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STATUS OF THE $\iota(1440)$ and $\theta(1640)$ AS GLUONIUM CANDIDATES*

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ABSTRACT

A review of the experimental evidence for the $\iota(1440)$ and $\theta(1640)$ states is presented. The measured properties of these states are compared with various theoretical predictions. A likely interpretation is that these states contain a large gluonic admixture.

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I. INTRODUCTION

One of the most intriguing aspects of Quantum Chromodynamics (QCD) is that it predicts an extensive spectrum of colorless, flavorless bound states of two or more gluons.[2] gluons ("gluonium") may be observable in the "Glueball-favored" channel:

$$J/\psi \rightarrow \gamma X, \tag{1}$$

as depicted in figure 1. Such states are expected to be produced with a branching fraction of order α/α_s:[3]

$$\frac{\Gamma(J/\psi \rightarrow \gamma gg)}{\Gamma(J/\psi \rightarrow ggg)} = 3.2\cdot(\alpha/\alpha_s) \simeq .1 \tag{2}$$

Pure gluonium states might be recognized by the following properties:

- They will be SU(3) flavor- and color- singlets, and therefore will not "fit" into any of the standard SU(3) $q\bar{q}$ multiplets.
- Since they contain no charged constituents, one would naively expect these states to couple in a flavor-independent way to their decay products. For example, the $\pi\pi$ branching fraction of a $J^{PC} = 2^{++}$ gluonium state would be three times that of $\eta\eta$.
- Gluonium states resulting from radiative J/ψ decay must have even charge conjugation, and may themselves decay to two pseudoscalers (PP) or two vectors (VV), but not to a vector and a pseudoscaler (PV).[4] Therefore, the observation of the $\iota(1440)$ decaying into $K^*(890)$ K would rule out its being a gluonium candidate.
- The allowed quantum numbers of the two-gluon ground state are $J^{PC} = 0^{++}$ and 2^{++}, while the first excited states have $J^{PC} = 0^{-+}$ and 2^{-+}.[2] The 1^{-+} state is forbidden by Yang's theorem.[5]
- Bag model calculations without intergluon interactions give masses of 960 MeV and 1260 MeV, for the ground state and first excited states, respectively,[6]

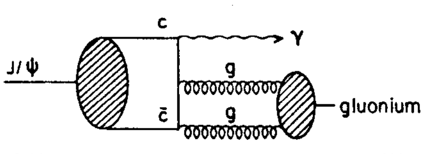

Fig. 1. Diagrammatic representation, in lowest order QCD, of the radiative decay of the J/ψ to gluonium.

while more sophisticated bag model calculations predict first excited state masses in the range of 1.5 - 2.0 GeV.[7]

- Gluonium states would be highly suppressed in two-photon collisions relative to the production of $q\bar{q}$ states.[8-10] Searches for the reactions $\gamma\gamma \to \iota(1440)$[11,12] and $\gamma\gamma \to \theta(1640)$[12,8] are summarized in references 8, 9 and 10. These results show that the two-photon widths ($\Gamma_{\gamma\gamma}$) times branching ratios (BR) for ordinary $q\bar{q}$ states are not significantly different than the 95% upper limits on $\Gamma_{\gamma\gamma}\cdot$BR obtained for the gluonium searches. While the absolute BRs for the $\iota(1440)$ and $\theta(1640)$ are not known, the two-photon width of the $\theta(1640)$ is expected to be about 20% of the f(1270) width, or about 600 eV.[10] Using an estimate of the J/ψ branching ratio into $\theta(1640)$ of 2% based on gluonic duality arguments,[13] and the measured product branching ratio[14]

$$BR(J/\psi \to \theta(1640))\cdot BR(\theta(1640) \to K^+K^-) = (6.0 \pm 0.9 \pm 2.5)\cdot 10^{-4}, \quad (3)$$

one obtains an estimate of 3% for the branching ratio of $\theta(1640)$ into K^+K^-.[10] The two-photon width times branching ratio is therefore about 20eV, far below the sensitivity of the present experiments.

While the "properties" mentioned above appear to make up a powerful tool in the search for gluonium states, their validity may be suspect.[15] In particular, the predicted gluonium states may mix strongly with the 1 - 2 GeV $q\bar{q}$ states having the same quantum numbers, making the search for this new form of matter potentially difficult.

