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GLUONIUM AND QCD IN THE J/ψ REGION*

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ABSTRACT

The nature of gluonium states is reviewed. QCD is tested in the J/ψ region obtaining guidelines for its applicability to the gluonium question. These guidelines along with other current theoretical models are used with new experimental results to examine the nature of the ι(1440) and θ(1640) mesons.

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I. Introduction and summary

The existence of an extensive spectrum of colorless, flavorless bound states of two or more gluons has been firmly predicted by quantum chromodynamics (QCD)[1]. These gluonic bound states have been given the rather unaesthetic name "glueballs". It is expected that the lower lying "glueball" states are bound states of mostly 2 gluons and in analogy to quarkonium, this system is called gluonium. It also expected that gluonium states should be by far easier to observe than other "glueballs" due to their relatively lower masses which are predicted to lie in the range 1 to 2 GeV.

Although the existence of gluonium has not yet been experimentally established, the interest in this new form of matter has increased considerably since the observation of two new mesons, the $\iota(1440)$[2,3] and the $\theta(1640)$[4], in a reaction thought to be a copious source of gluonium states[5], namely,

$$J/\psi \rightarrow \gamma X . \qquad (1)$$

However, the experimental search for such states has proven to be a difficult and confusing one with a number of guiding principles losing credibility as the field has matured. In section II of this review these elements of "glueball fantasy" are discussed and we conclude that there is no easy way of experimentally establishing the existence (or non existence) of gluonium states. What is necessary to determine the gluonium content of a candidate state is a detailed comparison with theory, particurlary QCD. But can we presently trust QCD to guide correctly? To partially answer this question, in section III experiment is compared to the predictions of QCD in the J/ψ region. After this somewhat introductory phase section IV presents recent and new experimental results on the $\iota(1440)$ and $\Theta(1640)$ from the Crystal Ball and Mark II detectors at SPEAR. The insights obtained from theory on the gluonium status of these candidates is discussed in section V. Finally, in section VI, other experiments that might help in properly assigning these candidate gluonium states are considered.

II. "Glueball Fantasy"

A number of guiding principles have been used in the past in the experimental search for gluonium states. Together they make up a seemingly powerful tool to distinguish gluonium states from valence quark-antiquark bound states. Three of the "guiding principles" are discussed below, their validity is clearly suspect.

a) By an extension of the OIZ rule gluonium state widths should be typically the geometric mean of OIZ allowed and OIZ suppressed decay widths[6], i.e.,

$$\Gamma_{\text{gluonium}} \sim \sqrt{\Gamma_{\text{OIZ allowed}} \ \Gamma_{\text{OIZ suppressed}}} \qquad (2)$$

Thus a gluonium state with mass ∿ 1.5 GeV should have,

$$\Gamma_g \sim \sqrt{\Gamma_f \ \Gamma_\phi} \sim 30 \text{ MeV}. \qquad (3)$$

This hypothesis has been more formally justified by using $SU(N)_{\text{color}}$ gauge theories and considering the limit of a large number of colors, N_c[7]. Strong evidence contradicting this hypothesis has recently been presented. The formal justification using theories with $N_c \to \infty$ is probably not true due to the failure in this limit to predict the $N_c = 3$ expectation in the gluonium case[8]. In any case, it has been stated that a proof exists that "glueball → gg is not suppressed in [the large N_c] limit ; instead it is completely allowed"[9]. One thus expects gluonium states to have typical hadronic widths[10].

b) Perturbative QCD indicates a large rate for the process shown in figure 1 [11], namely,

$$J/\psi \to \gamma g g. \qquad (4)$$

Various authors[5] have used duality principles and other ideas together with the perturbative result to show that gluonium states should be copiously produced in the process(1). This result, which is probably true, has been frequently extended to the expectation that any prominent signal in

(1) where X is an "ordinary" hadron means X is a gluonium state. At least two notable exceptions exist to this rule. The η and η' mesons, which by anyones definition are not gluonium states. In particular, the η' meson has close to the largest radiative width from the J/ψ measured to date (c.f. section III), and though having some gluonic content in its wave function[12,8] is not a gluonium state. Thus we might reasonably expect that gluonium states are produced strongly in (1) but that $q\bar{q}$ states may be also. Other evidence is needed to decide the question of gluonium vs quarkonium in each particular case[13].

c) As has been previously stated, gluonium states are flavorless. Thus it was initially the expectation that physical gluonium states would have flavor independent couplings to their decay channels. However, for the "light" gluonium states expected in the 1-2 GeV mass range, the J^{PC} is expected to have the values of 0^{++}, 0^{-+}, 2^{++}. Since many quarkonium states in this mass range have the same J^{PC} values, mixing with $q\bar{q}$ states can have an important influence on the decay channels and can lead to strongly non singlet behaviour[14,15,16]. Even for "pure" gluonium states mass effects coupled with the allowed phase space of the decay can effectively break flavor singlet symmetry[17,18].

We thus conclude that few simple rules exist in this game. A detailed experimental comparison with theory is needed to determine the gluonium content of a state. As many of the discussions and references in this section show, our ability to apply QCD correctly is an important element in this comparison.

III. A comparison of QCD to Experiment in the J/ψ region

Given the weight that QCD has in providing evidence that a state might or might not be a gluonium state, in this section a comparison between other predictions of QCD and experiment is made using data primarily obtained in the J/ψ region. An attempt is made to compare results obtained using only QCD as input; results obtained using potential models are generally not discussed.
In particular five subjects will be considered.

- The value of Λ, the QCD scale parameter.
- The mass spectrum of the charmonium states.
- The widths of the charmonium states.
- The radiative decays of the J/ψ to the ordinary 0^- mesons.
- The Branching ratio $J/\psi \rightarrow \eta_c\ (2984) + \gamma$.

Deep inelastic lepton - nucleon scattering (DIS) experiments have until recently indicated that the QCD scale parameter Λ had a value of about 500 MeV[19]. In 1978 the QCD sum rules of the ITEP Group[20] were used together with experimental data[21] on $R^{I=1}_{had}$ (s), for $s \lesssim 4\ \text{GeV}^2$, to obtain,[22] $\Lambda_{e^+e^-} \sim \Lambda_{\overline{MS}} \sim 100 - 200$ MeV.

Fig. 2 shows the data used and the results of the analysis[22].
The sumrule used is the following,

$$I_0 = \int_{4m_\pi^2}^{\infty} e^{-s/M^2} R^{I=1}_{had}(s)\,ds \simeq 3/2\, M^2 \left[1 + \frac{\alpha_s(M)}{\pi} + \frac{\pi^2}{3M^4} < 0 \mid (\alpha_s/\pi) G^a_{\mu\nu}\, G^a_{\mu\nu} \mid 0 > - \frac{448\pi^2\alpha_s}{81\ M^6} \left| < 0 \mid q\bar{q} \mid 0 > \right|^2 \right] \qquad (4)$$

Where M is a parameter (c.f. Fig. 2b), $< 0 \mid (\alpha_s/\pi) G^a_{\mu\nu} G^a_{\mu\nu} \mid 0 >$ is the nonperturbative value of the gluon "condensate" $< 0 \mid q\bar{q} \mid 0 >$ is the nonperturbative value of the quark "condensate". Both of these vacuum expectation values are zero in perturbation theory.

Using information from J/ψ production, important inputs are obtained[20].

$$< 0' \mid (\alpha_s/\pi) G^a_{\mu\nu} G^a_{\mu\nu} \mid 0 > \simeq (330 \text{ MeV})^4$$

$$< 0 \mid q\bar{q} \mid 0 > \simeq - (250 \text{ MeV})^3 \qquad (5)$$

Also $\alpha_s(M_{J/\psi}) \simeq 0.2$ is used, with

$$\frac{\alpha_s(M)}{\pi} = \frac{1}{4.5 \quad \ln(M/\Lambda_{e^+e^-})} \qquad (6)$$

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Results from the leptonic decays of the Υ and J/ψ as well as the most recent results from DIS all support the lower value for Λ. The results from DIS are summarized in table I[23].

The mass spectrum of the charmonium states can also be calculated using the ITEP sumrules [24,25] with only one additional constant as input, namely the current mass of the charmed quark[25]

$$M_c = 1.28 \text{ GeV}. \qquad (7)$$

Table II compares the QCD sumrule results obtained[25] to the experimental values. The agreement between the theory and experiment is typically better than 0.5%. It should be noted that potentially serious technical objections have been directed at some of the QCD sumrule mass evaluations.[26]

Table II shows the hadronic widths, Γ_{had} (MeV), leptonic widths, $\Gamma_{e^+e^-}$, and the $\gamma\gamma$ branching ratios,

$$B(J^{pc}) \equiv \frac{\Gamma(J^{pc} \to \gamma\gamma)}{\Gamma(J^{pc} \to \text{hadrons})} \qquad (8)$$

for the relevant charmonium states. The hadronic widths of the $\eta_c(2984)$ and the χ_c states have recently been obtained by the Crystal Ball experiment[27]. $\Gamma_{e^+e^-}$ is obtained from the particle data tables (PDT)[28], while $B(J^{pc})$ is from an older Crystal Ball measurement[29]. Also shown in the table are the predictions of QCD[30,31]. As Shifman pointed out in his lecture at the Lepton Photon Conference at Bonn last year[32], some interesting patterns of success and failure of the QCD predictions are evident when comparing the theoretical widths to the experimental values. $\Gamma_{e^+e^-}$ for the vector channel (1^3S_1 and 2^3S_1 states) are in excellent agreement as is Γ_{had} for the tensor channel (2^3P_2 state). However, the scalar and pseudoscalar channels (1^1S_0 and 2^3P_0 mesons) compare poorly. This is a pattern that the ITEP group has called attention to in the past[8]. They attribute this pattern of success and failure to the presence of a "direct instanton" non-perturbative interaction in the scalar and pseudoscalar case which, for mass scales $\lesssim$ 3 GeV, can strongly affect the accuracy of the QCD sumrule calculations in these channels.

