# NEW PARTICLE SPECTROSCOPY, QUARKONIUM AND GLUONIC MESONS

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# NEW PARTICLE SPECTROSCOPY, QUARKONIUM AND GLUONIC MESONS*

E. D. Bloom

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, U.S.A.*

Résumé — Des résultats expérimentaux récents concernant le quarkonium et des mésons gluoniques sont présentés et discutés. Des comparaisons sont faites avec la théorie. Des prédictions du quarkonium semblent en bon accord avec l'expérience. La question de la vérification expérimentale des mésons gluoniques est obscurcie par la difficulté de l'interprétation théorique.

Abstract — Recent experimental results on quarkonium and gluonic mesons are presented and discussed. Comparisons with theory are made. Quarkonium predictions seem to agree well with experiment. The question of the experimental verification of gluonic mesons is clouded by the difficulty of the theoretical interpretation.

1. Introduction and Summary — The exploration and understanding of the substructure of hadrons, presented in terms of quarks and gluons by quantum chromodynamics (QCD), has made considerable progress in the last ten years. This progress owes much to advances in $e^+e^-$ colliding beam machines, though many important results have also been obtained using hadron and photon beams on fixed targets. Indeed, due largely to the characteristics of the production mechanisms in $e^+e^-$ collisions, meson spectroscopy (as compared to baryon spectroscopy) has seen an explosive development over this time frame.

In this paper I will review the progress of meson spectroscopy over the last year or so with emphasis on results presented at this conference. The discussion naturally divides into two general areas, that of mesons made mostly of a quark and antiquark which I call quarkonium, and that of mesons made mostly of two or more gluons which I call gluonic mesons.

First, advances in quarkonium spectroscopy will be considered, beginning with a brief discussion of vector meson production in the $1.4 < \sqrt{s} < 2.2$ GeV mass region. Next, recent results on the hadronic decays of $\psi'$, and the decay $J/\psi \to \gamma\eta_c$ will be presented. The highlight of the section on quarkonium is the recently announced results on the radiative decays of the T'' which are discussed next. And, finally, some expectations for the future of this field are presented.

Second, the evidence for and against the existence of gluonic mesons will be reviewed. The experimental search for such mesons has proven to be a difficult and confusing one with a number of guiding principles losing credibility as the field has matured. Thus, this section begins with a review of these elements of "glueball fantasy." Next, the experimental evidence for some gluonic meson candidates is presented. The insites from theory on the status of some of these candidates is then considered. The section ends with a call for more experiments to help clarify the situation.

2. Quarkonium — Quarkonium[1] is the generic name for a meson composed of a quark and an antiquark. For u and d quarks with constituent mass about 350 MeV as well as s quarks with mass about 500 MeV quarkonium is a highly relativistic bound system, i.e., $v^2_{quark} \sim 1$. However, with the discovery of heavy quarkonium a reasonable approximation to a non-relativistic $q\bar{q}$ bound system has become available. The $c\bar{c}$

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system or charmonium, has a c-quark constituent mass of about 1500 MeV and $v^2_{c\text{-quark}} \sim 0.25$. Bottomium is still more non-relativistic with $M_b \sim 4900$ MeV and $v^2_{b\text{-quark}} \sim 0.1$. For all quarkonium systems, non-relativistic potential models have had predictive power. However, the calculations become more secure as the mass of bound quarks increases. In particular, simple models have worked well for the $c\bar{c}$ and $b\bar{b}$ bound systems. Figure 1[2] shows various successful potentials that have been used. For $0.1\ \text{fm} \leq r \leq 1.0\ \text{fm}$, the region probed by presently available quarkonium families, a flavor-independent potential has emerged which appears to be determined by the experimental data.

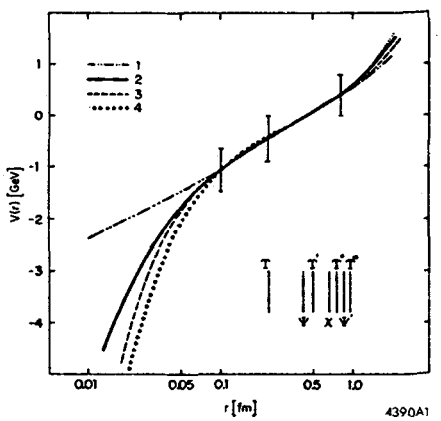


Fig. 1: Various successful potential which have been used to calculate $c\bar{c}$ and $b\bar{b}$ spectra and transition rates. The potentials (1), (3) and (4) have been shifted to coincide with (2) at $r = 0.5$ fm; the "error bars" indicate the uncertainty in absolute, r-independent normalization. Some states of the $c\bar{c}$ and $b\bar{b}$ spectrum are displayed at their mean square radii. See Ref. [2] for details.

a. Recent Results on Vector Meson Production in the Mass Range $1.4 < \sqrt{s} < 2.2$ GeV[3]

Figure 2 shows a summary of the vector meson spectrum and the details of a possible $1^-$ nonet recurrence. Table 1 shows a summary of data from $e^+e^-$ annihilation ($DM_1$ at DCI), and from 20-70 GeV photon beam energy photoproduction (WA4 and WA57 at CERN).

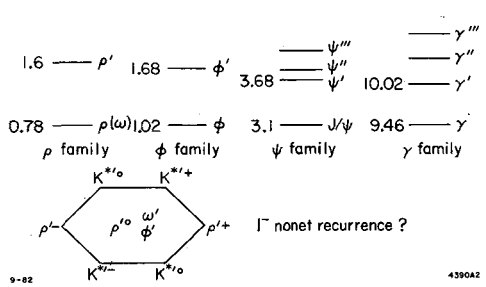


Fig. 2: A summary of the vector meson spectrum and the details of a possible $1^-$ $q\bar{q}$ nonet recurrence. From Ref. [3].

Table 1. A Summary of Some ρ', ω' and φ' Properties

| V | M (GeV) | Γ (GeV) | $\Gamma_{V_{ee}} B(V \to KK^*)$ (KeV) | $\Gamma_{V_{ee}} B(V \to K\bar{K})$ (KeV) | $\Gamma_{V_{ee}} B(V \to \omega\pi\pi)$ (KeV) |
|---|---|---|---|---|---|
| ρ' | 1.57 | 0.51 | 0.19 ± 0.04 | 0.024 ± 0.004 | 0.0 |
| ω' | 1.57 | 0.50 | 0.029 ± 0.005 | 0.0015 ± 0.0003 | 0.1 - 0.3 |
| φ' | 1.68 ± 0.01 | 0.185 ± 0.022 | 0.49 ± 0.5 | 0.036 ± 0.004 | <0.05 |

Using Table 1 plus other information from the experiments, we find an estimate for $\Gamma_{\phi' ee}$:

$$\Gamma_{\phi' ee} = \Gamma_{\phi' ee} B_{\phi' \to KK^*} (0.49) + \Gamma_{\phi' ee} B_{\phi' \to K\bar{K}} (0.04) + \Gamma_{\phi' ee} B_{\phi' \to \phi\eta} (\sim 0.1) + \Gamma_{\phi' ee} B_{\phi' \to \begin{vmatrix} 3\pi \\ 5\pi \end{vmatrix}} (0.05) \cong 0.68 \text{ KeV} \quad . \tag{1}$$

This result leads to the interesting comparison,

$$\Gamma_{\phi' ee}/\Gamma_{\phi_{ee}} \simeq 0.5 \quad , \quad \frac{\Gamma_{\psi' ee}}{\Gamma_{\psi_{ee}}} = 0.42 \pm 0.09 \quad , \quad \frac{\Gamma_{\Upsilon' ee}}{\Gamma_{\Upsilon_{ee}}} = 0.43 \pm 0.24 \quad , \tag{2}$$

when the last two ratios have been obtained from the particle data tables.[4]

b. Hadronic Decays of the $\psi'$[5] — The final states of the $\psi'$ are dominated by the following partial widths,

$$B(\psi' \to \gamma\chi_c) = 26.9 \pm 1.5\% \ ,[6] \quad B(\psi' \to \pi\pi J/\psi) = 50 \pm 3\% \ ,[4]$$
$$B(\psi' \to \eta J/\psi) = 2.8 \pm 0.6\% \ .[4] \tag{3}$$

It is of interest to study exclusive states which are produced in the process,

$$\psi' \to 3g \to \text{hadrons} \quad , \tag{4}$$

and compare rates with the same exclusive decays of the $J/\psi$.
Since,[1]

$$\Gamma(J/\psi,\psi' \to 3g) \propto \Gamma(J/\psi,\psi' \to e^+e^-) \propto \frac{|\phi_{J/\psi,\psi'}(0)|^2}{M^2_{J/\psi,\psi'}} \quad , \tag{5}$$

where $\phi_{J/\psi,\psi'}(0)$ are the charmonium wave functions at the origin, it seems natural to compare,

$$\frac{\Gamma(\psi' \to x)}{\Gamma(J/\psi \to x)} \quad \text{with} \quad \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \quad .$$

The Mark II collaboration at SPEAR has measured a large number of exclusive states of the $\psi'$ and $J/\psi$. The measurements were obtained from a sample of about $10^6 \psi'$ decays, and $4 \times 10^5$ $J/\psi$ decays. Final states with a $\pi^0$ require full reconstruction from the detection of both photons to clearly separate direct photon events. Experimentally, the comparisons of $J/\psi$ to $\psi'$ decays is easier if $B(\psi' \to x)/B(J/\psi \to x)$ is compared to $B(\psi' \to e^+e^-)/B(J/\psi \to e^+e^-)$ rather than ratios of partial widths. The two methods are clearly equivalent.

