^{++},\ 2^{-+},\ \ldots$$

Note that all C = −1 states are forbidden due to C conservation; also, that two massless gluons in a color singlet will not combine to form a 1^+ or 1^- state. We therefore have a selective hadronic sample in which to study, for low spins, the scalar, pseudoscalar, and tensor systems in the absence of such frequently irrritating background as the ρ and ρ' tails. Note also that C conservation excludes $X \to K_L K_S$: only $X \to K_S K_S$ will be observable. In the decay $\psi \to \gamma X$ ($X \to 2$ vectors), it is important that there will not be backgrounds due to $\psi \to \pi^0 VV$ or to radiative corrections, again due to C conservation.

We can therefore hope to gain considerable insight into the vector-vector ($\phi\phi$, $\rho\rho$, $\omega\omega$) states as well as the 0^+, 0^-, and 2^+ meson spectra. Let us examine the evidence in the light of gluonium candidacies:

3.2.1 $X \to \phi\phi$

The MARK III Detector has permitted a clean observation of the channel

$$\psi \to \gamma\phi\phi$$

through the $K\bar{K}$ decays of the ϕ's. The resulting $\phi\phi$ spectrum shows sharp structure at the mass $m(\phi\phi) = (2976 \pm 8)$ MeV/c^2. This clean signal, observed on top of a very small background (cf. Figure 7a), has been identified[17] with the η_c candidate state observed originally by the Crystal Ball Collaboration[18] in inclusive photon spectra of the same reaction. The $J^P = 0^-$ assignment confirming this identification was convincingly performed in this mode[17].

While this signal can thus be safely interpreted as the pseudoscalar $^1P_0$ $c\bar{c}$ quarkonium state, there is no hint at further structure in this channel. Is there compatibility with the existence of a broad $\phi\phi$ enhancement in the mass range of the g_T states mentioned above? Figure 7b shows the relatively low sensitivity of the MARK III set-up to that $K^+K^-K^+K^-$ channel (slow $K^\pm$ tend to coil in the magnetic field)[19]. Still, a truly prominent signal would be expected to show up in these data[20].

3.2.2 $X \rightarrow \rho\rho, \omega\omega$

Vector-vector enhancements have been reported for the $\rho^0\rho^0$ system by the MARK II collaboration[21] at SPEAR and, from $\gamma\gamma$ interactions, by TASSO[22] at PETRA. These signals, centered at about 1.6 to 1.7 GeV/c^2, have never found a clear interpretation, although the SPEAR data were presumed to be connected with the Θ (cf. Section 3.2.4) state, originally observed by the Crystal Ball Collaboration in the $\eta\eta$ final state.

Recent MARK III data[23] show clear evidence for structure in the mass region 1.6-1.9 GeV/c^2 in all three accessible nonstrange VV channels:

$$\begin{aligned} \psi &\rightarrow \gamma\rho^0\rho^0 \\ &\rightarrow \gamma\rho^+\rho^- \\ &\rightarrow \gamma\omega\omega \end{aligned}$$

Note that the $\omega\omega$ channel constitutes an experimental tour de force, with five photons and four charged tracks in the final state: the $\omega\omega$ enhancement clearly emerges from the appropriate LEGO plots shown in Figure 8. The $\rho^+\rho^-$ system was also studied by the Crystal Ball Collaboration[24].

We have very little if any understanding of what such vector-vector enhancements just above threshold are due to - except that they clearly stand out above every conceivable background. Is their prominent appearance in radiative ψ decay significant? Fortunately, a decay plane analysis of these two-vector systems permits a relatively straightforward spin-parity analysis (cf. Figures 9, 10). For both charge channels of the $\rho\rho$ system and for the $\omega\omega$ system, J^{PC} (VV) was determined to be predominantly 0^{-+}. This pseudoscalar assignment rules out identification with any known meson state. Note, however, that there may be some ancillary activity in the 2^{++} channel of the $\rho^0\rho^0$ system.

Does that make this enhancement a gluonium candidate? While its prominent showing in this channel might be seen as a diffractive hadronization of valence vector gluon pairs in terms of vector meson pairs, the large width bodes ill. Indeed, a one-resonance interpretation is far from compelling. It is my feeling that a fuller understanding of this system remains for the future (for possible KK, $\pi\pi$ decays, see Sections 3.2.3/.4 below).

3.2.3 $X \rightarrow K\bar{K}$

The flavor independence argument has frequently been interpreted as suggesting the KK channel as a singularly promising one for lower-mass gluonium searches (along with $\eta\eta$)[25]. It is in this channel that the state Θ (1700) was first confirmed by the MARK II Collaboration[26]. Poor resolution and low statistics, however, made the separate identification of this new state and the f'(1520) problematic.

The recent MARK III data on radiative ψ decays, with a total sample of 2.7 M events, and with good K/π separation in the relevant momentum range due to its efficient time-of-flight system, has changed the picture.

Figure 11 illustrates this: there are two well-separated peaks in the K^+K^- mass spectrum, permitting a new determination of the masses and widths of both f' and Θ:

$$m(f') = (1.525 \pm 0.014)\ \text{GeV}/c^2 \qquad m(\Theta) = (1.720 \pm 0.014)\ \text{GeV}/c^2$$

$$\Gamma(f') = (0.085 \pm 0.035)\ \text{GeV}/c^2 \qquad \Gamma(\Theta) = (0.130 \pm 0.020)\ \text{GeV}/c^2$$

$$BR^2(\psi \to \gamma f')(f' \to K^+K^-) = (6.0 \pm 1.4 \pm 1.2)\ 10^{-4}$$

$$BR^2(\psi \to \gamma\Theta)(\Theta \to K^+K^-) = (4.8 \pm 0.6 \pm 0.9)\ 10^{-4}$$

Given the satisfactory samples of events, a spin-parity analysis could be performed on both the f' and the Θ states in the K^+K^- channel; for both, the $J^{PC} = 2^{++}$ assignment is favored over the next choice (0^{++}) by a factor $> 10^3$.

Note these features: the f' state, well observed in hadronic interactions, fits well into the tensor meson octet; for the Θ state, there is no obvious quark model/SU_6 assignment; both appear with roughly equal weight in the KK channel; as we will see, only Θ is seen in the ππ channel. Measurements from the DM-2 detector at DCI[27] are in agreement with these data.

Following the $K\bar{K}$ invariant-mass distribution to higher values, MARK III finds an additional significant enhancement in both the K^+K^- and the K_SK_S channels. Limited statistics do not permit a definitive J^P assignment of this state, shown in Figures 12a, b. Its parameters are reported to be:

$$m(\xi) = (2218 \pm 3 \pm 10)\ \text{MeV}/c^2$$

$$\Gamma(\xi) < 40\ \text{MeV}/c^2,\ (95\%\ \text{C.L.})$$

$$BR^2(\psi \to \gamma\xi)(\xi \to K^+K^-) = (5.8 \pm 1.8 \pm 1.5)\ 10^{-5}$$

$$BR^2(\psi \to \gamma\xi)(\xi \to K_SK_S) \approx 6\times10^{-5}$$

Is this state a gluonium candidate? First note its limited statistical significance (it has not been seen by the DM2 Collaboration at DCI, who studied the same channel and report[27] a 3 S.D. significance for their non-observation of the effect; cf. Figure 12c. Theoretical speculations that it be interpreted as a Higgs candidate despite its relatively low mass were damped by its non-observation in the μμ channel. Once we accept the state's existence, it has to be taken as a serious contender for a gluonium: its $J^P = 2^{++}$ is compatible with the data; it is seen only in this gluon-rich channel; it finds no natural home in the quark model; its mass is in the expected range, and its width is small (compatible with either zero, or a semi-OZI suppression). Flavor independence remains a question mark: there is no significant signal in any other channel, but neither are the reported limits in disagreement with the assignment, as seen in Table 2[28]. More data are expected to be taken at SPEAR this fall, and should be awaited eagerly.

Table 2: Upper Limits for Various Branching Fractions of $\xi(2.2)$, 90%, C.L.

