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RADIATIVE DECAYS OF THE ψ' TO ALL-PHOTON FINAL STATES*

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ABSTRACT

A sample of 1.8×10^6 produced ψ''s collected by the Crystal Ball detector at SPEAR is used to measure branching ratios of selected radiative ψ' decays to non-charmonium states which decay into photons. A sample of 2.2×10^6 produced J/ψ's is used to measure the same radiative decays from the J/ψ. The ratios

$$\mathrm{BR}(\psi' \to \gamma \mathrm{f})/\mathrm{BR}(J/\psi \to \gamma \mathrm{f}) = 9 \pm 3\%$$
$$\mathrm{BR}(\psi' \to \gamma\theta)/\mathrm{BR}(J/\psi \to \gamma\theta) < 10\% - 15\%$$
$$\mathrm{BR}(\psi' \to \gamma\eta)/\mathrm{BR}(J/\psi \to \gamma\eta) < 1.8\%$$
$$\mathrm{BR}(\psi' \to \gamma\eta')/\mathrm{BR}(J/\psi \to \gamma\eta') < 2.6\%$$

have been obtained. (Upper limits are 90% confidence level. The upper limit for the radiative decay to the θ is uncertain due to the possible presence of an f′ signal in the J/ψ data.) Assuming these decays proceed via the annihilation of the initial quark and antiquark to a photon and two gluons, these ratios are predicted by lowest order QCD to be the same as the ratio of leptonic branching ratios of the ψ' and J/ψ, or 12.0 ±2.2%. There currently exists no compelling explanation for the discrepancy between the ratios measured for the last two decays and the theoretical expectation.

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I. Introduction

The measured branching ratios of the ψ' to non-charmonium states present a problem for lowest order QCD, as recently emphasized by a study performed by the Mark II collaboration.[2,3] In lowest order, the partial width of the J/ψ or ψ' to three gluons is proportional to the square of the wavefunction at the origin, as is the partial width to leptons. If it is assumed that the hadronization of the gluons is not substantially different at the mass of the ψ' than at the mass of the J/ψ, one obtains[2]

$$\frac{\mathrm{BR}(\psi' \to X)}{\mathrm{BR}(J/\psi \to X)} = \frac{\mathrm{BR}(\psi' \to 3g)}{\mathrm{BR}(J/\psi \to 3g)} = \frac{\mathrm{BR}(\psi' \to l^+l^-)}{\mathrm{BR}(J/\psi \to l^+l^-)} \tag{1}$$

where X is an arbitrary non-charmonium state, and l^+l^- denotes either e^+e^- or $\mu^+\mu^-$. Using the measured leptonic branching ratios of the J/ψ and ψ',[4] we expect

$$\frac{\mathrm{BR}(\psi' \to X)}{\mathrm{BR}(J/\psi \to X)} = 12.0 \pm 2.2\% \tag{2}$$

Table 1 shows the value of this ratio for several final states as reported by the Mark II.[2] As can be seen, most of the measured ratios are in good agreement with the theoretical prediction. However, two final states, $\rho\pi$ and $K^{*\pm}K^{\mp}$, are unobserved on the ψ' at levels five and sixteen below the predicted rate at 90% confidence level.

Final State X	Ratio (%)	Final State X	Ratio (%)
$p\bar{p}$	8.6 ±2.4	$2\pi^+2\pi^-\pi^0$	9.5±2.7
$p\bar{p}\pi^+\pi^-$	15.1 ±4.1	$3\pi^+3\pi^-\pi^0$	13.0 ±7.0
$K^+K^-\pi^+\pi^-$	22.2 ±9.0	$K^{*\pm}K^{\mp}$	< 2.07 (90% C.L.)
$p\bar{p}\pi^0$	14.0 ±6.3	$\rho\pi$	< 0.63 (90% C.L.)

Table 1 Ratios of ψ' to J/ψ branching ratios for hadronic decays (Mark II).