II. THE GLUONIUM CANDIDATES $\iota(1440)$ AND $\theta(1640)$.

A state a 1440 MeV was first seen in the reaction $J/\psi \to \gamma K^\pm K^0_s \pi^\mp$, by the Mark II collaboration at SPEAR.[16] They tenatively identified it as the E(1420), a state with $J^{PC} = 1^{++}$, as their experiment was not able to determine the J^P value. The existence of this state was soon confirmed by the Crystal Ball collaboration at SPEAR[17] in the reaction $J/\psi \to \gamma K^+K^-\pi^0$. Using 2.2 x 10^6 J/ψ decays, the Crystal Ball collaboration was able to measure the J^{PC} of the state as 0^{-+}.[18]

This 0^{-+} state may have been previosly observed in $p\bar{p}$ annihilations near threshold.[19] A clear preference for the assignment $J^{PC} = 0^{-+}$ was indicated in their publication, in which it was called the E meson. However, as the E(1420) designation has since been accepted[20] as the J^{PC} state seen in $\pi^- p$ interactions,[21] the Crystal Ball group, in collaboration with Mark II, has given a new name to this pseudoscalar state, the $\iota(1440)$[16].

Figure 2(a) shows the $K^+K^-\pi^0$ invariant mass distribution for events which satisfy 3C fits to the decay $J/\psi \to \gamma K^+K^-\pi^0$. The shaded events have $M_{K\bar{K}} < 1125$ MeV. A prominent signal centered at $(1440^{+20}{}_{-15})$ MeV, with a width of $(55^{+20}{}_{-30})$ MeV is evident in this figure.[18]

The $K\bar{K}\pi$ Dalitz plot from the Crystal Ball is shown in figure 2(b). Some clustering of events above and to the right of the dashed line (corresponding to a low $K\bar{K}$ mass enhancement) is evident. This enhancement has been associated with the $\delta(980)\pi$ decay of the resonance. One sees no evidence for K^* bands, which would indicate a preference for a vector-pseudoscalar decay of this state, although the situation is potentially confusing because of the limited phase space available for the decay and the fact that the K^* bands overlap in the region of the $\delta(980)$.

The spin of the $\iota(1440)$ resonance has been determined by a phase-shift analysis. Contributions from five partial waves were included in the fit: 1. $K\bar{K}\pi$ (phase space); 2. $\delta^0\pi^0 - 0^-$; 3. $K^*\bar{K}$ + c.c. $- 1^+$; 4. $K^*\bar{K}$ + c.c. $- 0^-$; 5. $\delta^0\pi^0 - 1^+$, and the three dominant waves are shown in figure 3(a-c), corrected for detection efficiency. The $K^*\bar{K}$ + c.c. $- 1^+$ contribution is rather small and

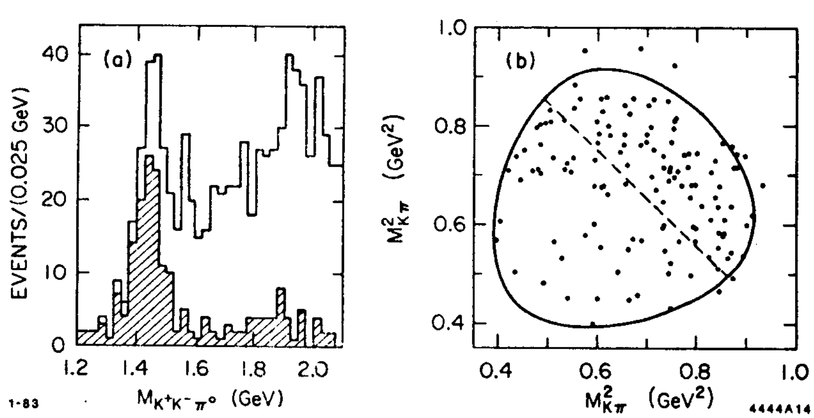

Fig. 2. (a) $K^+K^-\pi^0$ invariant mass distributions for events consistent with $J/\psi \to \gamma K^+K^-\pi^0$. The events in the shaded region have the further requirement that $M_{KK} < 1125$ MeV. (b) Dalitz plot for $J/\psi \to K^+K^-\pi^0$ events satisfying $1400 < M_{K\bar{K}\pi} < 1500$ MeV. The Dalitz plot boundary has $M_{K\bar{K}\pi} = 1450$ MeV. The dashed line shows $M_{K\bar{K}} = 1125$ MeV.

