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RECENT RESULTS IN CHARMONIUM SPECTROSCOPY*

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ABSTRACT

Three topics in charmonium spectroscopy are discussed: the evidence for χ states and their spin and parity assignments, the possibility of $c\bar{c}$ mixing in pseudoscalar states, and tests of the OZI rule.

I. INTRODUCTION

At the last meson spectroscopy conference the word "charmonium" had not yet been invented. Today it refers to a rich and detailed field of meson spectroscopy. I shall only have time today to touch on a few subjects which I have chosen because there are recent results bearing on them and because there are unanswered questions relevant to them which second generation e^+e^- detectors can explore. We shall first discuss the χ states, the evidence for their existence and their probable spins and parities. Next, we shall look at three topics which all have a bearing on the question of $c\bar{c}$ mixing in the pseudoscalar states: ψ radiative decays, the $\psi' \to \psi\eta$ decay, and inclusive η production in ψ decays. The final topic will be a brief mention of recent tests of the OZI rule in ψ decays.

Figure 1 is an attempt to summarize as much information on charmonium spectroscopy as possible in one drawing.[1] In $J^{PC}=1^{--}$ column there are the two spectacularly narrow resonances, the ψ and ψ'. Above the threshold for decay to charmed particles are three or more broader states, whose decays will be discussed by the next speaker.[2] The remaining states are reached from the ψ or ψ' by radiative transitions and thus have even C parity. There are three P-states which, as we shall see, are well established and for which there are experimentally favored spin assignments. There are also two other states which are less well established and which are normally assigned to be pseudoscalars, although there is no experimental evidence for that assignment. In the past few weeks, there has been new evidence from DORIS supporting the existence of both these states.

II. χ STATES

χ states[3] have been detected in $\psi' \to \gamma\chi$ decays by three techniques: (1) by detecting the hadronic decay of the χ's, (2) by detecting the ψ and one or both of the cascade photons in $\psi' \to \gamma\chi \to \gamma\gamma\psi$, and (3) by detecting monochromatic photons. We shall now discuss each of these techniques in turn.

A. χ Decays to Hadrons

These decays are detected by finding events in which the missing mass recoiling against all of the observed charged particles is consistent with

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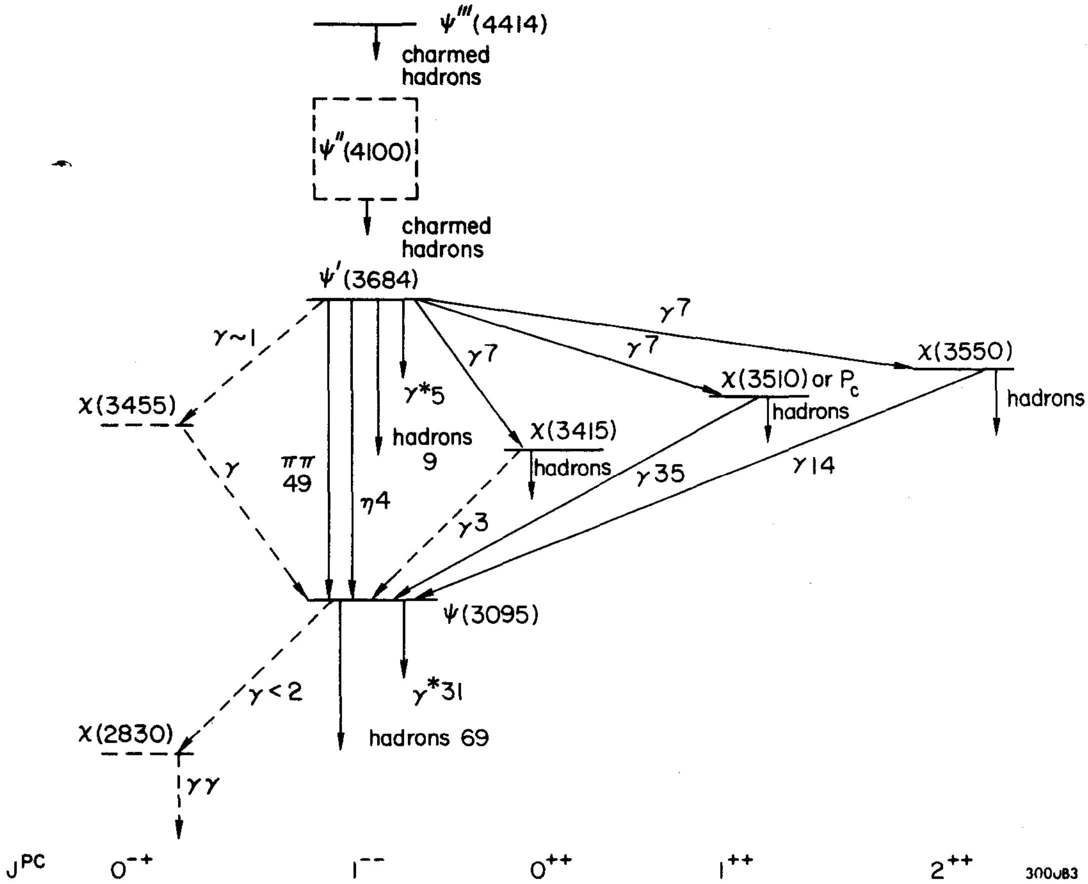