Decay Mode	Product BR Limit
$\xi \to \mu^+\mu^-$	$< 7.3 \times 10^{-6}$
$\to \pi\pi$	$< 2 \times 10^{-5}$
$\to K^*K$	$< 2.5 \times 10^{-4}$
$\to K^*\bar{K}^*$	$< 3 \times 10^{-4}$
$\to \eta\eta$	$< 7 \times 10^{-5}$
$\to p\bar{p}$	$< 2 \times 10^{-5}$

3.2.4 $X \to \pi^+\pi^-$

In this channel, usually dominated by the vector state ρ^0 and its recurrence, radiative decay supplies an unusual chance to take a look at the non-vector spectrum. After elimination of ρ^0 signals from a feedthrough of $\psi \to \pi^0\pi^+\pi^-$ events, where one photon from π^0 decay is mistaken for a token of radiative ψ decay, the other one evading detection (see the "feedthrough" ρ signal due to DM2 in Figure 13a), a relatively clearly structured $\pi\pi$ mass spectrum emerges (13b). These data, due to the MARK III Collaboration[29] then show a prominent $f \to 2\pi$ signal, an enhancement at the Θ mass, and a third one around 2.1 GeV/c². A 3-Breit-Wigner-resonance fit yields, for the Θ states, an overall branching fraction (taking mass and width from the $K\bar{K}$ mode):

$$BR^2(\psi \to \gamma\Theta)(\Theta \to \pi^+\pi^-) = (1.6 \pm 0.3 \pm 0.3)\ 10^{-4}$$

This is about a factor of 3 below the corresponding $\Theta \to KK$ mode, and may be understandable by virtue of the light quark masses in the $\pi\pi$ case. The $\Theta \to \pi^+\pi^-$ signal leads to a $J^P = 2^{++}$ assignment, just like the $K\bar{K}$ case. The enhancement at ~2.1 GeV/c² has not been studied in detail, or indeed assigned an interpretation. It is of normal hadronic width, and may be related to the H meson.

3.2.5 $X \to KK\pi$

One of the most-discussed gluonium candidates has been the $\iota(1440)$. Discovered by the Crystal Ball[30] and MARK II[31] Collaborations, who reported a width of only ~50 MeV, its more recent observations by the DM2 and MARK III Collaborations in the channels (cf. Figures 14a, b, c)

$\psi(\to \gamma\iota)(\iota \to K_S K^{\pm}\pi^{\mp})$	MARK III, DM2
$(\iota \to K^+K^-\pi^0)$	MARK III
$(\iota \to K_S K_S \pi^0)$	MARK III

have led to a more definitive assignment of its parameters:

$m(\iota) =$	(1456 ± 10) MeV/c^2	MARK III
	(1474 ± 15) MeV/c^2	DM2
$\Gamma(\iota) =$	(100 ± 10) MeV/c^2	MARK III
	(76 ± 16) MeV/c^2	DM2

Note that the new width measurements are compatible with normal hadronic widths. The combined branching fraction is

$$BR^2(\psi \to \gamma\iota)(\iota \to K\bar{K}\pi) = 5.0 \pm 0.5 \pm 0.7)\ 10^{-3} \quad .$$

Spin-parity analyses were performed by the Crystal Ball[24] and MARK III[32] Collaborations. Both report the assignment of pseudoscalar characteristics

$$J^P(\iota) = 0^- \quad .$$

The more recent MARK III analysis favors this assigment by factors of e^8(w.r.t. 1^+) and e^{13}(w.r.t. 1^-). Reference 30 reported a dominant decay through the two-body mode

$$\iota \to \delta\pi\ (\delta \to K\bar{K}).$$

Is the ι a good gluonium candidate? Mass and width cannot be claimed to be distinctive; its observed properties do not place it in an existing quark model multiplet. Flavor independence in its decay would certainly imply that, if $\iota \to \delta\pi$ dominates, the decay mode

$$\iota \to \delta\pi\ (\delta \to \eta\pi)$$

be equally observed. The MARK III looked for this mode but could not find any evidence, despite the presence of a good event sample for the $X \to \eta\pi\pi$ channel (see below). The quoted branching fraction

$$BR^3(\psi \to \gamma\iota)(\iota \to \delta^{\pm}\pi^{\mp})(\delta^{\pm} \to \eta\pi^{\pm}) < 3.9\times10^{-4} \qquad (90\%\ \text{C.L.})$$

is considerably below the level expected for flavor-independent decays.

3.2.6 $X \to \eta\pi\pi$

Both the Crystal Ball and MARK III Collaborations[33] searched for structures in this channel. While they do find signals for $\delta \to \pi\eta$ decays, no enhancement is seen in the $\eta\pi^+\pi^-$ mass spectrum for the ι region if the $\eta\pi^\pm$ mass is fixed at the $m(\delta)$ level (see Fig. 15). There is considerable structure in the 1250-1400 MeV/c² region, but there is no clear interpretation at this time. Note that an overall uncut $\eta\pi^+\pi^-$ mass plot has prominent η' and η_c signals. The η', well documented from hadronic reactions, shows up prominently in this "gluon-rich" channel. Does that make it a gluonium candidate? Its prominent and well-known (cf. Fig. 16 below) decay into $\gamma\rho$ rules out any interpretation that makes its valence constituents neutral (i.e., 2g). Still, a state with a branching fraction

$$BR(\psi \to \gamma\eta') \approx 10^{-3}$$

cannot be ignored in this context. The MARK III data on hadronic decays $\psi \to V^0\eta$ and $V^0\eta'$ ($V^0 = \rho^0, \omega, \phi$) can be used, in the framework of J. Rosner's formulation[34] of the valence content of η and η', to provide some useful insight into the question. If we accept his ansatz for the wave functions

$$|\eta\rangle = X_\eta|q\bar{q}\rangle + Y_\eta|s\bar{s}\rangle + Z_\eta|gg\rangle$$
$$|\eta'\rangle = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|gg\rangle$$

(where $q\bar{q} = 1/\sqrt{2}(u\bar{u} + d\bar{d})$), any deviation from $X^2 + Y^2 = 1$ indicates the presence of a gluonium component. As long as $Z = 0$, X and Y are the traditional mixing angles of the pseudoscalar nonet. Through a measurement of all accessible decays $\psi \to$ vector + pseudoscalar, the MARK III Collaboration[32] was able to show that, irrespective of the particular 3-gluon or electromagnetic annihilation mechanism, a global fit indicates that there is room for a valence gluon component in the η' wave function, whereas the η state is saturated by quarks:

$$X_\eta^2 + Y_\eta^2 = 1.1 \pm 0.2 \quad ,$$
$$X_{\eta'}^2 + Y_{\eta'}^2 = 0.63 \pm 0.18 \quad .$$

It is tempting to conclude that a sizeable component of the η' wave function is made up out of valence gluons in the absence of quarks. Note, however, that it is equally possible to ascribe the $Z_{\eta'}$ part to mixing with another accessible pseudoscalar state: $\iota(1440)$ would be a natural candidate, given its ready observability in radiative ψ decays.

3.2.7 $X \to \gamma\rho$

A search for radiative decays of the hadronic system X (i.e., for two uncorrelated photons in the ψ decay) has the advantage of ready interpretability in terms of substructure components: any hadronic state wih a prominent radiative decay mode is unlikely to be due entirely to uncharged valence constituents.

The most definitive results, from the Crystal Ball[24], DM2[27], and MARK III[32] Collaborations, exist on the doubly radiative decay

$$\psi \to \gamma X(X \to \gamma\rho^0;\ \rho^0 \to \pi^+\pi^-) \quad .$$

As we mentioned in the previous section, the decay $\eta' \to \gamma\rho$ is a prominent one; it is seen to dominate the mass plot of the appropriate $m(\pi^+\pi^-\gamma)$ combinations, in Figure 16a, b, c, for all three reported sets of results. It is equally clear, however, that there is more activity in these channels, although the details vary slightly between the three groups; a prominent enhancement is observed in the 1.4–1.5 GeV/c² region. A two-Breit-Wigner fit, as shown in Figure 16a, leads to

$$m(X \to \rho\gamma) = (1434 \pm 14)\ \mathrm{MeV/c^2}$$

$$\Gamma(X \to \rho\gamma) = (\ 133 \pm 32)\ \mathrm{MeV/c^2}$$

$$BR^2(\psi \to \gamma X)(X \to \gamma\rho) = (\ 1.1 \pm .24 \pm .25)10^{-4}$$

if we use f-meson parameters for a fit to its low-mass shoulder. These mass and width values are fully compatible with those mentioned above for the ι state. Are they to identify the $\gamma\rho$ enhancement as the ι? Further evidence can be gleaned from a spin-parity analysis, as given by the Crystal Ball and MARK III groups, and displayed in Figure 17: for the state decaying into $\gamma\rho$, a pseudoscalar assignment would lead to a $\sin^2\Theta_\gamma$ expectation, while $\rho \to \pi\pi$ decay predicts a $\cos\Theta_\pi$ distribution of $\rho\pi$ correlation angles. Both are favored by the data.