The radiative decays of the J/ψ to "ordinary" 0^{-+} mesons offers another test of QCD. New experimental results have been reported by the Crystal Ball collaboration[33] for the processes $J/\psi \to \gamma\ \eta(\eta')$ which disagree somewhat with previously published[34] Crystal Ball results. These new Crystal Ball results are in agreement within errors with three previous measurements[35,36,37].

The new results shown in table IV are derived from about 2×10^6 J/ψ decays or more than twice the number used in the old Crystal Ball analysis. Also, the previous Crystal Ball numbers used only the $\gamma\gamma$ decays of the η', while the new analysis uses the $\eta\pi^+\pi^-$, $\eta\pi^0\pi^0$ and $\gamma\rho^0$ decays as well. Table IV also shows a new Crystal Ball result for $J/\psi \to \gamma\pi^0$. This result is in good agreement with the only other measurement of this quantity by DASP[35]. One can understand $J/\psi \to \gamma\ \eta(\eta')$ in terms of QCD by using the ITEP sumrules[12]. Basically they calculate the diagram of Fig. 3; factorization is assumed. For the process of interest the two gluons are picked up in a $J^{PC} = 0^{-+}$ state and so the matrix element,

$$< 0 \mid j_{ps} \mid \eta\ (\eta') > = < 0 \mid \frac{3\ \alpha_s}{4\pi}\ G^a_{\mu\nu}\ \tilde{G}^a_{\mu\nu} \mid \eta\ (\eta') > \quad (9)$$

is operative.

For the η using $SU(3)_f$ symmetry and the Adler-Bell-Jackiw triangle anomaly yields,

$$< 0 \mid 3\, \alpha_s /4\pi \;\; G^a_{\mu\nu} \, \tilde{G}^a_{\mu\nu} \;\; \mid \eta > \simeq \sqrt{3/2}\; f_\pi \; M^2_\eta \qquad (10)$$

where $f_\pi \simeq 133$ MeV is the $\pi \to \mu\nu$ decay constant.

In the case of the η' current algebra is not sufficient to determine the matrix element (the η' is not a Goldstone meson), a real dynamical calculation is needed. Using the ITEP QCD sum rules they find,[12]

$$< 0 \mid 3\, \alpha_{s/4\pi} \;\; G^a_{\mu\nu} \, \tilde{G}^a_{\mu\nu} \mid \eta' > \simeq (0.7) \sqrt{3/2}\; f_\pi \; M^2_{\eta'} \qquad (11)$$

and so obtain,

$$\frac{\Gamma(J/\psi \to \gamma\eta')}{\Gamma(J/\psi \to \gamma\eta)} = \frac{\mid < 0 \mid J_{ps} \mid \eta' > \mid^2 \mid \vec{P}_{\eta'} \mid^3}{\mid < 0 \mid J_{ps} \mid \eta > \mid^2 \mid \vec{P}_\eta \mid^3} = 3.7 \,. \qquad (12)$$

$|\vec{P}_{\eta(\eta')}|$ is the absolute value of the momentum of the $\eta(\eta')$ in the decay.

They also find[12] using J/ψ pole dominance,

$$\Gamma(J/\psi \to \gamma\eta) = 79 \text{ ev.} \qquad (13)$$

The experimental values obtained from table III and table IV yield,

$$\frac{\Gamma_{exp}(J/\psi \to \gamma\eta')}{\Gamma_{exp}(J/\psi \to \gamma\eta)} = 4.7 \pm 1.1 \qquad (14)$$

and

$$\Gamma_{exp}(J/\psi \to \gamma\eta) = 55 \pm 12 \text{ ev.} \qquad (15)$$

The agreement between theory and experiment leads one to believe that there are gluonic components in the η' wave function[12]. Indeed one can estimate about a 10% gluonic component using the QCD sumrule results. This, however, does not mean that the η' is a gluonium state.

An interesting calculation, though somewhat irrelevant to the discussion here, using current algebra and the non vanishing of u and d quark mass difference shows that[38],

$$< 0 \mid 3\,\alpha_{s/4\pi} \quad G^a_{\mu\nu}\,\tilde{G}^a_{\mu\nu} \mid \pi^0 > \simeq (0.9)\sqrt{3/2}\; f_\pi\, M_\pi^2 \left(\frac{M_\mu - M_d}{M_\mu + M_d}\right). \qquad (16)$$

Note that except for the last factor due to isospin violation, the form of (16) is quite similar to (10) and (11). Scaling like $K\sqrt{3/2}\; f_\pi\, M_X^2$ where $K \simeq 1$. Unfortunately the radiative decay $J/\psi \to \gamma\pi^0$ does not test (16) since diagrams like those shown in Fig. 4 (vector dominance), which are messy to calculate, are estimated to dominate the decay amplitude.

The successes of QCD discussed above are tempered by a possible serious failure. One should be able to reliably calculate the branching ratic $J/\psi \to \gamma\eta_c$, and there are indications[32] that the theory fails here.
In the nonrelativistic potential model the calculation is trivial.

$$\Gamma_{\text{Pot theory}}(J/\psi \to \gamma\eta_c) = \alpha\,\frac{16}{3}\,k^3\,(e_q/2M_c)^2 \mid M_{if} \mid^2 \qquad (17)$$

with,

$$M_{if} = \int_o^\infty r^2 dr \quad \Psi_i(r)\;\Psi_f(r) J_o(kr/_2) \approx 1 \qquad (18)$$

since, $\Psi_i(r) \simeq \Psi_f(r)$ in this case, and $J_o(kr/2) \approx 1$.

Considering M_c as the constituent quark mass, the fits of almost all models yield M_c in the range,

$$M_c = 1.6 \pm 0.3 \text{ GeV} \qquad (19)$$

where the errors indicate upper bounds rather than 1 σ error bars. Thus we find,

$$\Gamma_{\text{Pot theory}}(J/\psi \to \gamma\eta_c) = (1690\,{}^{+\,870}_{-\,491})\; k^3 \left[\text{GeV}^3\right] \text{ KeV} \qquad (20)$$

or, with $M\eta_c = 2.982$ GeV ($k = 0.111$ GeV),

$$B_{\text{Pot theory}}(J/\psi \to \gamma\eta_c) = 3.7\,{}^{+\,1.9}_{-\,1.1}\,\%. \qquad (21)$$

This is to be compared to the final Crystal Ball result[39],

$$B\,(J/\psi \to \gamma\eta_c) = 1.20\,{}^{+\,0.36}_{-\,0.31}\,\%. \qquad (22)$$

By considering a dispersion relation in the amplitude for $\eta_c \rightarrow \gamma\gamma$ in one of the photons, J/ψ pole dominance, as shown in Fig. 5, becomes an excellent approximation to the total amplitude[40,41]. By using such a pole dominated dispersion relation together with local duality arguments[41] one obtains,

$$\Gamma_{QCD}(J/\psi \rightarrow \gamma\eta_c) = \alpha\,\frac{16}{9}\,k^3\,\frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{\Gamma(J/\psi \rightarrow e^+e^-)}\left(\frac{M_{J/\psi}}{M^3_{\eta_c}}\right)(1-0.28\;\alpha_s)\,. \quad (23)$$

This equation should be relativistically correct and correct to second order in α_s.

The similarity of this formula to (17), (18) is seen if one replaces the physical partial widths, $\Gamma(\eta_c \rightarrow \gamma\gamma)$, $\Gamma(J/\psi \rightarrow e^+e^-)$ by their lowest order QCD values,[42]

$$\Gamma^0_{QCD}\,(J/\psi \rightarrow e^+e^-) = \frac{4\,e_q^2\,\alpha^2\,|\,\Psi_{J/\psi}\,(0)\,|^2}{M^2_{J/\psi}} \quad (24)$$

and

$$\Gamma^0_{QCD}\,(\eta_c \rightarrow \gamma\gamma) = \frac{12\,e_q^4\,\alpha^2\,|\,\psi_{\eta_c}(0)\,|^2}{M^2_{\eta_c}} \quad (25)$$

Then, substituting in equation (23),

$$\alpha\,\frac{16}{9}\,k^3\,\frac{\Gamma^0_{QCD}(\eta_c \rightarrow \gamma\gamma)}{\Gamma^0_{QCD}(J/\psi \rightarrow e^+e^-)}\left(\frac{M_{J/\psi}}{M^3_{\eta_c}}\right)(1\;-\;0.28\;\alpha_s) =$$

$$\alpha\,\frac{16}{3}\,k^3\,\frac{|\,\Psi_{J/\psi}\,(0)\,|^2}{|\,\Psi_{\eta_c}(0)\,|^2}\,\frac{e^2_q}{M_{J/\psi}\,M_{\eta_c}}\,(\,1\,-\,0.28\,\alpha_s) \quad (26)$$

we find approximate equality with equation (17), (18) if

$$|\,\Psi_{J/\psi}(0)\,|^2 \approx |\,\Psi_{\eta_c}\,(0)\,|^2\;,\;\alpha_s \lesssim 0.3.$$

However, according to a recent QCD sumrule calculation[43] the wave functions at the origin for the J/ψ and η_c differ by as much as 40 % due to instanton effects in the 0^{-+} channel. This calculation gives,

$$\Gamma_{QCD}(\eta_c \to \gamma\gamma) \lesssim (4.2 \pm 0.4) \text{ KeV} \qquad (27)$$

where the upper limit is shown due to the neglect of the η_c' in the QCD sumrule used. Thus equation 23 yields,

$$B_{QCD}(J/\psi \to \eta_c\gamma) \lesssim 2.7 \% \qquad (28)$$

about the same as the lower limit of the potential model result and a factor of two higher than experiment. The persistence of this disagreement would pose a serious problem for QCD[32].