Fig. 1. Summary of observed charmonium states and transitions. States and transitions indicated by dashed lines are probable, but not well established. Numbers indicate branching fractions in percent. The symbol "γ^*" stands for second-order electromagnetic decays including decays to lepton pairs.

that of a photon.[4] In general there is insufficient resolution to distinguish between a photon and a π^0, but fortunately ψ' decays involving a single π^0 occur infrequently enough that they are not a severe background.

Figure 2 shows χ mass spectra obtained by this technique after a one constraint fit has been performed.[5] Figure 2a shows the data for $\chi \to 4\pi^{\pm}$. Here events with masses above 3.60 GeV/c^2 are consistent with the second-order electromagnetic decay $\chi \to 4\pi$. There are three other clear peaks at masses of about 3415, 3510, and 3550 MeV/c^2 each of which we identify with a χ state.

Figures 2b, 2c, and 2d show the mass plots for χ decays to $K^+K^-\pi^+\pi^-$, $3\pi^+3\pi^-$, and $\pi^+\pi^-$ or K^+K^-. The same three states are found in these plots, but not as clearly in all cases. In the $K^+K^-\pi^+\pi^-$ mode the $\chi(3510)$ is weak. In the $3\pi^+3\pi^-$ mode the $\chi(3510)$ and $\chi(3550)$ are not resolved. In the $\pi^+\pi^-$ or K^+K^- mode, the $\chi(3415)$ is quite clear and there are eleven events in the vicinity of the $\chi(3550)$ with an estimated background of only two or three events. There are only two events in the vicinity of the $\chi(3510)$ and these are

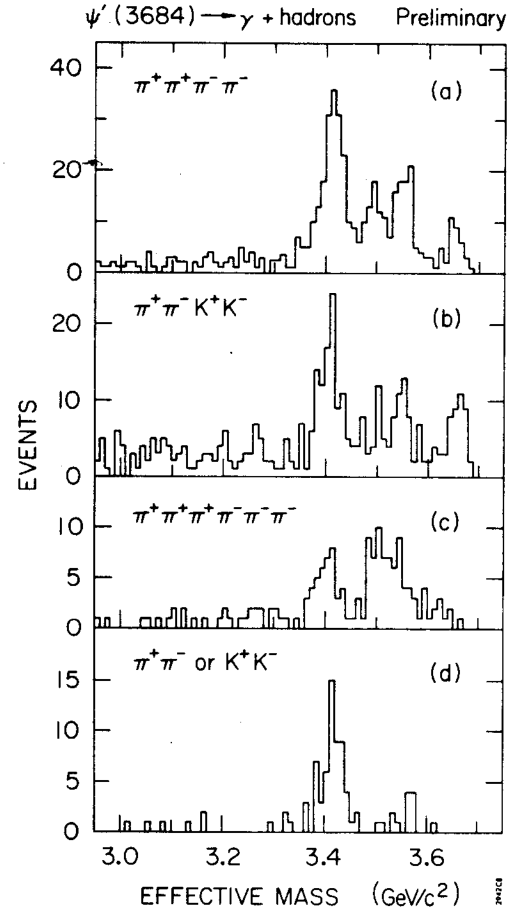

Fig. 2. Invariant χ mass distributions for $\psi' \rightarrow \gamma\chi$ for (a) $2\pi^+2\pi^-$, (b) $\pi^+\pi^-K^+K^-$, (c) $3\pi^+3\pi^-$, and (d) the sum of $\pi^+\pi^-$ and K^+K^-.

consistent with backgrounds. These decays into two pseudoscalars will be important when we consider the spin assignments of the χ states.

