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Experimental Review of J/ψ Decays

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Abstract

This is a review of J/ψ physics from e^+e^- colliders presented at the Charm Workshop in Beijing, China. The review includes a brief historical summary of J/ψ physics, a general discussion of theoretical models and detailed results on radiative and hadronic J/ψ decays from the Mark III , DM2, Crystal Ball and MARK II groups.

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1. Introduction

The study of J/ψ decays has produced many new results. With high statistics J/ψ data, the Mark III and DM2 groups have continued a study that begin with the MARK II and Crystal Ball groups in the early 1980's. The main focus of research has been the search for gluonium states. This progressed in the direct search for these states in radiative decays and in a study of hadronic decays, to understand light quark spectroscopy. In order to understand the evidence for gluonium states, the mesons predicted by the quark model must be thoroughly understood and high statistics J/ψ decays is providing an SU(3) flavor singlet source of mesons to probe the quark content of different mesons.

In this review we begin with a brief review of (1) the J/ψ discovery and (2) the early measurements of its quantum numbers and a short discussion of the e^+e^- detectors used in high statistics J/ψ studies. Next (3) a theoretical review is presented to provide guidelines of how to understand the J/ψ decays. The remaining sections cover major experimental results; (4) η_c decays, (5) two body hadronic decays, (6) inclusive radiative decays, (7) radiative decays into conventional mesons, π^0, η, η', f and f', and finally radiative decays into the new states, (8) the $\iota/\eta(1440)$ and the $E/f_1(1420)$, (9) the $\theta/f_2(1720)$, (10) the vector-vector resonance and (11) the $\xi(2.2)$.

1.1 J/ψ DISCOVERY

The J/ψ discovery was announced in November 1974 by the MIT-BNL group at Brookhaven and the SLAC-LBL group at SLAC. The MIT-BNL group[1] was studying the reaction,

$$p + Be \rightarrow e^+e^- + X$$

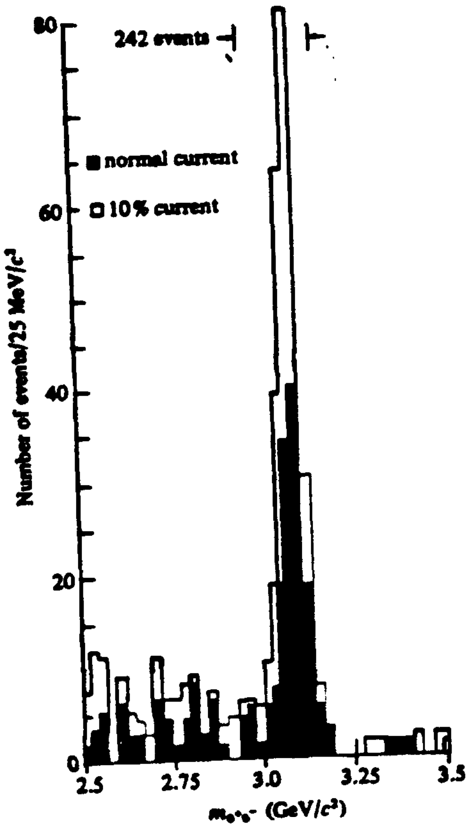
at $\sqrt{s} = 7.6$ GeV. With an extremely intense beam, $\sim 10^{12}$ protons/pulse, and a high resolution double arm spectrometer, they observed a narrow peak at $m(e^+e^-) = 3.1$ GeV/c^2 with a very small cross section, $\sigma \cong 10^{-34}$ cm^2. The e^+e^- mass distribution is shown in Fig. 1.

The SLAC-LBL group[2] at the e^+e^- storage ring, SPEAR, with the Mark I detector scanned the region around 3 GeV and observed a huge increase in multi-hadronic , $e^+e^-, \mu^+\mu^-$ and two body hadronic events at 3.105 GeV. The hadronic cross section as a function of $\sqrt{s}$ is shown in Fig. 2. The width of this resonance was less than the machine resolution, $\Gamma \leq 3$ MeV.

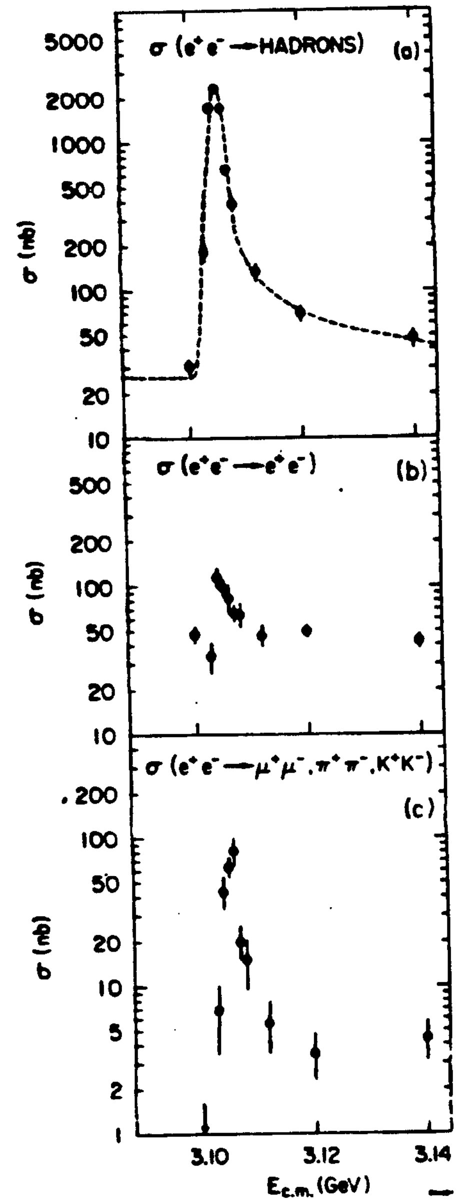
These results were immediately confirmed by groups[3] at the ADONE storage ring. All three results appeared in the same remarkable December 2, 1974 publication of Physical Review Letters.

1.2 e^+e^- DETECTOR

The principle e^+e^- detectors used for high statistics J/ψ physics are the Mark I,[4] MARK II ,[5] Crystal Ball,[6] DM2,[7] and the Mark III[8] detectors. The total number of produced J/ψ events taken by each detector is listed in table 1.1.



1. The e^+e^- mass distribution in the reaction $p + Be \rightarrow e^+e^- + X$ from the MIT-BNL group.[1]



2. The hadronic cross section in the reaction $e^+e^- \rightarrow$ hadrons (a), e^+e^- pairs (b), and muon, pion and kaon pairs (c), as a function of $\sqrt{s}$ from the SLAC-LBL group.[2]

Table 1.1 J/ψ Events Samples

# Produced J/ψ's	Run Date	Group
$\sim 150,000$	1974-1975	Mark I
1.3×10^6	Fall 78, Spring 79	MARK II
2.2×10^6	Fall 78, Spring 79, Fall 80	Crystal Ball
8.6×10^6	1982, Fall 83	DM2
5.8×10^6	Fall 82, Spring 83, Spring 85	Mark III

The Mark I detector, a general purpose e^+e^- detector, is the prototype for most e^+e^- experiments at PEP, PETRA, LEP, SLC and now BPC (Beijing). It featured a cylindrical spark chamber with 4 layers around the beam pipe inside a solenoidal magnet with 0.4 Tesla field. The drift chamber was enclosed by the 48 TOF counters and this was followed by the magnet coil and the shower counter (24 lead scintillator shower counters). The TOF resolution was about 500 ps. The shower counter was used to identify electrons.

The MARK II detector was a new detector built by the Mark I group and installed at SPEAR. It used a larger magnet with a 0.41 Tesla field and a large liquid argon calorimeter. The cylindical drift chamber contained 16 layers and was surrounded by 48 TOF counters with $\sim$ 300 ps resolution. The liquid argon calorimeter was installed behind the magnet coil and had eight modules covering $\sim$64% of the solid angle and an energy resolution of $0.14/\sqrt{E}$ GeV.

The Crystal Ball detector is a specialized neutral detector with 672 NaI crystals. It covers 94% of 4π and has an energy resolution of $\sigma_E/E = 0.026/E^{\frac{1}{4}}$. The beam pipe is surrounded by 3 layers of drift tubes with charge division readout. The crystals and the drift tubes enable identification of charged and neutral tracks, measurements of the direction of charge tracks and the measurement of the direction and energy of photons and electrons.

The DM2 experiment is at the ORSAY storage ring, DCI. The experiment was originally proposed to study resonance physics below the J/ψ. The detector has a 0.5 Tesla solenoidal magnet with proportional and drift chambers. The drift chamber is surrounded with 36 TOF counters and 36 water Cerenkov counters. The TOF resolution is 260 ps but the long bunch length of the DCI machine actually degrades the total TOF resolution to ~500 ps. The shower counter is a lead-scintillator proportional tube sandwich. The total coverage is 70% of 4π. The resolution is ~35% at 1 GeV.

The Mark III detector began running in 1982. It used the old Mark I magnet and replaced the original coil with a larger one to enable the insertion of a shower counter. The detector had a Beryllium beam pipe surrounded by a central trigger chamber with 400 micron resolution. This has been replaced in Summer 1987 with a high resolution straw chamber that should achieve 50 micron resolution. The main drift chamber has 24 axial sense wire planes and 6 stereo sense wire planes. Twelve of the axial planes have charge readout to enable energy loss measurements. Outside the drift chamber are 48 2" thick scintillation counters with phototube readout on each end. The TOF resolution is 170-200 picoseconds. Following the TOF counters is a 24 layer (12 radiation length) lead proportional tube shower counter with charge division readout. The resolution is $18\%/\sqrt{E(GeV)}$ and the chamber is efficient to detect photons with energies as low as 50 MeV/c^2. Beyond the shower counter is the magnet coil and flux return steel. Mounted outside the steel are two double layers of proportional tubes separated by 5" steel plates to provide muon detection. The table 1.2 summarizes relevant features.

The detectors have evolved with slightly better charged momentum resolution, but the important improvements are the low energy photon detection, larger solid angle coverage and better TOF resolution. In J/ψ physics virtually all the analyzed reactions were exclusive topologies. They include reactions such as $J/\psi \rightarrow \gamma\omega\omega$ which has four charged tracks and 5 photons. Many reactions were possible to measure because of kinematic constraint fits in topologies with photons improved the mass resolution in the 10-20 MeV/c^2 range. This was the key to overcoming the poor energy resolution of the shower counters.

Future detectors could improve the performance in several areas. This includes TOF measurement on the endcaps and high resolution measurements near the beam to enable reconstruction of soft tracks and very forward tracks.

Table 1.2 e^+e^- Detectors for J/ψ Physics

	σ_p/p (1 GeV)	σ_{TOF}	Shower E @ 100% eff.	Shower Counter Coverage
MARK I	20 MeV	400 pc	—	—
MARK II	18 MeV	300 pc	~400 MeV	65%
DM2	35 MeV	550 pc	~100 MeV	70%
Mark III	21 MeV	190 pc	~100 MeV	94%
CRYSTAL BALL	26 MeV for E_γ	—	—	93%

2. Early J/ψ Measurements

The early measurements of the J/ψ properties include the width, the spin-parity, G-parity, isospin and the SU(3) classification. These measurements were done by the Mark I, DASP, and Frascati groups.

2.1 J/ψ WIDTH

The resonant amplitude for a resonance produced in e^+e^- production that decays into a final state f

$$e^+e^- \rightarrow J/\psi \rightarrow f$$

at a center mass energy $\sqrt{s}$ and spin J is,

$$\sigma_f = \pi \frac{2J+1}{S} \frac{\Gamma_e \Gamma_f}{(m-\sqrt{s})^2 + (\Gamma/2)^2}$$

where Γ_e and Γ_f are the partial widths into e^+e^- and f, respectively. Experimentally, the resolution of the storage ring (SPEAR has an energy spread of 2.6 MeV) is too poor to measure the width directly. Instead, the widths are obtained by measuring the integral of the rate with a scan which will include the gaussian beam resolution. Defining $\Sigma_f = \int \sigma_f \, d\sqrt{s}$, then

$$\Sigma_e = \frac{6\pi^2}{m^2} \frac{\Gamma_e^2}{\Gamma} \ , \ \Sigma_\mu = \frac{6\pi^2}{m^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma} \ , \ \Sigma_h = \frac{6\pi^2}{m^2} \frac{\Gamma_e \Gamma_h}{\Gamma}$$

where Σ_e, Σ_μ, and Σ_h are the integrated e^+e^-, $\mu^+\mu^-$ and hadronic rates, respectively, over $\sqrt{s}$. With these quantities, the partial e^+e^-, $\mu^+\mu^-$, and hadronic widths can be derived. The measurements from the Mark I,[9] $\gamma\gamma$ (ADONE),[10] MEA (ADONE),[11] and DASP[12] groups and the Particle Data Group[13] summary are shown in table 2.1.