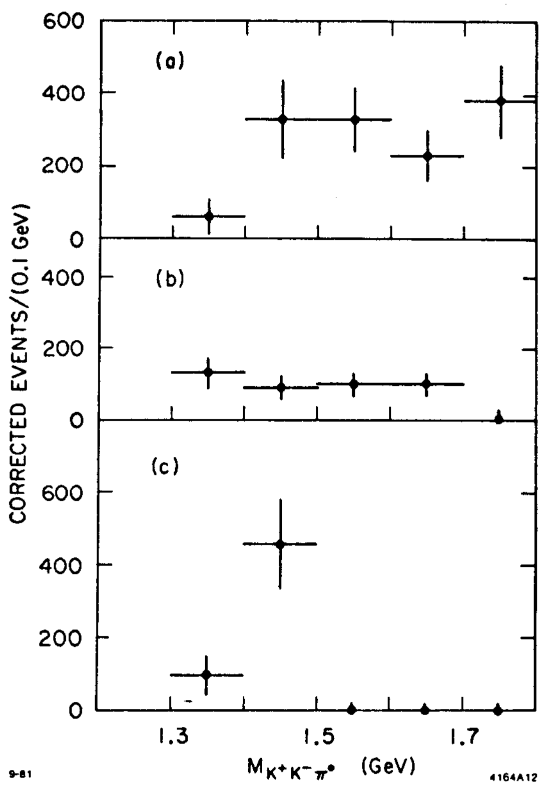

Fig. 3. Partial wave contributions to $J/\psi \to \gamma K^+K^-\pi^0$ versus $K\bar{K}\pi$ mass for (a) $K\bar{K}\pi$ phase space; (b) $K^*\bar{K}$ + c.c. and $J^P = 1^+$; (c) $\delta\pi$ with $J^P = 0^-$.

mass-independent, while the $\delta\pi - 0^-$ wave shows clear evidence for resonant structure in the 1400 - 1500 MeV ι mass bin. The $\delta\pi - 0^-$ decay mode is preferred over the $K^*\bar{K} - 1^+$, with the 90% confidence-level upper limit:

$$\frac{B(\iota \to K^*\bar{K} + c.c.)}{B(\iota \to K^*\bar{K} + c.c.) + B(\iota \to \delta\pi)} < .25 \ . \tag{4}$$

Since the analysis of the $\iota(1440)$ decay has shown a $\delta\pi$ dominance, the Crystal Ball collaboration has carried out a search[22] for the decays:

$$J/\psi \to \gamma\iota, \ \iota \to \eta\pi^+\pi^-, \tag{5}$$
and
$$J/\psi \to \gamma\iota, \ \iota \to \eta\pi^0\pi^0, \tag{6}$$

where the η is detected by its $\gamma\gamma$ decay mode. One experiment[23] finds the $\eta\pi$ branching fraction of the $\delta(980)$ to be 1.4 ± 0.6 times larger than the $K\bar{K}$ mode. One might therefore expect to see an appreciable ι signal in the $\eta\pi\pi$ channel.

The invariant mass spectra for the $\eta\pi^+\pi^-$ and $\eta\pi^0\pi^0$ channels from $J/\psi \to \gamma\eta\pi\pi$ decays are shown in figures 4(a) and 4(b), respectively. A prominent η' signal and a broad enhancement near 1700 MeV is evident. No significant subinvariant mass structure for this broad enhancement is seen in the Dalitz plots for the $\eta\pi\pi$ events with $1650 < M_{\eta\pi\pi} < 1850$ MeV.[22] Fitting both spectra to smooth back-

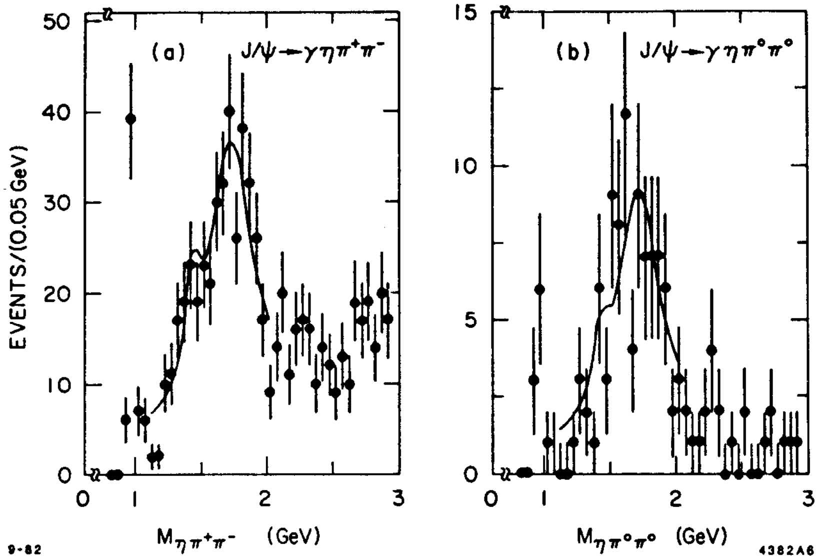

Fig. 4. $\eta\pi\pi$ mass spectrum from (a) $J/\psi \to \gamma\eta\pi^+\pi^-$ and (b) $J/\psi \to \gamma\eta\pi^0\pi^0$. The curves are fits including contributions for the $\iota(1440)$ as described in the text.

grounds and a Breit-Wigner line shape (the mass and width parameters were constrained to be the same for both channels) yields a mass and width of (1710 ± 45) MeV and (530 ± 110) MeV for this enhancement. Using the number of events in the peak as determined in this fit, one obtains the branching fractions:

$$BR(J/\psi \to \gamma\eta\pi^+\pi^-) = (3.5 \pm 0.2 \pm 0.7) \times 10^{-3}, \quad (7)$$
$$BR(J/\psi \to \gamma\eta\pi^0\pi^0) = (2.3 \pm 0.3 \pm 0.8) \times 10^{-3}, \quad (8)$$

where a Monte Carlo detection efficiency estimate of 18% (6.6%) for the $\eta\pi^{+-}$ ($\eta\pi^0\pi^0$) channel has been used. The first error is statistical and the second is systematic. The origin of the 1700 MeV enhancement is presently uncertain, although these branching ratios are comparable to the largest known radiative decays of the J/ψ.