B. χ Decays to $\gamma\psi$

Two methods have been used to detect the $\psi' \rightarrow \gamma\chi \rightarrow \gamma\gamma\psi$ cascade. In both methods the ψ is observed in its muon pair decay, so that the final state corresponds to $\psi' \rightarrow \gamma\gamma\mu^+\mu^-$.

In the first method, which has been used in the SPEAR magnetic detector, one detects $\mu^+\mu^-$ and observes a conversion of one of the photons in the 0.052 radiation lengths of material surrounding the beam pipe.[6] A one constraint fit is then performed to the event.

In the second method, which has been used both at SPEAR[6] and at DORIS,[7] both photons are detected in shower counters and the angle measurements are used to give a two constraint fit. This method provides worse resolution, but much higher statistics than the first method. It will prove useful when we discuss the angular distributions.

Whichever method is used, there are two solutions for each event since one does not know a priori which photon was emitted first. This two-fold ambiguity can be resolved by observing the widths of the reconstructed χ masses since the first photon will be monochromatic, while the second is Doppler shifted by the motion of the χ.

Figure 3 shows the $\gamma\psi$ masses obtained by the first method at SPEAR[8] and some preliminary and unpublished data from the DASP[9] and PLUTO[10] collaborations at DORIS. For these later data I don't know anything about the efficiency, resolution, or possible backgrounds; we shall have to rely on the internal consistency of the data to gauge these quantities. For the SPEAR data the rms mass resolution is 8 MeV/c^2 and the expected background is one event.

There are four clusters of events. The $\chi(3510)$ and $\chi(3550)$ are clearly visible and the two-fold ambiguity is resolved in favor of the higher mass states in agreement with the observation of χ's from their hadronic decays. The single events from SPEAR and DASP from the $\chi(3415)$ have now been

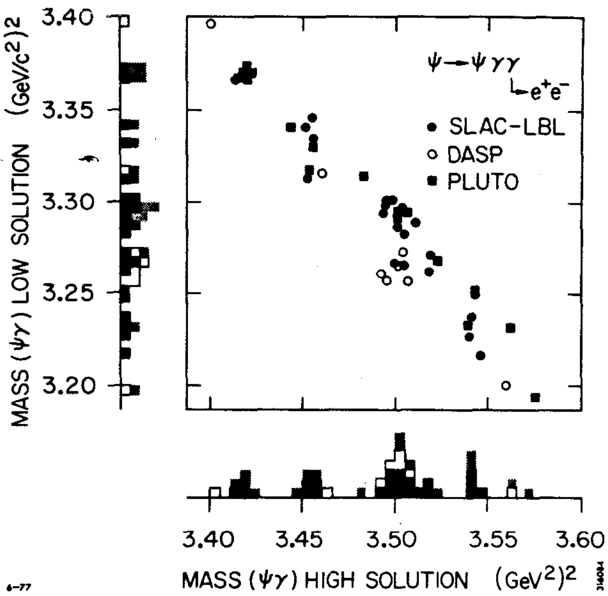

Fig. 3. Scatter plot of the two solutions for the mass of χ states in $\psi' \to \gamma\chi \to \gamma\gamma\psi$.

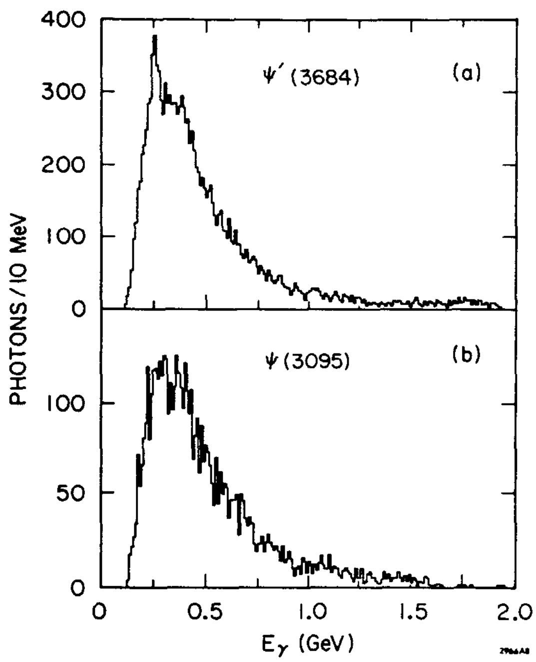

Fig. 4. Inclusive photon energy distributions for (a) ψ decays and (b) ψ' decays observed with converted photons in the SLAC-LBL magnetic detector at SPEAR.