Table 2.1 J/ψ Widths

Γ_e (KeV)	Γ_μ (KeV)	Γ_h (KeV)	Γ (KeV)	Group
4.8 ± 0.6	4.8 ± 0.6	59 ± 14	69 ± 15	Mark I
4.6 ± 0.8	—	59 ± 24	68 ± 26	$\gamma\gamma$ (ADONE)
4.6 ± 1.0	5.0 ± 1.0	50 ± 25	60 ± 25	MEA(ADONE)
4.4 ± 0.6	4.4 ± 0.6	—	58 ± 13	DASP
4.60 ± 0.39	4.85 ± 0.51	57.3 ± 10.9	63.0 ± 8.6	PDG

2.2 J/ψ SPIN-PARITY

The J/ψ spin-parity was determined from a study of the interference between $e^+e^- \to J/\psi \to \mu^+\mu^-$ and $e^+e^- \to \gamma \to \mu^+\mu^-$. For the different J/ψ spin-parity assignments the coupling is,

J^P	$\frac{d\sigma}{d\Omega}$
$0^\pm$	$\frac{2}{3}\frac{\alpha^2}{S}\left[\frac{3}{8}(1+\cos^2\theta) + \frac{g^4}{e^4}\frac{s^2}{(m^2-s)^2+m^2\Gamma^2}\right]$
1^-	$\frac{\alpha^2}{4s}(1+\cos^2\theta)\left[\frac{1-2g^2}{e^2}\frac{(m^2-s)s}{(m^2-s)^2-m^2\Gamma^2} + \frac{g^4}{e^4}\frac{s^2}{(m^2-s)^2+m^2\Gamma^2}\right]$
1^+	$\frac{\alpha^2}{4s}\left[(1+\cos^2\theta)(1+\frac{g^4}{e^4}\frac{s^2}{(m^2-s)^2+m^2\Gamma^2}) - 2\cos\theta\frac{g^2}{e^2}\frac{(m^2-s)s}{(m^2-s)^2+m^2\Gamma^2}\right]$

where $g^2 = 12\pi\Gamma_e/m$. The 1^{--} case has $\sigma_{\mu^+\mu^-}$ interference and the 1^+ case has a forward-backward asymmetry $(F-B/F+B)$. These measurements were done by the Mark I[14] and the ADONE[15] groups. The $\mu^+\mu^-$ cross section had a dip slightly below the peak of the J/ψ and the forward backward asymmetry of the $\mu^+\mu^-$ pairs was consistent with spin 1.

2.3 G-Parity and Isospin

The Mark I group[15] measured the pion multiplicity,

$$J/\psi \rightarrow n\pi\text{'s}$$

on and off the J/ψ peak. The ratio of the number of events with pions on and off the peak was about a factor 5-7 larger for odd pion decays (3,5,7) relative to even pion decays (4,6). This demonstrated that the G-parity was odd.

The isospin of the J/ψ can be determined by a study of the three body pion decay. In this topology the dominant mode is $J/\psi \rightarrow \rho\pi$. If the J/ψ is an isoscalar then,

$$B(J/\psi \rightarrow \pi^+\rho^-) = B(J/\psi \rightarrow \pi^-\rho^+) = B(J/\psi \rightarrow \pi^0\rho^0)$$

The Mark I group measured,

$$\frac{B(\rho^0\pi^0)}{B(\rho^+\pi^-) + B(\rho^-\pi^+)} = 0.59 \pm .17$$

which is consistent with $I = 0$.

2.4 SU(3) Classification

The SU(3) classification of the J/ψ can be identified by comparing the decays into pairs of mesons. The pattern of decays determines if the J/ψ is an SU(3) singlet, the eighth component an octet or a mixture. These measurements were performed by the Mark I[16] group in a study of hadronic decays. If the J/ψ has odd charge conjugation and it is an SU(3) singlet it cannot decay into K^+K^- or $K^*\bar{K}^*$ but instead into $K\bar{K}^*$ or $K\bar{K}^{**}$. The relative branching ratios are,

$$\frac{B(J/\psi \to K^+K^-)}{B(J/\psi \to K\bar{K}^*)} \cong 10^{-2}$$

For $J/\psi \to$ vector + pseudoscalars, an SU(3) singlet should decay equally into $\pi^+\rho^-$, $\pi^\circ\rho^\circ$, $\pi^-\rho^+$, K^+K^{*-}, K^-K^{*+}, $K^\circ\bar{K}^{*0}$, and $\bar{K}^\circ K^{*0}$. The branching ratios $(\times 10^{-3})$ are

$$\frac{\pi^+\rho^- + \pi^\circ\rho^\circ + \pi^-\rho^+}{3} : \frac{K^+K^{*-} + K^-K^{*+}}{2} : \frac{K^\circ\bar{K}^{*0} + \bar{K}^\circ K^{*0}}{2} = .43 : .32 : .27$$

For $J/\psi \to$ vector + tensor, an SU(3) singlet should decay equally into $\rho^\circ A_2$, K^{*0} $\bar{K}^{**0}$, ωf and $\phi f'$. Including phase space corrections the ratio of rates are,

$$1.0 : 0.9 : 1.01 : 0.78 = 1.0 : 1.0 \pm .5 : 0.7 \pm .3 : 0.3 \pm .2$$

where the left side is the prediction and the right side the branching ratios. The combined pattern of two-body decays is consistent for the J/ψ to be identified as an SU(3) singlet.

3. Introduction to J/ψ Models

In this section simple theoretical models are discussed to provide guidelines for an experimentalist understanding of J/ψ decays.[19] In the first section the general features are explained including the OZI rule and QCD predictions. The next section covers hadronic decays and the use of SU(3) symmetry. The last two sections cover radiative decays into conventional $q\bar{q}$ mesons and two gluon states.

3.1 General Features

The J/ψ is a vector, $J^{PC} = 1^{--}$ ($^3S_1$) bound state of $c\bar{c}$. The puzzling aspect of this high mass state was it was very narrow width, $\Gamma \simeq 70$ KeV. The qualitative explanation was given by the Okubo, Zweig, Iizuka (OZI) rule.[20] The rule states that decays with disconnected quark lines are suppressed relative to decays with continuous quark lines. Another paraphrase of this rule is decays are suppressed if initial state quarks annihilate and final state quarks materialize.

Examples of OZI allowed decays are $\phi \to K^+K^-$ and $\psi'' \to D^+D^-$, $D^0\bar{D}^0$. The decay rates are listed in table 3.1.

Table 3.1 OZI allowed decays

Decay	Percentage
$\phi \to K^+K^-$	50%
$\phi \to K_S K_L$	35%
$\phi \to 3\pi$	15%
$\psi'' \to D^+D^-$	$\sim$ 50%
$\psi'' \to D^0\bar{D}^0$	$\sim$ 50%

The OZI violating ϕ decay into 3π is very suppressed because the decay into K^+K^- and $K_S K_L$ is actually phase space suppressed and hence the matrix element for the OZI allowed relative to the suppressed decay is very large. The ψ'' is above $c\bar{c}$ threshold and decays into open charm whereas the J/ψ is below $c\bar{c}$ threshold and cannot decay into states with open charm. Hence, the initial charm quarks annihilate and the final state light quarks materialize. The pattern of J/ψ decays, in contrast to the above table, is strikingly different. Instead of a few large decays there are many small two body decays that are at most a few tenths of a percent.

The quantitative aspects of the OZI rule and the J/ψ decays are provided by Quantum Chromodynamics (QCD). The key features for this discussion are;

1) Quarks are color triplets
2) Quark interactions occur via an octet of 8 massless color gauge bosons called gluons.
3) Quark-gluon strong coupling constant, $\alpha_s(Q^2)$ depends on the momentum transfer, Q^2 and as Q^2 increases $\alpha_s(Q^2)$ decreases.
4) Gluons can self interact.
5) Hadrons are color singlets and gluons are flavorless.

The QCD predictions for the J/ψ width give quantitative evidence for the third feature or what is often called asymptotic freedom.[21] The leptonic width procedes via the annihilation diagram, and the rate is

$$\Gamma(J/\psi \rightarrow e^+e^-) = \frac{4\alpha^2 q^2}{m^2} | R(0) |^2$$

The hadronic decay procedes via the three gluon diagram,

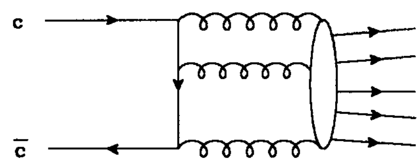


Diagram 1. Hadronic J/ψ Decays

and the rate is

$$\Gamma(J/\psi \to 3g) = \frac{40}{81\pi}(\pi^2 - 9)\frac{\alpha_s^3}{m^2} \mid R(0) \mid^2$$

The ratio becomes,

$$\frac{\Gamma(J/\psi \to \text{hadrons})}{\Gamma(J/\psi \to e^+e^-)} = \frac{5}{18\pi}(\pi^2 - 9)\frac{\alpha_s^2}{\alpha^2}(\frac{2/3}{q})^2$$

and since, $\Gamma(J/\psi \to e^+e^-) = 4.8$ and $\Gamma(J/\psi \to \text{hadrons}) = 69$ KeV we obtain, $\alpha_s(m = 3.1) \cong 0.2$. When this is applied to the ϕ we obtain $\alpha_s(m = 1.02) \cong 0.5$ and this is quantitative evidence for asymptotic freedom.

3.2 Hadronic Decays

The J/ψ, as explained in Section 2.4, is an SU(3) singlet. The two-body decays into pairs on SU(3) octets can be predicted if SU(3) symmetry were exact. An example is the decay $J/\psi \to$ vector + tensor. The exact SU(3) symmetric decay would predict,

$$\rho A_2 : \omega f : \phi f' = 3 : 1 : 1$$

Using more precise measurements, correcting for phase space and normalizing to the ρA_2 rate are

$$\rho A_2 : \omega f : \phi f' = 3 : 0.8 \pm 0.3 : 0.5 \pm .2$$

In the vector + pseudoscalar modes, the ratio of $\rho\pi$ to $K^{\pm}K^{\mp *}$ is expected to be 1.5 and the measurement is ~ 3. These results demonstrate that the J/ψ behaves approximately as an SU(3) singlet with minor corrections. These corrections[22] includes SU(3) breaking terms for the quark mass differences and the electromagnetic diagrams. The Rosner formulation[23] defined the wavefunction as a combination of non-strange, strange and non-$q\bar{q}$ components,

$$x|\ \frac{u\bar{u}+d\bar{d}}{2}\rangle + y|\ s\bar{s}\rangle + z|\ gg\rangle$$

where $|\ gg\rangle$ represents the non-$q\bar{q}$ part of the wavefunction and x, y and z are coefficients. This formulation provided a simple framework to connect vector radiative decays and the $\gamma\gamma$ widths of pseudoscalar and tensors. These methods are techniques of measuring the quark content of mesons with electromagnetic probes ($\gamma\gamma$ widths and radiative decays) and strong probes (hadronic J/ψ decays).

The early predictions were applied to understand the quark content of the η and η' in $J/\psi \rightarrow$ vector + pseudoscalar decays. The model predicted the non-$q\bar{q}$ content of the η' was 35%. An extension[24] of this model to include the double OZI (DOZI) violating terms,

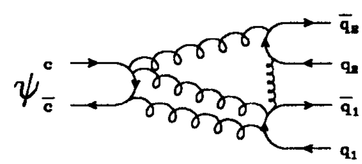


Diagram 2. Double OZI violating J/ψ Decays

produced a fit where the η' was completely made up of $q\bar{q}$. The model had a $\sim 10\%$ DOZI violation and this yielded a η, η' mixing angle of $\theta = -19^o$ which is quite compatible with the mixing angle from $\gamma\gamma$ experiments on the η and η'.[25]

3.3 Radiative J/ψ Decays to Conventional $q\bar{q}$ States

In this section the radiative decays to conventional $q\bar{q}$ states are discussed for the pseudoscalars and tensors. The basic diagrams[26] for these decays are,

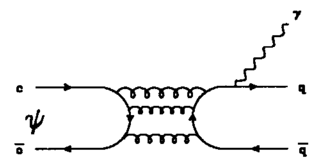


Diagram 3. Radiative diagram I.

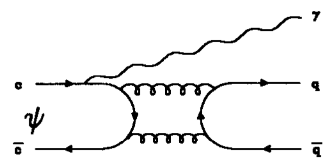


Diagram 4. Radiative diagram II.

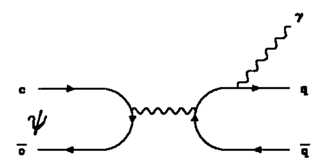


Diagram 5. Radiative diagram III.

In diagram I, the photon emission occurs after the OZI emission. The $q\bar{q}$ states produced in this way have the SU(3) quantum numbers of the photon. In diagram II, the photon emission occurs before the OZI emission and the $q\bar{q}$ state is an SU(3) singlet. In the last diagram the J/ψ decay occurs via a virtual photon and the $q\bar{q}$ state has the same quantum numbers as resonances seen in $\gamma\gamma$ production. The rates into $J/\psi \to \gamma + (A_2,\ f,\ f')$, (π^0, η, η') are shown in table 3.3a.