Table 2 lists the branching ratios and ratio of branching ratios obtained by the Mark II. The ratio of branching ratios should be compared to,

$$B(\psi' \to e^+e^-)/B(J/\psi \to e^+e^-) = 12.2 \pm 2.4\% \ .[4] \tag{6}$$

All measured ratios are in good agreement with (6) except the $\rho\pi$ and KK* final states which are about a factor of 10 low. Why this occurs is presently not understood.

c. The Branching Ratio for $J/\psi \to \gamma\eta_c$ (2982) — In his talk at the Lepton Photon Conference last year, Shifman[7] pointed out a seemingly significant difference between the theoretical calculation of the branching ratio for

$$J/\psi \to \gamma\eta_c \ (2982) \quad , \tag{7}$$

and the experimental measurement from the Crystal Ball Collaboration. He indicated that the persistence of this disagreement would pose a serious problem for QCD. The transition (7) is an M1 transition and was expected to be described to a very good approximation by the simple non-relativistic potential model.[1]

Table 2. Mark II Results for $B(J/\psi,\psi' \to x)$ and $B(\psi' \to x)/B(J/\psi \to x)$

| Final State | $B(J/\psi \to x)$ % | $B(\psi' \to x)$ % | $\frac{B(\psi' \to x)}{B(J/\psi \to x)}$ % |
|---|---|---|---|
| $p\bar{p}$ | 0.22 ± 0.02 | 0.023 ± 0.005 | 10.0 ± 2.4 |
| $p\bar{p}^{o}$ | 0.09 ± 0.02 | 0.013 ± 0.005 | 13.9 ± 6.3 |
| $K^+K^-\pi^+\pi^-$ | 0.72 ± 0.23 | 0.16 ± 0.04 | 22.0 ± 8.0 |
| $2\pi^+2\pi^-\pi^o$ | 3.25 ± 0.55 | 0.25 ± 0.04 | 7.6 ± 1.3 |
| $\omega\pi^+\pi^-$ | 0.60 ± 0.11 | 0.07 ± 0.02 | 10.8 ± 3.8 |
| $3\pi^+3\pi^-\pi^o$ | 2.68 ± 0.99 | 0.34 ± 0.16 | 12.8 ± 6.0 |
| $K^{*\pm}K^{\pm}$ $\hookrightarrow K^{\pm}\pi^o$ | 0.092 ± 0.018 | <0.002 90% CL | <1.96 |
| $\rho^o\pi^o$ | 0.410 ± 0.051 | <0.003 90% CL | <0.87 |
| $\rho^{\pm}\pi^{\pm}$ | 0.95 ± 0.10 | <0.014 90% CL | <1.47 |
| $e^+e^-$ | --- | --- | 12.2 ± 2.4 |

$$\Gamma(J/\psi \to \gamma\eta_c) = \alpha \frac{16}{3} k_\gamma^3 \left(\frac{e_q}{2M_q}\right)^2 |M_{if}|^2 \quad . \tag{8}$$

where,

$$M_{if} = \int_o^\infty r^2 dr\ \psi_i(r)\ \psi_f(r)\ j_o(k_\gamma r/2) \quad . \tag{9}$$

In this model one expects $\psi_i \approx \psi_f$ and $j_o(k_\gamma r/2) \approx 1$; it then follows that $M_{if} \approx 1$. Note that in (8) and (9) $k_\gamma$ is the energy of the transition photon, $e_q$ is the charge of the charmed quark and $M_q$ its constituent mass. However, what is the value of $M_q$ for charmonium? The fits of almost all models yield $M_c$ in the range,

$$M_c = 1.6 \pm 0.3 \text{ GeV} \quad . \tag{10}$$

Thus we find,

$$B_{\text{Pot theory}}\ (J/\psi \to \gamma\eta_c) = \left(1690\ {}^{+870}_{-491}\right) k_\gamma^3\ [\text{GeV}]\ \text{KeV} \quad . \tag{11}$$

Or with $M_{\eta_c} = 2.982$ GeV, ($k_\gamma = 0.111$ GeV),

$$B_{\text{Pot theory}} = 3.7\ {}^{+1.9}_{-1.1}\ \% \quad . \tag{12}$$

This is to be compared to the final Crystal Ball result,[6]

$$B_{\text{exp}}\ (J/\psi \to \gamma\eta_c) = 1.20\ {}^{+0.36}_{-0.31}\ \% \quad . \tag{13}$$

By considering a dispersion relation in the amplitude for $\eta_c \to \gamma\gamma$ in one of the photons, $J/\psi$ pole dominance, as shown in Fig. 3, becomes an excellent approximation to the total amplitude.[8,9] By using such a pole dominated dispersion relation together with local duality arguments[9] one obtains,

$$\Gamma_{QCD}\ (J/\psi \to \gamma\eta_c) = \alpha \frac{16}{9} k_\gamma^3 \frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(J/\psi \to e^+e^-)} \left(\frac{M_{J/\psi}}{M_{\eta_c}^3}\right) (1-0.28\ \alpha_s) \quad . \tag{14}$$

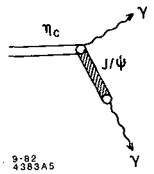


Fig. 3: A diagrammatic representation of $J/\psi$ pole dominance of the process $\eta_c \to \gamma\gamma$.

This equation should be relativistically correct and correct to second order in $\alpha_s$.

The similarity of this formula to Eq. (8) is seen if one replaces the physical partial widths, $\Gamma(\eta_c \to \gamma\gamma)$, $\Gamma(J/\psi \to e^+e^-)$ by their lowest order QCD values,[10]

$$\Gamma^o_{QCD}\ (\eta_c \to \gamma\gamma) = \frac{12\ e_q^4\ \alpha^2\ |R_{\eta_c}(0)|^2}{M^2_{\eta_c}} \quad , \tag{15}$$

and,

$$\Gamma^o_{QCD}\ (J/\psi \to e^+e^-) = \frac{4\ e_q^2\ \alpha^2\ |R_{J/\psi}(0)|^2}{M^2_{J/\psi}} \tag{16}$$

R(0) is the radial wavefunction at the origin. Then, substituting in Eq. (14),

$$\begin{aligned} &\alpha\ \frac{16}{9}\ k_\gamma^3\ \frac{\Gamma^o_{QCD}\ (\eta_c \to \gamma\gamma)}{\Gamma^o_{QCD}\ (J/\psi \to e^+e^-)}\ \left(\frac{M_{J/\psi}}{M^3_{\eta_c}}\right)\ (1-0.28\ \alpha_s) \\ &= \alpha\ \frac{16}{3}\ k_\gamma^3\ \frac{|R_{J/\psi}(0)|^2}{|R_{\eta_c}(0)|^2}\ \frac{e_q^2}{M_{J/\psi}\ M_{\eta_c}}\ (1-0.28\ \alpha_s) \end{aligned} \tag{17}$$

we find approximate equality with Eq. (8) when $|M_{if}|^2 \approx 1$, and,

$$|R_{J/\psi}(0)|^2 \approx |R_{\eta_c}(0)|^2 \quad , \quad \alpha_s \leqq 0.3 \quad , \tag{18}$$

in Eq. (17). Note that in non-relativistic potential models, condition (18) is expected. However, according to a recent QCD sumrule calculation[11] the wave functions at the origin for the $J/\psi$ and $\eta_c$ differ by as much as 40% due to instanton effects in the $0^{-+}$ channel. This calculation gives,

$$\Gamma_{QCD}\ (\eta_c \to \gamma\gamma) \leqq (4.2 \pm 0.4)\ \text{KeV} \quad , \tag{19}$$

where the upper limit is due to the neglect of the $\eta_c'$ in the QCD sumrule used. Thus, Eq. (14) yields,

$$B_{QCD}\ (J/\psi \to \gamma\eta_c) = \frac{\Gamma_{QCD}(J/\psi \to \gamma\eta_c)}{\Gamma_{exp}(J/\psi \to \text{all})} \leqq (2.7 \pm 1.0)\% \quad . \tag{20}$$

Note that Eqs. (14) and (20) use a number of experimental measurements which have errors. These errors have to be propagated properly in the formulae to obtain the error estimate in Eq. (20).

Thus, the result (20) is not in severe disagreement with experiment (Eq. (13)) within errors.

Interestingly, the potential model calculation is saved by the work of Kang-Sucher-Feinberg.[12] Their calculations were developed to try to explain the small branching fraction observed for $J/\psi \to \gamma X$ (2820),[10,12] and failed to do so. However, as applied to $J/\psi \to \gamma\eta_c$ (2920),[13] greater success is obtained. Briefly, in their calculation the $|M_{if}|^2$ of Eq. (8) is given by[13]

$$|M_{if}|^2 = \left(M_{J/\psi}^2 + M_{\eta_c}^2\right) I^2 / \, 2M_{J/\psi}^2 \tag{21}$$

where

$$I = \left\langle f \left| 1 - \frac{k_\gamma^2 r^2}{24} - \frac{2\, P_{\eta_c}^2}{3\, M_c^2} - \frac{V_s}{M_c} \right| i \right\rangle \quad . \tag{22}$$

In the above formula $V_s$ is the scalar confining potential.