IV Two possible candidates for gluonium states and some of their properties

a) $\iota(1440)$, 0^{-+} Meson

A state at 1440 Mev was first seen in the reaction,

$$J/\psi \to \gamma K^{\pm} K^0_S \pi^{\mp}, \qquad (29)$$

by the Mark II collaboration at SPEAR[2]. They tentatively identified it as E(1420), a state with $J^{PC} = 1^{++}$, as their experiment was not able to determine the J^Pvalue. The existence of this state was soon confirmed by the Crystal Ball collaboration at SPEAR[44] using the reaction,

$$J/\psi \to \gamma K^+ K^- \pi^0. \qquad (30)$$

However, much more J/ψ data was needed (2.2×10^6 decays in total) before the Crystal Ball Collaboration was able to measure the J^P of the state as 0^-.[3]

This 0^{-+} state may have been previously observed in $p\bar{p}$ annihilations[45]. The state seen in the $p\bar{p}$ case was named E(1420). However, the 0^{-+} assignment from that experiment was not considered conclusive[28,46] and so the E(1420) was accepted to be the $J^{PC} = 1^{++}$ state seen in $\pi^- p$ interactions[47]. Thus the Crystal Ball and Mark II collaborations (in collaboration) have named[3] the 0^{-+} state seen in J/ψ radiative decays the $\iota(1440)$.

The properties of the ι as measured by the Mark II and Crystal Ball Collaborations are shown in table V. Thus

$$B(J/\psi \to \gamma\iota) \gtrsim B(J/\psi \to \gamma\eta'). \qquad (31)$$

b) $\Theta(1640)$, 2^{++} Meson.

This state was first observed in the process

$$J/\psi \to \gamma\eta\eta, \quad \eta \to \gamma\gamma \qquad (32)$$

by the Crystal Ball Collaboration at SPEAR[4]. The analysis was based on a sample of 2.2×10^6 J/ψ events.

Fig. 6a shows the $\eta\eta$ invariant mass distribution for events consistent with $J/\psi \to \gamma\eta\eta$ after a 5 c fit has been performed. Only events with $\chi^2 < 20$ are shown. The solid curve represents a fit to one Breit-Wigner resonance plus a flat background. The dashed curve represents a fit to two Breit-Wigner resonances, one with mass and width fixed at the f'[28] and variable amplitude, the other with all three parameters variable; a flat background is also included. Because of the limited statistics, it is not possible to establish whether the Θ peak is one or two peaks (the Θ and f'). However, it is probably most reasonable to assume that the f' is present and fit for its amplitude. This was not done in reference 4; however, it was done in reference reference 18, and I will also use the two resonance fit here. The spin of the Θ was determined from a maximum likelihood fit to the angular distribution $W(\Theta\gamma, \Theta\eta, \phi\eta)$ for the process

$$J/\psi \to \gamma\Theta, \quad \Theta \to \eta\eta \,. \tag{33}$$

$\Theta\gamma$ is the polar angle of the γ with respect to the beam axis, and $(\Theta\eta, \phi\eta)$ are the polar and azimuthal angles of one of the η's with respect to the γ direction in the Θ rest frame. ($\phi\eta = 0$ is defined by the electron beam direction.) The probability for the spin 0 hypothesis relative to the spin 2 hypothesis is 0.045. (Spins greater than 2 were not considered.) The $\eta\eta$ decay establishes the parity as +.

Figures 6 b and 6 c show the $|\cos\Theta\gamma|$ and $|\cos\Theta\eta|$ distributions respectively. Although the spin determination depends on information which cannot be displayed in these projections, it is clear that the $|\cos\Theta\eta|$ distribution plays the major role in the preference for spin 2. (The solid curves in the Figures show the best fit distributions for spin 2, the dotted curves are the expected distributions for spin 0.). This is primarily due to the excess of events with $|\cos\Theta\eta| > 0.9$. The inset in Fig. 6b shows these events on an expanded scale. This is no evidence that these events are anomalous. The Crystal Ball and the Mark II have searched for,

$$J/\psi \to \gamma\Theta, \quad \Theta \to \pi\pi. \tag{34}$$

Fig. 7 shows the Mark II results for the charge π's from 720 k J/ψ decays and the Crystal Ball results for the π^0's from 2200 k J/ψ decays. The binning in $M_{\pi\pi}$ is 50 Mev/bin for both experiments. As summarized in table VI only upper limits were obtained from both experiments.

The Mark II Collaboration has obtained a preliminary measurement of the process,

$$J/\psi \rightarrow \gamma\Theta, \quad \Theta \rightarrow K^+K^-. \qquad (35)$$

In this analysis 1.32×10^6 J/ψ decays were used. Events were selected which have exactly 2 oppositely charged tracks, identified as kaons by time of flight and kinematic fit χ^2. An observed photon was not required in the events and so 1-C fits were used to reduce background. The π^0 backround was not excluded, but was confined predominantly to masses above $M(K^+K^-) = 2.0$ Gev. The level of the backround from $J/\psi \rightarrow \pi^+\pi^-\pi^0$, and $J/\psi \rightarrow \gamma f\ (\pi^+\pi^-)$ is less than 5 %.

The data were kinematically fit with one constraint to the hypothesis,

$$J/\psi \rightarrow K^+K^-(\gamma). \qquad (36)$$

$\chi^2 < 7$ was required for accepted events.

Fig. 8 shows the resulting preliminary, uncorrected K^+K^- mass spectrum. Prominent peaks at the f' and Θ masses are evident. This mass spectrum was fit in the mass region,

$$1.16 < M_{K^+K^-} < 1.89 \text{ GeV}, \qquad (37)$$

using a maximum likelihood fit to the form,

$$f(M_{K^+K^-}) = A + \frac{B}{(M^2_{K^+K^-} - M^2_\Theta)^2 + M^2_\Theta\Gamma^2_\Theta} + \frac{C}{(M^2_{K^+K^-} - M^2_{f'})^2 + M^2_{f'}\Gamma^2_{f'}}. \qquad (38)$$

$M_{f'}$ and $\Gamma_{f'}$ are fixed at their accepted values[28] while A, B, C, M_Θ and Γ_Θ are determined by the fitting procedure. The results of the fit are summarized in table VI. Note that the fit region did not extend below $M_{K^+K^-} = 1.16$ and above 1.89 GeV due to difficulty with backgrounds.

The Mark II also reports[48] a signal in the process,

$$J/\psi \to \gamma\rho^0\rho^0,\ \rho^0\rho^0 \to \pi^\pm\pi^\pm\pi^\mp\pi^\mp \qquad (38)$$

Fig. 9 shows their 4π mass spectrum for events that satisfy the $\rho^0\rho^0\gamma$ hypothesis.

The Mark II Collaboration interprets this spectrum as a combination of $\gamma\rho^0\rho^0$ phase space and a resonance described by a Breit-Wigner with constant width. A maximum likelihood fit to this hypothesis yields,

$$M_{res.} = 1650 \pm 50 \text{ MeV}$$

$$\Gamma_{res.} = 200 \pm 100 \text{ MeV} \qquad (39)$$

These values are comparable to the mass and width of the Θ shown in table VI.

Also, they obtain,

$$B(J/\psi \to \gamma\rho^0\rho^0, M_{\rho^0\rho^0} < 2 \text{ GeV}) = (1.25 \pm 0.35 \pm 0.4) \times 10^{-3}. \qquad (40)$$

Assuming an I = 0 structure to the decay we find,

$$Br(J/\psi \to \gamma\rho\rho,\ M_{\rho\rho} < 2 \text{ GeV}) = (3.75 \pm 1.05 \pm 1.2) \times 10^{-3}. \qquad (41)$$

This branching ratio is approximately equal to the $\iota(1440)$ and η' branching ratios. As a strong note of caution the Mark II Collaboration states that much more data is needed to establish the connection, if any, between the $\rho\rho$ structure and the Θ meson. It should be noted that $\rho\rho$ enhancements in this mass range have previously been reported in hadronic reactions[49] and observed in final states produced by photon-photon collisions[50]. Fig. 10 shows such an enhancement from the paper of H. Braun et al. The process studied was,

$$p\bar{p} \to 3\pi^+3\pi^-\pi^0 \quad \text{at } 5.7 \text{ GeV/c} \qquad (42)$$

c) Information from the inclusive γ spectrum.

Fig. 11a shows a preliminary inclusive γ spectrum, from the Crystal Ball Collaboration[51], for the process,

$$J/\psi \rightarrow \gamma X. \qquad (43)$$

Structures at the ι and η' masses are evident with a broad structure in the region of Θ also clearly seen.
The unfolding of this spectrum is a difficult task which has yet to be done. However, a plausible scenario for such a future unfolding is shown in Fig. 11b. What this figure suggests is that:

$$B(J/\psi \rightarrow \gamma\iota(1440)) \simeq B(J/\psi \rightarrow \gamma\eta'(958)) \; ; \qquad (44)$$

There is room for the f which is known to have about 30% the rate of the η'; the region of the Θ seems to have a much larger branching ratio, indeed,

$$B(J/\psi \rightarrow \gamma\Theta(\text{Region})) \gtrsim 2\text{-}3 \; B(J/\psi \rightarrow \gamma\iota). \qquad (45)$$

If the presently known contributions in the Θ (Region) are added up we obtain,

$$B(J/\psi \rightarrow \gamma\Theta(\text{Region})) > B(J/\psi \rightarrow \gamma\Theta + \gamma\rho\rho) \approx (5.4 \pm 1.7) \times 10^{-3} \qquad (46)$$

This is already the largest branching ratio seen in J/ψ radiative decays except for that of the $\eta_c(2984)$.