A class of decays not considered in the Mark II study was that of radiative decays. The lowest order expression for the partial width of the J/ψ or ψ' to a photon and two gluons also depends on the square of the wavefunction at the origin,[5] and we again expect

$$\frac{\mathrm{BR}(\psi' \to \gamma Y)}{\mathrm{BR}(J/\psi \to \gamma Y)} = 12.0 \pm 2.2\% \tag{3}$$

for any non-charmonium hadronic state Y. We describe here a comparative study of radiative decays of the ψ' and J/ψ using the Crystal Ball detector at SPEAR. The Crystal Ball has been described elsewhere;[6] its main component is a highly segmented array of NaI(Tl) crystals covering 94% of 4π. As such, the detector is optimized for photon detection, and we restrict this study to decays of the ψ' and J/ψ which contain only photons in the final state. Specifically, we measure the branching ratios of the reactions J/ψ, $\psi'\to\gamma f$, $\gamma\theta$, $\gamma\eta$, and $\gamma\eta'$. We measure the branching ratios BR ($J/\psi,\psi'\to\gamma f$) and BR ($J/\psi,\psi'\to\gamma\theta$) with standard exclusive analyses. The reactions $J/\psi,\psi'\to\gamma\eta$ and $J/\psi,\psi'\to\gamma\eta'$ are studied via final states consisting of seven or more photons, necessitating the use of an analysis in which not all of the photons are seperately identified.

We search for the decays $J/\psi,\psi' \to \gamma f$ via the $\pi^0\pi^0$ decay mode of the f. Figure 1a shows the $\pi^0\pi^0$ invariant mass distribution for events which are consistent with the hypothesis $J/\psi \to \gamma\pi^0\pi^0$; Fig. 1b shows the same plot for the ψ' data.† The J/ψ plot is fit to three non-interfering Breit-Wigner line shapes and a third-order polynomial background. The lowest-mass Breit-Wigner (corresponding to the f) has variable mean and width. The two higher-mass Breit-Wigner line shapes are included to account for structures seen at 1.7 and 2.1 GeV in the $\pi^+\pi^-$ invariant mass distribution in the decay $J/\psi \to \gamma\pi^+\pi^-$ by the Mark III collaboration.[7] The means and widths of these line shapes are fixed to the best fitted values found in the Mark III study. We fit the analogous ψ' distribution with a flat background and a single Breit-Wigner line shape with mean and width fixed to the best fitted values for the f signal on the J/ψ. We obtain the following branching ratios:

$$\begin{aligned} \mathrm{BR}(J/\psi \to \gamma f) &= (1.7 \pm 0.1 \pm 0.5) \times 10^{-3} \\ \mathrm{BR}(\psi' \to \gamma f) &= (1.5 \pm 0.4 \pm 0.5) \times 10^{-4} \\ \frac{\mathrm{BR}(\psi' \to \gamma f)}{\mathrm{BR}(J/\psi \to \gamma f)} &= 9 \pm 3\% \end{aligned} \tag{4}$$

where the first errors are statistical and the second systematic.‡ This value of BR $(J/\psi \to \gamma f)$ agrees with the average value obtained from other experiments, $(1.6 \pm 0.4)\times 10^{-3}$, and the ratio of branching ratios is consistent with the theoretical expectation in Eq. (3).