It is therefore probably justified, if not compelling, that we identify the state X with the ι. This assignment, in conjunction with the branching fraction mentioned above, makes the ι less likely to be interpretable as a pure gluonium[35].

4. Glueball Candidate Ratings, Fall 1984

The preceding review of evidence that may be interpreted as telling us about various candidate states for hadronic composites of two valence gluons has tried to assemble the criteria chosen in Section 1 as our safest bet to make such an identification. All the states discussed are, to the best of our knowledge, SU_3 singlets that do not naturally fit into any established quark model multiplet; the only exception to this statement is the η', the mass (and mixing with other pseudoscalar) of which has long presented a problem. All of them, except for the η', are seen only in what has been called gluon-rich channels. We therefore feel justified in supplying a rating system based on our knowledge and our stated prejudice (that only simple criteria will be taken into account, and that only pure $|gg\rangle$ candidacy will be considered, again with the exception of the η' case). We feel justified, and, indeed, compelled to include part of the η' wave function in our considerations simply due to its prominent visibility in the radiative decay of ψ(3.1), and its problematic appearance in the usual SU_6 quark model assignment.

Here then is our entry for the market ratings of the gluonium commodity trade:

Table 3: Simple-minded gluonium checklist:

CANDIDATE STATE:	g_T [1,2,3]	VV	ι	Θ	ξ	(η')
J^{PC}	2^{++}	0^{-+}	0^{-+}	2^{++}	?	0^{-+}
SU_3 singlet?	yes	yes	yes	yes	yes	?
mass [GeV/c²]	~2.2	1.7	1.4	1.7	2.2	0.96
width [GeV/c²]	0.2	0.2	0.1	0.13	<0.04	0.01
seen in several channels?	no	yes	yes	yes	K^+K^- K_SK_S	yes
flavor independent decay?	probably not	?	no	maybe	?	?
radiative mode?	no	no	yes	no	no	yes
seen only in gluon-rich channel?	?	?	yes	yes	yes	no
RATING (1...10)	2	1	2	3	5	(5)

We can see that all masses are in the proper approximate mass range to fit into the framework of Figure 2. Narrow widths exist only for ξ and η'. Flavor independent decay is ill checked for most candidate states, looks halfway promising only for Θ. Prominent radiative decay modes mitigate against (probably) ι and, certainly, η' as pure gluonia. Since, however, we are judging η' as part-gluonium only, the ratings in the last line will become understandable, albeit subjective: no candidate state has a higher than 50% likelihood of being found to consist of two valence gluons alone. ξ(if it survives) looks most promising; as "partial gluonium", η' looks promising.

If there is any chance for a "smoking gun" candidate, it has to be ξ[36]. Are we likely to find completely satisfactory evidence for gluonia in the absence of any candidate state that fulfills most of our criteria? Not very. But then clear answers are not always at the end of an experimental search. We may have to be more modest in our expectations of what a new phenomenology, including the self-coupling of the gauge bosons of QCD, will do for us. Indeed it may well be that hybrid states ($|q\bar{q}g\rangle$, etc.) will be more successful in giving us indications on valence gluons. But that will be written in another chapter, which will require a great deal more experimental work.

Acknowledgment

I would like to thank my colleagues in the MARK III Collaboration, and several members of the Crystal Ball Collaboration, as well as Dr. Sam Lindenbaum of CCNY and Brookhaven, for discussions on the results mentioned here. The warm hospitality of Nathan Isgur, Gabriel Karl, and Pat O'Donnell at this Institute is much appreciated.

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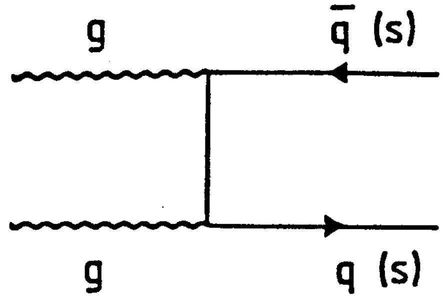

Fig. 1 Gluonium hadronization: overlap with resonant hadronic modes in the J^P channel in question will affect decay width.

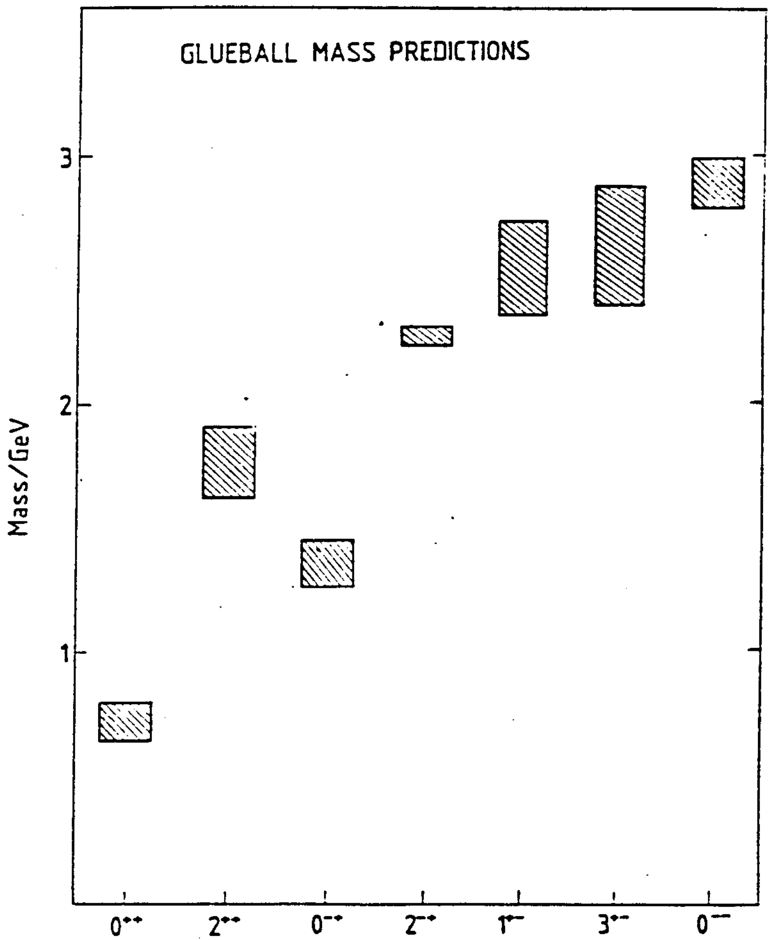

Fig. 2 Gluonium masses: shaded regions, for the J^{PC} channels indicated on the abscissa, span the predictions of typical ground state masses from bag, lattice, and potential model calculations (Compilation due to C. Peterson, unpublished).