V. Insight from theory on the gluonium status of the candidates

a) ι(1440).

A number of theorists have made insistent arguments that the ι(1440) is a 0^{-+} gluonium state[52]. Others have suggested that ι is a member of the radially excited 0^{-+} nonet of $q\bar{q}$ mesons[53,13], but certainly not a gluonium state[8,32].

Why can't the ι belong to the 2^1S_0 nonet of $q\bar{q}$ mesons? The major arguments against this[52] are:

- i) ι(1440) has the wrong mass to fit with the "other" 2^1S_0 nonet members.
- ii) The radiative decay of the ι from the J/ψ is too large.

Unfortunately both of these arguments are presently uncertain. First, as has been pointed out by others[28] the 2^1S_0 nonet is not at all well established. The favored members of the 2^1S_0 nonet used in reference 52 (Chanowitz and Donogne) are the π (1270), K'(1400) and ζ (1275). I quote from the revised 1982 particle data tables (CERN and LBL):

π'(1270)- Not a well established resonance,
K'(1400)- only appears in the meson listing, it's omitted from the table because it needs confirmation.
ζ (1275) or η(1275)- Not in the PDT tables, "seen in phase shift analysis of ηππ awaits confirmation".

This is a rather unsavory cast of resonances on which to base a secure argument.

Second is the question of the large radiative decay of the J/ψ to the ι. Consider the relationship of $B(J/\psi \to \gamma\iota)$ to $B(J/\psi \to \gamma\eta')$. The ι being a 0^{-+} meson we can extend the ITEP formalism used in section III to describe the decays to γη and γη'[12].

$$\frac{B(J/\psi \to \gamma\iota)_{QCD}}{B(J/\psi \to \gamma\eta')_{QCD}} \simeq \frac{|\langle 0 | J_{ps} | \iota \rangle_{QCD}|^2}{|\langle 0 | J_{ps} | \eta' \rangle_{QCD}|^2} \frac{|\vec{p}_\iota|^3}{|\vec{p}_{\eta'}|^3} \qquad (47)$$

where $\langle 0 | J_{ps} | \eta' \rangle_{QCD}$ is given by equation (11) and

$$\langle 0 | J_{ps} | \iota \rangle_{QCD} \simeq C_\iota \sqrt{3/2}\, f_\pi M_\iota^2 . \qquad (48)$$

Note that ,

$$\frac{B(J/\psi \to \gamma\iota)}{B(J/\psi \to \gamma\eta')} \simeq 1 \Rightarrow C_\iota \simeq 0.55\, C_{\eta'} \simeq 0.39. \qquad (49)$$

This value of C_ι is considered a quite reasonable estimate by Novikov and Shifman[54] if the ι is a radial excitation of the η'. Perhaps this result can be formally justified. (Also see reference 13.)

One should remember, however, that due to nonperturbative effects, the 0^- channel is rather tricky in this mass range and beyond; this was shown in section III. The tensor channel which decouples from direct instantons should be easier to understand.

b) $\Theta(1696)$

Almost every theory, including the Bag model,[55] the ITEP QCD sum rules[8], Lattice gauge theory calculations[56], predict a 2^{++} gluonium state at about 1700 MeV, e.g. the ITEP estimate is

$$M_{2^{++}} = 1.650 \pm 350 \text{ MeV}. \qquad (50)$$

The tensor gluonium channel does not couple to large nonperturbative (instantons) effects[8], and so simple models may have validity for understanding 2^{++} gluonium. For example, even nonrelativistic constituent models of gluonium as bound states of massive gluons find the 2^{++} mass at about 1600 MeV.[9]

The mixing of a 2^{++} gluonium state or a 2^{++} radially excited $q\bar{q}$ state with the ground state $q\bar{q}$ 2^{++} mesons can have a major impact on the mass and decay systematics of

all the 2^{++} states[13,14,16]. One of these mixing models initially developed by Rosner[14] and recently refined by Schnitzer[16] mixes the f meson with a 2^{++} gluonium state predicted by Rosner to have a mass,
$M_{2^{++}} = 1660 \pm 210$ MeV. Schnitzer who developed his model after the Θ was discovered treats the problem more completely by including the f' in the mixing scheme.
In reference 13 it is assumed that the Θ is 2^{++} $q\bar{q}$ radial excitation which mixes with the f and f' ground state. Another interpretation of the Θ is that it is a 4 quark state[57,18].

$$\Theta_{4q} = s\bar{s}(u\bar{u} + d\bar{d}), \qquad (51)$$

with fall appart mode $\phi\omega$.
In each of these models a definite prediction is made for the $\eta\eta$, KK and $\pi\pi$ (and in one case the $\rho\rho$) decay modes of the Θ.

. Θ related to 2^{++} gluonium state[16],

$$\frac{B(\Theta \to \eta\eta)}{B(\Theta \to K\bar{K})} < 0.2 \quad , \quad \frac{B(\Theta \to \pi\pi)}{B(\Theta \to K\bar{K})} < 1 \; (\simeq 0) \qquad (52)$$

. Θ related to 2^{++} $q\bar{q}$ radial excitation[13],

$$\frac{B(f' \to K\bar{K})}{B(\Theta \to K\bar{K})} > 1 \quad , \quad \frac{B(\Theta \to \eta\eta)}{B(\Theta \to K\bar{K})} \approx 0.25 \qquad (53)$$

$$\frac{B(\Theta \to \pi\pi)}{B(\Theta \to K\bar{K})} > 1$$

. Θ related to 2^{++} $q\bar{q}q\bar{q}$ state,[57,18] (equation 51),

$$\frac{B(\Theta \to \eta\eta)}{B(\Theta \to KK^{-})} = 0.5 \qquad B(\Theta \to \pi\pi) = 0$$

$$B(\Theta \to \rho\rho) = 0 \qquad (54)$$

The data yields the following values (see table VI),

$$\frac{B(\Theta \rightarrow \pi\pi)}{B(\Theta' \rightarrow K\bar{K})} < 1, \quad \frac{B(\Theta \rightarrow \eta\eta)}{B(\Theta \rightarrow K\bar{K})} = 0.33 \pm 0.2, \quad \frac{B(f' \rightarrow K\bar{K})}{B(\Theta \rightarrow K\bar{K})} \ll 1 . \tag{55}$$

On comparing (55) with (52),(53) and (54) we conclude,

- 2^{++} gluonium hypothesis is consistent with data.
- 2^{++} radial excitation hypothesis fails badly.
- 2^{++} $q\bar{q}q\bar{q}$ is consistent with (55); however, if the Mark II's $\rho\rho$ enhancement is associated with the Θ, this hypothesis is ruled out. There may also be problems for the 4q interpretation with the large radiative decay of the Θ from the J/ψ obtained by adding just the $\eta\eta$ and $K\bar{K}$ modes.

VI What further experiments might help in properly assigning candidate states.

There are a large number of experiments which can contribute greatly to the understanding of the nature of the ι and Θ . I list some of these below.

i) The Mark II Collaboration measures the J^P of K^+K^- enhancement in the Θ mass region.

ii) The Crystal Ball and or Mark II Collaborations measure the J^P of the $\rho\rho$ enhancement in the Θ mass region.

iii) The Crystal Ball Collaboration unfolds the inclusive γ spectrum from the J/ψ.

iv) High statistics data are needed from threshold to $w \sim 2$ GeV for the process[50], $\gamma\gamma \to X$. (56) Since gluons have no electric charge while quarks do, this process should not copiously produce gluonium states.

v) Much more J/ψ data is needed, on the order of 4 million events, to better measure $\iota \to \pi\pi\eta, \ldots$ etc., $\Theta \to \pi\pi$, $K\bar{K}$, $\eta\bar{\eta}$, ... etc. Also a more careful study of the 1 to 2 GeV. mass region is needed for the process $J/\psi \to \gamma X$.

vi) Need 1-2 Million Υ decays and very good mass resolution to study $\Upsilon \to \gamma X$.

vii) pp or $p\bar{p}$ production of gluonium via gluon fusion[58] offers independent verification of gluonium states.

viii) $\pi^- p \to \phi\phi\eta$ is an OZI suppressed reaction and should not be a strong production channel unless gluonium couples to the $\phi\phi$ system[59,18]. New data is now becoming available.

As these experiments are completed the confusion in the gluonium sector will hopefully abate somewhat.