Table 3.3a Tensor and Pseudoscalar Predictions

Diagram	A_2	f	f'	π^0	η	η'
I	9	1	2	3	$\cos^2\theta$	$\sin^2\theta$
II	0	4	2	0	$\sin^2\theta$	$\cos^2\theta$
III	9	25	2	3	$(\cos\theta - \sin\theta\ 2\sqrt{2})^2$	$(\sin\theta - \cos\theta\ 2\sqrt{2})^2$

where $\eta = \eta_8\ \cos\theta + \eta_1 \sin\theta$, $\eta' = -\eta_8 \sin\theta + \eta_1,\ \cos\theta$. From the $\gamma\gamma$ experiments[24] on the η and η', the angle is $\theta \cong -19.3°$. The experimental branching ratios are shown in table 3.3b.

Table 3.3b Tensor and Pseudoscalar Rates

Mode	Rate (%)
$J/\psi \to \gamma A_2$	not seen
$J/\psi \to \gamma\pi^0$	0.004 ± 0.001
$J/\psi \to \gamma f$	$0.136 \pm 0.008 \pm .022$
$J/\psi \to \gamma f'$	$0.06 \pm .014 \pm .012$
$J/\psi \to \gamma\eta$	$0.086 \pm .008$
$J/\psi \to \gamma\eta'$	$0.42 \pm .05$

The f, f' ratios, normalized by phase space, are

$$\frac{B(J/\psi \to \gamma f)/p_f^5}{B(J/\psi \to \gamma f')/p_{f'}^5} \cong 1.4$$

where $B(f' \to K\bar{K}) = 1.0$ is assumed. If the f and f' are ideally mixed we expect 2. The η, η' rates, normalized by phase space, are

$$\frac{B(J/\psi \to \gamma\eta)/P_\eta^3}{B(J/\psi \to \gamma\eta')/P_{\eta'}^3} \cong .17$$

This ratio predicts a mixing angle of 22° which agrees with $\gamma\gamma$ experiments. The $J/\psi \to \gamma\pi^0$ rate is very small and can be related via the vector dominance model to $J/\psi \to \rho\pi$. The overall pattern of decays agrees very well with diagram II. The simple picture of diagram II reproduces the data and it may be unnecessary to add gluonic or $c\bar{c}$ components to the η or the η'.[17,18]

3.4 RADIATIVE DECAYS TO GLUONIC STATES

The existence of colorless, flavorless, quarkless isoscalar states made up of gluons was suggested soon after the J/ψ discovery.[28] The gluonium states may be produced in radiative J/ψ decays in the following diagram,

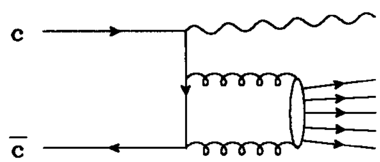


Diagram 6. Radiative J/ψ Decays

The rate, to order α_s, is

$$\frac{\Gamma(J/\psi \to \gamma gg)}{\Gamma(J/\psi \to ggg)} = \frac{36}{5}\frac{\alpha q^2}{\alpha_s} = \frac{16}{5}\frac{\alpha}{\alpha_s} \approx 10\%$$

A naive picture for two gluon resonances is to treat the gluons in analogy to the quark model.[29] Adding up the orbital and spin angular momentum and forming color singlets which are symmetric under interchange of gluon indices yields the spin-parity states listed in table 3.4.

Table 3.4 J^{PC} spin-parity of 2 gluon states

L	S=0	S=1	S=2
0	0^{++}	—	2^{++}
1	—	$0^{-+}, 1^{-+}, 2^{-+}$	—
2	2^{++}	—	$0^{++}, 1^{++}, 2^{++}, 3^{++}, 4^{++}$

The states should be even g-parity and if the gluons are on mass shell, spin 1 states should be suppressed. In radiative J/ψ decays odd pion states are not seen and spin 1 states appear to be suppressed.

In addition, the gluonic states should have the following features,

1. Flavor Symmetry
2. Masses in the 1-2 GeV/c^2 Region
3. Suppressed in $\gamma\gamma$ Production
4. Widths, 10-30 MeV/c^2

Flavor symmetry follows from being formed from two flavorless gluons.[30] The decays of a state into pairs of pseudoscalars should follow,

$$K\bar{K} : \eta\eta : \pi\pi = 3 : 0.5 : 6$$

Flavor symmetry may be altered from other considerations. It has been suggested that cavity perturbation in the MIT bag model will depend on the quark mass and could produce a larger coupling to heavier quark states. The coupling of gluons to quarks may enhance $s\bar{s}$ production relative to $u\bar{u} + d\bar{d}$.[31] This enhancement of strange meson production in glueball candidates, the θ and the ι, is observed. Other general arguments have been applied to glueball decays into two pseudoscalars.[32] It may be possible that flavor symmetry is changed by rescattering effects. These could cause large corrections as are seen the Cabbibo depressed decays $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$.[27]

The bag model[33] provides qualititive estimates of glueball masses. In this model, gluons are confined to a spherical cavity. The modes of the gluon fields are transverse electric (TE) with parity $(-1)^{J+1}$ and transverse magnetic (TM) with parity $(-1)^J$. The boundary conditions lead to equations of constraint which enable mass predictions. The lowest lying $(TE)^2$ gluon states will have a mass near one GeV/c^2 with $J^{PC} = 0^{++}$ and 2^{++}. The lowest lying $(TM)^2$ gluon states will have a mass near 1.6 GeV/c^2 with $J^{PC} = 0^{++}$ and 2^{++}. The mixed (TM)(TE) gluon states will have a mass near 1.3 GeV/c^2 with $J^{PC} = 0^{-+}, 1^{-+}, 2^{-+}$.

In addition to the Bag Model, QCD lattice gauge theories are refining calculations and estimate a scalar glueball mass near 1 GeV. Unfortunately most of these predictions of the glueball mass spectrum have not had the success the charmonium model has had in predicting the mass spectrum of the χ states. One major problem is the lack of any evidence for scalar glueball candidates in J/ψ radiative decays.

The widths of glueball candidates have been expected to be narrow, 10-30 MeV. This follows from a loose interpretation of the OZI rule. The gluons in the glueball would annihilate and create a $q\bar{q}$ pair that would form the meson secondaries. This process is OZI suppressed and should cause the state to be narrow. This explanation is controversial and not widely accepted.[34]

The glueball states are expected to be suppressed in $\gamma\gamma$ production since they have no charge. The $\gamma\gamma$ production of the pseudoscalars, η and η', and the tensors, f and f', are well understood. The partial widths couple as, $\Gamma_{\gamma\gamma} \propto q^4$. A means of quantifying the glueball character of states has been suggested by Chanowitz.[35] The ratio, called stickyness, is defined for a state X as

$$S_X = \frac{\Gamma(J/\psi \to \gamma X)/PS(J/\psi \to \gamma X)}{\Gamma(X \to \gamma\gamma)/PS(X \to \gamma\gamma)}$$

The stickyness ratio will be large for gluonium states. We expect resonances with large gluonic components to be produced in radiative J/ψ decays and resonances with large $q\bar{q}$ components to be produced in $\gamma\gamma$ productions. This pattern is observed for the iota and theta mesons as will be discussed in later sections.

4. η_c Decays

The η_c ($J^{PC} = 0^{-+}$, ${}^1S_0$) is the lowest lying $c\bar{c}$ state. Since it is spin zero it will couple to two photons or two gluons. The two photon diagram,[36]

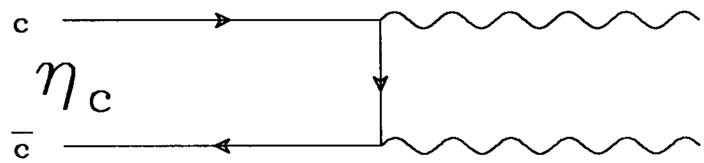


Diagram 7. Two gamma decay of the η_c

will have a partial rate,

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{4\alpha^2}{m^2}\, q^4 \mid R(0) \mid^2 \, * \, 3$$

and the two gluon decay diagram,

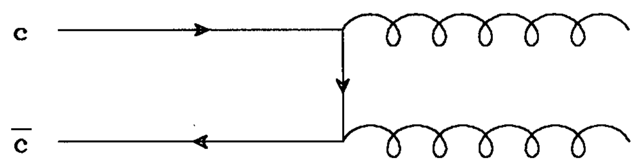


Diagram 8. Two gluon decay of the η_c

will have a partial rate,

$$\Gamma(\eta_c \to gg) = 4 \, * \, \frac{2}{3}\, \frac{\alpha_s^2}{m^2} \mid R(0) \mid^2$$

These partial widths can be compared to the J/ψ decays, yielding

$$\frac{\Gamma(\eta_c \to \text{hadrons})}{\Gamma(J/\psi \to \text{hadrons})} = \frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(J/\psi \to e^+e^-)} = 3\, q^2$$

which predicts $\Gamma(\eta_c \to \gamma\gamma) = 9$ KeV.

The transition rates for a quark spin flip will be an M1 transition for the radiative decay from a vector to a pseudoscalar,

$$\Gamma(^3S_1 \rightarrow ^1 S_0) = \frac{16}{3}\,(2J_f+1)\left(\frac{q}{2m_q}\right)^2 \alpha \mid m_{if} \mid^2 \omega^3.$$

For $m(J/\psi) = 3.095$ and $m(\eta_c) = 2.980$, the width is predicted to be

$$\Gamma(J/\psi \rightarrow \gamma\eta_c) = 2.4 \text{ KeV}$$

and yields a branching ratio, $B(J/\psi \rightarrow \gamma\eta_c) \cong 3\%$.

4.1 η_c HISTORY

The first claim for the observation of the η_c was from the DASP[37] group in the mode, $J/\psi \rightarrow \gamma\ \eta_c,\ \eta_c \rightarrow \gamma\gamma$. The mass was $2.82 \pm .014$ GeV/c^2 and the rate was $B(J/\psi \rightarrow \gamma\eta_c) \cdot B(\eta_c \rightarrow \gamma\gamma) = (1.4 \pm 0.4) \times 10^{-4}$. Theoretically, the $m(J/\psi) - m(\eta_c)$ mass difference and the product branching ratios were both too large. The Crystal Ball group[38] searched for this decay in $J/\psi \rightarrow \gamma\gamma\gamma$ and set a limit of $< 1.0 \times 10^{-4}$ at 90% C.L. Later the Crystal Ball and MARK II groups had evidence for the η_c mass near 2.98 GeV/c^2. The Crystal Ball group[39] looked into the inclusive modes $J/\psi \rightarrow \gamma + X$ and $\psi' \rightarrow \gamma + X$ and observed a state in both data sets at $m(\eta_c) = 2984 \pm 5$ Mev/c^2 with a width of $\Gamma(\eta_c) = 11.5^{+4.5}_{-4.0}$ MeV/c^2 and branching ratios of $B(J/\psi \rightarrow \gamma\eta_c) = (1.27 \pm 0.36)\%$ and $B(\psi' \rightarrow \gamma\eta_c) = (0.28 \pm 0.06)\%$. The MARK II group[40] looked into ψ' radiative into the exclusive states $p\bar{p}$, 4π, $\pi\pi KK$, $\pi\pi p\bar{p}$ and $K_S K^{\pm}\pi^{\mp}$. They observed a peak at 2980 ± 8 MeV/c^2 and a width < 40 MeV/c^2.