augmented by a surprisingly large cluster of events from PLUTO. I understand that the efficiency of their apparatus is high in this mass region.

The new element in Fig. 3 is the cluster of events at 3454 MeV/c^2. The original four events from SPEAR have been joined by an additional four from DORIS. It seems unlikely that this cluster is due to background. Nevertheless, these eight events are the only evidence for this possible state.

C. Monochromatic Photons

In order to measure the branching ratio for $\psi' \to \gamma\chi$, it is necessary to detect the monochromatic photons. Two measurements of this type have now been performed. The first comes from the magnetic detector at SPEAR.[8] Photons were detected by observing conversions in the material around the beam pipe. For low energy photons, the rms energy resolution is about 2% for this technique. Photon energy spectra from ψ and ψ' decays are shown in Fig. 4. A peak is seen in the ψ' spectrum at 261 MeV, corresponding to the $\chi(3415)$. The branching fraction for $\psi' \to \gamma\chi(3415)$ from these data is 0.075 ± 0.026. The other χ states correspond to lower photon energies and are not visible because of rapidly falling acceptance in this region.

A special experiment was conducted at SPEAR to search for monochromatic photons by a collaboration from Maryland, Pavia, Princeton, San Diego, SLAC, and Stanford (MPPSDSS).[11] Arrays of large NaI crystals were used to detect the photons with about 5% rms energy resolution. The data from ψ and ψ' decays are

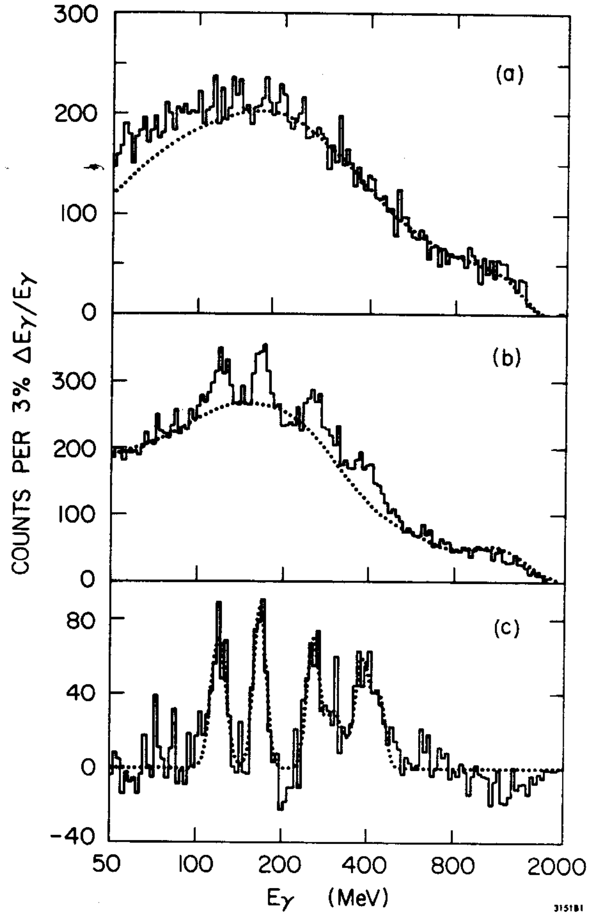

Fig. 5. Inclusive photon energy distributions for (a) ψ decays and (b) ψ' decays measured by the MPPSDSS experiment at SPEAR. Part (c) shows the ψ' distributions with backgrounds subtracted. The dotted curves represent Monte Carlo calculations and fits.