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Table I

Values of Λ_{LO} obtained from DIS

For references to experiments see reference 23

Experiment	Λ_{LO}(MeV)(No higher twist)	Λ_{LO}(MeV) (With higher twist)
GGM	190^{+160}_{-120}	700
BEBC	210 ± 95	---
CHARM	$290 \pm 120 \pm 100$	290 ± 120
CDHS	190^{+80}_{-70}	200 ± 20
EMC (Fe)	$122^{+22}_{-20}{}^{+114}_{-70}$	---
EMC (H_2)	$110^{+58}_{-46}{}^{+124}_{-69}$	---
BCDMS	$85^{+60}_{-40}{}^{+90}_{-70}$	---

Table II

The masses of the charmonium states, theory vs. Experiment

State	Measured Mass (MeV)	Calculated Mass (MeV)	Comments	References
$1'S_0$	2982 ± 5 [+]	3010 ± 20	Predicted using QCD sum rules	24,25
2^3P_2	3553.9-± 0.5 [+]	3560 ± 10	Calculated from QCD sum rules after the masses of the ^3P states were known	25
2^3P_1	3508.4 ± 0.4 [+]	3500 ± 10		
2^3P_0	3412.9 ± 0.6 [†]	3410 ± 10		
$2'S_0$	3592 ± 5 [+]	---	To be calculated soon	
$2'P_0$	---	3510 ± 10	Predicted using QCD sum rules	25

[+] Values measured by the Crystal Ball

[†] Value measured by the Mark II

Table III

The widths of some charmonium states, QCD vs experiment

States	Measured Γ_{full} (MeV)	Measured Γ_{had} (MeV)$^{+}$	QCD, Γ_{had} (MeV)	Measured $\Gamma_{e^+e^-}$ (KeV)	QCD $\Gamma_{e^+e^-}$ (KeV)	Measured-B^{+}	QCD-B*
1^3S_1	$(63 \pm 9).10^{-3}$	$(47.9 \pm 9.2).10^{-3}$	$(68 \pm 33).10^{-3}$ †	4.4 ± 0.9	~ 5	---	---
1^1S_0	12.4 ± 3.4	12.4 ± 3.4	6 - 8	---	---	$< 1.3 \times 10^{-3}$	$(6.0 \pm 1.0).10^{-4}$
2^1S_0	< 8 (95% CL)	< 8 (95% CL)	---	---	---	---	---
2^3P_2	$2.1^{+1.0}_{-0.7}$	$1.7^{+1.1}_{-0.8}$	1.7 - 2.3	---	---	$(7.5 \pm 2.4).10^{-4}$	$(1.0 \pm 0.2).10^{-3}$
2^3P_1	$1.7^{+0.3}_{-1.7}$	---	$0.34^{+0.32}_{-0.18}$ †	---	---	---	---
2^3P_0	$16.1^{+1.5}_{-1.3}$	$16.0^{+1.5}_{-1.3}$	6.2 - 7.6	---	---	$< 5.10^{-4}$ (90% CL)	$(7.2 \pm 0.9).10^{-4}$

$^{+}$ when possible a correction is made for leptonic and radiative decay modes, e.g., $\Gamma\ (\chi \to \gamma\ J/\psi)$

* the theoretical widths in the table and used together with $\Gamma(J^{pc} \to \gamma\gamma)$ from QCD to obtain QCD-B. Reference 31 was used for $\Gamma(\eta_c \to \gamma\gamma)$, Reference 30 for $\Gamma(\chi_j \to \gamma\gamma)$

† obtained from the measured $\Gamma_{e^+e^-}$ (1^3S_1), $\Gamma_{had}(2^3P_2)$ and table II of reference 31. Note that reference 31 obtains $R_{+h} \equiv \Gamma(2^3P_0 \to gg) \,/\, \Gamma(2^3P_2 \to gg) = 6.8 \pm 0.4$, $R_{exp} = 10.4 \pm 5.6$

Table IV

Crystal Ball Collaboration measurements of $J/\psi \rightarrow \gamma\pi^0$, $\gamma\eta$, $\gamma\eta'$

$Br(J/\psi \rightarrow \gamma\pi^0) = (3.6 \pm 1.1 \pm 0.7) \times 10^{-5}$

$Br(J/\psi \rightarrow \gamma\eta) = (0.88 \pm 0.08 \pm 0.11) \times 10^{-3}$

η' decay mode	$Br(J/\psi \rightarrow \gamma\eta') \times 10^3$
$\eta' \rightarrow \eta\pi^+\pi^-$	$3.9 \pm 1.0 \pm 1.1$
$\eta' \rightarrow \eta\pi^0\pi^0$	$4.2 \pm 0.6 \pm 0.6$
$\eta' \rightarrow \gamma\rho^0$	$4.1 \pm 0.4 \pm 0.6$
$\eta' \rightarrow \gamma\gamma$	$4.4 \pm 0.9 \pm 0.5$
Average	$4.1 \pm 0.3 \pm 0.6$

Table V

$\iota(1440)$ Parameters

Parameter	Mark II[2]	Crystal Ball[3]
M (MeV)	$1440 {}^{+10}_{-15}$	$1440 {}^{+20}_{-15}$
Γ (MeV)	$50 {}^{+30}_{-20}$	$55 {}^{+20}_{-30}$
$B\,(J/\psi \rightarrow \gamma\iota) \times B\,(\iota \rightarrow K\bar{K}\pi)$[a]	$(4.3 \pm 1.7) \times 10^{-3}$ [b]	$(4.0 \pm 0.7 \pm 1.0) \times 10^{-3}$ [c]
C	+	+
J^P	---	0^-

a) I = 0 is assumed in the Isospin correction.

b) This product branching ratio has been increased by 19 % as compared to the value published in reference 2. This accounts for the differential efficiency correction from the spin 1 to spin 0 case as discussed in the reference.

c) The first error is statistical, the second is systematic.

Table VI

Summary of Θ parameters and f' branching ratios obtained from fit of Θ and f' to mass distributions

Parameter	Crystal Ball	Mark II
M (MeV)	1670 ± 50 ($\eta\eta$)	1700 ± 20 (K^+K^-)
M (MeV)	160 ± 80	156 ± 30
$B(J/\psi \to \gamma\Theta) \times B(\Theta \to \eta\eta)$	$(3.8 \pm 1.6) \times 10^{-4}$	---
$B(J/\psi \to \gamma\Theta) \times B(\Theta \to K\bar{K})$[a]	---	$(12.4 \pm 1.8 \pm 5.0) \times 10^{-4}$
$B(J/\psi \to \gamma\Theta) \times B(\Theta \to \pi\pi)$[a]	$< 6 \times 10^{-4}$ (90 % c.L.)	$< 3.6 \times 10^{-4}$(90 % c.L.)
$B(J/\psi \to \gamma f') \times B(f' \to \eta\eta)$	$(0.9 \pm 0.9) \times 10^{-4}$	---
$B(J/\psi \to \gamma f') \times B(f' \to K\bar{K})$	---	$(1.6 \pm 0.5 \pm 0.8) \times 10^{-4}$

a) I = 0 structure of the Θ decay is assumed

Figure Captions

1. First order perturbative QCD diagram for $J/\psi \to \gamma gg$.

2. a) Data from Novasibirsk and Orsay [21] for I=1 part of R_{had} vs $\sqrt{s}$.

   b) Sum rate (equation 4) for I_0; experiment (LHS) is shown by hatched region, theory (RHS) by solid curve vs the parameter M.

3. The QCD diagram used to calculate $J/\psi \to \gamma\eta(\eta')$.

4. The leading diagram for the process $J/\psi \to \gamma\pi^0$.

5. J/ψ pole dominance used in the dispersion relation for $\eta_c \to \gamma\gamma$.

6. a) The $\gamma\gamma$ mass distribution from the process $J/\psi \to \gamma\eta\eta$ for $M_{\eta\eta} < 2.5$ GeV. The solid curve represents a fit to one Breit-Wigner resonance plus a flat background. The dashed curve represents a fit to two Breit-Wigner resonances, one with mass and width fixed at the f'[28] and variable amplitude, the other with all three parameters variable; a flat background is also included.

   b) $|\cos\theta_\gamma|$ and b) $|\cos\theta_\eta|$ distributions for $J/\psi \to \gamma\theta$, $\theta \to \gamma\gamma$. Solid curves are best fit distributions for spin 2. Dashed curves are the expected distributions for spin 0. The insert shows events with $|\cos\theta_\eta| > 0.9$ with expanded scale. Data is from the Crystal Ball Collaboration.

7. a) $M_{\pi\pi}$ mass distribution from $J/\psi \to \gamma\pi^+\pi^-$ (the Mark II Collaboration) the fit represents fit to f(1270) plus background.

   b) $M_{\pi^0\pi^0}$ mass distribution from $J/\psi \to \gamma\pi^0\pi^0$ (Crystal Ball Collaboration). The solid curve represents a fit to f(1270) plus background. The dashed curve represents the background estimate.

8. A preliminary $M_{K^+K^-}$ distribution from $J/\psi \to (\gamma)\ K^+K^-$ (Mark II Collaboration). The solid line is the fit described in the text (cf equation 38). Signals at the f' and θ are obtained.

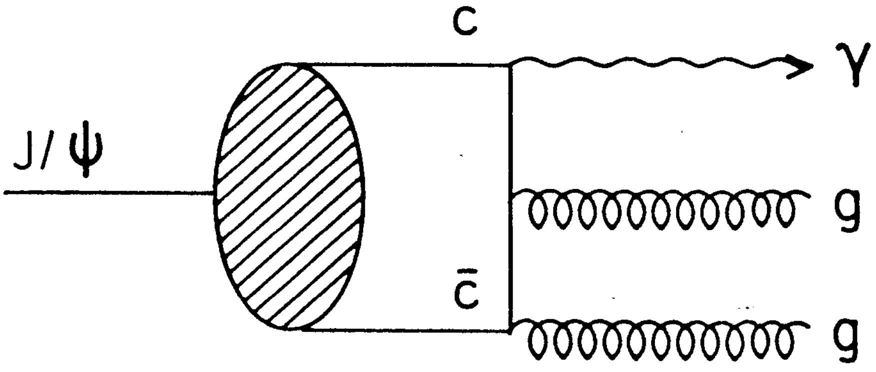
9. The $\rho^0\rho^0$ mass spectrum obtained from the analysis [48] of the process $J/\psi \to \gamma 2\pi^+ 2\pi^-$ (Mark II Collaboration).