For $M_c$ = 1.8 GeV, pure scalar confinement (pure vector confinement) yields,[13]

$$B_{\text{Pot theory}}\ (J/\psi \to \gamma\eta_c) \cong 1\%\ (2\%) \quad . \tag{23}$$

while for $M_c$ = 1.6 GeV, one finds,

$$B_{\text{Pot theory}}\ (J/\psi \to \gamma\eta_c) \simeq 1.3\%\ (2.7\%) \quad . \tag{24}$$

In both cases good agreement is found with experiment (Eq. (13)) if scalar confinement dominates. Scalar confinement is preferred for other reasons as well.[1]

It thus seems that a major disagreement between theory and experiment in the J/ψ region, $B(J/\psi \to \gamma\eta_c)$ has been resolved.

d. The Observation of Some $P_b$ States at CESR — Figure 4 shows what most theories expect for the $n^3S_1$, $n^3P_J$ spectrum of the $b\bar{b}$, or bottomium, system. The $^3S_1$ bound states, Υ, Υ', and Υ'' have already been known for some time,[1] and by now non-relativistic potential models describe most of the observations related to these states with reasonable accuracy. One area which has been almost totally unexplored is that of the $n^3P_J$ states in the $b\bar{b}$ system. This is because the necessary statistics have until recently been unavailable. As in indicated in Fig. 4, there is some disagreement among potential models (two are shown as examples) as to the expected mass splitting and photon transition rates between states. However, most models predict the spectrum of $^3P_J$ states shown in the figure.

There has been some controversy in the past over the energy scale to be used in the Υ system. Cornell and DESY have obtained somewhat different masses for the Υ (though within stated experimental errors), and this difference has been ascribed to calibration inaccuracies at either or both of the storage rings. A new result from Novosibirsk,[14]

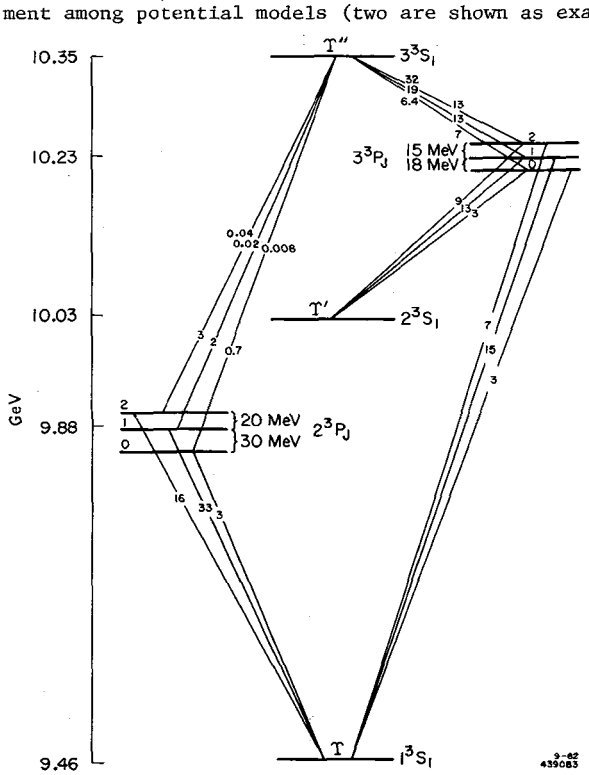


Fig. 4: The $^3S^3P$ spectrum which many theories expect for the $b\bar{b}$ bound system. The energy of the bound states is shown in GeV on the ordinate scale. Typical expectations for the $^3P_J$ fine structure is also shown. Two examples of transition rates are shown for $n^3S_1 \to \gamma n^3P_J$ transitions. The top set of numbers is from Ref. [2], the bottom set from Ref. [18]. Only the results from Ref. [18] are shown for the $n^3P_J \to \gamma(n-1)^3S_1$ transitions. See also Ref. [1].

$$M_T = 9459.7 \pm 0.6 \qquad (25)$$

is in close agreement with the DESY value. A resonance depolarization technique which accurately calibrates the energy of the VEP II storage ring yields the very small error.[15]

The first measurement of a photon signal that is likely coming from $3^3S_1 - 3^3P_J$ transitions in the T system has been reported by the CUSB detector.[16] Figure 5 shows their inclusive photon spectrum obtained from the decays of 64.7 k hadronic

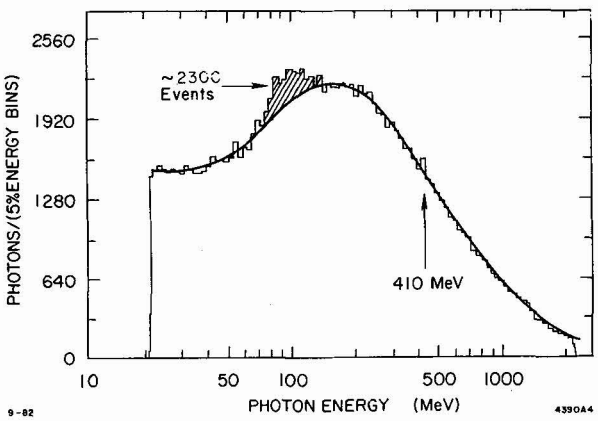


Fig. 5: The CUSB Collaboration's[16] inclusive photon spectrum obtained at the peak of the T" resonance at CESR. 67.4 k hadronic decays make up the spectrum of which 37.3 k are estimated to be T" decays. The solid line is a background calculated as described in the text. About 2 k events are seen in excess of the smooth background at about 100 MeV. The positions of the $3^3S_1 \to \gamma 2^3P_J$ transition, with $E_\gamma \sim 410$ MeV is also shown.

events. These events were obtained with the storage ring set at the peak of the T" resonance. It is estimated that 37.3 k of these events are T" resonance decays. The group has also obtained 13.8 k T resonance decays. The photon excess seen in Fig. 5 around 100 GeV is not seen in the T data, and is ascribed by the CUSB group as arising from the process,

$$3^3S_1(b\bar{b}) \to \gamma + 3^3P_J(b\bar{b}) \quad . \qquad (26)$$

The background curve shown in the figure is derived from the 13.8 k T and 12.3 k continuum events which were also obtained, and a Monte Carlo calculation of the $\pi^o\pi^o$ transitions. Subtracting the background fit in the region of the photon excess yields about 2300 (2289) photons above a background of 37.5 k counts, a statistically convincing effect. There is no sign of structure elsewhere in the spectrum and the agreement between the measurements and the calculated background is very good except in the 100 MeV region. When a slice of 12 bins around the signal is removed an excellent fit of the model background to the data is obtained with an $\chi^2$ value of 64 for 74 d.o.f. Figure 6 shows the result of subtracting the calculated background from the data. An impressive bump is evident at $E_\gamma \sim 100$ MeV; no statistically significant bump is seen at any other energy.

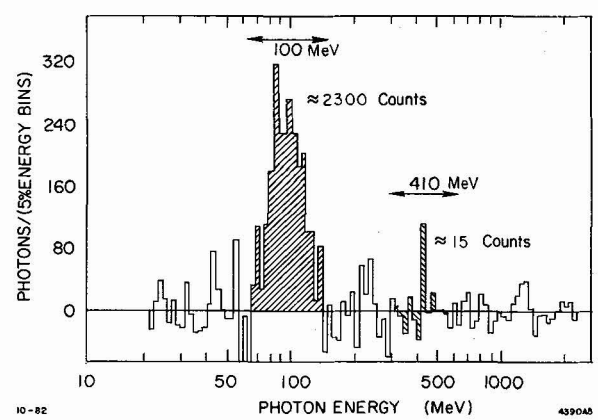


Fig. 6: The photon signal obtained from the data shown in Fig. 5 by subtracting the smooth curve from the measured data. An impressive bump is seen at about 100 MeV, with no other structure evident. A twelve bin slice about 410 MeV yields about 15 counts.

Using a 17% photon efficiency, obtained from Monte Carlo studies, the CUSB group finds

$$B(3^3S_1 \rightarrow 3^3P_J) = (33 \pm 3 \pm 3\%) \quad . \tag{27}$$

The CUSB group and the CLEO group have also looked for the processes,

$$3^3S_1(T'') \rightarrow \gamma\, 3^3P_J \rightarrow \gamma\, 2^3S_1(T') \rightarrow \ell^+\ell^- \tag{28}$$

and,

$$3^3S_1(T'') \rightarrow \gamma\, 2^3P_J \rightarrow \gamma\, 1^3S_1(T) \rightarrow \ell^+\ell^- \tag{29}$$

and,

$$3^3S_1(T'') \rightarrow \gamma\, 2^3P_J \rightarrow \gamma\, 1^3S_1(T) \rightarrow \ell^+\ell^- \tag{30}$$

Figure 7 shows the CUSB results for $\ell^+\ell^- = e^+e^-$, Fig. 8 for $\ell^+\ell^- = \mu^+\mu^-$.[16]

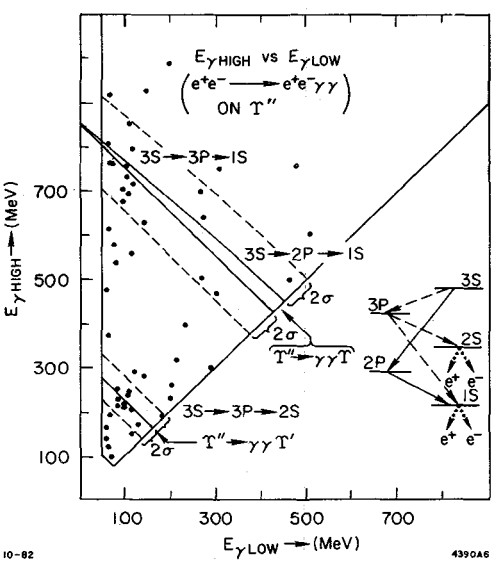


Fig. 7: The lower photon energy versus the higher energy photon from $T'' \rightarrow \gamma\gamma e^+e^-$ events. The $2\sigma$ resolution bands are shown. The data is from CUSB.[16]