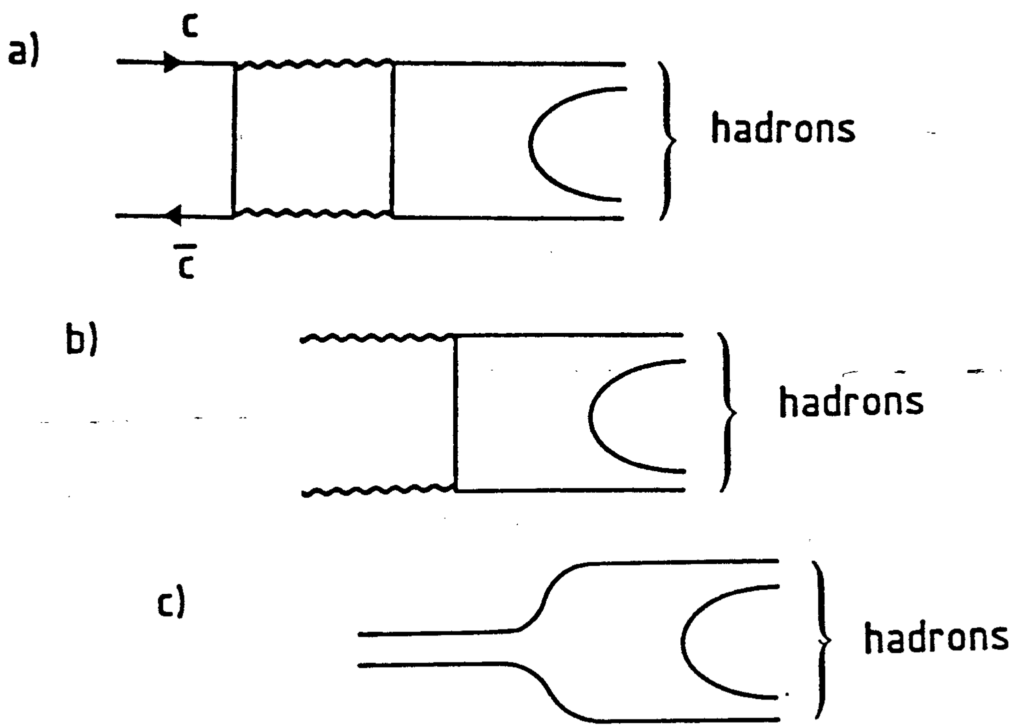

Fig. 3 Visual aids for an estimate of gluonium decay width, a OZI suppression (a few MeV); b gluonium decay ~"√OZI" (order 10 MeV); c unsuppressed strong hadronization (order 100 MeV).

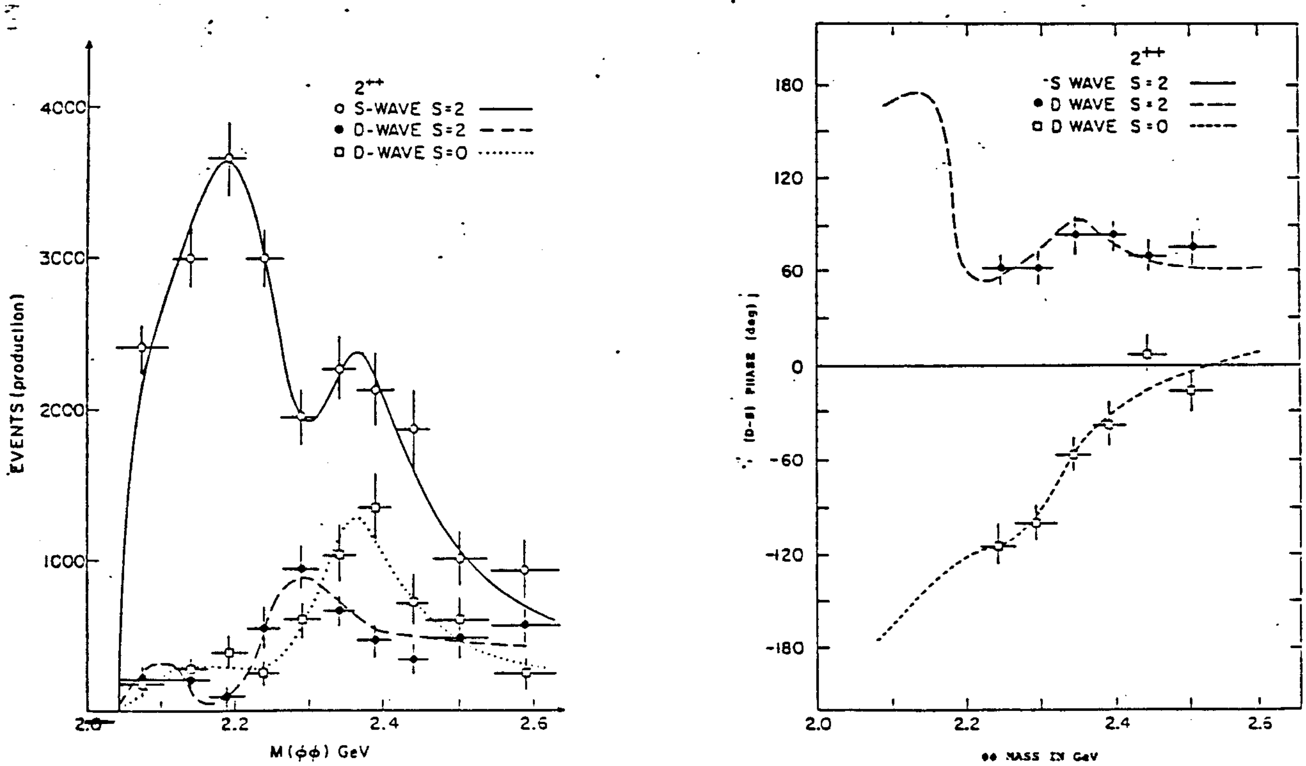

Fig. 4 BNL-CCNY data on the reaction $\pi^- p \to \phi\phi n$: a measured cross section fitted by three $J^{PC} = 2^{++}$ partial waves; b the phase difference between two D and the S wave shows the need for three component waves.

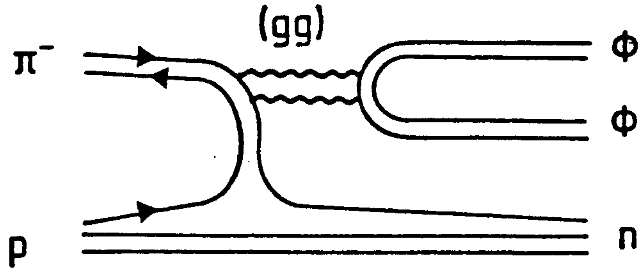

Fig. 5 Production of a resonant $\phi\phi$ system through OZI forbidden disconnected diagram.

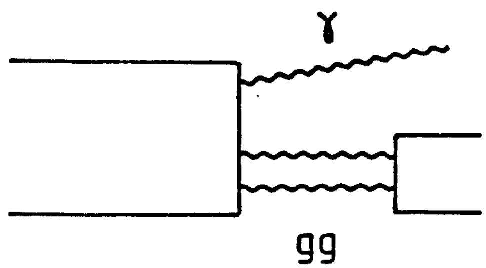

Fig. 6 Annihilation of a $c\bar{c}$ system into 3 vectors: one real photon which serves as an experimental tag, and two gluons. This diagram is expected to favor gluonium formation.

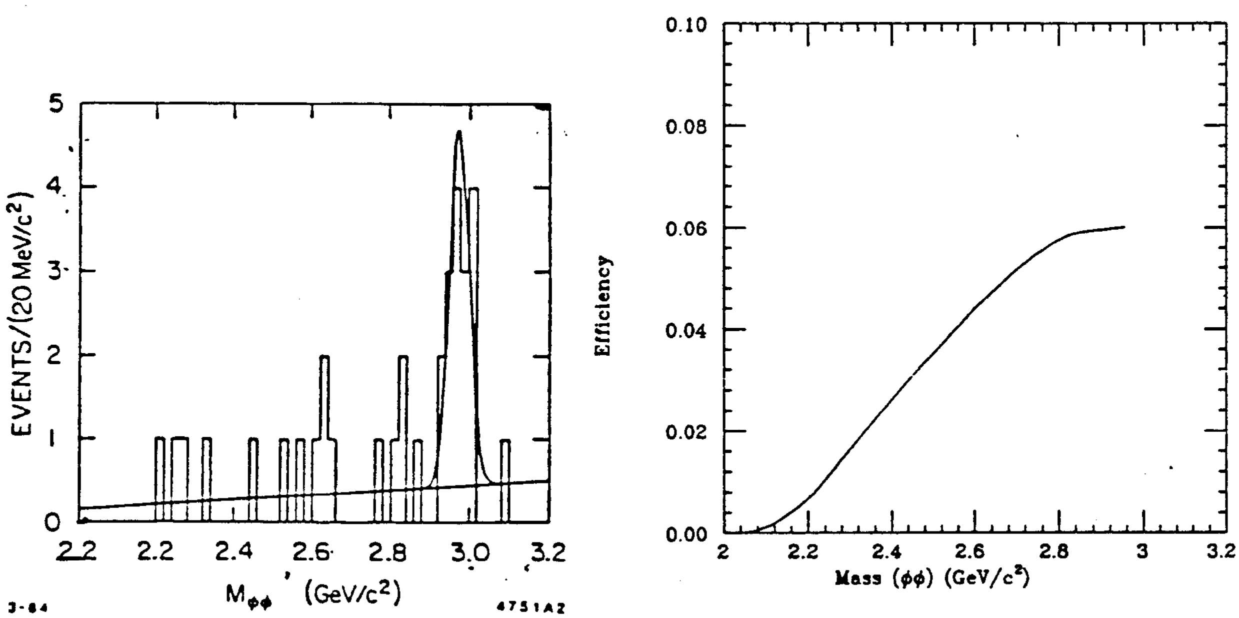

Fig. 7 a The mass spectrum of the $\phi\phi$ system observed in theradiative decay $\psi \to \gamma\phi\phi$ by the MARK III Collaboration[17]; b efficiency of the MARK III detector for $\phi\phi$ detection as a function of $m(\phi\phi)$[19].