The solid curves shown in figures 4(a-b) have been obtained by refitting the $\eta\pi\pi$ invariant mass spectra with a term for the ι. The background shapes and mass and width of the ι were fixed but the mass and width of the Breit-Wigner line shape describing the 1700 MeV enhancement were allowed to vary in this fit. Using this procedure, the following upper limit is obtained:

$$\frac{BR(J/\psi \to \gamma\iota)\cdot BR(\iota \to \eta\pi\pi)}{BR(J/\psi \to \gamma\iota)\cdot BR(\iota \to K\bar{K}\pi)} < 0.5 \text{ (90\% confidence level)} \quad (9)$$

This upper limit appears to be in conflict with the hypothesis that the $K\bar{K}$ decay of the $\iota(1440)$ is dominated by $\delta\pi$. Palmer and Pinsky[24] can accomodate the $\iota(1440)$ as a gluonium state despite its small $\eta\pi\pi$ branching ratio, by taking into account the cancellation between the $\iota \to \delta\pi \to (\eta\pi)\pi$ and $\iota \to \eta\epsilon \to \eta(\pi\pi)$ amplitudes and SU(3) violations seen in the decay of the δ. In this model,

$$20\% < BR(\iota \to \eta\pi\pi)/BR(\iota \to K\bar{K}\pi) < 110\% \tag{10}$$

Another possible interpretation of the $\iota(1440)$ is that it is the isosinglet member of the radially excited 0^{-+} nonet containing the $\pi(1275)$ as the only established state,[25] If such a nonet contains the K′(1440) and $\zeta(1275)$ as suggested by Chanowitz,[26] then the mass of the ι would be too low to fit with the other radially excited 0^- states[26]. Secondly, if the ι were the radially excited η', then the branching ratio $BR(J/\psi \to \gamma\iota) > 4.0 \times 10^{-3}$ which is larger than the rate $BR(J/\psi \to \gamma\eta')$ and would be somewhat difficult to explain. Such an anomaly could occur if the ground and excited states were significantly mixed.[27]

In summary, the $\iota(1440)$ satisfies many of the properties expected for gluonium states. Its radiative decay from the J/ψ is larger than any other transition to a non-charmonium state. It appears to decay exclusively to two pseudoscalars, rather than to a vector and a pseudoscalar. Finally, more work must be done to clarify the radially excited 0^- nonet states, and to continue to search for the $\iota(1440)$ in gluonium-disfavored channels such as two-photon collisions.

The $\theta(1640)$ was first seen by the Crystal Ball collaboration[28] in the process

$$J/\psi \to \gamma\eta\eta, \ \eta \to \gamma\gamma. \tag{11}$$

Starting with 2.2×10^6 produced J/ψ decays, figure 5(a) shows the $\eta\eta$ invariant mass distribution for events from reaction (11), after a 5C fit has been performed. Only events with $\chi^2 < 20$ have been kept. The solid curve is a fit to a flat background and a Breit-Wigner resonance where the mass, width and amplitude are allowed to vary. The dashed curve includes an additional contribution from the f′(1515) resonance, where its mass and width are fixed, but the amplitude is allowed to vary.[29] The two-resonance fit yields the following θ resonance parameters and branching ratio:

$$M_\theta = (1670 \pm 50)\ \text{MeV}, \tag{12}$$
$$\Gamma_\theta = (160 \pm 80)\ \text{MeV}, \tag{13}$$
$$BR(J/\psi \to \gamma\theta)\cdot BR(\theta \to \eta\eta) = (3.8 \times 1.6) \times 10^{-4}. \tag{14}$$