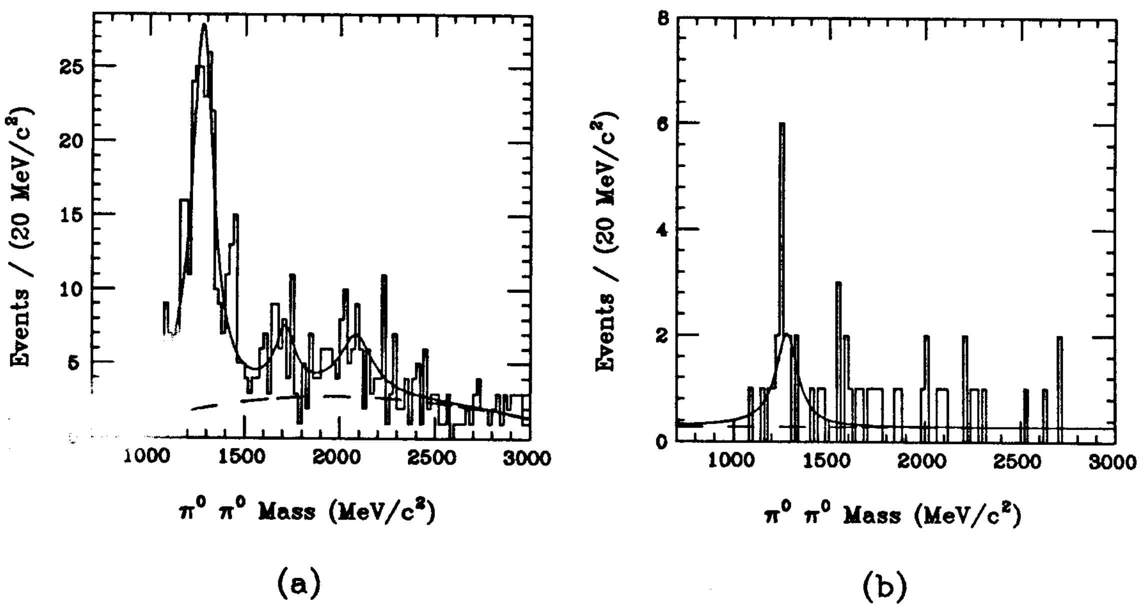

Fig. 1 $\pi^0\pi^0$ invariant mass distributions in (a) $J/\psi \to \gamma\pi^0\pi^0$ and (b) $\psi' \to \gamma\pi^0\pi^0$. (Fits described in text.)

We have performed a similar search for the decays $J/\psi,\psi' \to \gamma\theta$ via the $\eta\eta$ decay mode of the θ, with each η decaying to $\gamma\gamma$. Figure 2a shows the $\eta\eta$ invariant mass distribution of events which are consistent with the hypothesis $J/\psi \to \gamma\eta\eta$. The solid line shows a fit to a single Breit-Wigner line shape and a flat background.

† Events consistent with the processes $J/\psi, \psi' \to \omega\pi^0$, $\omega \to \gamma\pi^0$ have been eliminated.

‡ The systematic errors are dominated by the variations of the amplitudes when alternate fitting functions (e.g., with no structures at 1.7 and 2.1 GeV) are used.