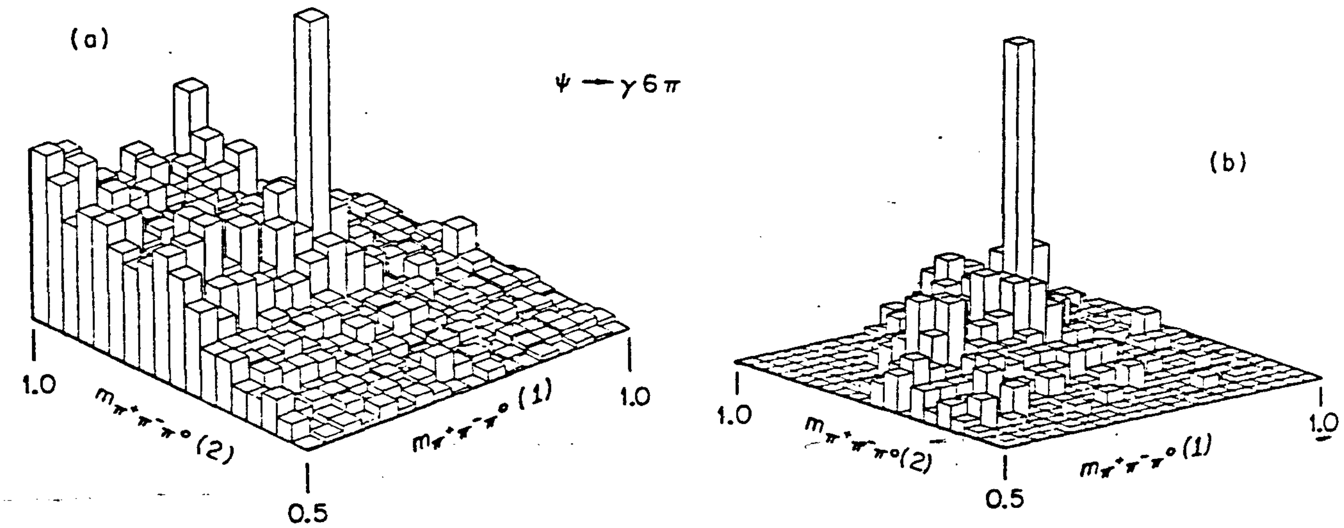

Fig. 8 Three-dimensional histograms ("Lego plots") of $\pi^+\pi^-\pi^0$ masses for radiative ψ decay ($\psi \rightarrow \gamma\pi^+\pi^-\pi^0\pi^+\pi^-\pi^0$), a for all 6π masses; b for $1.6 \leq m_{6\pi} \leq 1.9$ GeV/c²; there are 4 entries per event[23].

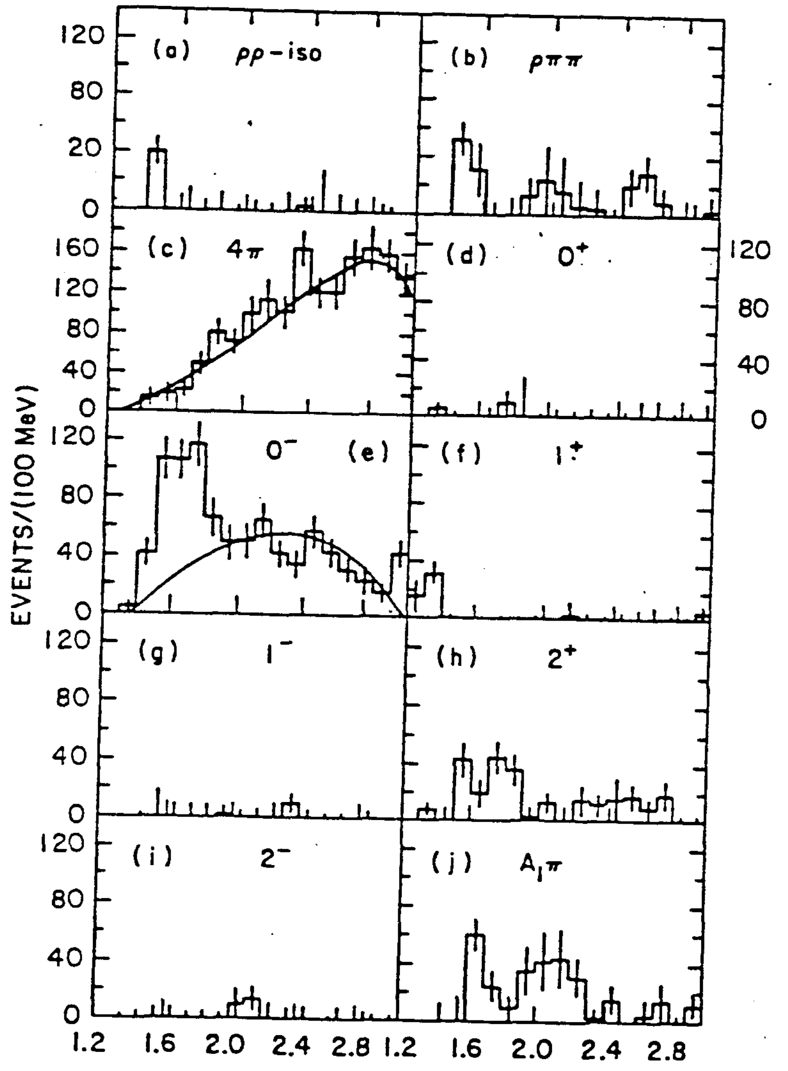

Fig. 9 Spin-parity analysis of the 4π system in the process $\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$, as detected by MARK III. The 4π mass is weighted with the fraction of each of the 10 channels indicated, as determined by a 10-channel fit. Structure is seen mainly in the 0^- channel, in addition to some activity in the 2^+ channel.