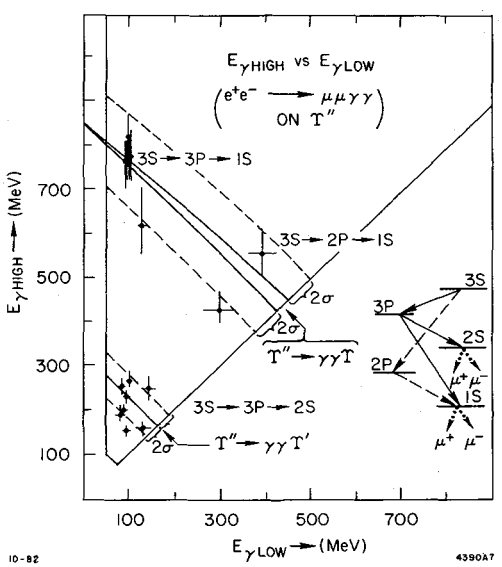


Fig. 8: The lower photon energy versus the higher photon energy from $T'' \rightarrow \gamma\gamma\mu^+\mu^-$ events. The $2\sigma$ resolution bands are shown. The data is from CUSB.[16]

Figures 9 and 10 show the CLEO results for $\ell^+\ell^- = \mu^+\mu^-$.[16] Considering the CUSB results first, the $\gamma\gamma\mu^+\mu^-$ data have considerably less background than the $\gamma\gamma e^+e^-$ data,

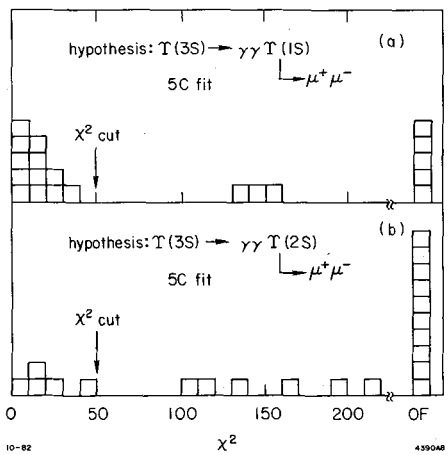


Fig. 9: The $\chi^2$ distribution from 5-c fits to events with hypothesis, a) $T(3S) \rightarrow \gamma\gamma T(1S) \rightarrow \gamma\gamma\mu^+\mu^-$, and b) $T(3S) \rightarrow \gamma\gamma T(2S) \rightarrow \gamma\gamma\mu^+\mu^-$. The data are from the CLEO Collaboration.[16] Events are accepted with $\chi^2 \leq 50$.

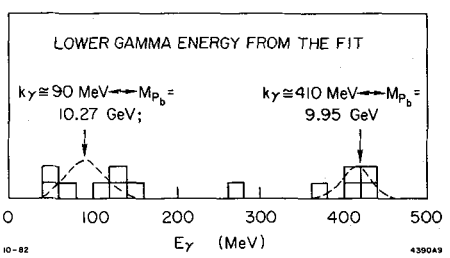


Fig. 10: The lower photon energy distribution obtained from the fits discussed in the text and Fig. 9. The CLEO Collaboration[16] claims two peaks indicating the observation of two $P_b$ states, one at $k_\gamma \simeq 90$ MeV, the other at $k_\gamma \simeq 410$ MeV.

but both show signals for processes (28) and (29). Only an upper limit is obtained for process (30) in the CUSB experiment based on the $\mu^+\mu^-$ data of Fig. 8 alone. The CLEO results shown in Fig. 9 indicate the $\chi^2$ distribution resulting from 5-c fits to process (29) and (30) in part (a) and process (28) in part (b). The events at $\chi^2 \leq 50$ yield the results of Fig. 10, the distribution of the lower photon energy from the fit. An indication of a signal is seen at about 100 MeV confirming the CUSB result. However, a signal is also seen at about 410 MeV which could arise from process (30).

The CLEO Collaboration states that these data indicate the presence of even charge conjugation intermediate states centered at M = 9.92 and 10.24 GeV which are identified as members of the $2^3P_J$ and $3^3P_J$ triplets of the bottomium system, respectively. Table 3 summarizes the CUSB and CLEO results on the radiative decays.

On examination of Table 3 and Fig. 6, several seeming contradictions arise. First, the measured cascade branching ratio from CLEO for process (30), implies the existence of a monochromatic photon at ~410 MeV which should be evident in Figs. 5 and 6. Using the CUSB data in Fig. 6 and their quoted resolution, I obtain an ~90% C.L. upper limit above the smooth background fit of about 230 counts. This corresponds to an inclusive branching ratio $\sum_J B\left(3^3S_1 \rightarrow \gamma\, 2^3P_S\right) < 3.0\%$ using the 17% photon efficiency quoted by the CUSB group for 100 MeV photons, and scaling to the CUSB result for $\sum_J B\left(3^3S_1 \rightarrow \gamma\, 3^3P_J\right)$. The CUSB photon efficiency should be higher for 400 MeV photons, yielding an even smaller upper limit at ~410 MeV. It has also been pointed out to me[17] that a similar problem exists in comparing the other cascade results to the data in Figs. 5 and 6 in that significant lines at about 200 MeV and 800 MeV would be expected given the cascade branching values of Table 3. The region about 800 MeV is particularly disturbing since it has a rather small background. The resolution of these apparent difficulties awaits more statistics, and results from other experiments.

In addition to determining the absolute branching fraction for the 3S → 3P transition, the CUSB group has attempted to gain some information on the splitting of the 3P lines and the individual branching ratio from the 3S to each of the $3^3P_J$ states. Figure 11 shows the way they calibrate their absolute energy scale for photons in the 100 MeV region using the $\pi^0$ mass. After an initial energy calibration with low energy sources and Bhabha electrons, an additional correction derived from a 7% observed shift of the $\pi^0$ mass is applied to photons. Note that ~50-200 MeV are typical photon energies derived from $\pi^0$'s decaying from the T'. The energy resolution for photons is obtained from a Monte Carlo simulation of the detector. Figure 12 shows the energy resolution obtained at $E_\gamma = 100$ MeV. A fit is made of first one, then two lines and finally three lines, with mass and amplitude of the lines

Table 3. Data Summary from CUSB and CLEO Collaborations on $P_b$ States

| Transition (See Fig. 3) | Br % (CUSB) | Br % (CLEO) |
|---|---|---|
| 3S → 3P (inclusive) | 33 ± 3 ± 3 | --- |
| 3S → 2P (inclusive) | <3 (~90% C.L.) | --- |
| 3S → 3P → 2S | 5.8 ± 2.6 | 4.8 ± 4.0 |
| 3S → 3P → 1S | 4.2 ± 1.5 | 2.4 ± 1.9 |
| 3S → 2P → 1S | <2.7 (90% C.L.) | 3.1 ± 2.2 |

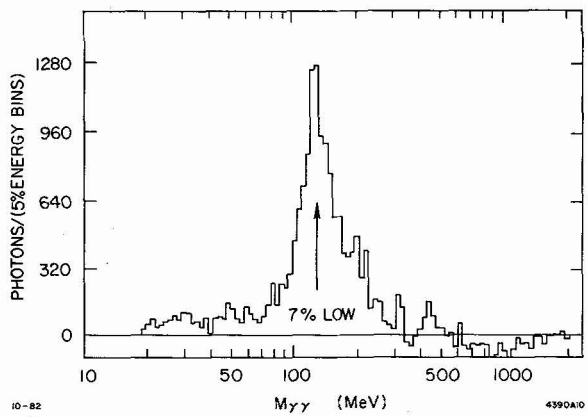


Fig. 11: $M_{\gamma\gamma}$ distribution from CUSB.[16] The $\pi^o$ mass is about 7% low. These data are used to calibrate the photon energy scale as discussed in the text.

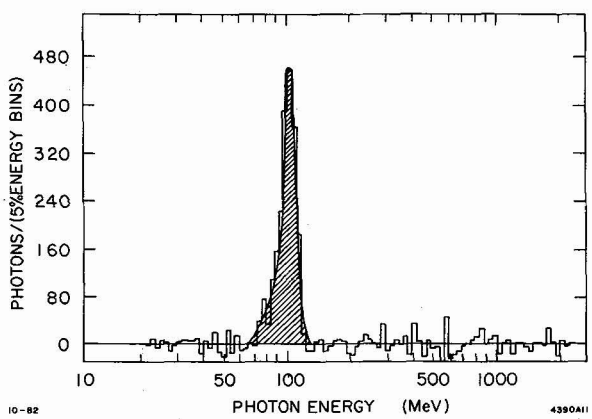


Fig. 12: The CUSB detector's photon energy resolution curve at about $E_\gamma$ = 100 MeV, as determined from Monte Carlo calculations.

variable, width fixed at the Monte Carlo resolution. The best fit favored three lines. Figure 13 shows the data with the three-line fit superimposed. Figure 14 shows the fit applied to the Cascade data, and Table 4 summarizes the results of the fits and compares these results to some model calculations. Note that only the c.o.g. are shown as the predictions are most reliable for this quantity. The comparison between experiment and theory is quite good. The agreement for the line positions obtained in the inclusive and exclusive cases is very good.