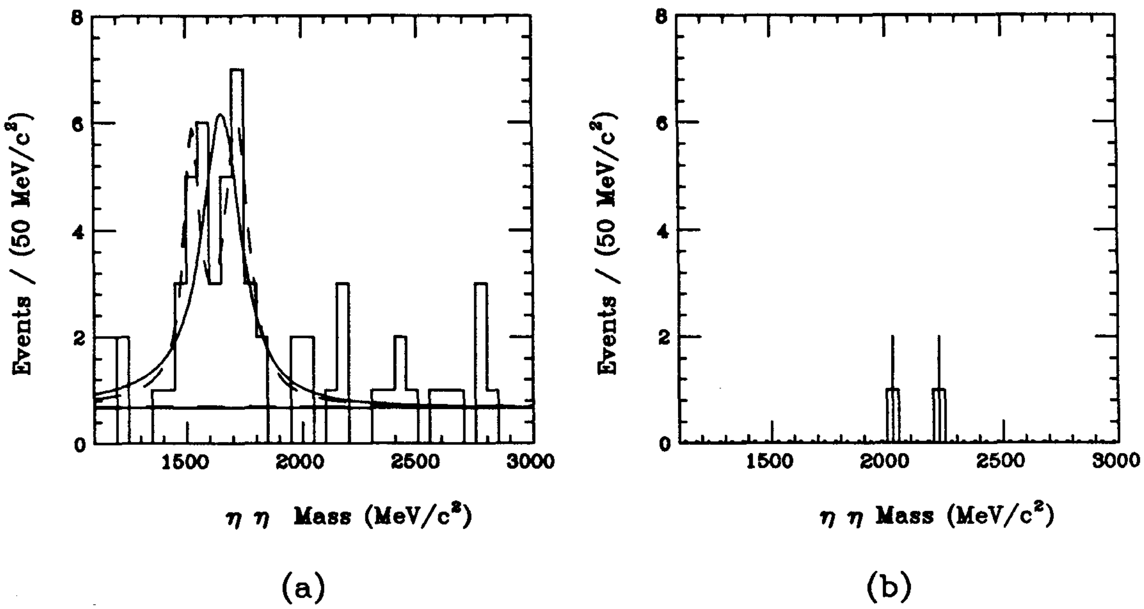

Fig. 2 $\eta\eta$ invariant mass distributions in (a) $J/\psi \to \gamma\eta\eta$ and (b) $\psi' \to \gamma\eta\eta$. (Fits described in text.)

We designate this structure $\theta(1640)$ and obtain

$$\mathrm{BR}(J/\psi \to \gamma\theta(1640))\mathrm{BR}(\theta \to \eta\eta) = (5.8 \pm 1.4 \pm 1.5) \times 10^{-4} \tag{5}$$

consistent with the original Crystal Ball measurement of this product branching ratio, (4.9 ±1.4 ±1.0) $\times 10^{-4}$.[8] § However, since this observation three experiments (Mark II,[3] Mark III,[7] and DM2[9]) have searched for the θ in $J/\psi \to \gamma K^+K^-$. All three experiments have evidence for structure in the K^+K^- invariant mass plot in the region of the θ but resolve two peaks rather than one. The lower mass peak is associated with the f′(1515), while the higher mass peak is again designated θ. We shall refer to this structure as $\theta(1720)$. Motivated by the results of these experiments, we refit the distribution shown in Fig. 2a to two Breit-Wigner line shapes (with masses and widths fixed to the best fitted values found for the f′ and $\theta(1720)$ in the Mark III study) as shown by the dashed line. We obtain

$$\begin{aligned} \mathrm{BR}(J/\psi \to \gamma f')\mathrm{BR}(f' \to \eta\eta) &= (1.9 \pm 0.8 \pm 0.5) \times 10^{-4} \\ \mathrm{BR}(J/\psi \to \gamma\theta(1720))\mathrm{BR}(\theta(1720) \to \eta\eta) &= (2.6 \pm 0.8 \pm 0.7) \times 10^{-4} \end{aligned} \tag{6}$$

Figure 2b shows the same distribution for the ψ' data.¶ There are no events near the mass of the f′ or θ, and we set upper limits of

$$\frac{\mathrm{BR}(\psi' \to \theta(1640))}{\mathrm{BR}(J/\psi \to \theta(1640))} < 10\% \tag{7}$$

or

$$\frac{\mathrm{BR}(\psi' \to f')}{\mathrm{BR}(J/\psi \to f')} < 22\%; \qquad \frac{\mathrm{BR}(\psi' \to \theta(1720))}{\mathrm{BR}(J/\psi \to \theta(1720))} < 15\% \tag{8}$$

depending on the number of structures assumed to be present in the J/ψ data.

§ The same dataset was used in this analysis and the original analysis. The small difference between the two values of the branching ratio obtained is attributable to differences in the analysis procedures.

¶ The efficiency for the ψ' analysis is 35% lower than that for the J/ψ analysis because events consistent with the decay $\psi' \to \eta J/\psi$, $J/\psi \to 3\gamma$ are eliminated.