shown in Fig. 5. There are no significant peaks in the ψ spectrum, but four clear peaks are apparent in the ψ' spectrum. The first three correspond to the $\chi(3550)$, $\chi(3510)$ and $\chi(3415)$, and the last is from the Doppler broadened photon in $\chi(3510) \rightarrow \gamma\psi$ decay. The branching fractions for $\psi' \rightarrow \gamma\chi$ are 0.072 ± 0.023, 0.071 ± 0.019, and 0.070 ± 0.020 for the $\chi(3415)$, $\chi(3510)$, and $\chi(3550)$, respectively. The $\chi(3455)$ is not seen and the upper limit on the branching fraction is 0.025 at the 90% confidence level. The branching fractions for $\psi' \rightarrow \gamma\chi(3415)$ determined by these two experiments are in excellent agreement.

D. Spins and Parities

Although we have not explicitly determined the spin of any of the χ states, we now have enough information to give an experimentally preferred assignment under the mild, but powerful, assumption that we are dealing with the low lying states of a fermion-antifermion system.

We will assume that the possible spin-parity states are those expected from S and P states, 0^-, 0^+, 1^+, and 2^+. We shall then go through a series of arguments which exclude certain spin-parity assignments for certain states. At the end, if we make the additional assumption that each of the four spin states should be assigned to one of the four χ states, we obtain a unique solution.

The first piece of evidence for spin assignments comes from χ decays to two pseudoscalars, $\pi^+\pi^-$ or K^+K^-. The possible J^{PC} states for two pseudoscalars are 0^{++}, 1^{--}, 2^{++}, etc. The χ states have even C since they are reached by radiative transitions from the ψ'. Therefore any χ state which decays to $\pi^+\pi^-$ or K^+K^- must have $J^P=0^+$, 2^+, etc. In Fig. 2 there is overwhelming evidence that the $\chi(3415)$ decays to $\pi^+\pi^-$ or K^+K^- and there is strong evidence for the $\chi(3550)$ decay to $\pi^+\pi^-$ or K^+K^-.

The other technique which can be used to determine χ spins is a study of angular distributions of the photons. The most information comes from the $\psi' \rightarrow \gamma\chi \rightarrow \gamma\gamma\psi \rightarrow \gamma\gamma\mu\mu$ cascade.[12-14] There are five independent angles as illustrated in Fig. 6. For spin 0, the distribution is unique,

$$W(\theta, \phi, \Theta, \theta', \phi') = (1 + \cos^2 \theta)(1 + \cos^2 \theta') \quad . \tag{1}$$

For other spins, the distributions are quite complex and depend on which multipoles are excited. A study has been made at SPEAR of these distributions for the $\chi(3510)$ using the second method of detecting cascade events.[15]

Figure 7 shows a plot of corrected events as a function of cos θ'. The curves are the predicted distributions for various $\chi(3510)$ spin hypotheses, assuming pure dipole decay of both the ψ' and the χ. Spin zero is excluded by over four standard deviations. Spin one fits well and spin two slightly less well.

To investigate the spin one and two cases in more detail we plot the results of the full five dimensional fit in Figs. 8 and 9. These figures show the relative likelihood function vs. the relative dipole and quadrupole amplitudes for each decay. For simplicity the octupole amplitude for spin two has been assumed to be zero. Contours are plotted in one standard deviation units assuming that the likelihood function is Gaussian. For spin one (Fig. 8) there are four local maxima corresponding to the four combinations of either pure dipole or pure quadrupole decay. The case in which both decays are pure dipole is the most likely, although the other combinations cannot be excluded on experimental grounds. Equal mixtures of dipole and quadrupole amplitudes, which correspond to pure helicity amplitudes, are excluded for the spin one hypothesis.

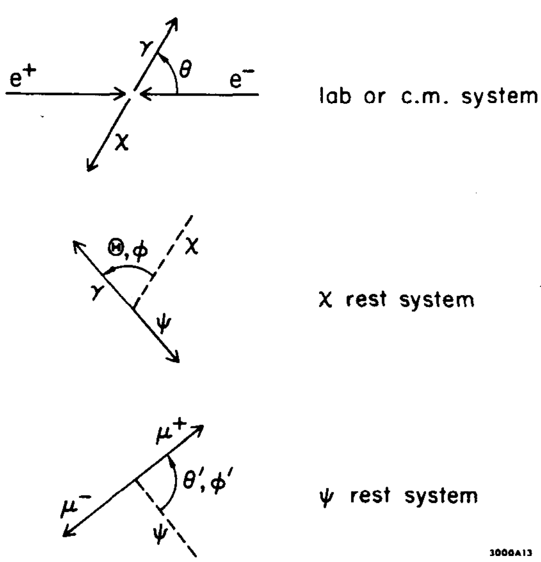

Fig. 6. Definition of angles for the cascade decay $\psi' \rightarrow \gamma\chi \rightarrow \gamma\gamma\mu^+\mu^-$.