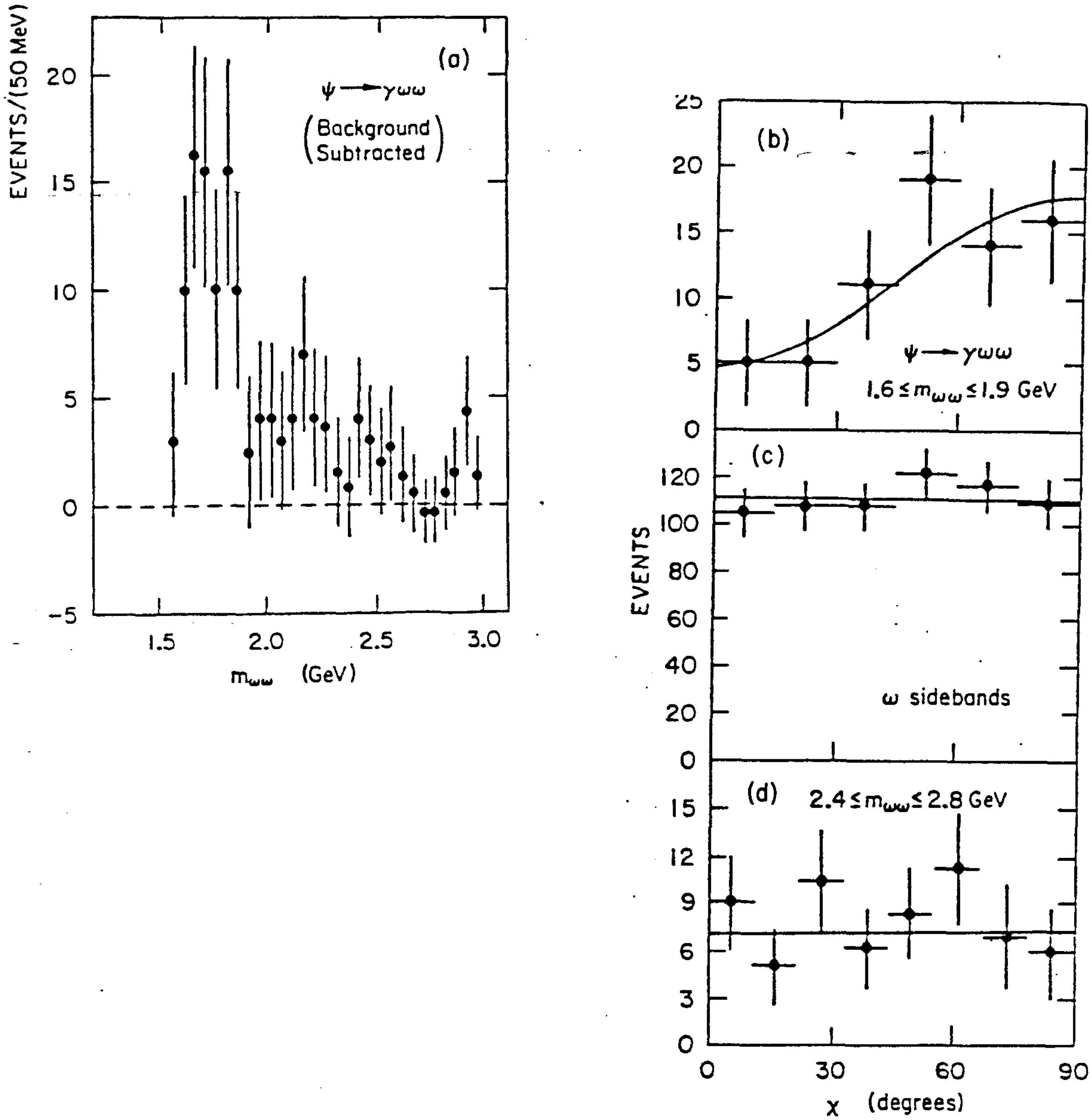

Fig. 10 Spin-parity analysis for the ωω system (MARK III). a background-subtracted mass distribution for the ωω system; b correlation angle distribution for the signal region, and c for the ω sidebands; and d for a higher m(ωω) region. The $(a + b \sin^2 X)$ shape of Fig. 10b is typical for the $J^P = 0^-$ case.

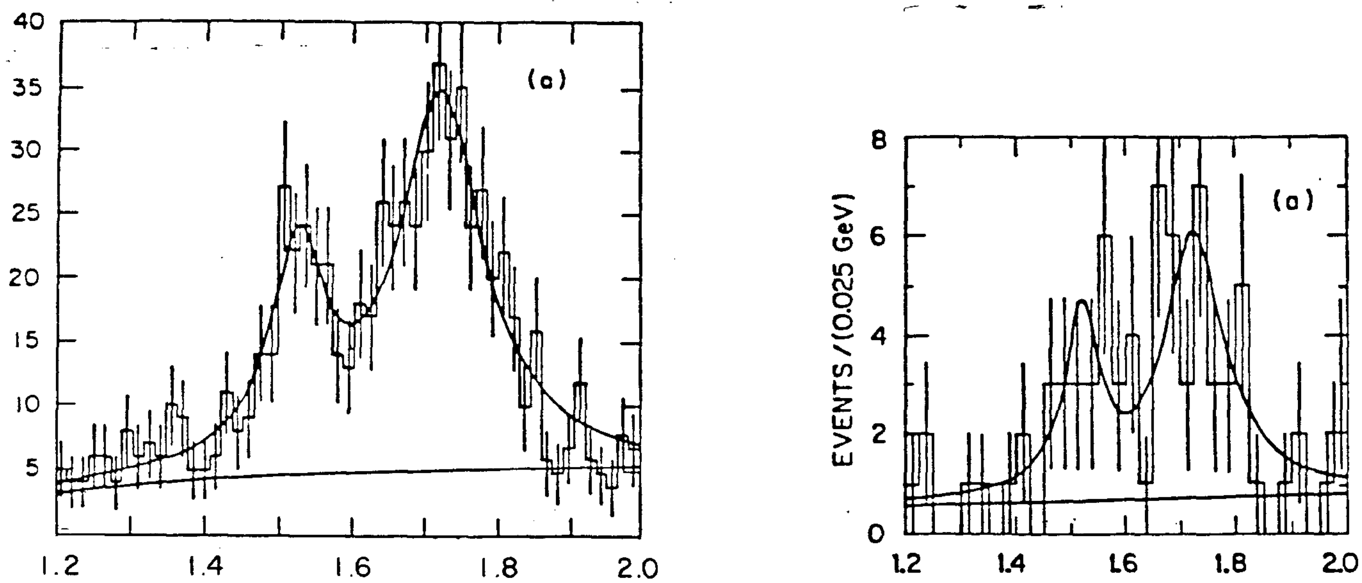

Fig. 11 Mass distribution of the $K\bar{K}$ system from radiative ψ decay (MARK III). A clear separation of the f' and θ states is obvious in <u>a</u> the K^+K^- system; <u>b</u> the K_sK_s system shows marginal agreement.