III. $J/\psi,\psi'\to\gamma\eta$ and $J/\psi,\psi'\to\gamma\eta'$

The search for these decays via the two-photon decay modes of the η and η' is complicated by background from the QED process $e^+e^- \to (\gamma)\gamma\gamma$. We search instead for these processes via the decays $\eta\to 3\pi^0$ and $\eta'\to\eta\pi^0\pi^0$, where the η in the latter case subsequently decays into two photons or three π^0's. In general, the observed topology of these decay chains will be as shown schematically in Figure 3. On one side of the event there is a hard photon corresponding to the direct photon in the radiative J/ψ or ψ' decay. On the other side of the event is a cluster of photons from the decay of the η or η' confined to a cone of small angle due to the low masses of the η and η' relative to their energies in these decays. The showers from the photons in these clusters almost always overlap, making the determination of the four-vectors of the individual γ's with a standard exclusive analysis essentially impossible.

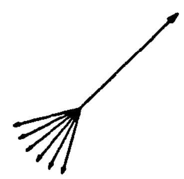

Fig. 3 Schematic representation of the decays $J/\psi,\psi'\to\gamma\eta,\gamma\eta'$.

We instead search for these decay chains by selecting events which are "jet-like", i.e., which have a large asymmetry in the observed crystal energies. On that side of the event with the lower multiplicity, we identify the cluster with the largest energy as coming from the direct photon. We take the invariant mass of the remainder of the event *using the crystal energies alone* without attempting to allocate these energies to individual tracks. The invariant mass so obtained is termed the "global shower" invariant mass. It should be noted that such an analysis is inclusive since any decay of the type $\psi' \to \gamma Y$, $Y \to$ n photons will be included (regardless of the number n of photons) if Y is sufficiently light. Additional cuts can be applied to suppress or enhance certain topologies. Specifically, we demand that there be greater than or equal to four tracks in the event to suppress background from the QED process $e^+e^- \to (\gamma)\gamma\gamma$. In addition, the requirement that there be a high energy π^0 in the event enhances the detection efficiency for the decay chain $J/\psi,\psi' \to \gamma\eta$, $\eta \to 3\pi^0$ as compared to other topologies. (As mentioned previously, we cannot extract the individual four-vector's of the photons from the decay of the η. However, we are sometimes able to identify the invariant mass of a pair within the cluster.)

Figure 4a shows the result of this analysis with the high energy π^0 requirement when applied to the J/ψ data; Fig. 4b shows the same plot for the ψ' data. The low energy peak in the J/ψ distribution corresponds to the decay $J/\psi \to \gamma\eta$, $\eta \to 3\pi^0$ and contains over 300 events. Using a Monte Carlo calculation of the efficiencies, we derive the following branching ratio and upper limits:

$$\begin{aligned} \mathrm{BR}(J/\psi \to \gamma\eta) &= (1.01 \pm 0.06 \pm 0.16) \times 10^{-3} \\ \mathrm{BR}(\psi' \to \gamma\eta) &< 2.0 \times 10^{-5} \\ \frac{\mathrm{BR}(\psi' \to \gamma\eta)}{\mathrm{BR}(J/\psi \to \gamma\eta)} &< 1.8\% \end{aligned} \tag{9}$$

The measurement of the branching ratio from the J/ψ agrees with the Particle Data Group[4)] average of $(0.86 \pm 0.09) \times 10^{-3}$, but the ratio of branching ratios has an upper limit which is roughly a factor of six