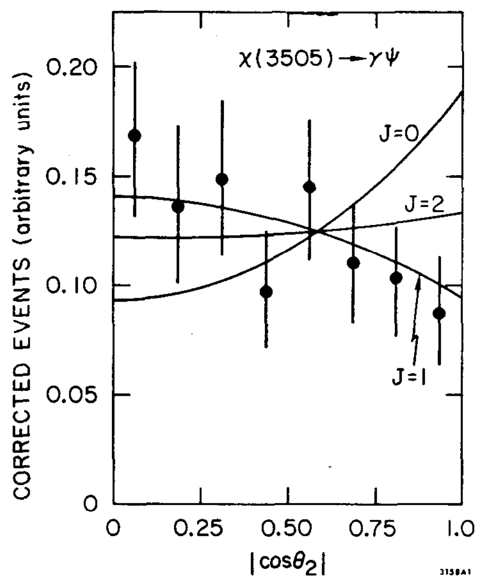

Fig. 7. Yield vs. $|\cos \theta'|$ as defined in Fig. 6 for $\chi(3510)$. The curves give predictions for various χ spins assuming pure dipole transitions.

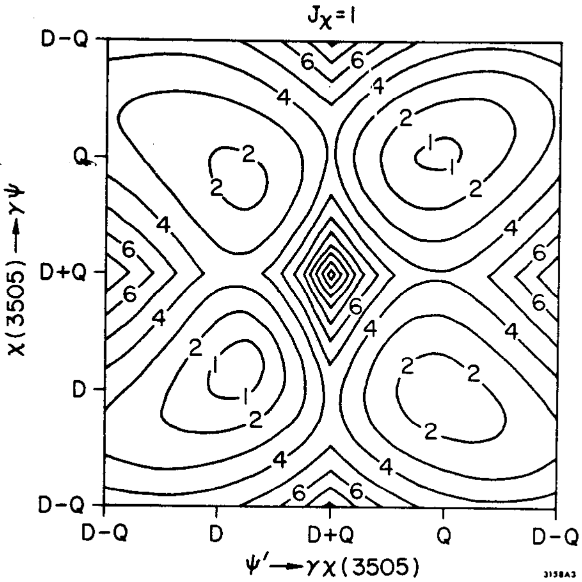

Fig. 8. Likelihood function assuming $\chi(3510)$ has spin one as a function of the relative dipole and quadrupole amplitudes for each decay. The contours are in standard deviations in the likelihood function. D indicates pure dipole decay and Q indicates pure quadrupole decay. D±Q indicate equal dipole and quadrupole amplitudes with the relative phase indicated. The scale is linear in the square of either amplitude.

For spin 2 (Fig. 9) there are two local maxima, neither of which correspond to any simple combination of amplitudes. If we require that both decays should be pure dipole transitions, then spin 2 is disfavored relative to spin 1 by 2.3 standard deviations.

The angular distribution of the photon in the production of the $\chi(3415)$ and the $\chi(3550)$ has been studied in $\chi\rightarrow 4\pi$ and $\chi\rightarrow K^+K^-\pi^+\pi^-$ decays.[5] Figure 10 shows the θ distributions when χ's are detected in these modes. The angular distribution must be of the form

$$W(\theta) \propto 1 + \alpha \cos^2\theta \quad , \qquad (2)$$

and from Eq. (1), α=1 for spin 0. Fits for α to all of the data for all hadronic modes give

$$\alpha = 0.3 \pm 0.4 \quad \text{for } \chi(3550), \qquad (3)$$

$$\alpha = 0.1 \pm 0.4 \quad \text{for } \chi(3510), \qquad (4)$$

and

$$\alpha = 1.4 \pm 0.4 \quad \text{for } \chi(3415). \qquad (5)$$

Thus, the $\chi(3415)$ is consistent with spin 0, but the $\chi(3550)$ is inconsistent with spin 0 to about two standard deviations.