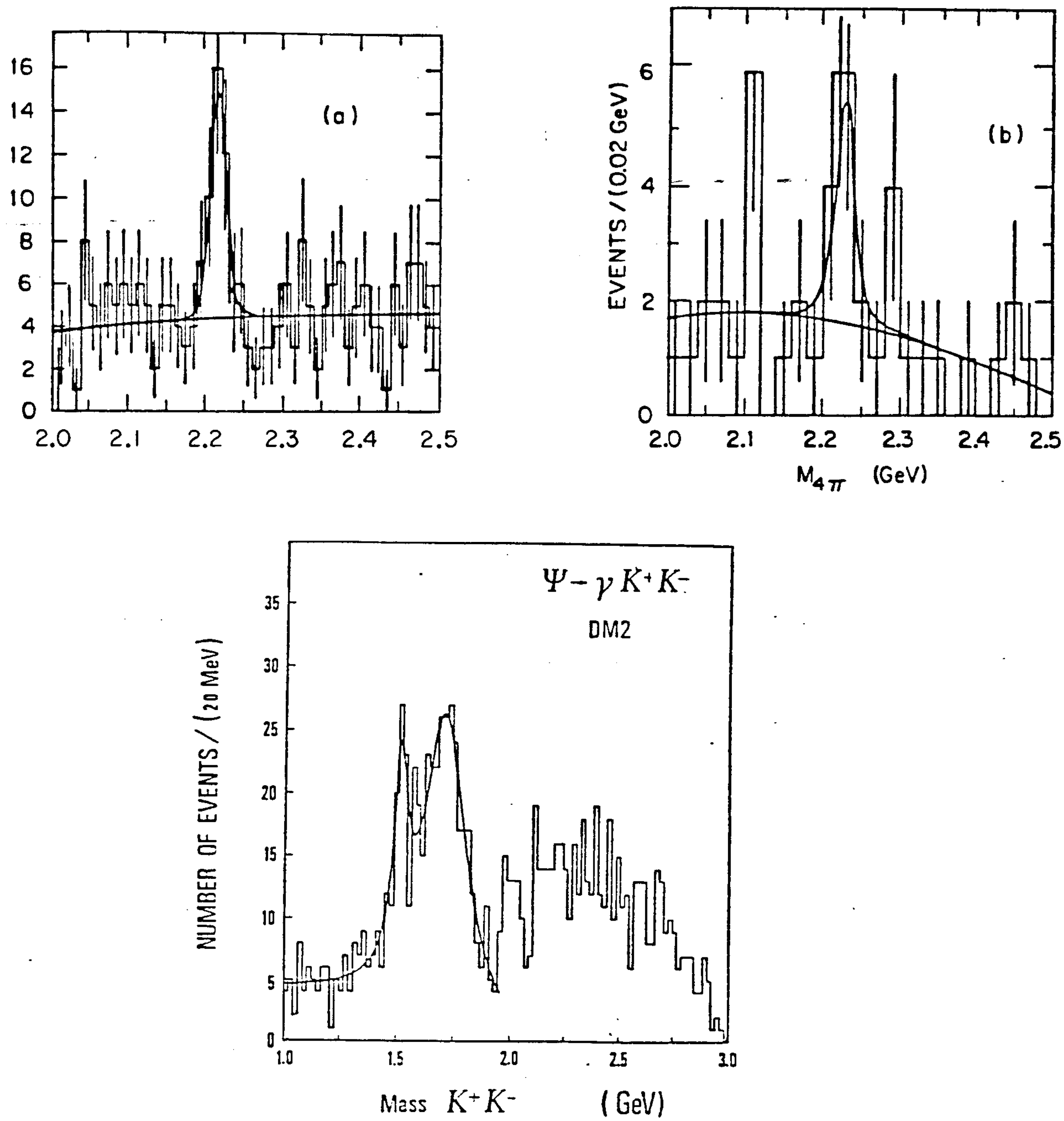

Fig. 12 Data on the $K\bar{K}$ channel at $2.0 \le m(K\bar{K}) \le 2.5$; the MARK III results show a narrow state in both K^+K^- (a) and K_sK_s (b); the DM2 data show no recognisable signal for a resonant state (c).

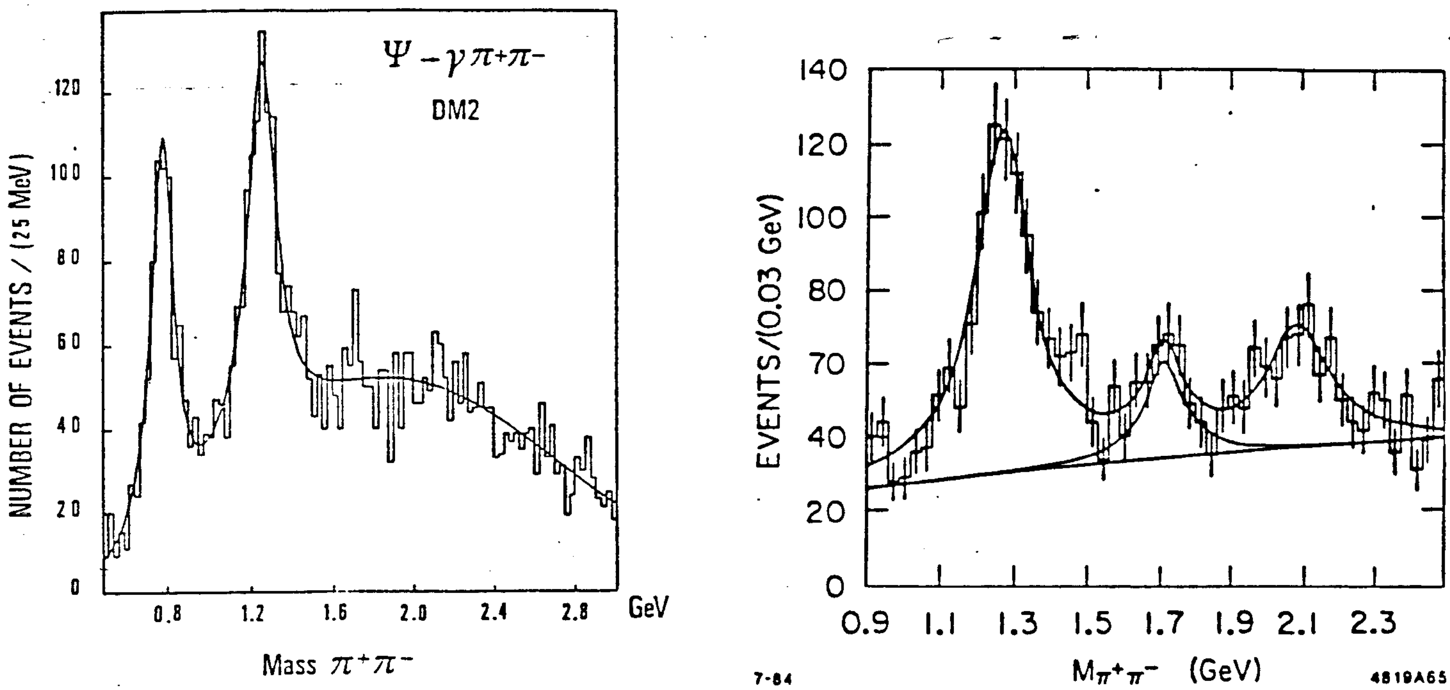

Fig. 13 Radiative ψ decay into $\gamma\pi^+\pi^-$, a the DM-2 detector signal includes feedthrough from the $\pi^0\pi^+\pi^-$ channel, simulating the forbidden $\gamma\rho^0$ decay (see text); b the MARK III data show distinctive structure in the f, θ and 2.1 GeV/c^2 regions.

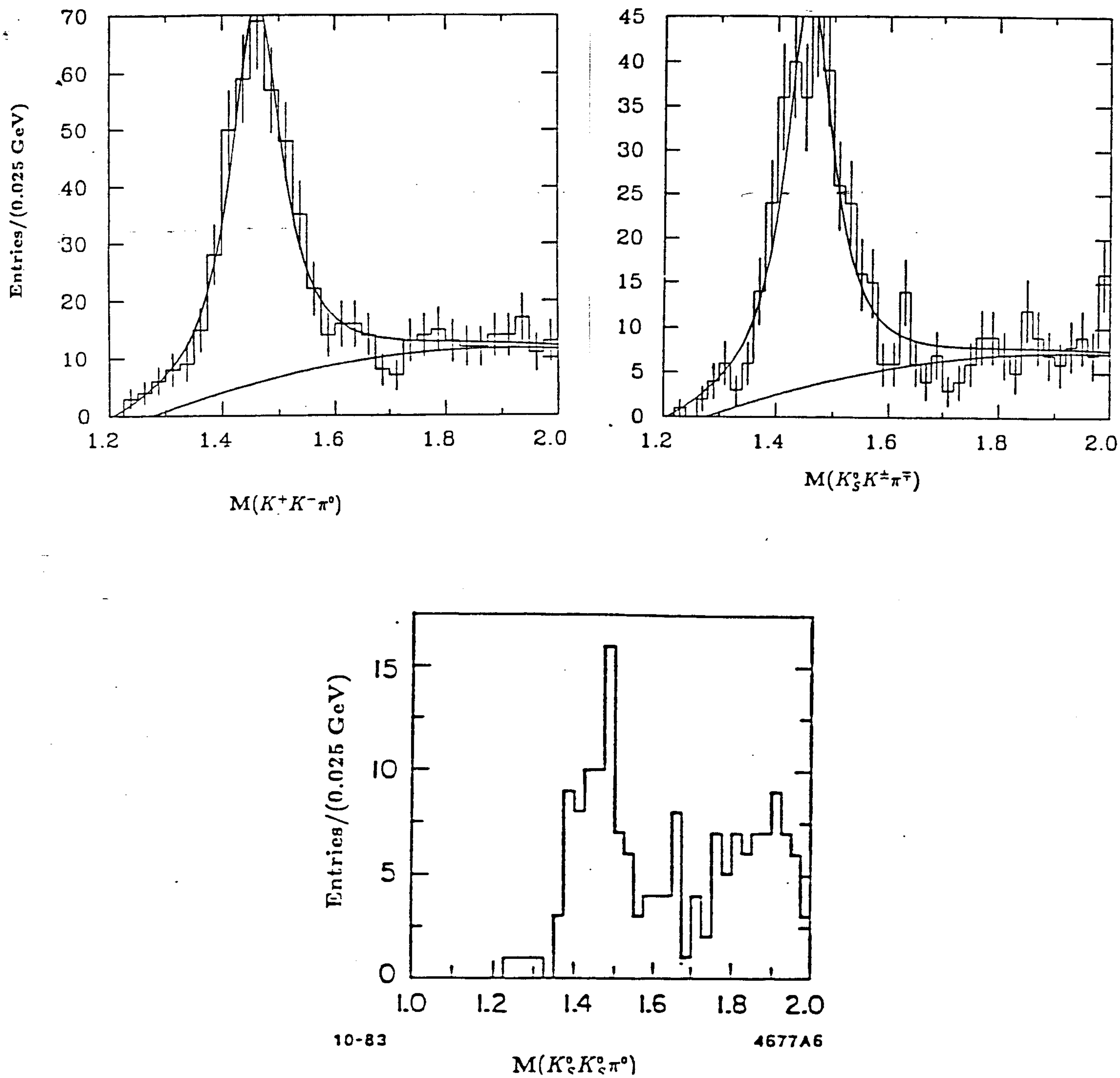

Fig. 14 MARK III data on the radiative decay $\psi \to \gamma K\bar{K}\pi$. Clear signals for the production of $\iota(1456)$ production are observed in three different channels, a $K^+K^-\pi^0$; b $K^0K^\pm\pi^\mp$; c $K^0\bar{K}^0\pi^0$ (J. Richman, Cal Tech thesis, in preparation.