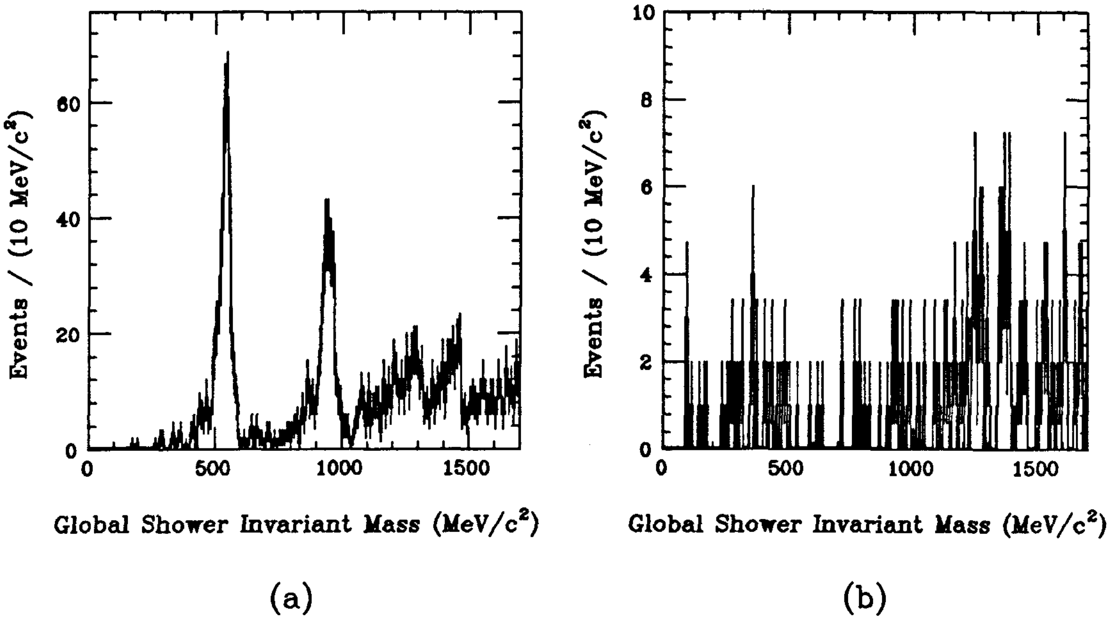

Fig. 4 Global shower invariant mass distribution (high energy π^0required) in (a) J/ψ data and (b) ψ' data.

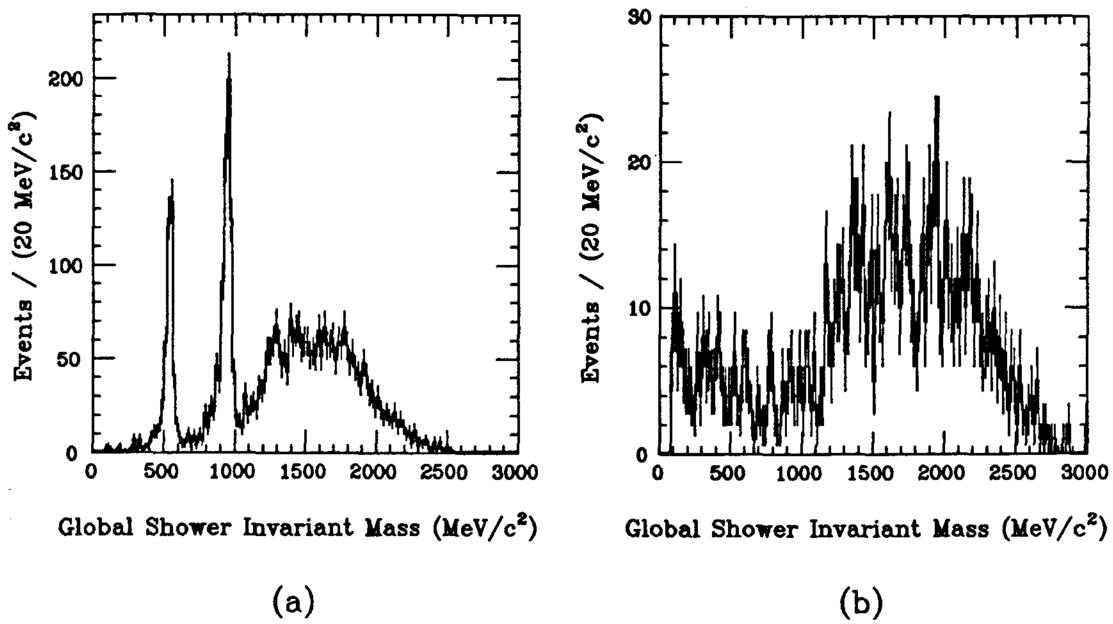

Fig. 5 Global shower invariant mass distribution (no high energy π^0requirement) in (a) J/ψ data and (b) ψ' data.