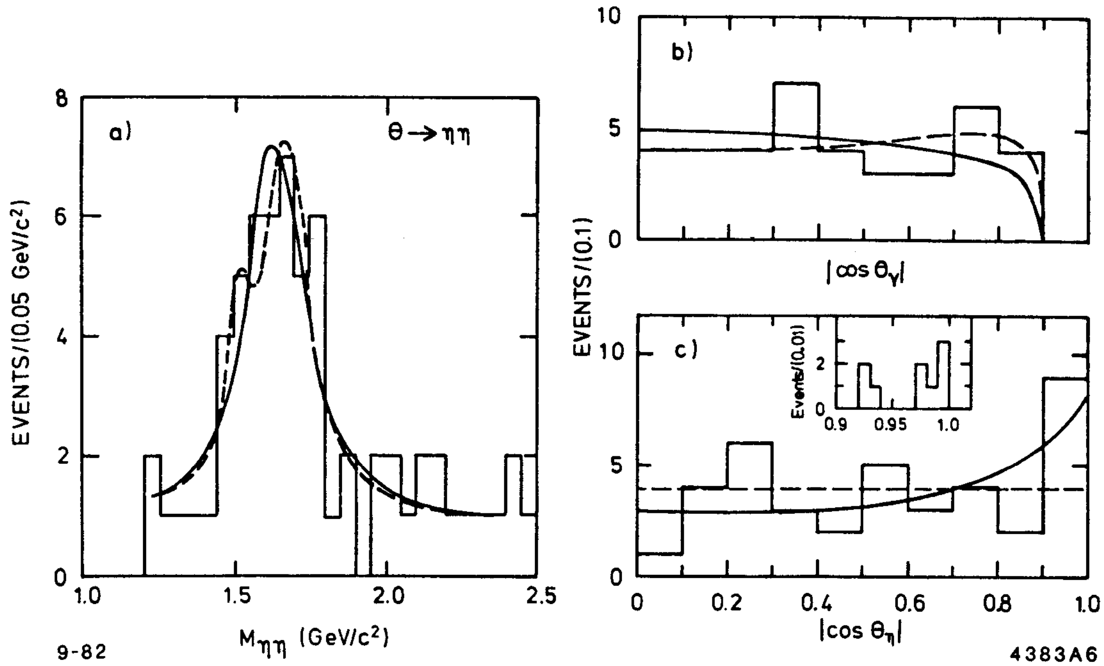

Fig. 5. (a) The $\eta\eta$ mass distribution from reaction (11). The solid curve is a fit to a flat background and one Breit-Wigner resonance. The dashed curve is a fit to two Breit-Wigner resonances, one fixing the mass and width at the f′(1515) but variable amplitude, and the second with all three parameters variable. A flat background is also included. (b) $|\cos(\theta_\gamma)|$ and (c) $|\cos(\theta_\eta)|$ distributions for reaction (11). Solid (dashed) curves are best-fit distribution for a spin 2 (spin 0) θ. The inset shows the $|\cos(\theta_\eta)|$ distribution on an expanded scale.

The spin of the θ was determined from a maximum liklihood fit to the angular distribution $W(\theta_\gamma,\theta_\eta,\phi_\eta)$ for process (11), assuming a maximum spin complexity of 2. The spin 0 to spin 2 hypothesis is 0.045, and the $\eta\eta$ decay established the parity as even. In figures 5(b-c), the $|\cos(\theta_\gamma)|$ and $|\cos(\theta_\eta)|$ projections are shown. Although the spin determination depends upon information which cannot be displayed in these projections, the spin 2 hypothesis (solid curves) is favored over the spin 0 case (dashed curves). The $|\cos(\theta_\eta)|$ variable clearly plays an important role in distinguishing the two hypotheses, mainly due to an excess of events in the $|\cos(\theta_\eta)| > .9$ bin. The inset in figure 5(c) shows these events on an expanded scale, and there is no evidence for an anomalous distribution in this region.

Figure 6 shows the invariant mass spectra from a preliminary Mark II measurement[14,15] of the process $J/\psi \to \gamma K^+K^-$, using 1.32×10^6 J/ψ decays. In the upper figure, the final state photon was not necessarily detected. In a 1C fit to the hypothesis $J/\psi \to (\gamma)K^+K^-$, events were kept if $\chi^2 < 7$. The solid curve in this

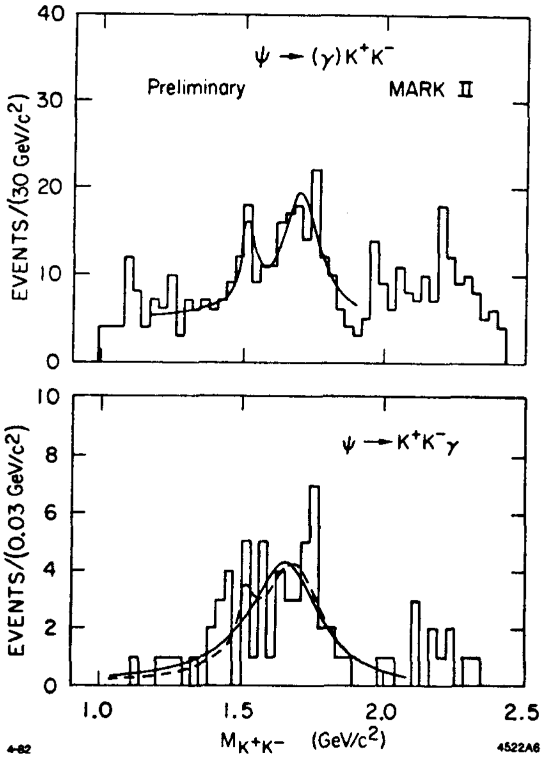

Fig. 6. Preliminary Mark II K^+K^- invariant mass spectra from the reactions $J/\psi \to (\gamma)K^+K^-$, where the γ may go undetected (1C fit), and $J/\psi \to K^+K^-\gamma$, where all final state particles are observed. The solid curve in the upper figure is a two-resonance Breit-Wigner fit to the θ and f′(1515) as described in the text. In the lower figure, the solid curve is a fit to one Breit-Wigner shape only, while the dashed curve includes a contribution from the f′(1515) (fixed mass and width, variable amplitude).