10. The $M_{2\pi^+2\pi^-}$ distributions obtained in the process $p\bar{p} \to 3\pi^+3\pi^-\pi^0$ selected for $2\pi^+2\pi^-$ systems having two distinct $\pi^+\pi^-$ mass combinations in the various M_{+-} intervals as indicated. Here N_c and N represent respectively the total number of combinations and the total number of events entering in the histograms. The curves in (a),

(b) and (c) are normalized to the total number of combinations and represents the phase space predictions. In (d) the curve is obtained by fitting the data with an incoherent mixture of phase space and a Breit-Wigner function. (H. Braun et al. [49]).

11) a) A preliminary inclusive ψ spectrum from the process $J/\psi \rightarrow \gamma X$ obtained by the Crystal Ball Collaboration.

b) A plausible scenario for a future unfolding of the spectrum. See text for explanation.



9-82

Fig. 1

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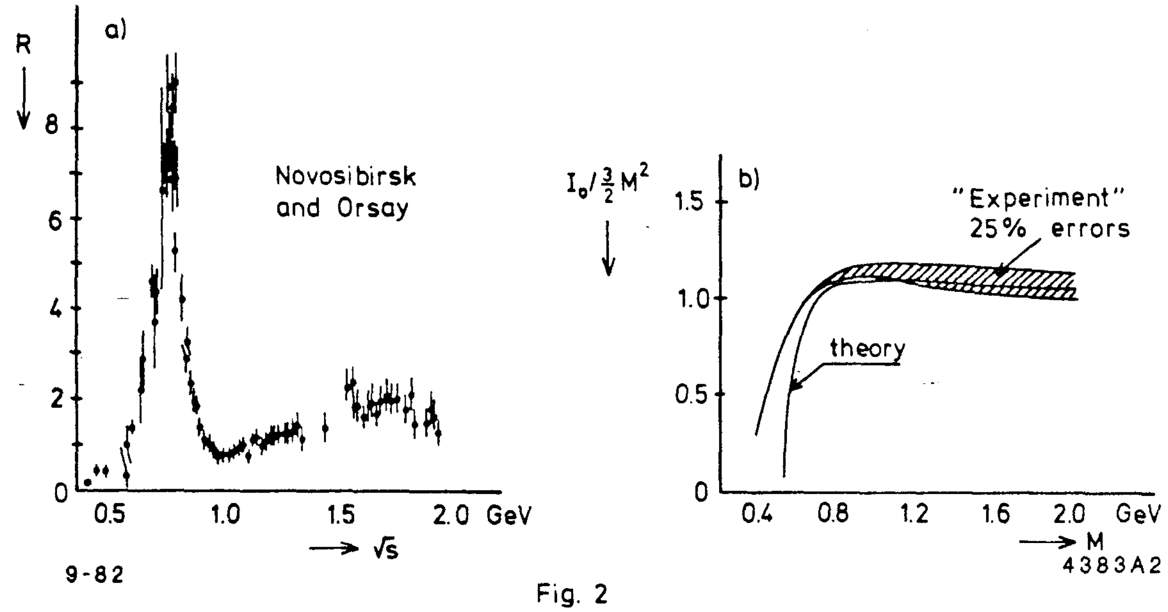


R
a)
8
6
4
2
0
0.5
1.0
1.5
2.0 GeV
√s
Novosibirsk and Orsay
9-82
$I_0/\frac{3}{2}M^2$
b)
1.5
1.0
0.5
0
0.4
0.8
1.2
1.6
2.0
GeV
M
"Experiment" 25% errors
theory
4383A2

Fig. 2

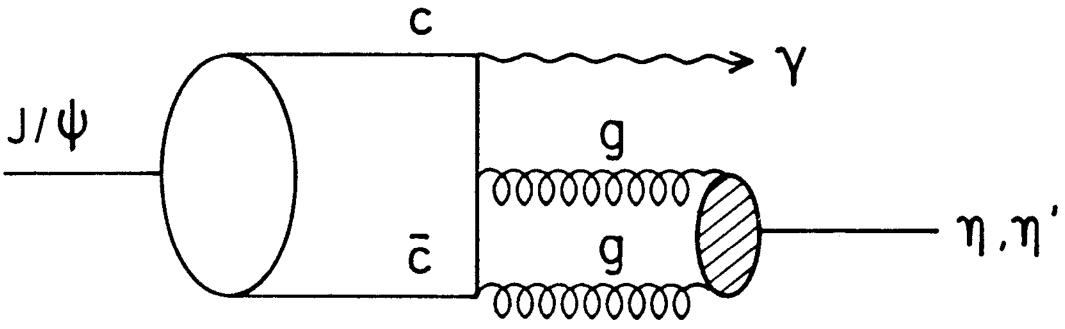
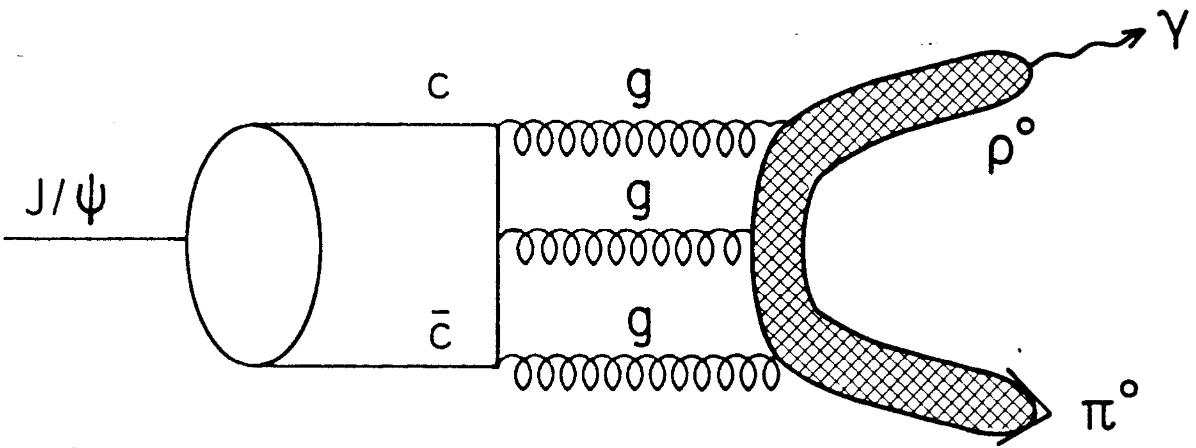