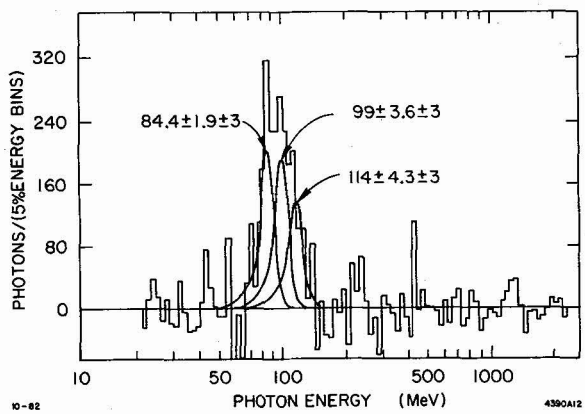


Fig. 13: A three-line fit made by the CUSB Collaboration[16] to the data of Fig. 6. The line shape used is shown in Fig. 12, only the amplitude and mean position of the three lines are allowed to vary in the fit. The photon energies obtained from the fit for each line are shown in MeV. The relative matrix element intensities obtained from the fit are $\Gamma(3^3S_1 \to 3^3P_J\gamma)/[k_\gamma^3\ (2J+1)] = 1.0 \pm 0.3,\ 1.0,\ 1.4 \pm 0.5$.

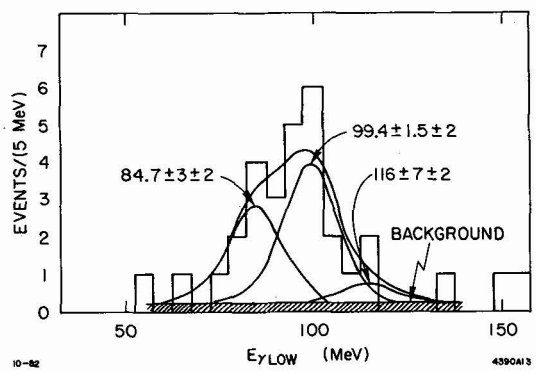


Fig. 14: The lower photon energy spectrum obtained from cascade events by including events in the $\pm 2\sigma$ bands shown in Figs. 7 and 8. Also shown is a three-line fit made by the CUSB Collaboration. In addition to the three photon lines, a flat background in included. The photon energies obtained from the fit to each line are shown in MeV. They are in very good agreement with the energies obtained in the fit to the inclusive spectrum in Fig. 13.

Table 4. Comparison of CUSB c.o.g. for $3^3P_J$ States with Theory

| CUSB [16] | Ref. [2] | Ref. [18] | Ref. [19] |
|---|---|---|---|
| 10.25 GeV | 10.25 GeV | 10.27 GeV | 10.24 GeV |

e. Experimental Expectations — In the next year or two one can expect a rapid expansion of our knowledge of the charmonium and bottomonium systems. This is due to the following developments:

- CESR is retooling for higher luminosity, a factor of 3-5 is projected.
- The ARGUS and Crystal Ball detectors are now installed at DORIS II, and DORIS II is operating at the T and T'.
- DCI at ORSAY has obtained 1.5 million J/ψ decays.
- The Mark III detector at SPEAR has obtained ~1 million J/ψ decays.

In addition, with the large samples of T decays expected over the next years, perhaps samples of 1-2 million decays, it will be possible to observe weak neutral

current effects which are predicted to be about 1% in T decays.[20] This can be accomplished by observing final state polarization correlations, or by using initial longitudinal polarization in $e^+e^-$ collisions.

3. Gluonic Mesons — The existence of an extensive spectrum of colorless, flavorless bound states of two or more gluons has been firmly predicted by quantum chromodynamics (QCD).[21] These gluonic bound states have been given the name, by their inventors,[22] gluonic mesons. It is expected that the lower lying gluonic meson states are bound states of mostly two gluons and in analogy to quarkonium, this system is called gluonium. It also is expected that gluonium states should be by far easier to observe than other gluonic mesons 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 $\iota(1440)$[23,24] and the $\theta(1640)$,[25] in a reaction thought to be a copious source of gluonium states,[26] namely,

$$J/\psi \rightarrow \gamma X \quad , \tag{31}$$

as shown in Fig. 15. 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.

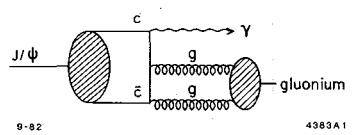


Fig. 15: Diagrammatic representation, in lowest order QCD, of the radiative decay of the J/ψ to gluonium.

a. "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.

i) By an extension of the OIZ rule gluonium state widths should be typically the geometric mean of OIZ allowed and OIZ suppressed decay widths,[27] i.e.,

$$\Gamma_{\text{gluonium}} \sim \sqrt{\Gamma_{\text{OIZ allowed}} \; \Gamma_{\text{OIZ suppressed}}} \quad . \tag{32}$$

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

$$\Gamma_g \sim \sqrt{\Gamma_f \; \Gamma_\phi} \sim 30 \text{ MeV} \quad . \tag{33}$$

This hypothesis has been more formally justified by using $SU(N)_{color}$ gauge theories and considering the limit of a large number of colors $N_c$.[28] Strong evidence contradicting this hypothesis has recently been presented. The formal justification using theories with $N_c \rightarrow \infty$ is probably not true due to the failure in this limit to predict the $N_c = 3$ expectation in the gluonium case.[29] In any case, it has been stated that a proof exists that "glueball" $\rightarrow$ gg is not suppressed in the [large $N_c$] limit; instead it is completely allowed.[30] One thus expects gluonium states to have typical hadronic widths.[31]

ii) Perturbative QCD indicates[32] a large rate for the process

$$J/\psi \rightarrow \gamma gg \quad . \tag{34}$$

Various authors[26] have used duality principles and other ideas together with the perturbative result to show that gluonium states should be copiously produced in the process.(31) This result, which is probably true, has been frequently extended to the expectation that any prominent signal in (31) where X is an "ordinary" hadron means X is a gluonium state. At least two notable exceptions exist to this rule,

the $\eta$ and $\eta'$ mesons, which by anyone's definition are not gluonium states. In particular, except for the $\eta_c$, the $\eta'$ meson has close to the largest radiative branching ratio from the $J/\psi$ measured to date[33] at about 0.4%. Though it probably has some gluonic content in its wave function,[34,29] it is not a gluonium state. Thus, we might reasonably expect that gluonium states are produced strongly in (31) but that $q\bar{q}$ states may be also. Other evidence is needed to decide the question of gluonium versus quarkonium in each particular case.[35]

iii) As has been previously stated, gluonium states are flavorless. Thus, it was initially expected that physical gluonium states would have flavor independent couplings to their decay channels. However, for the "light" gluonium states predicted 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 behavior.[35,37,38] Even for "pure" gluonium states, mass effects coupled with the allowed phase space of the decay can effectively break flavor singlet symmetry.[39,40] We thus conclude that a 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.

b. Some Candidates for Gluonium States and Some of Their Properties

i) $\iota(1440)$, $0^{-+}$ Meson — A state at 1440 MeV was first seen in the reaction,

$$J/\psi \to \gamma K^{\pm} K_S^0 \pi^{\pm} \quad , \tag{35}$$

by the Mark II collaboration at SPEAR. 23 They tentatively identified it as 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[41] using the reaction,

$$J/\psi \to \gamma K^+ K^- \pi^0 \quad . \tag{36}$$

However, much more $J/\psi$ data was needed ($2.2 \times 10^6$ decays in total) before the Crystal Ball collaboration was able to measure the $J^P$ of the state as $0^-$.[24]

This $0^{-+}$ state may have been previously observed in $p\bar{p}$ annihilations.[42] The state seen in the $p\bar{p}$ case was named E(1420). However, the $0^{-+}$ assignment from that experiment was not considered conclusive[4,43] and so the E(1420) was accepted to be the $J^{PC} = 1^{++}$ state seen in $\pi^- p$ interactions.[44] Thus, the Crystal Ball and Mark II collaborations (in collaboration) have named[24] the $0^{-+}$ state seen in $J/\psi$ radiative decays the $\iota(1440)$.

The properties of the $\iota$ as measured by the Mark II and Crystal Ball collaborations are shown in Table 5. Thus,

$$B(J/\psi \to \gamma\iota) \geq B(J/\psi \to \gamma\eta') \quad . \tag{37}$$

One new result, from the Crystal Ball,[45] shown in Table 5, is an upper limit for the process,

$$B(J'\psi \to \iota)\ B(\iota \to \eta\pi\pi) \quad . \tag{38}$$

This upper limit is in mild conflict with the hypothesis that the $K\bar{K}\pi$ decay of the $\iota$ is dominated by $\delta\pi$,[23,24] an important element in the spin parity analysis of the $\iota$.

ii) $\theta(1640)$, $2^{++}$ Meson — This state was first observed in the process,

$$J/\psi \to \gamma\eta\eta \quad , \quad \eta \to \gamma\gamma \tag{39}$$

by the Crystal Ball collaboration at SPEAR.[25] The analysis was based on a sample of $2.2 \times 10^6$ $J/\psi$ events. Figure 16a 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'[4] and variable amplitude, the other

Table 5. ι(1440) Parameters

| Parameter | Mark II [23] | Crystal Ball [24] |
|---|---|---|
| M(MeV) | $1440\ ^{+10}_{-15}$ | $1440\ ^{+20}_{-15}$ |
| Γ(MeV) | $50\ ^{+30}_{-20}$ | $55\ ^{+20}_{-30}$ |
| $B(J/\psi \to \gamma\iota) \times B(\iota \to K\bar{K}\pi)$[a] | $(4.3 \pm 1.7) \times 10^{-3}$[b] | $(4.0 \pm 0.7 \pm 1.0) \times 10^{-3}$[c] |
| $B(J/\psi \to \gamma\iota) \times B(\iota \to \eta\pi\pi)$[d] | --- | $<2 \times 10^{-3}$ (90% C.L.) |
| 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 Ref. [23]. 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.