4.2 HADRONIC η_c MEASUREMENTS

The Mark III[41] and the DM2[42] groups have continued to study the η_c by measuring many η_c hadronic decay modes in radiative J/ψ decays. The η_C mass distributions for different hadronic decay modes from the Mark III group are shown in Fig. 3. The various decay modes are summarized in table 4.2. The Mark III masses have an average of 2982 MeV, the DM2 value is about 10 MeV lower. The most precise mass measurement is $2982^{+2.7}_{-2.3}$ MeV from the ISR $p\bar{p}$ gas jet experiment.[43]

The $\eta_c \rightarrow$ vector - vector decays disagree between the Mark III and DM2 values. For an SU(3) singlet η_c decay the vector decays should be

$$K^{*0}K^{*0} : \phi\phi : \rho\rho : \omega\omega = 0.5 : 1 : 1 : 1$$

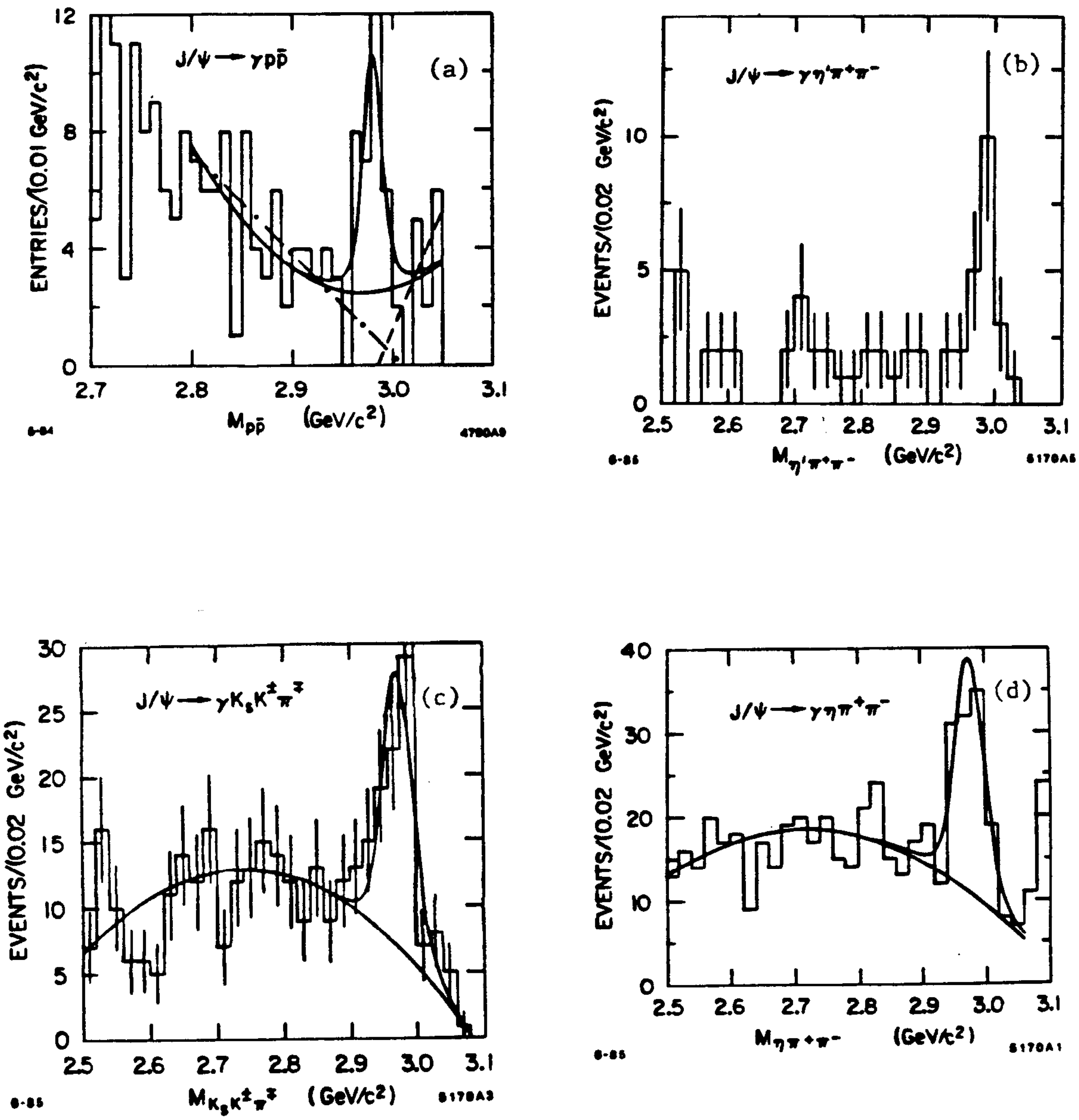
The Mark III values of the ratios are

$$K^{*0}K^{*0} : \phi\phi : \rho\rho : \omega\omega = \ .22 \pm .13 \ : \ 1 \ : < 0.64 \ : < .34$$

and for the DM2 values the ratios are

$$\phi\phi : \rho\rho = 1 : 1.66 \pm 0.5$$

The DM2 value for the $\phi\phi$ channel is lower than the Mark III value and the DM2 observes a $\rho^0\rho^0$ signal whereas the Mark III group sets an upper limit. The Mark III η_c publication discussed the trend of larger rates with $s\bar{s}$ content. The two DM2 measurements are compatible with exact SU(3) flavor symmetry.



3. The η_C mass distributions for $\eta_C \to p\bar{p}$ (a), $\eta_C \to \eta'\pi^+\pi^-$ (b), $\eta_C \to K_S K^\pm \pi^\mp$ (c), and $\eta_C \to \eta\pi^+\pi^-$ (d) from the MARK III group.[41]

4.3 η_c SPIN-PARITY TEST

The η_c spin-parity was first measured by Mark III in the sequential decay, $J/\psi \to \gamma\eta_c$, $\eta_c \to \phi\phi$. In the decay sequence where both ϕ's decay into K^+K^-, the ϕ decay planes are orthogonal for odd parity and parallel for even parity.[44] This can be generalized for arbitrary spin.[45]

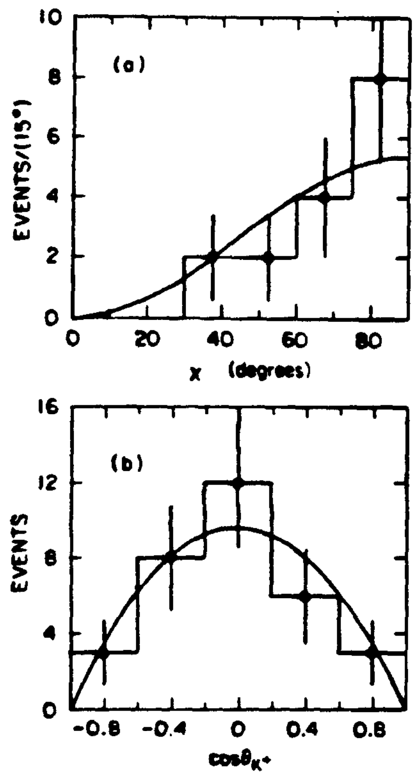
The most sensitive variable to test the spin is the azimuthal angle, χ, between the ϕ decay planes. When integrated over all other angles, the distribution has the form

$$\frac{dn}{d\chi} = 1 + \beta \cos(2\chi)$$

where β will different values depending on the spin, The χ angle distribution was fit for different spin-parity hypothesis and compared to $J^{PC} = 0^{-+}$. The angular distributions are shown in in Fig. 4. The Mark III[46] and DM2[47] results are shown in table 4.3.

Table 4.3 η_c spin-parity tests

J^P	$L_{\phi\phi}$	β	Mark III Likelihood	DM2 Likelihood
0^-	1	-1	1	1
0^+	0	$+.667$	1.8×10^8	1.2×10^{12}
1^-	1	0	2200	2.8×10^4
1^+	2	0	2200	2.8×10^4
2^+	0	$+.07$	5100	8.3×10^4
2^-	1	$-.4$	55	192
2^-	3	$-.6$	12	26
0^+	2	$+.333$	-	1.0×10^7



4. The χ angle (a) and the K^+ angle (b) in the ϕ rest frame distributions with the pseudoscalar hypothesis curve from the MARK III group.[46]

All values relative to $J^P = 0^-$ are largely excluded. The test can be extended to include all the angles to the joint distribution

$$\frac{d^3n}{d\chi d\ \cos\theta_1\ d\ \cos\theta_2} = -\ \beta\sin^2\theta_1\sin^2\theta_2\sin^2\chi + \frac{1}{2}(1+\beta)$$
$$(\sin^2\theta_1\cos^2\theta_2 + \cos^2\theta_1\sin^2\theta_2 + \frac{1}{2}\sin 2\theta_1\sin 2\theta_2\cos\chi)$$

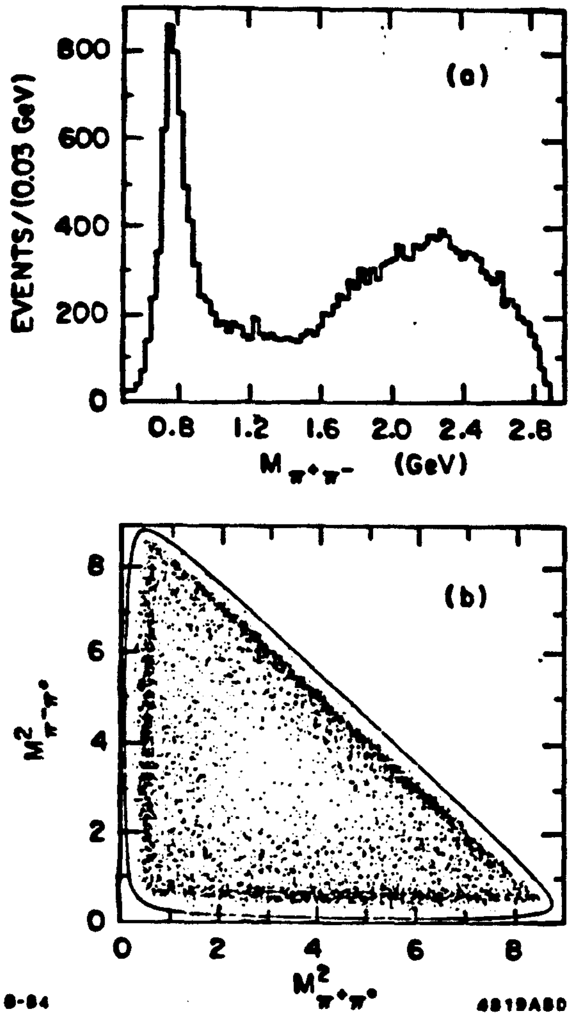
where θ_1 and θ_2 are the polar angles of the two K^+'s in their respective ϕ rest frames. The likelihood rejection of the $J^P = 2^-$ (F wave) case improves to 120 (Mark III) and 150 (DM2).

5. Review of $J/\psi \to$ Vector + Pseudoscalars

The hadronic decay $J/\psi \to$ Vector + Pseudoscalars has been extensive measured by the MARK III group[51] and recently by the DM2 group.[40] The Dalitz plot of the decay $J/\psi \to \rho\pi$ from MARK III group is shown in Fig. 5. The results are summarized in table 5.

Table 5. Vector-Pseudoscalar rates

Decay Mode	Final State	Branching Ratio $\times 10^{-3}$	
		MARK III	DM2
$\rho\pi$	$\pi^+\pi^-\pi^0$	$13.3 \pm 0.3 \pm 1.5$	12.7 ± 9
$K^{*+}K^- + K^{*-}K^+$	$K^\pm\pi^\mp K_S$	$5.0 \pm 0.23 \pm 0.6$	5.4 ± 4.4
	$K^+K^-\pi^0$	$6.0 \pm 0.3 \pm 0.7$	—
$K^{*0}\overline{K^0} + \overline{K^{*0}}K^0$	$K^\pm\pi^\mp K_S$	$3.9 \pm 0.2 \pm 0.6$	$3.9 \pm .6$
$\omega\eta$	$\pi^0\pi^+\pi^-\eta$	$1.9 \pm 0.2 \pm 0.3$	1.5 ± 2.5
	$\pi^0\pi^+\pi^-\pi^+\pi^-\pi^0$	—	1.2 ± 2.2
$\omega\eta'$	$\pi^0\pi^+\pi^-\gamma\rho^0$	$0.39 \pm 0.11 \pm 0.06$	$.40 \pm .11$
	$\pi^0\pi^+\pi^-\eta\pi^+\pi^-$	$0.43^{+.19}_{-.22} \pm 0.07$	—
$\phi\eta$	K^+K^-+ neutrals	$0.69 \pm 0.07 \pm 0.08$	—
	$K^+K^-\eta$	$0.64 \pm 0.15 \pm 0.08$	$.58 \pm .16$
	$K^+K^-\pi^0\pi^+\pi^-$	$0.61 \pm 0.14 \pm 0.08$	$.70 \pm .13$
$\phi\eta'$	$K^+K^-\gamma\rho^0$	$0.39 \pm 0.10 \pm 0.06$	$.45 \pm .08$
	$K^+K^-\eta\pi^+\pi^-$	$0.365 \pm 0.04 \pm 0.05$	$.36 \pm .07$
$\omega\pi^0$	$\pi^0\pi^+\pi^-\pi^0$	$0.67 \pm 0.06 \pm 0.11$	$.51 \pm 0.8$
$\rho^0\eta$	$\pi^+\pi^-\eta$	$0.18 \pm 0.02 \pm 0.04$	$.19 \pm .05$
$\rho^0\eta'$	$\pi^+\pi^-\eta\pi^+\pi^-$	< 0.1	$.08 \pm .03$
$\phi\pi^0$	$K^+K^-\pi^0$	< 0.013	< 0.013



5. The $\pi^+\pi^-$ mass distribution (a) and the Dalitz plot (b) of the decay $J/\psi \rightarrow \rho\pi$ from the MARK III group.[48]

These measurements enable tests of the quark content of mesons. The J/ψ hadronic decay should follow the decay of an SU(3) singlet with small electromagnetic and SU(3) corrections. There are purely electromagnetic decays which are observed ($J/\psi \to \rho\eta$ and $\omega\pi^0$). The Mark III publication included a model that estimated the quark content of the η and η' and found the $q\bar{q}$ content accounting for $\sim 65\%$ of the η'. The rest could be attributed to gluons. Later the model was refined[24] to include small OZI breaking terms (and another parameter) which now predicts the η' to be fully accountable in term of $q\bar{q}$ content.