figure is a five-parameter fit to the θ(1640) and f′(1515) resonances with two Breit-Wigners and a constant background in the mass range $1.16 < M_{K^+K^-} < 1.89$ GeV. Difficulties in background estimation precluded fitting outside this mass region. In this fit, the mass and width of the f′(1515) were fixed, but the f′ amplitude and the θ(1640) mass, width and amplitude were allowed to vary. The results of this fit yielded the θ resonance parameters[15,14]:

$$M_\theta = (1708 \pm 30)\ \text{MeV}, \qquad (15)$$
$$\Gamma_\theta = (156 \pm 20)\ \text{MeV}. \qquad (16)$$

The product branching ratio obtained from this fit is given by equation (3), where the first error is statistical and the second error is an estimate of the systematic uncertainty in the magnitude and shape of the background. The product branching ratio for the f′(1515) in this channel is[14]:

$$BR(J/\psi \to \gamma f')\cdot BR(f' \to K^+K^-) = (0.9 \pm 0.3 \pm 0.5) \times 10^{-4} \qquad (17)$$

In order to estimate the spin of the θ(1640), the Mark II has performed a maximum liklihood fit to the angular distribution $W(\theta_\gamma,\theta_K,\phi_K)$, for events in which both charged kaons and radiative photon were detected, and for $1550 < M_{K^+K^-} < 1850$ MeV. The invariant K^+K^- mass spectrum for events satisfying the fully constrained decay $J/\psi \to \gamma K^+K^-$ is shown in the lower portion of figure 6.

The solid curve in the figure is a fit to one Breit-Wigner form, and the dashed curve contains a contribution from the f′(1515). A prominent signal in the region of the θ(1640) is seen over almost no background. Results from the maximum liklihood fit to the θ angular distribution favor spin 2 over spin 0 at the 78% confidence level. While this determination of the θ(1640) spin is not convincing, the combined Mark II and Crystal Ball measurements favor spin 2 to spin 0 at the 99% confidence level.

Both the Crystal Ball and Mark II collaborations have searched for other decay modes of the θ(1640). Figures 7(a) and 7(b) show the results of searchs for the decays

$$J/\psi \to \gamma\theta,\ \theta \to \pi^+\pi^- \quad \text{(Mark II)}, \tag{18}$$

and

$$J/\psi \to \gamma\theta,\ \theta \to \pi^0\pi^0 \quad \text{(Crystal Ball)}. \tag{19}$$

A prominent f(1270) signal is seen in both cases [30,31,32], but no significant structure in the region of the θ(1640) is visible.The 90% confidence level upper limits of 6×10^{-4} and 3.6×10^{-4} have been set by the Crytsal Ball[16] and Mark