[d] Reference [45]: Note that one experiment gives $B(\delta \to \eta\pi\pi)/B(\delta \to K\bar{K}) = 1.4 \pm 0.6$, see Ref. [46], and $\iota \to \delta\pi$ has been measured as the dominant decay for the $K\bar{K}\pi$ final state.[23,24]

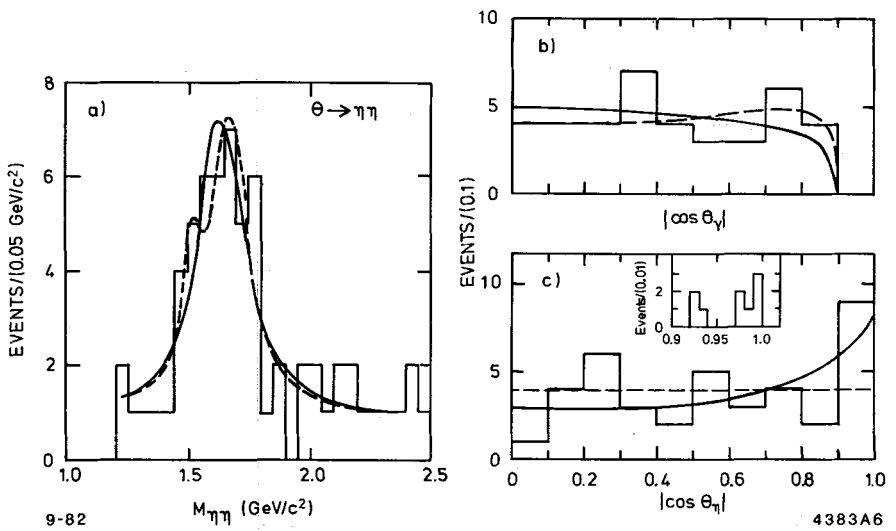


Fig. 16: a) The γγ mass distribution from the process $J/\psi \to \gamma\eta\eta$ for $M_{\eta\eta} < 2.5$ GeV. The solid curve represents a fit to one Breit-Wigner resonance plus a flat background. The dashed curve represents a fit to two Breit-Wigner resonances, one with mass and width fixed at the f' and variable amplitude, the other with all three parameters variable; a flat background is also included. b) $|\cos\theta_\gamma|$. c) $|\cos\theta_\eta|$ 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 are from the Crystal Ball Collaboration.

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 Ref. [25]; however, it was done in Ref. [40] 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

$$J/\psi \to \gamma\theta \quad , \quad \theta \to \eta\eta \quad . \tag{40}$$

$\theta_\gamma$ 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 ηη decay establishes the parity as +. Figures 16b and 16c 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 dashed 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. 16c shows these events on an expanded scale. This is not evidence that these events are anomalous.

The Crystal Ball and the Mark II have searched for,

$$J/\psi \to \gamma\theta \quad , \quad \theta \to \pi\pi \quad . \tag{41}$$

Figure 17 shows the Mark II results for the charge π's from 720 K J/ψ decays and the Crystal Ball results for the $\pi^o$'s from 2200 k J/ψ decays. The binning in $M_{\pi\pi}$ is 50 MeV/bin for both experiments. As summarized in Table 6, only upper limits were obtained from both experiments.

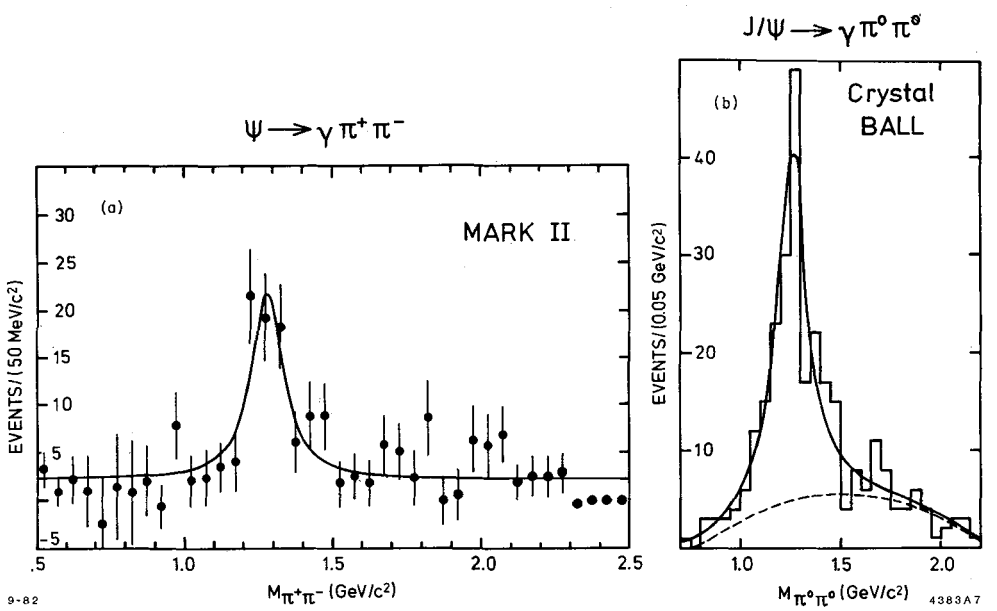


Fig. 17: a) $M_{\pi\pi}$ mass distribution from $J/\psi \to \gamma\pi^+\pi^-$ (the Mark II Collaboration) the fit represents fit to f(1270) plus background. b) $M_{\pi\pi}$ mass distribution from $J/\psi \to \gamma\pi^o\pi^o$ (Crystal Ball Collaboration). The solid curve represents a fit to f(1270) plus background. The dashed curve represents the background estimate.

Table 6. Summary of θ Parameters and f' Branching Ratios Obtained from fit of θ and f' to Mass Distributions

| Parameter | Crystal Ball [40] | Mark II |
|---|---|---|
| M(MeV) | 1670 ± 50 ($\eta\eta$) | 1700 ± 20 ($K^+K^-$) |
| Γ(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.

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

$$J/\psi \to \gamma\theta \quad , \quad \theta \to K^+K^- \quad . \tag{42}$$

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

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

$$J/\psi \to K^+K^-(\gamma) \quad . \tag{43}$$

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

Figure 18 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,

$$1.6 < M_{K^+K^-} < 1.89 \text{ GeV} \quad , \tag{44}$$

using a maximum likelihood to fit to the form,

$$f(M_{K^+K^-}) = A + \frac{B}{\left(M^2_{K^+K^-} - M^2_\theta\right)^2 + M^2_\theta \Gamma^2_\theta} + \frac{C}{\left(M^2_{K^+K^-} - M^2_{f'}\right)^2 + M^2_{f'}\Gamma^2_{f'}} \quad . \tag{45}$$

$M_{f'}$ and $\Gamma_{f'}$ are fixed at their accepted values[4] while A, B, C, $M_\theta$ and $\Gamma_\theta$ are determined by the fitting procedure. The results of the fit are summarized in Table 6. 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[47] a signal in the process,

$$J/\psi \to \gamma\rho^o\rho^o \quad , \quad \rho^o\rho^o \to \pi^\pm\pi^\pm\pi\,\pi \quad . \tag{46}$$

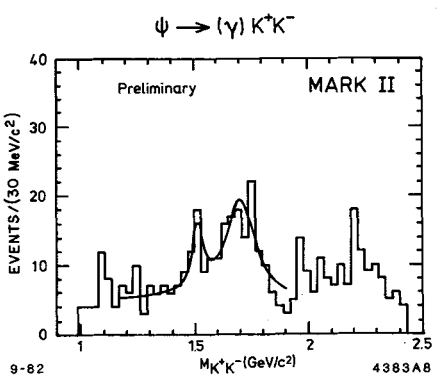


Fig. 18: A preliminary $M_{K^+K^-}$ distribution from $J/\psi \to (\gamma)\ K^+K^-$ (Mark II Collaboration). The solid line is the fit described in the text (cf Eq. (45)). Signals at the f' and θ are obtained.

Figure 19 shows their $4\pi$ mass spectrum for events that satisfy the $\gamma\rho^o\rho^o$ hypothesis.

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

$$M_{res.} = 1650 \pm 50 \text{ MeV}$$
$$\Gamma_{res.} = 200 \pm 100 \text{ MeV} \quad . \tag{47}$$

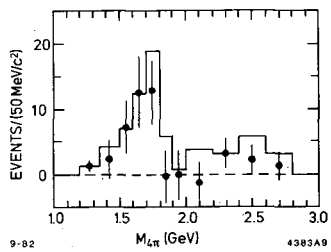


Fig. 19: The $\rho^o\rho^o$ mass spectrum obtained from the analysis[47] of the process $J/\psi \to \gamma 2\pi^+ 2\pi^-$ (Mark II Collaboration).

These values are comparable to the mass and width of the $\theta$ shown in Table 6. Also, they obtain,

$$B(J/\psi \to \gamma\rho^o\rho^o,\ M_{\rho^o\rho^o} < 2 \text{ GeV})$$
$$= (1.25 \pm 0.35 \pm 0.4) \times 10^{-3} \quad . \tag{48}$$

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

$$Br(J/\psi \to \gamma\rho\rho,\ M_{\rho\rho} < 2 \text{ GeV}) = (3.75 \pm 1.05 \pm 1.3) \times 10^{-3} \quad . \tag{49}$$

This branching ratio is approximately equal to the $\iota(1440)$ and $\eta'$ branching ratios. As a strong not 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 $\theta$ meson.