below the theoretically expected value. Figures 5a and 5b show the results of the same analyses without the high energy π^0 requirement. The peak at the η' mass in the J/ψ plot contains more than 700 events, and we obtain

$$\begin{aligned} \mathrm{BR}(J/\psi \to \gamma\eta') &= (4.1 \pm 0.5 \pm 0.7) \times 10^{-3} \\ \mathrm{BR}(\psi' \to \gamma\eta') &< 1.4 \times 10^{-4} \\ \frac{\mathrm{BR}(\psi' \to \gamma\eta')}{\mathrm{BR}(J/\psi \to \gamma\eta')} &< 2.6\% \end{aligned} \tag{10}$$

Again, the measurement of the branching ratio from the J/ψ agrees with the Particle Data Group[4)] average of $(3.6 \pm 0.5) \times 10^{-3}$, but the ψ' decay appears to be suppressed by a factor of at least four compared to theory.

IV. Summary

Table 2 summarizes the results of this study. We give two results for the radiative decay to the θ, depending on whether an f' contribution is included in the fit to the J/ψ distribution.

Final State γY	BR($\psi' \to \gamma Y$)	BR($J/\psi \to \gamma Y$)	Ratio (%)
γf	$(1.5 \pm 0.4 \pm 0.5) \times 10^{-4}$	$(1.7 \pm 0.1 \pm 0.5) \times 10^{-3}$	9 ± 3
$\gamma\theta(1640)$ or	$< 1 \times 10^{-4}$	$(5.8 \pm 1.4 \pm 1.5) \times 10^{-4}$	< 10
$\gamma\theta(1720)$, $\theta \to \eta\eta$	$< 1 \times 10^{-4}$	$(2.6 \pm 0.8 \pm 0.7) \times 10^{-4}$	< 15
$\gamma\eta$	$< 2.0 \times 10^{-5}$	$(1.01 \pm 0.06 \pm 0.16) \times 10^{-3}$	< 1.8
$\gamma\eta'$	$< 1.4 \times 10^{-4}$	$(4.1 \pm 0.5 \pm 0.7) \times 10^{-3}$	< 2.6

Table 2 Ratios of ψ' to J/ψ branching ratios for radiative decays (Crystal Ball).

From the Mark II and Crystal Ball results, we see that four decays ($\rho\pi$, $K^{*\pm}K^{\mp}$, $\gamma\eta$, and $\gamma\eta'$) are suppressed on the ψ' compared to the lowest-order QCD prediction relative to the corresponding J/ψ decays. Some models have been put forth to explain this suppression. G. Karl and W. Roberts[10] have suggested that there is an oscillation in the amplitude for three gluons to hadronize to the $\rho\pi$ and $K^{*\pm}K^{\mp}$ final states which has a node at the mass of the ψ'. W. Hou and A. Soni[11] postulate the existence of a glueball near 2 GeV which mixes with the J/ψ to enhance the decays $J/\psi \to \rho\pi$ and $J/\psi \to K^{*\pm}K^{\mp}$ but is too far in mass from the ψ' to enhance its decays. H. Fritzsch and J. D. Jackson[12] have proposed a model of the decays $J/\psi \to \gamma\eta$ and $J/\psi \to \gamma\eta'$ in which the J/ψ radiates a hard photon to a virtual η_c which then couples to the $c\bar{c}$ component of the η and η'. Presumably a similar mechanism involving the ψ' and the η_c' could describe the decays $\psi' \to \gamma\eta$ and $\psi' \to \gamma\eta'$. There is no dependence on the wavefunction at the origin in such a model, so our original expectation of a ratio of branching ratios of $12.0 \pm 2.2\%$ would be in error. However, the expected suppression from such a mechanism (if any) has not yet been calculated.

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