The total decay rate of $J/\psi \to$ vector + pseudoscalars has been a puzzle. When compared to the ψ' decay rates for vector + pseudoscalars the J/ψ rates are much too large. The relative rates should be proportional to the leptonic rates,

$$\frac{B(\psi' \to hadrons)}{B(J/\psi \to hadrons)} \sim \frac{B(\psi' \to e^+e^-)}{B(J/\psi \to e^+e^-)} = 0.135 \pm 0.023$$

but the $\rho\pi$ and $K^*\bar{K}$ rates are a factor 20 too large for the J/ψ. Several predictions claim that this could be evidence for a vector glueball state near 3 GeV that mixes with the J/ψ causing an anomalous rate in certain vector+pseudoscalar modes.[52]

The hadronic decays are being extended to $J/\psi \to$ Vector + Tensor and Vector + Scalar. Since the quark content of the tensor nonet is well known, precise measurements in this sector will enable further tests of the models. In the decays into Vector + Scalar, the $J/\psi \to \phi S^*$ is quite evident whereas the decay $J/\psi \to \rho\delta$ is not observed.[50] If the δ isovector member of the scalar nonet, $J/\psi \to \rho\delta$ should be as large in the vector-scalar decay as $J/\psi \to \rho\pi$ is in the vector-pseudoscalar decays. This is additional evidence suggesting that the S^* and the δ are not the members of the scalar nonet.

6. Radiative Decays, $\gamma\pi^0$, $\gamma\eta$, $\gamma\eta'$ γf, $\gamma f'$

The J/ψ radiative decays to conventional pseudoscalars, π^0, η, η' and tensors f, f' are important tests of our understanding of the mechanisms for J/ψ radiative decays and tests of mixing.

6.1 $J/\psi \to \gamma\pi^0$

The decay, $J/\psi \to \gamma\pi^0$ is expected to occur via vector meson dominance through $J/\psi \to \rho^0\pi^0$. The measurements by the DASP,[53] DM2,[54] and Crystal Ball[55] groups are listed in table 6.1.

Table 6.1 $J/\psi \to \gamma\pi^0$ rates

$B(J/\psi \to \gamma\pi^0) \times 10^{-5}$	Group
7.3 ± 4.7	DASP
$3.7 \pm .7 \pm .6$	DM2
$3.6 \pm 1.1 \pm 0.7$	CB

The rate expected from VDM is

$$\Gamma(J/\psi \to \gamma\pi^0) = \frac{4\pi\alpha}{g_\rho^2}\Gamma(J/\psi \to \rho^0\pi^0) \approx 1\ eV$$

This predicts a rate of $\simeq 2 \times 10^{-5}$ which is in agreement with the above measurements.

6.2 $J/\psi \to \gamma'\eta,\ \gamma\eta'$

The radiative decays for the η and η' have been measured into modes, $\eta \to \gamma\gamma$, $\pi^0\pi^+\pi^-$ and $\eta' \to \gamma\gamma$, $\eta\pi^+\pi^-$, $\gamma\rho^0$. All measurements are in excellent agreement, The η results from the CNTR,[56] DASP,[57] Crystal Ball,[58] and DM2[54] groups are listed in table 6.2a.

Table 6.2a $J/\psi \to \gamma\eta$ rates

$B(J/\psi \to \gamma\eta) \times 10^{-3}$	Mode	Group
1.3 ± 0.4	3γ	CNTR
0.82 ± 0.10	3γ	DASP
$0.88 \pm 0.08 \pm 0.11$	3γ	CB
$.85 \pm .39 \pm .15$	$\gamma\gamma\gamma$	DM2

The η' results from the CNTR,[60] DASP,[61] MARK II ,[62] Crystal Ball,[63] DM2,[54] and Mark III[64] groups are listed in table 6.2b.

Table 6.2b $J/\psi \to \gamma\eta'$ rates

$B(J/\psi \to \gamma\eta') \times 10^{-3}$	Mode	Group
2.4 ± 0.7	$\gamma\gamma\rho$	CNTR
2.9 ± 1.1	$\gamma\gamma\gamma$	DASP
3.4 ± 0.7	$\gamma\gamma\rho$	MKII
$4.1 \pm 0.3 \pm 0.6$	$\gamma(\eta\pi\pi, \gamma\gamma, \gamma\rho)$	CB
$4.8 \pm .49 \pm .86$	$\gamma\gamma\gamma$	DM2
$4.7 \pm 0.2 \pm 0.7$	$\gamma\gamma\rho$	MK3

Assuming the decay procedes through an SU(3) flavor singlet coupling; the relative rates are

$$\frac{B(J/\psi \to \gamma\eta')/p^3_{\eta'}}{B(J/\psi \to \gamma\eta)/p^3_{\eta}} = \frac{1}{\tan^2\theta}$$

where θ is mixing angle. The measurements predict an angle of $\theta = -22°$. This is in very good agreement with the angle $\theta = -23° \pm 3° \pm 1°$ from the Gilman and Kauffman estimate.[25] This implies that the $\eta - \eta'$ mixing is quite conventional and may not need to be altered by additional gluonic coupling of the η or η'. Many models[65] were developed to explain what appeared to an anomalously large η' rate that was implied when a mixing angle of $\theta = -11^0$ is assumed as predicted by the quadratic mass mixing formula.

6.3 $J/\psi \to \gamma f_2(1285)$, $\gamma f_2'(1515)$

The radiative decays into the tensors, $f_2(1285)$ and $f_2'(1515)$ are summarized in the following tables. The f results from the PLUTO,[66] DASP,[67] Crystal Ball,[68] Mark III ,[69] and DM2[54] group are listed in table 6.3a.

Table 6.3a $J/\psi \to \gamma f$ rates

$B(J/\psi \to \gamma f(1270)) \times 10^{-3}$	Mode	Group
2.0 ± 0.7	$\gamma\pi^+\pi^-$	PLUTO
1.2 ± 0.6	$\gamma\pi^+\pi^-$	DASP
1.38 ± 0.39	$\gamma\pi^0\pi^0$	CB
$2.0 \pm .12 \pm .34$	$\gamma\pi^+\pi^-$	MK3
$1.5 \pm .36 \pm .23$	$\gamma\pi^+\pi^-$	DM2
$1.04 \pm .22 \pm .18$	$\gamma\pi^0\pi^0$	DM2

The f' results from the MARK II ,[70] Mark III ,[69] and DM2[54] groups are listed in table 6.3b.

Table 6.3b $J/\psi \to \gamma f'$ rates

$B(J/\psi \to \gamma f') \times 10^{-3}$	Mode	Group
1.8 ± 1.0	γK^+K^-	MK2
$3.0 \pm 0.7 \pm 0.6$	γK^+K^-	MK3
$1.5 \pm 0.3 \pm 0.3$	$\gamma K_S K_S$	DM2
$2.5 \pm 0.6 \pm 0.4$	γK^+K^-	DM2

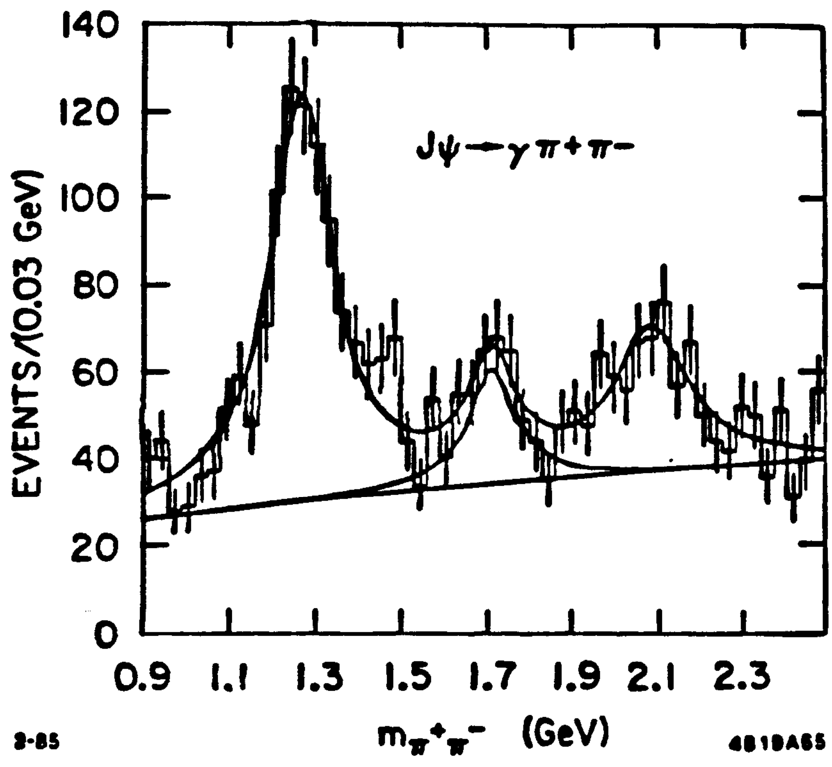
The $\pi^+\pi^-$ mass distribution in the decay $J/\psi \to \gamma\pi^+\pi^-$ and the K^+K^- mass distribution in the decay $J/\psi \to \gamma K^+K^-$ are shown in Figs. 6 and 7.

The helicity amplitudes for the f have been measured by PLUTO,[71,66] Crystal Ball,[72] Mark III ,[69] and DM2[54] groups and the measurements (x=helicity 1/0 and y=helicity 2/0) which included a phase in the fit are listed in table 6.3c.

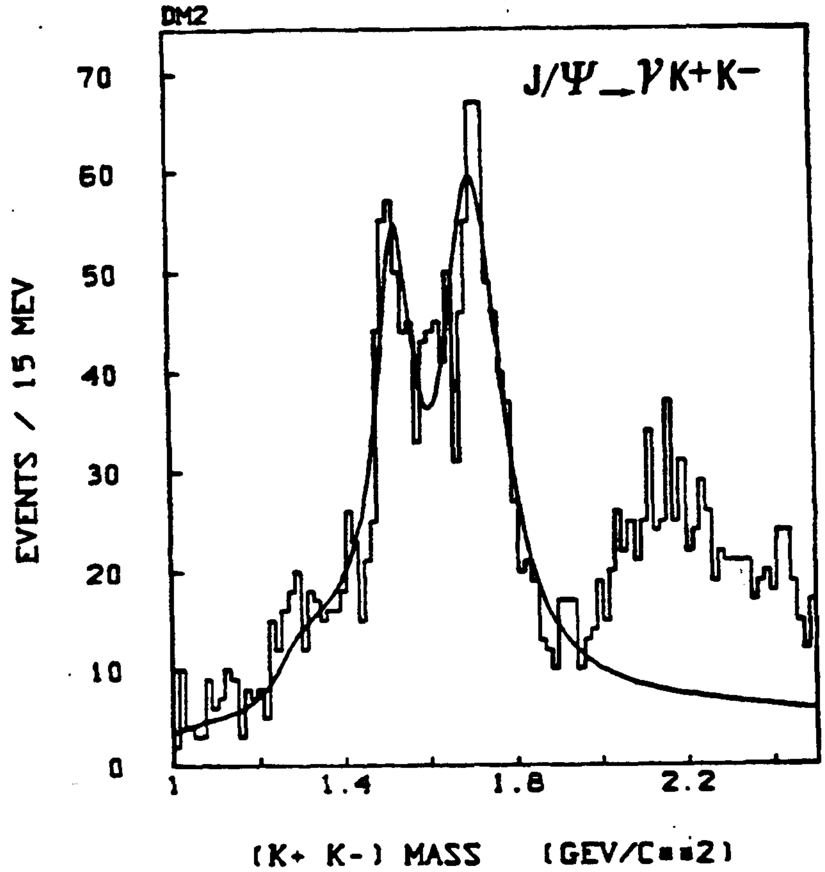
Table 6.3c f Helicity Amplitudes

x	y	ϕ	Group
0.6 ± 0.1	0.2 ± 0.2	near 0	Mark III
1.1 ± 0.1	0.2 ± 0.1	near 0	DM2

All the values are consistent with $x \cong 1$ and $y \cong 0$ where the helicity 2 amplitude is zero. This has been calculated by Korner *et al.*,[73] to lowest order QCD and x and y are predicted to have roughly equal values. Another model by Li and Shen[74] assume a gluonium hypothesis for the f and obtain a suppression of helicity. A conjecture



6. The $\pi^+\pi^-$ mass distribution in the decay $J/\psi \to \gamma\pi^+\pi^-$ from the MARK III group.[60]



7. The K^+K^- mass distribution in the decay $J/\psi \rightarrow \gamma K^+K^-$ from the DM2 group.[64]

by Close[75] suggests helicity 2 could be suppressed because $L_Z \cong 0$ for the $q\bar{q}$ pair.

The ratio of the f, f' rates is predicted to be,

$$\frac{B(J/\psi \to \gamma f')/P.S.\ (f')}{B(J/\psi \to \gamma f)/P.S.\ (f)} = \tan^2\theta$$

If we use the value $\theta = 35°$ from two photon measurements and we assume a form of the matrix elements[73] we obtain excellent agreement.