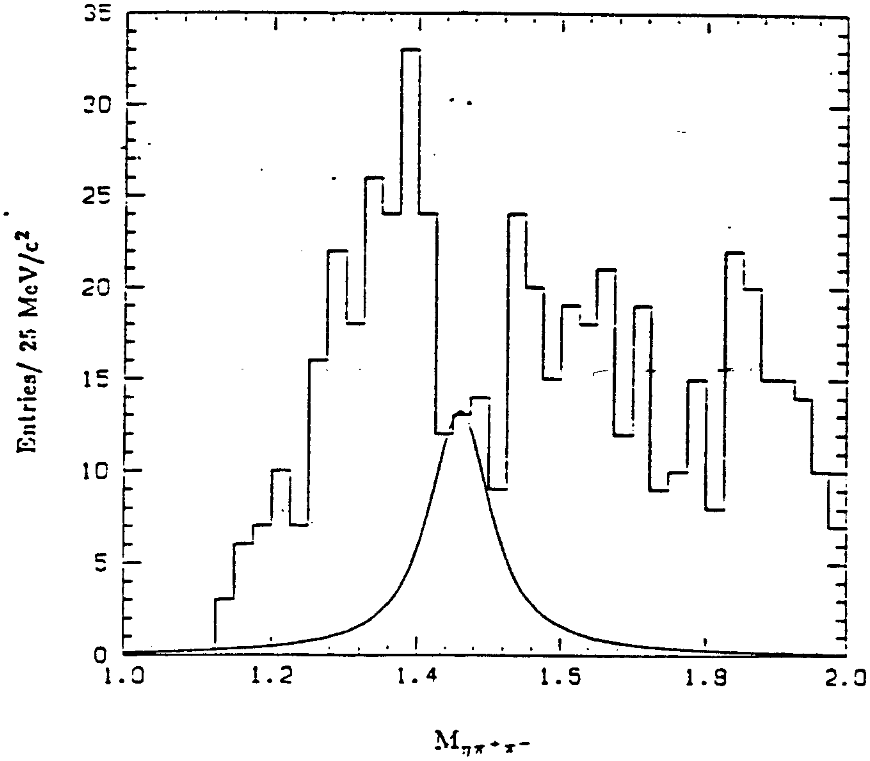

Fig. 15 Absence of the decay $\psi \to \gamma\iota$, $\iota \to \delta\pi$, $\delta \to \eta\pi^{\pm}$ as observed in the MARK III data sample of $\psi \to \gamma\eta\pi^{+}\pi^{-}$ decays. Appropriately cut $\eta\pi^{+}\pi^{-}$ distributions show no signal in the ι mass region.

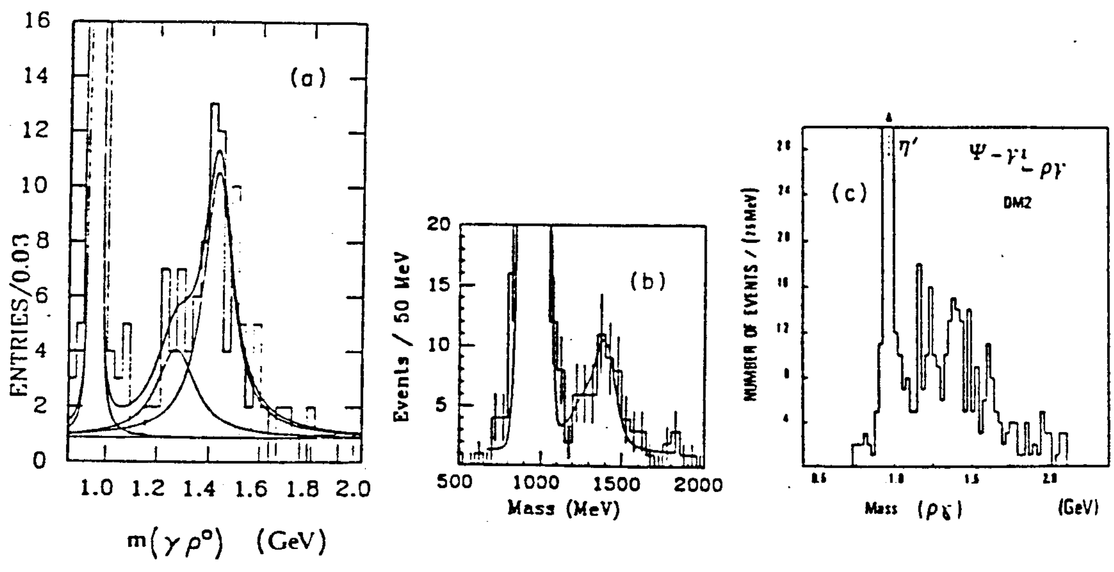

Fig. 16 Evidence from the MARK III, Crystal Ball and DM2 detectors on the decays $\psi \to \gamma(\gamma\rho)$. a, b show compatible evidence on an enhancement in the region of $m(\gamma\rho) \approx m(\iota)$; c DM-2 does not permit a firm conclusion.

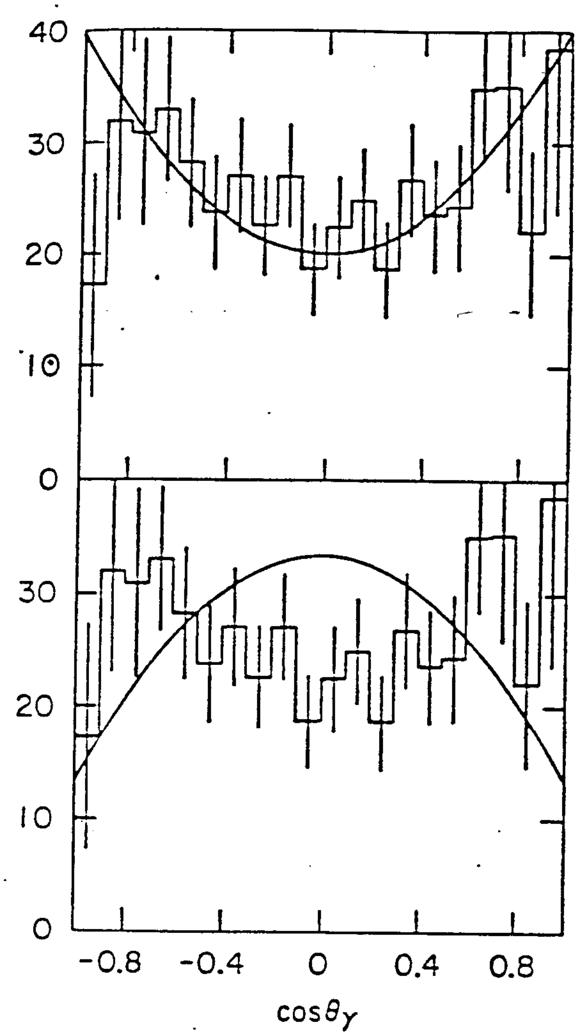

Fig. 17 Spin-parity analysis of the $\gamma\rho^{\circ}$ system of Fig. 16a: a $J^P = 0^-$ fit is vastly preferable to a $J^P = 1^+$ fit (b).