$\rho\rho$ enhancements in this mass range have previously been reported in hadronic reactions[48] and observed in final states produced by photon-photon collisions.[49] Figure 20 shows such an enhancement from the paper of H. Braun, et al.[48] The process studied was,

$$p\bar{p} \to 3\pi^+ 3\pi^- \pi^o \text{ at } 5.7 \text{ GeV/c} \quad . \tag{50}$$

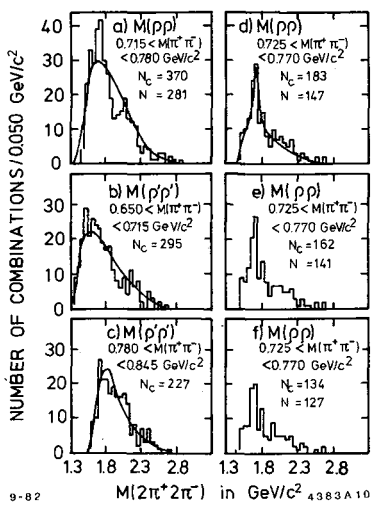


Fig. 20: The $M_{2\pi^+2\pi^-}$ distributions obtained in the process $p\bar{p} \to 3\pi^+3\pi^-\pi^o$ selected for $2\pi^+2\pi^-$ systems having two distinct $\pi^+\pi^-$ mass combinations in the various M+- intervals as indicated. Here $N_c$ and N represent, respectively, the total number of combinations 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 represent 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.[48]).

New results from the Crystal Ball Collaboration have been presented at this Conference[45] on the process,

$$J/\psi \to \gamma\eta\pi\pi \quad . \tag{51}$$

Figure 21 shows the $M_{\eta\pi^+\pi^-}$ and $M_{\eta\pi^o\pi^o}$ distributions obtained from the analysis of $2.2 \times 10^6$ J/$\psi$ decays. A large signal at $M_{\eta\pi\pi} = M_{\eta'}$ is evident as is a broad enhancement centered at about 1700 MeV. Figure 22 shows the Dalitz plots for the $\eta\pi^+\pi^-$

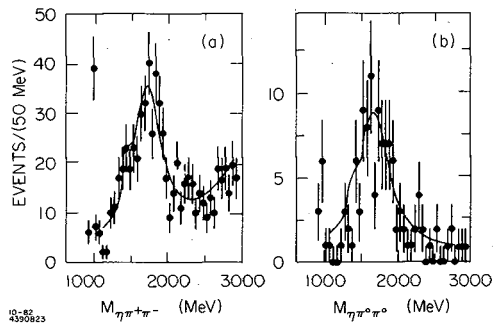


Fig. 21: a) $\eta\pi^+\pi^-$ and b) $\eta\pi^0\pi^0$ mass spectra for $J/\psi \to \gamma\eta\pi\pi$ events. The solid curve is a two resonance fit, one resonance fixed at the $\iota$ mass and width and having variable amplitude, the other having all parameters variable. The mass, width and amplitude of the broad structure seen in the figures is essentially given by Eqs. (52) and (53). The $\iota$ upper limit obtained from the fit is given in Table 5.

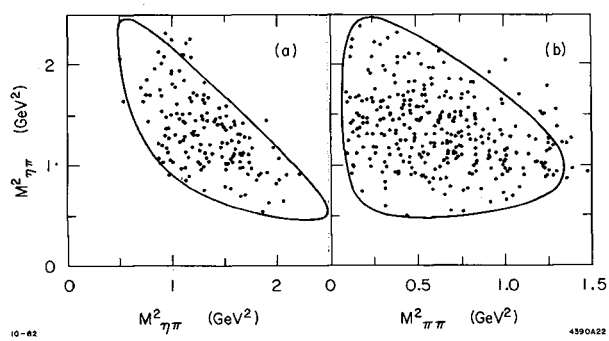


Fig. 22: The Dalitz plots for $J/\psi \to \gamma\eta\pi^+\pi^-$ events with $1600 < M_{\eta\pi\pi} < 1850$ MeV. The boundaries are calculated for $M_{\eta\pi\pi} = 1710$ MeV. Note that part (b) has two entries per event.

events with $1600 < M_{\eta\pi\pi} < 1850$ MeV. The boundaries are calculated for $M_{\eta\pi\pi} = 1700$ MeV. No structure is seen in these Dalitz plots, and thus the broad enhancement is apparently not strongly associated with a $\delta$, or any other resonances in either $\eta\pi^\pm$ or $\pi^+\pi^-$. For example, the decay $\delta \to \eta\pi$ would produce bands in the region of $M^2_{\eta\pi} = 0.96$ GeV$^2$.

The Crystal Ball Collaboration suggests three possible interpretations for this new enhancement. First, the $\eta\pi\pi$ mass distribution for events with a prompt $\gamma$ may be quite different from Lorentz invariant phase space. Then the enhancement could arise from the (non-resonant) decay of the $J/\psi$ to a photon plus two gluons. Secondly, the enhancement could be a group of resonances. A third possibility is that it is a single resonance. The data may be fit with a single Breit-Wigner line shape. For the fit, the $\eta\pi^+\pi^-$ and $\eta\pi^0\pi^0$ mass spectra are fit simultaneously with the mass and width parameters constrained to be the same for both channels. A constant background was assumed for the $\eta\pi^0\pi^0$ channel. For $\eta\pi^+\pi^-$, the background was determinded by fitting the $\gamma\gamma\pi^+\pi^-$ mass spectrum for events with a $\gamma\gamma$ mass combination in the $\eta$ sidebands ($320 < M_{\gamma\gamma} \lesssim 470$ MeV or $610 < M_{\gamma\gamma} < 760$ MeV). The fit has a $\chi^2$ of 66 for 69 d.o.f. and results in,

$$\begin{aligned} M &= 1710 \pm 45 \text{ MeV} \quad , \\ \Gamma &= 530 \pm 110 \text{ MeV} \quad , \end{aligned} \tag{52}$$

where the errors include estimates of the systematic uncertainty.

Using the number of events in the peak, as determined by the fit and an efficiency obtained from Monte Carlo calculations of 18% (6.6%) for $J/\psi \to \gamma\eta\pi^+\pi^-$ ($\gamma\eta\pi^0\pi^0$), one obtains the branching ratios,

$$\begin{aligned} B(J/\psi \to \gamma\eta\pi^+\pi^-) &= (3.5 \pm 0.2 \pm 0.7) \times 10^{-3} \quad , \\ B(J/\psi \to \gamma\eta\pi^0\pi^0) &= (2.3 \pm 0.3 \pm 0.7) \times 10^{-3} \quad , \end{aligned} \tag{53}$$

when the first error is statistical and the second is systematic. These branching ratios when added are comparable or larger than those for the $\iota$ and $\eta'$.

The fit shown in Fig. 21 also includes a term for the ι, from which the upper limit in Table 5 was obtained. The addition of the ι term does not effect the results (52), (53) within the quoted error.

The results discussed on exclusive radiative decays of the J/ψ can be combined with inclusive measurements to create an interesting, plausible scenario. Figure 23a shows a preliminary inclusive γ spectrum, from the Crystal Ball Collaboration,[50] for the process,

$$J/\psi \to \gamma X \quad . \tag{54}$$

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. 23b. What this figure suggests is that:

$$B\left(J/\psi \to \gamma\iota(1440)\right) \simeq B\left(J/\psi \to \gamma\eta'(958)\right) \quad ; \tag{55}$$

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,

$$B\left(J/\psi \to \gamma\theta(\text{region})\right) \approx 2\text{-}3\ B(J/\psi \to \gamma\iota) \quad . \tag{56}$$

If the presently known contributions in the θ (region) are added up we obtain

$$B\left(J/\psi \to \gamma\theta(\text{region})\right) > B(J\psi \to \gamma\theta + \gamma\rho\rho + \gamma\eta\pi\pi) = (11.2 \pm 2.0) \times 10^{-3} \quad . \tag{57}$$

This is almost the largest branching ratio seen in J/ψ radiative decays being about that of the $\eta_c(2982)$.

Other candidates for gluonic mesons have been presented at this conference. Table 7 summarizes these results. It has been thought for some time that $\pi^- p \to \phi\phi n$ would be a good place to search for gluonic mesons since this process may be otherwise OZI suppressed.[40,51]

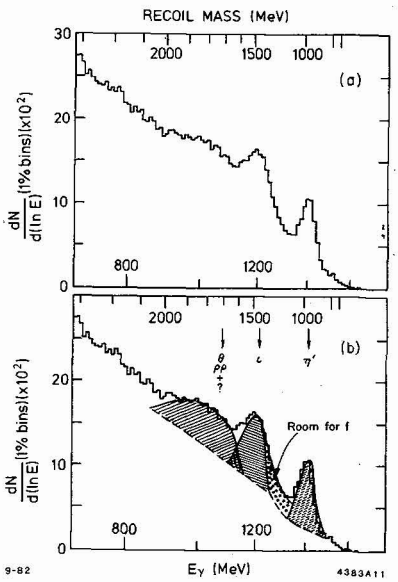


Fig. 23: a) A preliminary inclusive γ spectrum from the process J/ψ → γX obtained by the Crystal Ball Collaboration.
b) A plausible scenario for a future unfolding of the spectrum. See text for explanation.