7. Review of the $\iota/\eta(1440)$ and $E/f_1(1420)$ Mesons

The $\iota/\eta(1440)$ and $E/f_1(1420)$ mesons* are of great interest in hadron spectroscopy. The $E/f_1(1420)$ meson was first observed in 1967 decaying into $K\bar{K}\pi$. There has been experimental controversy as to whether its spin is 0^{-+} or 1^{++}. The $\iota/\eta(1440)$ is a resonance seen in radiative J/ψ decays in $K\bar{K}\pi$ with a slightly higher mass and width than that of the $E/f_1(1420)$. In this section the experimental evidence for the iota is reviewed, the $E/f_1(1420)$ results are summarized and the interpretations are discussed.

The $\iota/\eta(1440)$ resonance was first observed by the Mark II group[76] in $J/\psi \rightarrow \gamma K_S K^{\pm}\pi^{\mp}$. It was identified as the $E/f_1(1420)$ since the mass and width were similar. Later the Crystal Ball group[77] performed an isobar analysis on the resonance in the mode $J/\psi \rightarrow \gamma\pi^0 K^+K^-$ and reported it was $J^{PC} = 0^{-+}$ with a dominant quasi-two body mode $J/\psi \rightarrow \gamma\iota$, $\iota \rightarrow \delta\pi$, $\delta \rightarrow K^+K^-$. The Crystal Ball group named this resonance the ι, emphasizing it was not the $E/f_1(1420)$, although the $E/f_1(1420)$ has been reported to be $J^{PC} = 0^{-+}$ in several experiments as will be discussed later. The parameters of the $\iota/\eta(1440)$ from the MARK II ,[76] Crystal Ball,[77] Mark III ,[64] and DM2.[54] are listed in table 7a. The $K\bar{K}\pi$ mass distribution from the decay $J/\psi \rightarrow \gamma K\bar{K}\pi$ from the DM2 group is shown in Fig. 8.

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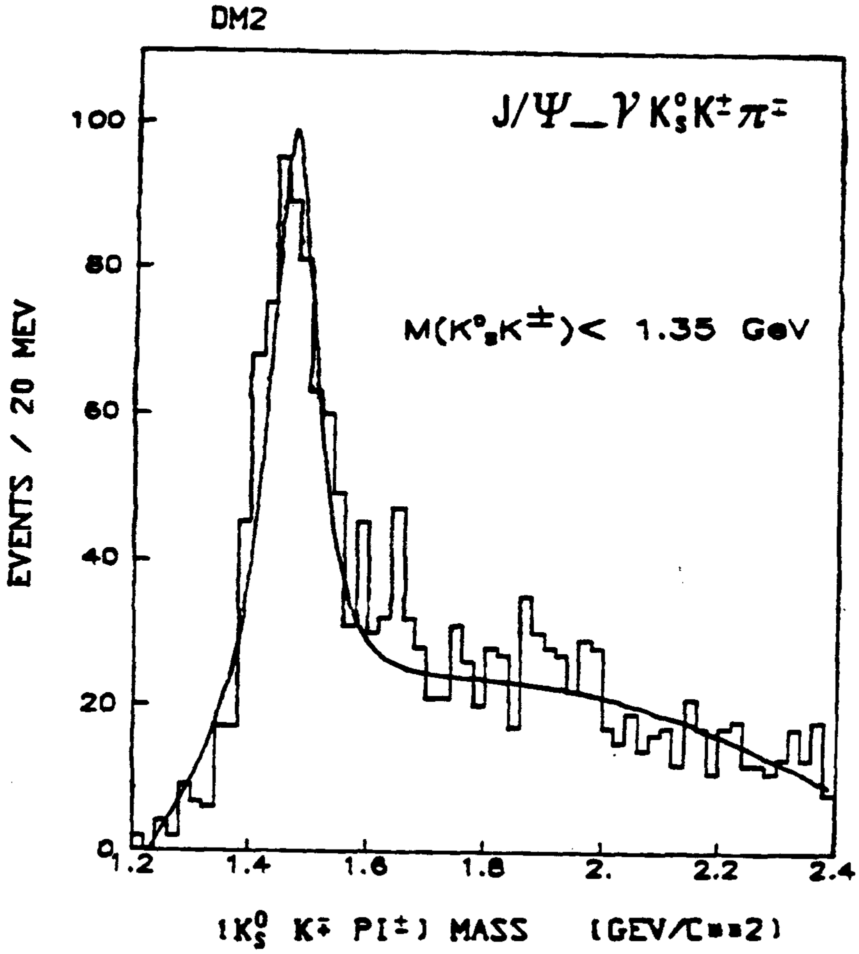
* The iota , D, and E mesons have been renamed the $\eta(1440)$, $f_1(1285)$, and $f_1(1420)$, respectively, by the Particle Data Group. In this paper they will be called the $\iota/\eta(1440)$, $D/f_1(1285)$, and $E/f_1(1420)$.



8. The $K\bar{K}\pi$ mass distribution from the decay $J/\psi \to \gamma K\bar{K}\pi$ from the DM2 group.[54]

Table 7a. Iota parameters

Mass	Γ	$B(J/\psi \to \gamma\iota) \times 10^{-3}$	Mode	Group
$1440.0 \pm 10.0 \pm 15.0$	$50 \pm 30 \pm 20$	4.3 ± 1.7	$K_S K^{\pm}\pi^{\mp}$	MK2
$1440.0 \pm 20.0 \pm 15.0$	$55 \pm 20 \pm 30$	4.3 ± 1.2	$K^+K^-\pi^0$	CB
1461 ± 5	101 ± 10	$4.9 \pm 0.2 \pm 0.8$	$K^+K^-\pi^0$	MK3
$1456 \pm 5 \pm 6$	$95 \pm 10 \pm 15$	$5.0 \pm 0.3 \pm 0.8$	$K_S K^{\mp}\pi^{\pm}$	MK3
1451 ± 3	96.6 ± 10	$4.1 \pm .5 \pm 6$	$K^+K^-\pi^0$	DM2
$1460 \pm 3 \pm 8$	$100 \pm 12 \pm 15$	$4.1 \pm 0.6 \pm 0.9$	$K_S K^{\mp}\pi^{\pm}$	DM2

The ι has been spin-parity analyzed with the Jacob-Berman technique for decays into 3 pseudoscalars. This method is independent of the quasi-two body decays in the $K\bar{K}\pi$ system. The results from the both Mark III[64] and DM2[54] groups are $J^{PC} = 0^{-+}$.

The line shape of the ι as seen in $K^+K^-\pi^0$, $K_S K^{\pm}\pi^{\mp}$, and $K_S K_S \pi^0$ has been fit[78] and it does not fit a single Breit-Wigner curve decaying into 3-body phase space. The study concluded that the line shape could be fit by a curve with two Breit-Wigner resonances or a single Breit-Wigner resonance decaying into a coupled channel with K^*K and $\delta\pi$.

In $\gamma\gamma$ production the $\iota/\eta(1440)$ has not been seen, the upper limit is given as $\Gamma_{\iota(1440)\to\gamma\gamma} \cdot B(\iota/\eta(1440) \to K\bar{K}\pi) < 1.6$ KeV at 95% C.L.[79] This aspect plus the large radiative branching ratio provide strong evidence for the $\iota/\eta(1440)$ to be identified as a gluonium state. When stickiness ($S_X = \frac{\Gamma(J/\psi\to\gamma X)/K_\gamma^3}{\Gamma(X\to\gamma\gamma)/m_X^3}$) is compared between the $\iota/\eta(1440)$, the η' and the η, there is a dramatic increase for the $\iota/\eta(1440)$,

$$S_\eta \ : \ S_{\eta'} \ : \ S_{\iota/\eta(1440)} = 1 \ : \ 4 \ : > 65$$

The ι decay into $\iota \to \delta\pi$, $\delta \to \eta\pi$ has been investigated. The results from the Crystal Ball,[80] Mark III ,[59] and DM2 groups[42] are quite similiar. There is no evidence for $\iota \to \delta\pi$, $\delta \to \eta\pi$. In the spectrum there is evidence for $\delta \to \eta\pi$ but there is a structure at the $D/f_1(1285)$ region and below 1400 MeV. In fact there is a dip at the E/ι region at 1440 MeV. The mass of the upper structure is summarized in table 7b.

Table 7b. $\eta\pi\pi$ resonance parameters

Mode	Mass	Γ	BR(10^{-4})	Group
$\eta\pi^+\pi^-$, $\eta \to \gamma\gamma$	1391.5	52 ± 9	$4.1 \pm 3 \pm 1$	DM2
$\eta\pi^+\pi^-$, $\eta \to \gamma\gamma$	$1382 \pm .6$	69 ± 23	$5.2 \pm 1.8 \pm .5$	Mark III
$\eta\pi^+\pi^-$, $\eta \to 3\pi$	1400 ± 7	62 ± 16	$5.2 \pm 1.2 \pm 0.5$	Mark III

The radiative decay of the ι into $\gamma\rho^0$ has been investigated by the Crystal Ball,[81] DM2,[54] and Mark III groups.[64] The event statistics is limited but there is a structure near 1400 MeV. The results are listed in table 7c.

Table 7c. $\gamma\rho$ Resonance Paramters

Mode	Mass	Γ	BR(10^{-4})	Group
$\gamma\rho^0$	$1420 \pm 15 \pm 20$	$133 \pm 55 \pm 30$	$1.1 \pm .24 \pm .25$	MK3
$\gamma\rho^0$	1401 ± 18	174 ± 44	$0.9 \pm 0.2 \pm .14$	DM2
$\gamma\rho^0$	1390 ± 25	185^{+110}_{-80}	$1.9 \pm .5 \pm .4$	CB

The structure was fit with a single Breit-Wigner. It is possible the structure includes contributions from the $\eta(1275)$ and $\iota/\eta(1440)$ shifting the combined mass to $\sim$ 1440 MeV. There has been no definitive spin-parity determination, although the angular distributions are consistent with $J^{PC} = 0^{-+}$.

In hadronic production, the study of the $E/f_1(1420)$ meson has a long and controversial history.[82] The results are summarized in Table 7d.[83]

Table 7d. E Hadronic Production

Reaction	Mode	J^{PC}	Group
$p\bar{p} \to E\pi\pi, E \to K\bar{K}\pi$	$\delta\pi, K^*K$	0^{-+}	Ballion *et al.*, 1967
$\pi^- p \to En, E \to K\bar{K}\pi$	K^*K	1^{++}	Dionisi *et al.*, 1980
$(\pi^+/p)p \to (\pi^+/p)E, E \to K\bar{K}\pi$	K^*K	1^{++}	Armstrong *et al.*, 1984
$\pi^- p \to En, E \to \eta\pi\pi$	$\delta\pi$	0^{-+}	Ando *et al.*, 1985
$\pi^- p \to En, E \to K\bar{K}\pi$	$\delta\pi$, K^*K	0^{-+}	Chung *et al.*, 1985
$\gamma\gamma^* \to E, E \to K\bar{K}\pi$	$K^*K(?)$	1^{++}	TPC, MARK II , 1986

The hadronic production results indicate either two or more wrong results or two or more states ($J^{PC} = 0^{-+}$ and 1^{++}). The $\gamma\gamma^*$ results yield conclusive evidence that there is a 1^{++} meson at 1.42 GeV/c^2. If there is a 0^{-+} meson at 1.42 GeV/c^2, perhaps the iota is a compound resonance with one part being this pseudoscalar seen hadronic production. In addition this state has not been seen in the following modes[84,85,86] listed in table 7e.

Table 7e. Reactions not producing the E or iota

Mode	Group
$\gamma\gamma \to \iota, \iota \to K\bar{K}\pi$	TPC(Aihara)
$\gamma\gamma \to E, E \to \eta\pi\pi$	CB(Cooper)
$K^- p \to E\Lambda, E \to K\bar{K}\pi$	LASS(Aston)
$\gamma\gamma^* \to E, E \to \eta\pi\pi$	MARK II (Gidal)

Unraveling the ι/E puzzle is an important issue in meson spectroscopy. Aside from the spin-parity question, the combined experimental data is not explained by the naive quark model. The quark content of the E is inconsistent in production and decay. The reasons to believe the E is mostly $u\bar{u} + d\bar{d}$ are:

a) It is produced in $\pi^- p$ production

b) It is produced in $\gamma\gamma^*$ production.

c) It appears to be produced in $J/\psi \to \omega E$ and not $J/\psi \to \phi E$.[87]

The reasons to believe the E is mostly $s\bar{s}$ are:

1) E decays into $K\bar{K}\pi$, mostly KK* and not $\delta\pi$.

2) If the D and E are the 1^{++} isoscalars, the heavier E should contain $s\bar{s}$ quarks.

In addition a resonance in $K\bar{K}\pi$, called the $D'(1530)$[88] has been claimed to the 1^{++} isoscalar partner of the $D/f_1(1285)$. If this is correct, the E becomes an extra 1^{++} meson that does not fit into the quark model nonets.