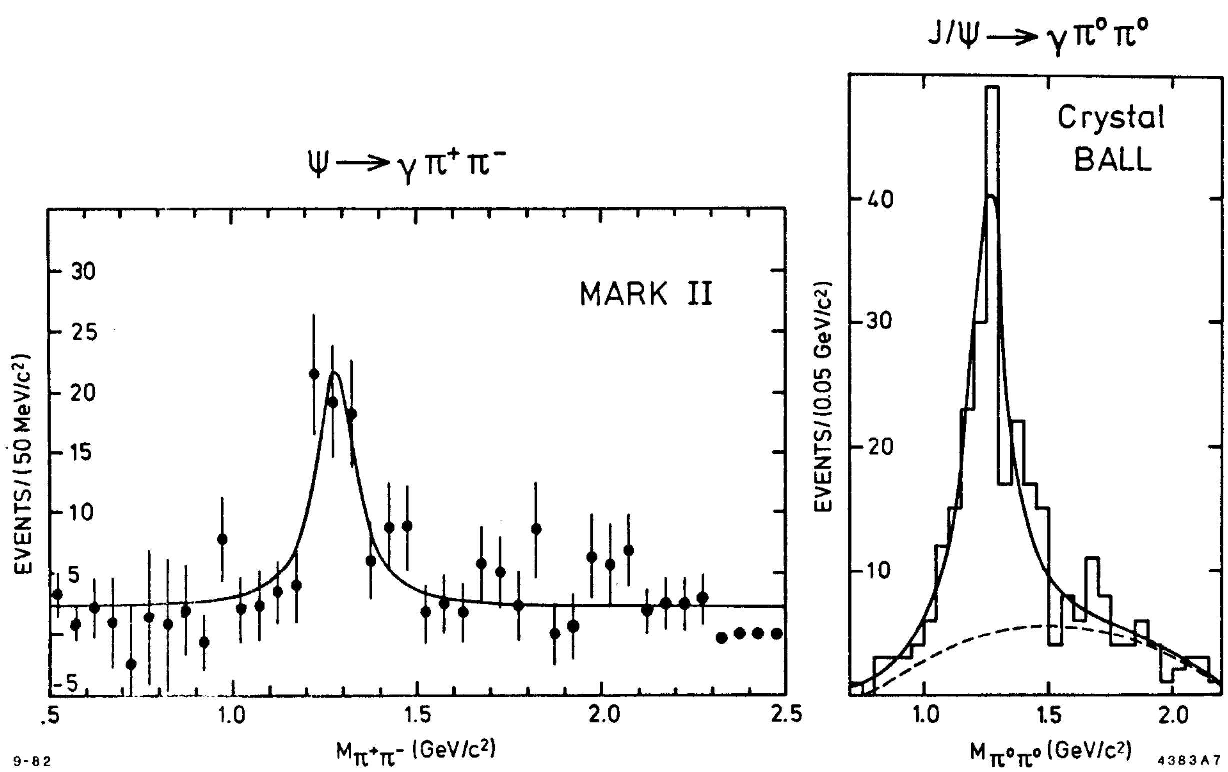

Fig. 7. $M_{\pi\pi}$ invariant mass distributions from (a) $J/\psi \to \gamma\pi^+\pi^-$ (Mark II collaboration) and (b) $J/\psi \to \gamma\pi^0\pi^0$ (Crystal Ball collaboration). The solid curves represent fits to the f(1270) plus background, which is shown explicitly in (b) as a dashed curve.

II[14] collaborations, respectively, for the product branching ratio $BR(J/\psi \to \gamma\theta)\cdot BR(\theta \to \pi\pi)$. Isospin correction factors have been applied in both cases.

The Mark II collaboration has also reported[33] a signal near the $\theta(1640)$ in the process

$$J/\psi \to \gamma\pi^+\pi^-\pi^-\pi^- \quad . \tag{20}$$

The $\rho\rho$ content in several four-pion mass bins was extracted with an analysis which took into account $\pi^0 2\pi^+ 2\pi^-$ background, nonresonant four-pion production and $\rho\rho$ signal. The result of this analysis is shown in figure 8 as a histogram of variable bin width. The data points with error bars show the $\rho\rho$ signal when the $\rho\pi\pi$ yield is accounted for. A Breit-Wigner fit to the solid points gives

$$M_{\rho\rho} = (1650 \pm 50) \text{ MeV}, \tag{21}$$
$$\Gamma_{\rho\rho} = (200 \pm 100) \text{ MeV}, \tag{22}$$

for the resonance parameters, and a branching fraction

$$BR(J/\psi \to \gamma\rho\rho) = (3.75 \pm 1.05 \pm 1.3) \times 10^{-3}, \; M_{\rho\rho} < 2.0 \text{ GeV} \tag{23}$$

when an I=0 structure to the decay was assumed.[15] This branching ratio is comparable to the ι and η', but the Mark II states that much more data is needed to establish the connection (if any) between the $\rho\rho$ structure and the $\theta(1640)$.

The results which have been presented on the exclusive decays of the $\iota(1440)$ and $\theta(1640)$ can be compared with the inclusive process,

$$J/\psi \to \gamma X, \tag{24}$$

which is shown in figure 9. Prominent peaks corresponding to the η' and $\iota(1440)$ recoil masses are evident. The tails of the $\iota(1440)$ resonance may include other

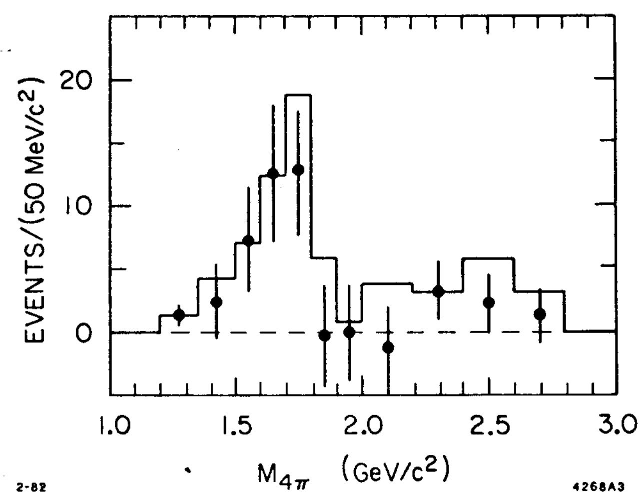

Fig. 8. The $\rho^0\rho^0$ mass spectrum obtained from the analysis of process (20).