Table 7. Additional Gluonic Meson Candidates

| Name | $I^G$ | $J^{PC}$ | Mass (MeV) | Full Width | Partial Width |
|---|---|---|---|---|---|
| From BLN/CUNY $\pi^- p \to \phi\phi n$ [52] | | | | | |
| $g_t(2160)$ | $0^+$ | $2^{++}$ | 2160 ± 37 | 315 ± 62 | $\Gamma_S/\Gamma_D = 100$ ≈ S wave |
| $g'_t(2310)$ | $0^+$ | $2^{++}$ | 2310 ± 72 | 192 ± 50 | $\Gamma_D/\Gamma_S = 37$ ≈ D wave |
| From TASSO [49] | | | | | |
| $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ | -- | -- | 2100 ± 10 | 94 ± 21 | $\Gamma_{\gamma\gamma}$*Br*(2J+1) = 1.6 ± .4 KeV |

Two candidates have emerged from a partial wave analysis of the $\phi\phi$ system from new BLN/CUNY data presented at this conference.[52] The TASSO group has also presented a candidate[49] seen in $e^+e^- \to e^+e^-\pi^+\pi^-\pi^+\pi^-$. One would expect, however, that since gluons have zero electric charge, such a process would be an unlikely place to see gluonic meson production.

c. Insight from Theory on the Gluonium Status of the Candidates

i) $\iota(1440)$ — A number of theorists have made insistent arguments that the $\iota(1440)$ is a $0^{-+}$ gluonium state.[53] Others have suggested that $\iota$ is a member of the radially excited $0^{-+}$ nonet of $q\bar{q}$ mesons,[54,35] but certainly not a gluonium state.[29,7] Why can't the $\iota$ belong to the $2^1S_0$ nonet of $q\bar{q}$ mesons? The major arguments against this[53] are:

- $\iota(1440)$ has the wrong mass to fit with the "other" $2^1S_0$ nonet members.
- The radiative decay of the $\iota$ from the $J/\psi$ is too large.

Unfortunately, both of these arguments are presently uncertain. First, as has been pointed out by others[4] the $2^1S_0$ nonet is not at all well established. The favored members of the $2^1S_0$ nonet used in Ref. [53] (Chanowitz and Donogne) are the $\pi(1270)$, $K'(1440)$ and $\zeta(1275)$. I quote from the revised 1982 particle data tables[4]:

$\pi'(1270)$ — Not a well established resonance,
$K'(1400)$ — only appears in the meson listing, it is omitted from the table because it needs confirmation,
$\zeta(1275)$ or $\eta(1275)$ — not in the PDT tables, "seen in phase shift analysis of $\eta\pi\pi$ 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 $J/\psi$ to the $\iota$. Consider the relationship of $B(J/\psi \to \gamma\iota)$ to $B(J/\psi \to \gamma\eta')$. The $\iota$ being a $0^{-+}$ meson we can extend the ITEP formalism used to describe the decays to $\gamma\eta$ and $\gamma\eta'$.[34]

$$\frac{B(J/\psi \to \gamma\iota)_{QCD}}{B(J/\psi \to \gamma\eta')_{QCD}} \simeq \frac{|\langle 0|J_{ps}|\iota\rangle_{QCD}|^2}{|\langle 0|J_{ps}|\eta'\rangle_{QCD}|^2} \frac{|\vec{p}_\iota|^3}{|\vec{p}_{\eta'}|^3} \tag{58}$$

where,

$$\langle 0|J_{ps}|\eta'\rangle_{QCD} \simeq (0.7)\ \sqrt{3/2}\ f_\pi M_{\eta'}^2, \tag{59}$$

and,

$$\langle 0|J_{ps}|\iota\rangle_{QCD} \simeq C_\iota\ \sqrt{3/2}\ f_\pi M_\iota^2 \tag{60}$$

$f_\pi \simeq 133$ MeV is the $\pi \to \mu\nu$ decay constant, and $|\vec{p}_\iota(\eta')|$ is the absolute value of the momentum of the $\iota(\eta')$ in the decay. Note that

$$\frac{B(J/\psi \to \gamma\iota)}{B(J/\psi \to \gamma\eta')} \simeq 1 \to C_\iota \simeq 0.55 C_{\eta'} = 0.39 \tag{61}$$

This value of $C_\iota$ is considered a quite reasonable estimate by Novikov and Shifman[55] if the $\iota$ is a radial excitation of the $\eta'$. Perhaps this result can be formally justified. (Also see Ref. [35].)

One should remember, however, that due to nonperturbative effects, the $0^-$ channel is rather tricky in this mass range and beyond.[29] The tensor channel which decouples from direct instantons should be easier to understand.

ii) $\theta(1696)$ — Almost every theory, including the Bag model,[56] the ITEP QCD sum rules,[29] Lattice gauge theory calculations,[57] predict a $2^{++}$ gluonium state at about 1700 MeV, e.g., the ITEP estimate is

$$M_{2^{++}} = 1650 \pm 350 \text{ MeV} \tag{62}$$

The tensor gluonium channel does not couple to large nonperturbative (instantons) effects,[29] 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.[30]

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.[35,36,38] One of these mixing models initially developed by Rosner[36] and recently refined by Schnitzer[38] 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 Ref. [35] 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.[58,40]

$$\theta_{4q} = s\bar{s}(u\bar{u} + d\bar{d}) \quad , \tag{63}$$

with fall apart mode $\phi\omega$.

In each of these models a definite prediction is made for the ππ, KK and ηη (and in one case the ρρ) decay modes of the θ.

- θ related to $2^{++}$ gluonium state,[38]

$$\frac{B(\theta \to \eta\eta)}{B(\theta \to K\bar{K})} < 0.2 \quad , \quad \frac{B(\theta \to \pi\pi)}{B(\theta \to K\bar{K})} < 1 \ (\simeq 0) \tag{64}$$

- θ related to $2^{++}$ $q\bar{q}$ radial excitation,[35]

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

$$\frac{B(\theta \to \pi\pi)}{B(\theta \to K\bar{K})} > 1 \tag{65}$$

- related to $2^{++}$ $q\bar{q}q\bar{q}$ state, 58,40 (Eq. 62),

$$\frac{B(\theta \to \eta\eta)}{B(\theta \to K\bar{K})} = 0.5 \qquad B(\theta \to \pi\pi) = 0$$

$$B(\theta \to \rho\rho) = 0 \tag{66}$$

The data yield the following values (see Table 6),

$$\frac{B(\theta \to \pi\pi)}{B(\theta \to K\bar{K})} < 1 \quad , \quad \frac{B(\theta \to \eta\eta)}{B(\theta \to K\bar{K})} = 0.33 \pm 0.2 \quad , \quad \frac{B(f' \to K\bar{K})}{B(\theta \to K\bar{K})} \ll 1 \quad . \tag{67}$$

On comparing (67) with (64), (65), and (66) we conclude,

- $2^{++}$ gluonium hypothesis is consistent with the data.
- $2^{++}$ radial excitation hypothesis fails badly.
- $2^{++}$ $q\bar{q}q\bar{q}$ is consistent with (67); however, if the Mark II's ρρ 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 ηη and $K\bar{K}$ modes.

d. 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 and other gluonic meson states. I list some of these below:

i) The Mark II Collaboration measures the $J^P$ of $K^+K^-$ enchancement in the θ mass region.

ii) The Crystal Ball and/or Mark II Collaborations measure the $J^P$ of the ρρ 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 ~ 2 GeV for the process, $\gamma\gamma \to \chi$. Since gluons have no electric charge while quarks do, this process should not copiously produce gluonium states.

v) Much more $J/\psi$ data is needed, on the order of 4 million events, to better measure $\iota \to \pi\pi\eta$, ... 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 $J/\psi \to \gamma\chi$.

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

vii) pp or $p\bar{p}$ production of gluonium via gluon fusion[59] offers independent verification of gluonium states.

viii) Presently available data on $\pi^- p \to \phi\phi n$ is somewhat limited. Much more data would be useful in exploring high mass gluonic meson production.[60]

ix) Photo production, via vector dominance could be useful in exploring $\rho^o\rho^o$ final states,[61] or perhaps $\theta$ production as shown in Fig. 24.

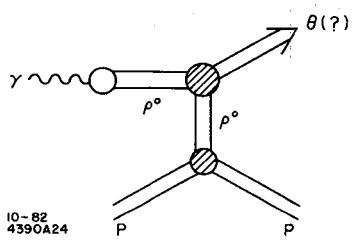


Fig. 24: A possible mechanism for $\theta$ photoproduction if $\theta \to \rho^o\rho^o$.

As these experiments are completed over the next few years, hopefully the present confusion in the gluonic meson sector will abate somewhat.

Acknowledgements — I would like to thank my scientific secretaries, Dr. D. Olivier and Dr. B. Pietrzyk for their substantial help during the Conference. I also express my appreciation to the organizers of the conference for an interesting and exciting ten days of physics in Paris.

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Discussion

*A. Efremov. (Dubna). - There is one more argument against ι(1440) as a gluonium. It is a model of strong mixing in the radially excited pseudo-scalar nonet, which is based on analogy with mixing in the ground-state nonet (A.T. Filippov Prepr. JINR E2-82-394). Comparing the predicted mass formulae and ratios of the isoscalar particle production with existing data on the π'(1205), ζ(1275) and ι(1440) resonances one concludes that all these states can be placed in the radial nonet. The prediction of this model for $\eta \to \gamma\gamma$ is 0.65 - 0.75 KeV, which is larger than the value quoted by Particle Data Group.*