What is the 1^{++} $E/f_1(1420)$? A possible suggestion[89] is that it is a hybrid state $g(u\bar{u} + d\bar{d})$. This would allow $\gamma\gamma^*$ production and decay into $s\bar{s}$ final states. The exciting possibility is that the state is infact an exotic $J^{PC} = 1^{-+}$ hybrid state. Other models include non-ideal mixing[82] and a different nonet ($J^{pc} = 1^{+-}$) assignment.[90]

8. Review of the $\theta(1700)$ Resonance

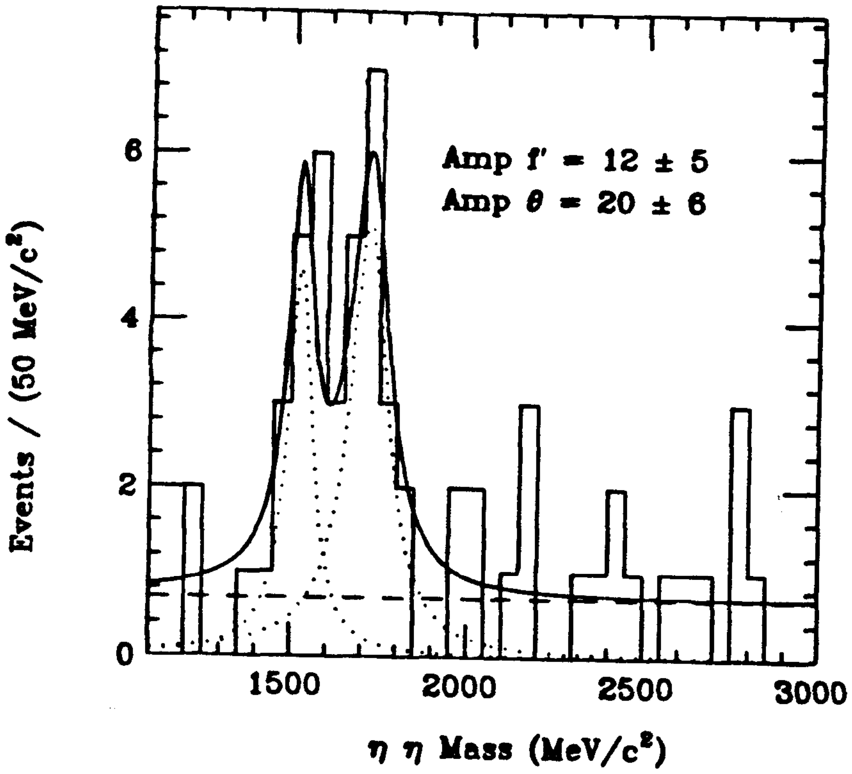
The $\theta(1700)$ was first observed in the reaction $J/\psi \to \gamma\eta\eta$ by the Crystal Ball group.[77] They obtained spin-parity measurement of $J^{PC} = 2^{++}$. The measurement did not separate the f' signal. Later the Mark II group observed the θ in the mode $J/\psi \to \gamma K^+K^-$ and attempted to separate out the f' signal from the θ. The high statistics data from the Mark III[69] and the DM2 group[54] data provide clear evidence that the f' and the $\theta(1700)$ appear separated in $J/\psi \to \gamma K^+K^-$ and $\gamma K_S K_S$. The $J/\psi \to \gamma\eta\eta$ mode from the Crystal Ball group[91] has been reanalyzed with the f' and θ signals fitted in the mass distribution. The $\eta\eta$ mass distribution from the decay $J/\psi \to \gamma\eta\eta$ from the Crystal Ball group is shown in Fig. 9. The results are summarized in table 8a.

Table 8a. Theta parameters

MODE	MASS(MeV)	Γ(MeV)	BR(10^{-4})	GROUP
K^+K^-	1707 ± 10	166 ± 33	$4.6 \pm 0.7 \pm 0.7$	DM2
K^+K^-	1720 ± 7	132 ± 15	$4.8 \pm 0.6 \pm 0.9$	MarkIII
$\eta\eta$	$1655 \pm 33 \pm 5$	219^{+74}_{-54}	$2.6 \pm .8 \pm .7$	CB

The spin-parity of the θ has been determined by the Mark III and DM2 groups to be $J^{PC} = 2^{++}$. The helicity applitudes appear in roughly equal amounts which is very different from the f' which has very little helicity 2.

A search for the θ in $\gamma\gamma$ production has been done by the TPC[92] and TASSO[93] groups. Their upper limits are summarized in Table 8b.



9. The $\eta\eta$ mass distribution from the decay $J/\psi \to \gamma\eta\eta$ from the Crystal Ball group.[91]

Table 8b. $\gamma\gamma$ Productions Upper limits

MODE	$\Gamma_{\gamma\gamma}$(KeV)	GROUP
K^+K^-	<.28	TASSO
K^+K^-	<.10	TPC

Comparing the stickiness ratio, S_x, we observe

$$S_f \ : \ S_{f'} \ : \ S_\theta = 1 \ : \ 7 \ :> 14$$

It is evident that the θ is again quite different from the f and f'.

There is preliminary evidence that the θ decays into $\theta \rightarrow \pi^+\pi^-$. There is a peak in the $\pi^+\pi^-$ mass distribution with a mass and width consistent with the θ although the spin-parity analysis has not been done. If this is the θ the hadronic decay rates are

$$\mathrm{K\bar{K}} \ : \ \eta\eta \ : \ \pi\pi = 3 \ : \ 1 \ : \ 0.8$$

If the θ decayed as a pure singlet we expect

$$\mathrm{K\bar{K}} \ : \ \eta\eta \ : \ \pi\pi = 3 \ : \ 0.5 \ : \ 6$$

The $\pi^+\pi^-$ rate appears to be suppressed. It may be possible that the $s\bar{s}$ enhancement from Bag cavity perturbation is at work. It has been suggested that final state interactions cause this distortion.[27] This may be similiar to the problems that cause $B(D^0 \rightarrow \pi^+\pi^-) \neq B(D^0 \rightarrow K^+K^-)$ in Cabbibo suppressed decays.

A very striking result has been obtained by the LASS group.[94] They observe the f' in the reaction $K^-p \to \mathrm{K\bar{K}\Lambda}$ but not the θ. In this formation experiment $s\bar{s}$ resonances are produced. This indicates the θ is not is an $s\bar{s}$ resonance although it decays into $\mathrm{K\bar{K}}$ and $\eta\eta$.

There is evidence that the θ is produced in the reaction $J/\psi \to \omega\theta$ and $\phi\theta$. The DM2[40] and Mark III[95] groups observe a mass peak in the $\mathrm{K\bar{K}}$ mass distribution recoiling from the ω. In the $\phi\theta$ mode, the $\mathrm{K\bar{K}}$ mass recoiling against the ϕ appears as a shoulder above the f'.

The evidence for the θ to be identified as a glueball is fairly impressive. The key points are;

1. It is produced in radiative J/ψ decays.

2. It is not produced in $\gamma\gamma$ nor $s\bar{s}$ production.

3. The helicity of the θ is very different from the f and f'.

4. It decays with approximate flavor symmetry.

9. Vector-Vector resonances in $J/\psi \rightarrow \gamma + (\rho\rho,\ \omega\omega, \phi\phi,\ \omega\phi)$

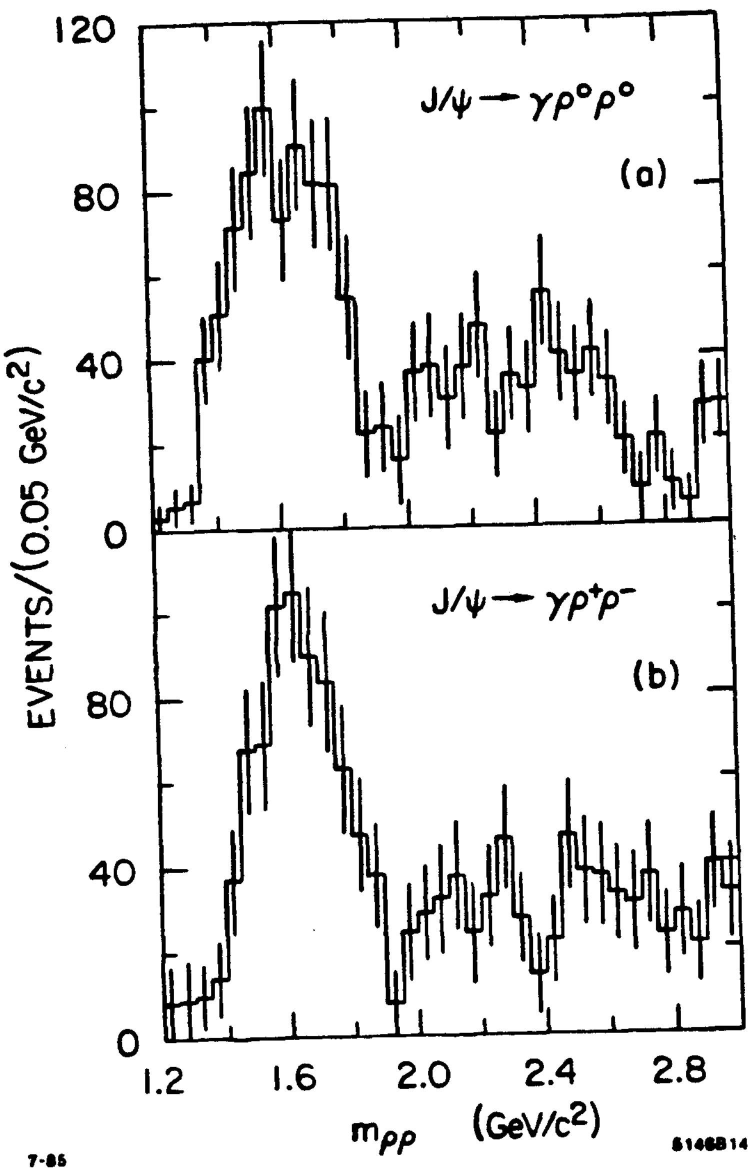
The radiative J/ψ decay into two vector meson combinations, ρ, ω, and ϕ, has been measured. The MARK II group[103] originally observed a large $\rho^0\rho^0$ signal near threshold at 1.7 GeV/c^2. This was thought to be associated with the θ resonance. Later the Mark III group[96] observed the same resonance in $\rho^0\rho^0$ and $\rho^+\rho^-$ and determined it spin parity to be largely pseudoscalar and not tensor. The DM2 group[54] has confirmed this result.

The search was extended to $\omega\omega$,[97,98] $\phi\omega$,[99] and $\phi\phi$[100,101] by the Mark III and DM2 groups. Both the $\omega\omega$ and $\phi\phi$ channels have a large pseudoscalar resonance near threshold. The spin-parity techniques used in these channels are similiar to the analysis performed on the $\eta_c \rightarrow \phi\phi$. The OZI violating decay into $\phi\omega$ has a small signal and a cluster of events near 2.23 GeV/c^2. The $\rho\rho$ mass distribution in the decay $J/\psi \rightarrow \gamma\rho\rho$ from the Mark III group is shown in Fig. 10 and the $\phi\phi$ mass distribution in the decay $J/\psi \rightarrow \gamma\phi\phi$ from the DM2 group is shown in Fig. 11. The results are summarized in table 9.

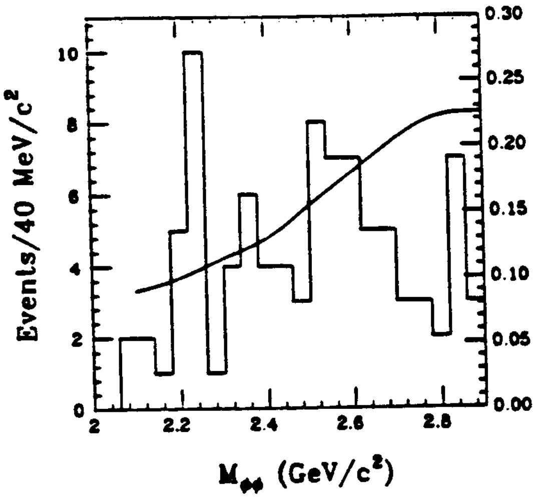
What is this vector-vector resonance near threshold? A pseudoscalar decay into two vectors is surprising because the vectors must be in a p-wave. Unless there is a VDM like connection between vector gluons and vector mesons this is unexpected. The glueball candidate $\phi\phi$ tensor, $g_T(2240)$, has not been identified in the 2 GeV region.[102] A possible solution[104] is this resonance is part of a single large pseudoscalar resonance that includes the ι. This would produce resonances in channels that would rise at threshold and fall when new channels are opening up in other modes.