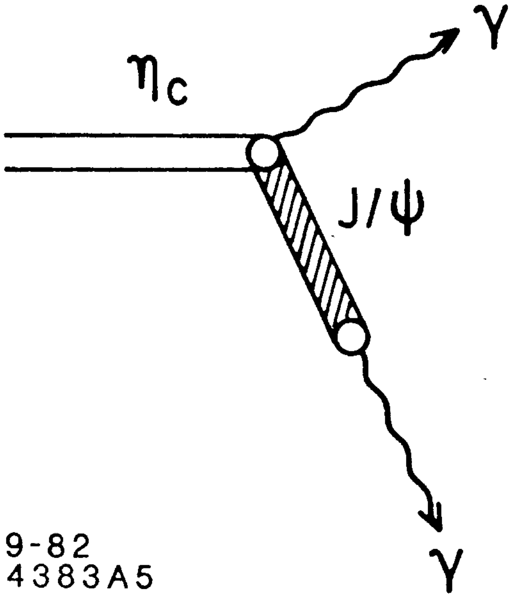
Fig. 3



9-82

Fig. 4

4383A4



9-82
4383A5

Fig. 5

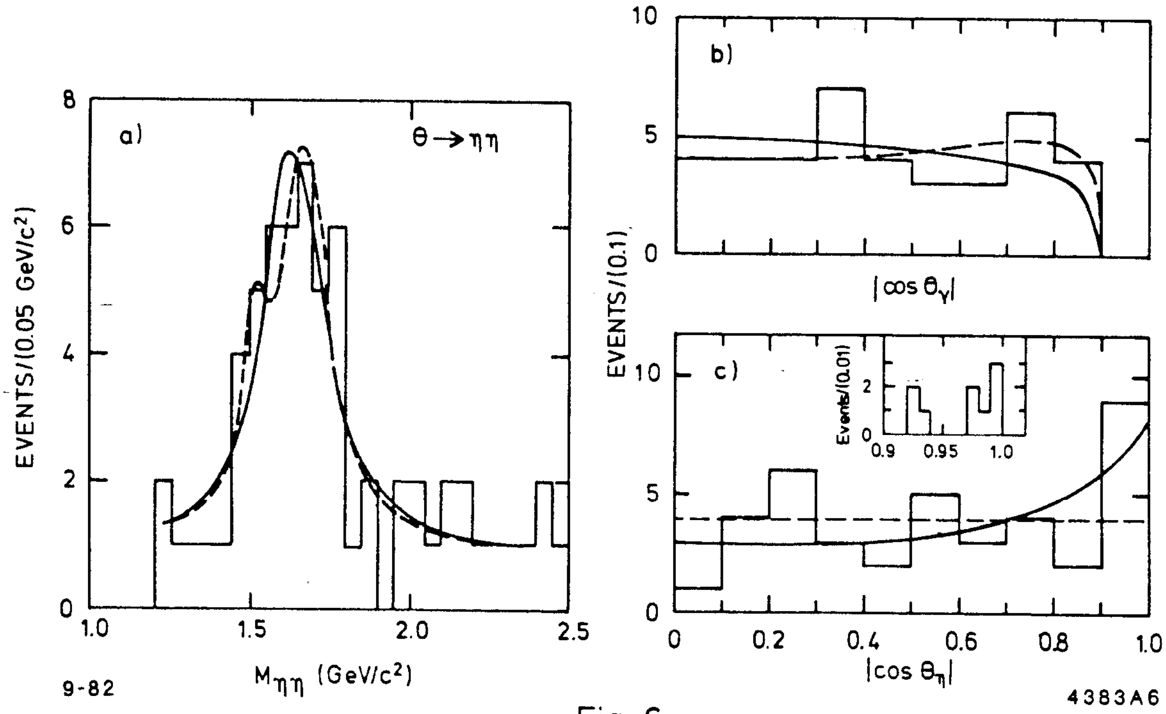
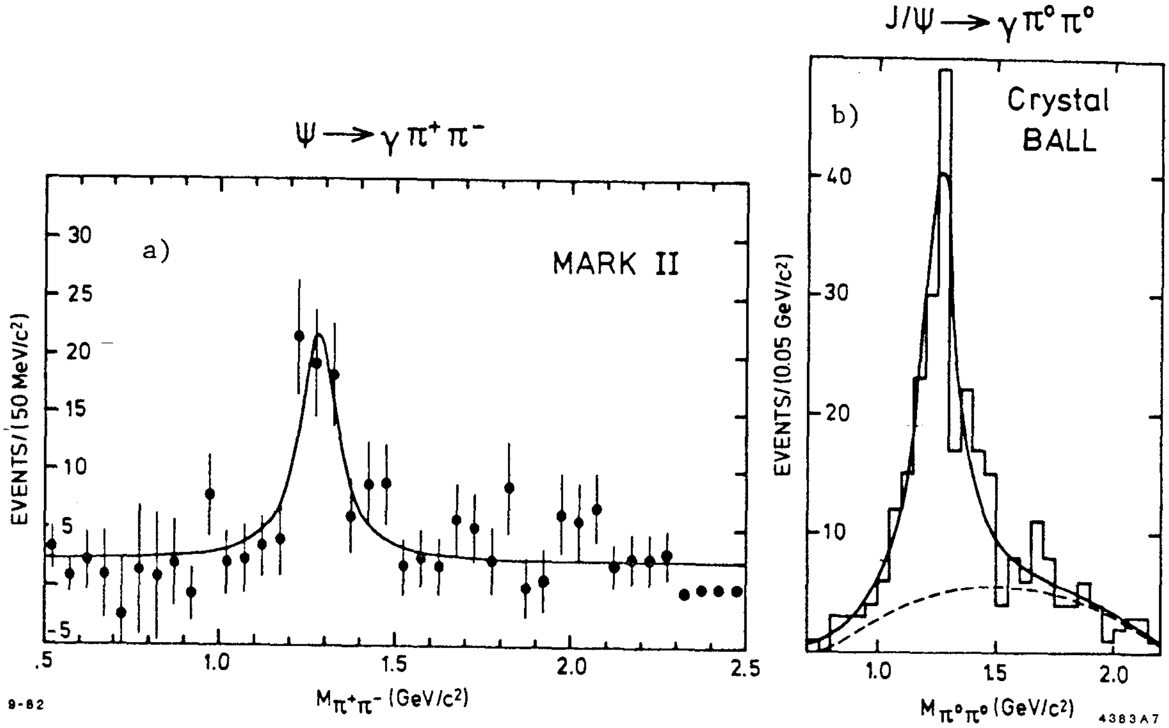
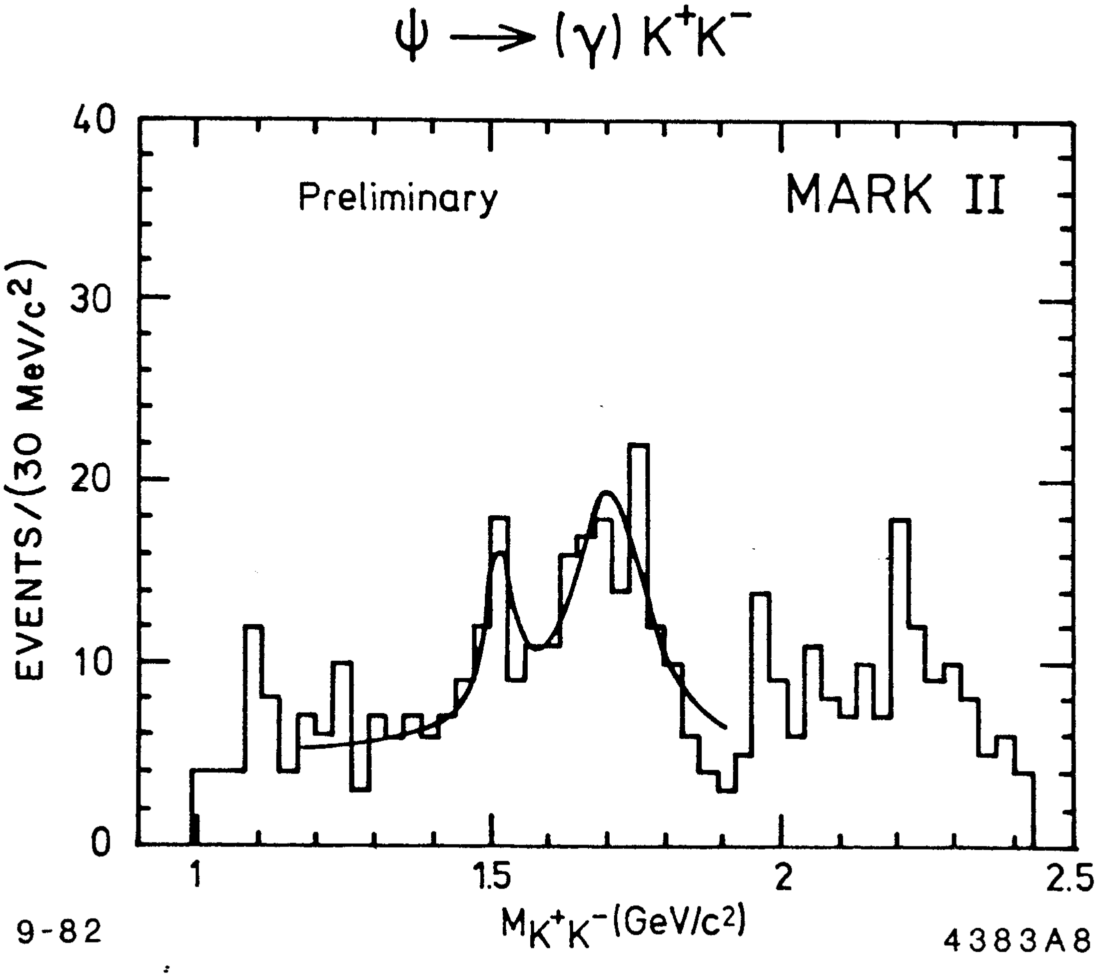

a)
θ → ηη
EVENTS/(0.05 GeV/c²)
0
2
4
6
8
1.0
1.5
2.0
2.5
M_ηη (GeV/c²)
9-82
b)
10
5
0
|cos θ_γ|
EVENTS/(0.1)
c)
10
5
0
0
0.2
0.4
0.6
0.8
1.0
|cos θ_η|
Events/(0.01)
2
0
0.9
0.95
1.0
4383A6

Fig. 6



$\psi \to \gamma \pi^+ \pi^-$
a)
MARK II
EVENTS/(50 MeV/c^2)
30
25
20
15
10
5
-5
.5
1.0
1.5
2.0
2.5
$M_{\pi^+\pi^-}$ (GeV/c^2)
9-82
$J/\psi \to \gamma \pi^0 \pi^0$
b)
Crystal
BALL
EVENTS/(0.05 GeV/c^2)
40
30
20
10
1.0
1.5
2.0
$M_{\pi^0\pi^0}$ (GeV/c^2)
4383A7

Fig. 7



$\psi \rightarrow (\gamma)\, K^+K^-$
Preliminary
MARK II
EVENTS/(30 MeV/c²)
0
10
20
30
40
1
1.5
2
2.5
$M_{K^+K^-}$ (GeV/c²)
9-82
4383A8