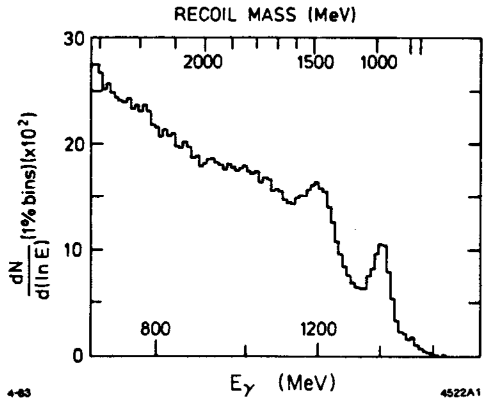

Fig. 9. A preliminary inclusive γ spectrum from the process $J/\psi \to \gamma X$ near the high energy endpoint.

known states such as the f(1270) and f′(1515). In this plot, it appears that the inclusive rates to the $\iota(1440)$ and η' are comparable.

In addition, a structure which is wider than, but close to the $\theta(1640)$ mass is also visible. This enhancement is most probably a complex superposition of states, including the θ, $\eta\pi\pi$ enhancement and $\rho\rho$ peak mentioned earlier. A strong effort is presently being made to remove the contamination due to energetic (E_π > 800 MeV) π^0s whose photon showers coalesce. Until this is done, no quantitative statements can be made about the photonic transition rates in this part of the inclusive spectrum.

One of the most serious objections to the gluonium interpretation of the $\theta(1640)$ is the lack of an appreciable $\pi\pi$ decay mode.[29] As was mentioned earlier, the mixing of a 2^{++} gluonium or radially excited state with the 2^{++} ground states can have a major impact on the masses and decay systematics of all the 2^{++} states. First consider the possibility that the $\theta(1640)$ is a radial excitation which mixes with the f(1270) and f′(1515)[27]. Figure 10 shows the prediction of this model superimposed on the Mark II data. This model also predicts the ratios:

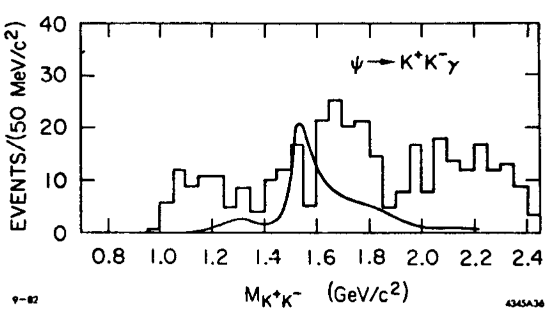

Fig. 10. Invariant K^+K^- mass from the reaction $J/\psi \to \gamma K^+K^-$, where the photon is not necessarily detected, as measured by the Mark II collaboration (histogram)[14] The curve is a prediction using the radial excitation model in ref. 27

$$\frac{BR(\theta \to \pi\pi)}{BR(\theta \to K\bar{K})} > 1, \quad \frac{BR(\theta \to \eta\eta)}{BR(\theta \to K\bar{K})} \simeq .25, \quad \frac{BR(f' \to K\bar{K})}{BR(\theta \to K\bar{K})} > 1. \tag{25}$$

Another possibility is that the $\theta(1640)$ is a 2^{++} $q\bar{q}q\bar{q}$ state,[34] with flavor content $s\bar{s}(u\bar{u} + d\bar{d})$ and fall-apart mode $\omega\phi$. This model makes the following predictions:

$$\frac{BR(\theta \to \eta\eta)}{BR(\theta \to K\bar{K})} = .5, \quad BR(\theta \to \pi\pi) = 0, \quad BR(\theta \to \rho\rho) = 0, \tag{26}$$

Finally, we consider a model in which a 2^{++} gluonium state is allowed to mix with both the f(1270) and f′(1515):[35]

$$\frac{BR(\theta \to \pi\pi)}{BR(\theta \to K\bar{K})} \simeq 0, \quad \frac{BR(\theta \to \eta\eta)}{BR(\theta \to K\bar{K})} < .20, \tag{27}$$

From the data, the following ratios are obtained:

$$\frac{BR(\theta \to \pi\pi)}{BR(\theta \to K\bar{K})} < 1, \quad \frac{BR(\theta \to \eta\eta)}{BR(\theta \to K\bar{K})} = .33 \pm .22, \quad \frac{BR(f' \to K\bar{K})}{BR(\theta \to K\bar{K})} \ll 1. \tag{28}$$

Equation (3) has been multiplied by an isospin correction factor of 2 to obtain the result in equation (28).

On comparing equation (28) with (25),(27) and (26), we conclude that the 2^{++} gluonium interpretation is consistent with the data and the 2^{++} radial excitation model fails badly. The four-quark model is also inconsistent with the data if the Mark II $\rho\rho$ enhancement is indeed the $\theta(1640)$. The large radiative decay of the θ obtained by adding the $\eta\eta$ and $K\bar{K}$ modes also presents problems for this model.

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