Table 9. Vector-Vector rates

MODE	MASS(GeV)	$BR(10^{-4})$	GROUP
$\rho^0\rho^0$	<2.0	$47 \pm 3 \pm 9$	Mark III
$\rho^+\rho^-$	<2.0	—	Mark III
$\omega\omega$	<2.0	$12.2 \pm .7 \pm 3.1$	Mark III
$\omega\omega$	<2.0	$14.1 \pm 2 \pm 4.2$	DM2
$\phi\omega$	1.7 - 3.1	$1.4 \pm 2.5 \pm .28$	Mark III
$\phi\phi$ (K^+K^-)	<2.9	$3.1 \pm .3 \pm .6$	DM2
$\phi\phi$ (K^+K^-)	2.1-2.4	$3.4 \pm .8$	Mark III
$\phi\phi$ $(K_S K_L)$	2.1-2.4	$3.0 \pm .6$	Mark III



10. The $\rho^0\rho^0$ (a) and the $\rho^+\rho^-$ (b) mass distributions in the decay $J/\psi \to \gamma\rho\rho$ from the MARK III group.[96]



11. The $\phi\phi$ mass distribution in the decay $J/\psi \to \gamma\phi\phi$ from the DM2 group.[98]

10. Review of $J/\psi \rightarrow \gamma\xi(2.2)$

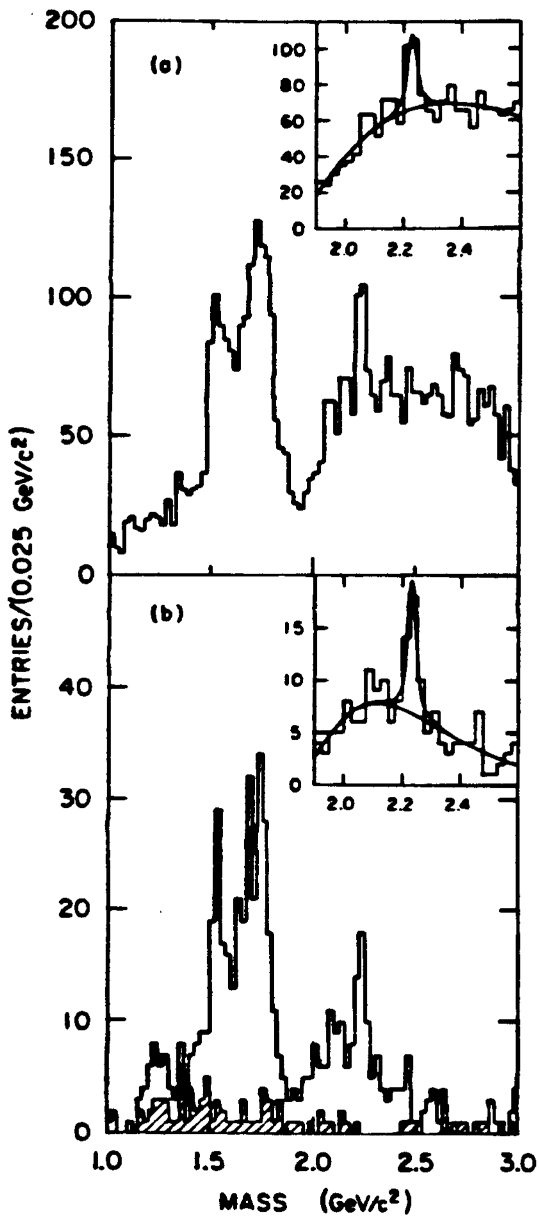
In summer 1983 the Mark III group presented new results for a narrow state, the $\xi(2.2)$, seen in radiative J/ψ decays into $K\bar{K}$.[106] The signal, $J/\psi \rightarrow \gamma\xi$, $\xi \rightarrow K^+K^-$ had a branching ratio of $(3.8 \pm 1.3 \pm 0.9) \times 10^{-5}$ and a statistical significance of ~ 4.7 standard deviations based on 2.7 million J/ψ decays. Later the DM2[107] searched for this state in their first data sample and didn't see it. Subsequently, the Mark III group ran again at the J/ψ and confirmed the signal.[105] At the same time the DM2 group[54] finished analyzing their complete data sample (8.3 million J/ψ events) and set an upper limit for the state. The K^+K^- and K_SK_S mass distributions in the decay $J/\psi \rightarrow \gamma K\bar{K}$ from the Mark III group are shown in Fig. 12 and the K_SK_S mass distribution from the DM2 group is shown in Fig. 13. The final results are listed in table 10a.

Table 10a. $J/\psi \rightarrow \gamma\xi(2.2)$ rates

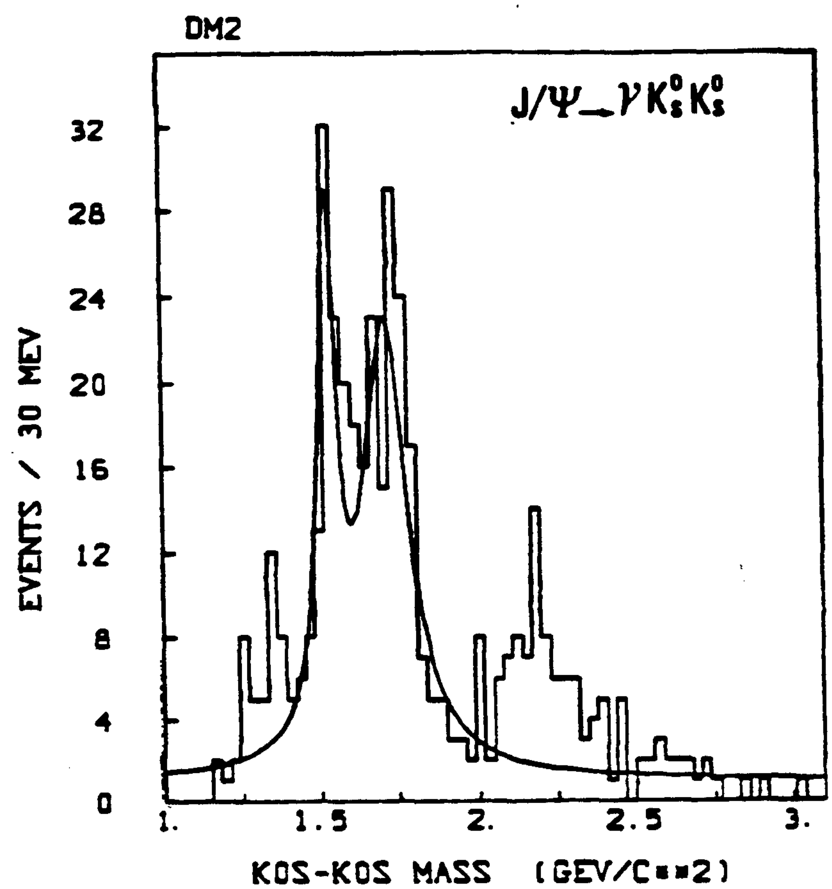
Decay	Mode	Mass	Width	BR$\times 10^{-5}$	Group
$J/\psi \rightarrow \gamma\xi$	γK^+K^-	$2.230 \pm .006 \pm .014$	$.026^{.020}_{.016} \pm .017$	$4.2^{+1.7}_{-1.4} \pm 0.8$	Mark III
$J/\psi \rightarrow \gamma\xi$	γK_SK_S	$2.232 \pm .007 \pm .007$	$.018^{+.020}_{-.015} \pm .010$	$3.1^{1.6}_{1.3} \pm 0.7$	Mark III
$J/\psi \rightarrow \gamma\xi$	γK^+K^-	—	0	< 1.2	DM2
$J/\psi \rightarrow \gamma\xi$	γK_SK_S	—	0	< 2.0	DM2

Other groups have searched for this state in different modes and reactions. The search includes production in Υ decays, $p\bar{p}$ annihilation, π^-p and K^-p reactions. In the later two there is evidence for a resonance near 2.2 GeV/c^2.

In Υ decays, the CLEO group[108] looked in the reaction, $\Upsilon(1s) \rightarrow \gamma\xi$, $\xi \rightarrow K^+K^-$ and K_SK_S. A limit of 2×10^{-4} and 9×10^{-5} has been



12. The K^+K^- (a) and K_SK_S (b) mass distributions in the decay $J/\psi \to \gamma K\bar{K}$ from the MARK III group.[105]



13. The $K_S K_S$ mass distribution in the decay $J/\psi \to \gamma K_S K_S$ from the DM2 group.[54]

set at 90% C.L. In $p\bar{p}$ annihilation, the BNL[109] and LEAR(PSI70)[110] groups have set upper limits for $B(\xi \to p\bar{p}) \times B(\xi \to K^+K^-)$ for different spins and widths listed in table 10b.

Table 10b. $\xi(2.2) \to p\bar{p}$ upper limits

Spin(J^{PC})	Γ (MeV)	Limit (10^{-4})	Group
0^{++}	3.5	16	BNL
0^{++}	35	5.6	BNL
2^{++}	3.5	5.1	BNL
2^{++}	35	1.8	BNL
0^{++}	1	30	LEAR
0^{++}	3	18	LEAR
0^{++}	30	5.4	LEAR
2^{++}	1	7.7	LEAR
2^{++}	3	4.6	LEAR
2^{++}	30	1.3	LEAR

In $\pi^- p$ production, the GAMS group[111] reported a narrow structure at 2.22 GeV in the $\eta\eta'$ mode in the reaction $\pi p \to \eta\eta'\, n$, with incident pion beams at 38 and 100 GeV. The angular distributions are consistent with $J \geq 2$. Another unpublished result,[112] in the reaction $\pi^- p \to K_S K_S +$ neutrals, reported a peak at 2.2 GeV/c^2 with an incident pion momentum at 175 GeV/c. In $K^- p$ production, the LASS group[84] has evidence for a structure near 2.2 GeV in the reaction $K^- p \to K_S K_S \Lambda$. This structure again appears to have an angular distribution consistent with $J \geq 2$.

The theoretical models include identification as a high spin $s\bar{s}$ state,[113] a $\Lambda\bar{\Lambda}$ bound state,[114] a Higgs boson,[115] a glueball,[116] a hybrid state,[31] a technidilaton,[117] a neutral color scalar,[118] a Regge occurance,[119] a 4-quark state,[119] and a techipion.[120] The simpliest model, a high spin $s\bar{s}$ state, predicts an $\eta\eta'$ decay and production in $s\bar{s}$ formation experiments such as $K^- p \to K\bar{K}\Lambda$. The narrow width has been predicted by a such model[113] but disputed in another calculation.[114] Many models were developed to explain the narrow width. The conventional $s\bar{s}$ quark model prediction, predicts the $\eta\eta'$ decay and would be expected to appear in $K^- p$ production. The narrow width in some models[113] is found to be wide by other calculations.[114]

11. Summary

The results from high statistics J/ψ experiments are providing new insights into meson spectroscopy. The main thrust has been the study of radiative J/ψ decays to understand the two gluon spectrum predicted by QCD. Other topics under investigation include the hadronic decays to measure the light quark content in mesons.

The J/ψ radiative spectrum appears to quantitatively follow the predictions for states formed from two gluons. The pseudoscalars and tensors decay at rates consistent with SU(3) symmetry. There are new resonances, the iota and the theta, which do not appear to seen in hadronic production and do not seem to fit into the conventional $q\bar{q}$ nonets. The large radiative J/ψ branching ratios and the small $\gamma\gamma$ upper limits support the glueball interpretation. The detailed theoretical predictions of the mass spectrum and the decays into specific mesons are not well understood.

The $E/f_1(1420)$ meson ($J^{PC} = 1^{++}$ case) has become even more puzzling with new measurements. The recent results indicate that the $E/f_1(1420)$ is being produced via non-strange quarks even though it decays into $K\bar{K}\pi$ and behaves as an $s\bar{s}$ state.

In other radiative decays, the $\xi(2.2)$ appears to be a high spin state now seen in $\pi^- p$ production in $\eta\eta'$ and in $K^- p$ production in $K\bar{K}$. There are pseudoscalar vector-vector resonances formed near threshold in $\rho\rho$, $\phi\phi$ and $\omega\omega$. These could be separate channels of a large single multi-channel resonance.

In hadronic decays, the $J/\psi \to$ Vector + Pseudoscalar branching ratios have been measured and now the $J/\psi \to$ Vector + Tensor and Vector + Scalar branching ratios are being determined. Models can fit the Vector + Pseudoscalar decays with conventional $\eta - \eta'$ mixing angles. The decay $J/\psi \rightarrow \delta\rho$ is missing suggesting that the δ is not the 0^{++} nonet isovector.

The results in the near future will continue to come from the analysis on the existing data from the DM2 and Mark III groups and possibly new results in gluonium resonances from LEAR. Any fundamental discoveries, such as the discovery of a scalar state in radiative decays or an exotic meson, will have to come from a very high statistics J/ψ study. The DM2 group has closed down. The Mark III group has not taken any new data (since early 1986) due to the SLC upgrade at SLAC and is not scheduled to run until mid 1988. Unless SPEAR luminosity could be significantly increased it is doubtful that the Mark III group would run at the J/ψ. The Beijing Spectrometer, BES, at the e^+e^- collider, BEPC, will have the opportunity to run at the J/ψ and could accomplish a high statistics study in the early 1990's.

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