Fig. 8

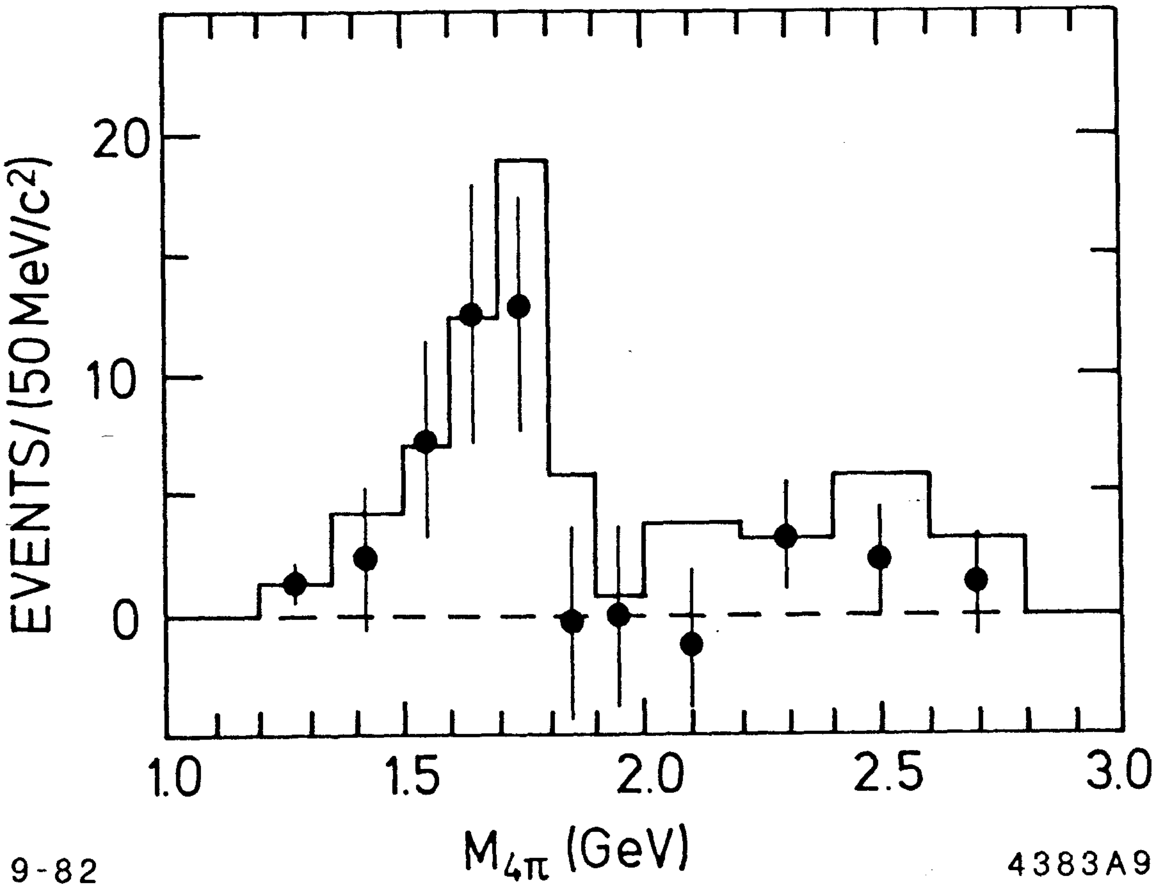
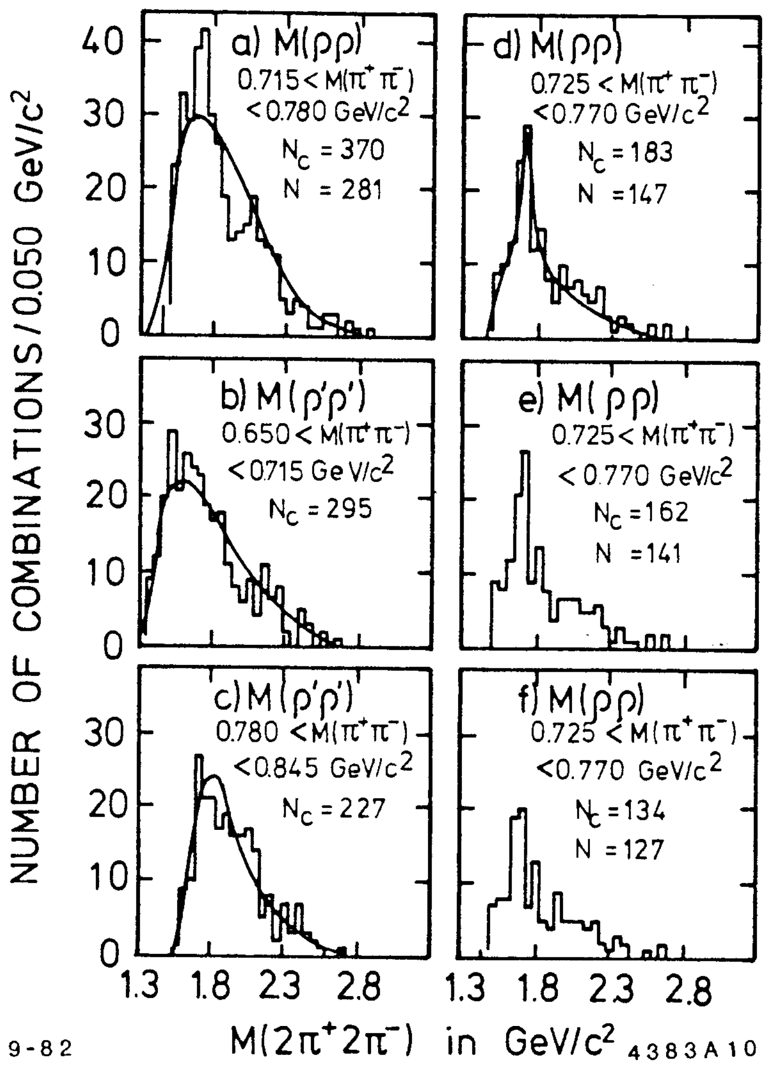
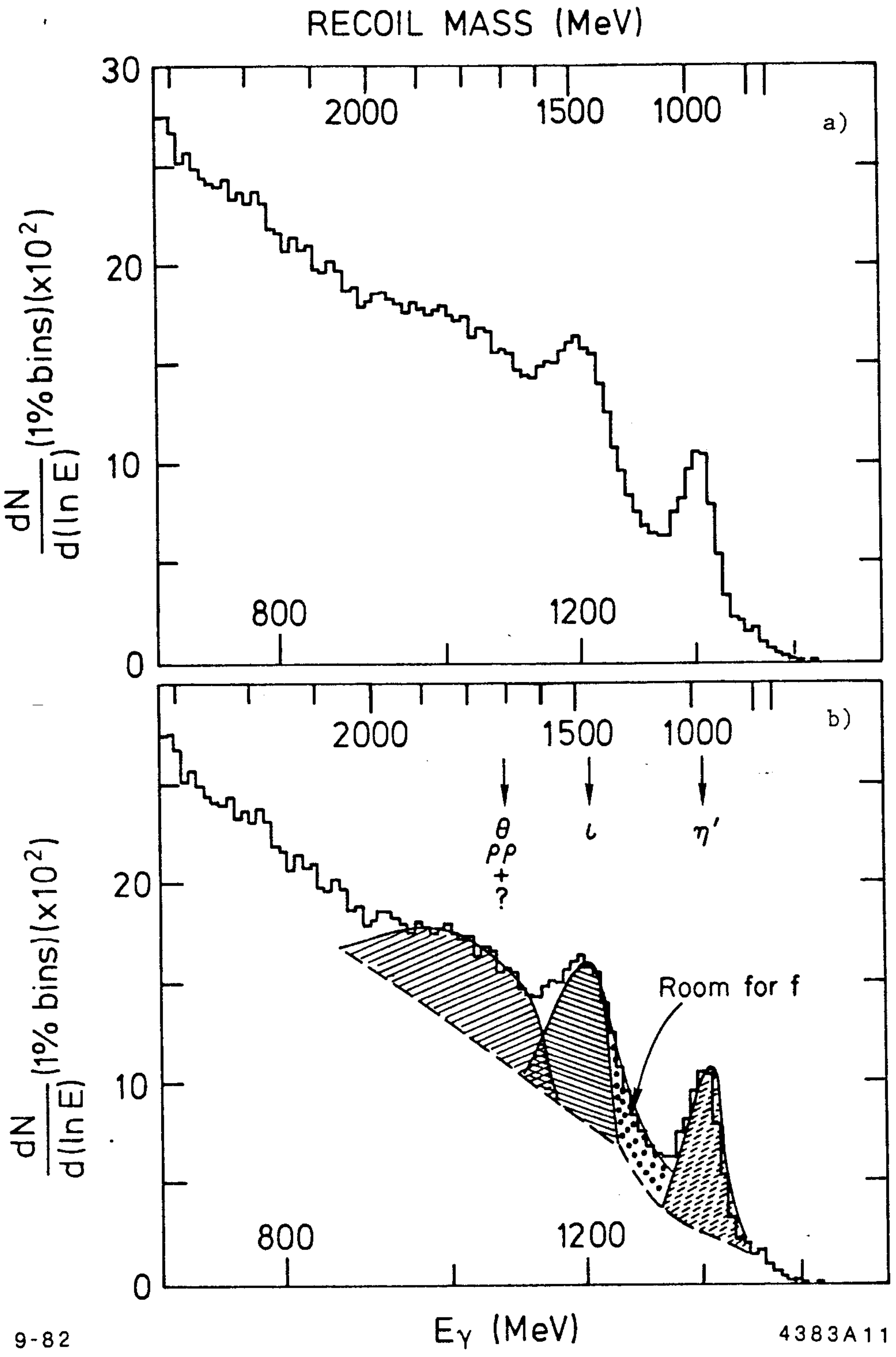


Fig. 9



NUMBER OF COMBINATIONS/0.050 GeV/c^2
a) M(ρρ)
0.715 < M(π⁺π⁻) < 0.780 GeV/c^2
N_c = 370
N = 281
b) M(ρ′ρ′)
0.650 < M(π⁺π⁻) < 0.715 GeV/c^2
N_c = 295
c) M(ρ′ρ′)
0.780 < M(π⁺π⁻) < 0.845 GeV/c^2
N_c = 227
d) M(ρρ)
0.725 < M(π⁺π⁻) < 0.770 GeV/c^2
N_c = 183
N = 147
e) M(ρρ)
0.725 < M(π⁺π⁻) < 0.770 GeV/c^2
N_c = 162
N = 141
f) M(ρρ)
0.725 < M(π⁺π⁻) < 0.770 GeV/c^2
N_c = 134
N = 127
40
30
20
10
0
1.3
1.8
2.3
2.8
M(2π⁺2π⁻) in GeV/c^2
9-82
4383A10

Fig. 10



9-82

4383A11

Fig. 11