All of these arguments are summarized in Table I. A number of conclusions can be drawn: Without any assumptions, none of the three well established states, $\chi(3415)$, $\chi(3510)$, or $\chi(3550)$, can be pseudoscalar. Also if the $\chi(3550)$ has a spin below 4, its spin-parity must be 2^+. If we assume that the four candidate spin states each correspond to one of the four χ states, there is a unique assignment:

State	
$\chi(3550)$	2^+
$\chi(3510)$	1^+
$\chi(3445)$	0^-
$\chi(3415)$	0^+ .

Note that the $\chi(3455)$ has been assigned to be a pseudoscalar, not because we know anything about it, but because that was the only slot left. There are other possibilities. Jaffe suggested that this state could be

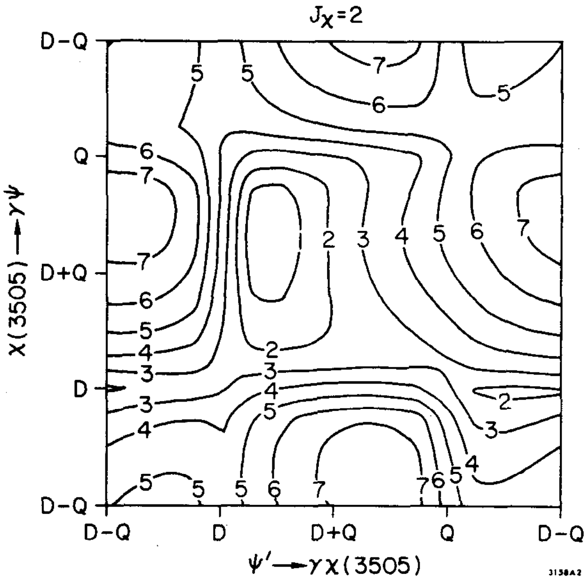

Fig. 9. Likelihood function assuming $\chi(3510)$ has spin two. See caption for Fig. 8.

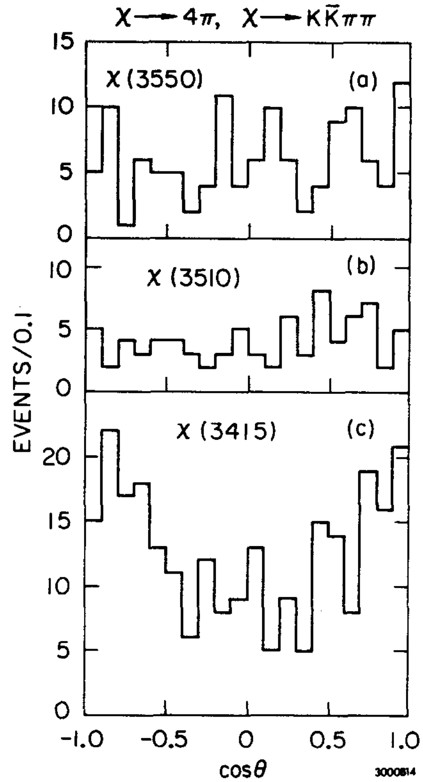

Fig. 10. Distribution of $\cos\theta$ for $\psi' \to \gamma\chi$, $\chi \to 2\pi^+\pi^-$ or $K^+K^-\pi^+\pi^-$.

an exotic[16] and Harari suggested that it could be a singlet D state, $J^{PC}=2^{-+}$.[17]

E. Comparisons to Theoretical Models

The data on P states appear to be in reasonable agreement with most charmonium models. First, the order of the state is correct. In all models the 2^+ state should be heaviest and the 0^+ state should be lightest. Second, the ratio of $\psi' \to \gamma\chi$ partial widths is in agreement with simplest assumption: that they should be proportional to the phase space factor for dipole transitions. We expect:

$$
\begin{aligned}
&(\psi' \to \chi(3550)) : (\psi' \to \chi(3510)) : \chi(\psi' \to \chi(3415)) \\
&= \quad 5k^3 \quad : \quad 3k^3 \quad : \quad k^3 \quad , \\
&= \quad 1.0 \quad : \quad 1.4 \quad : \quad 1.6
\end{aligned}
\qquad (6)
$$

where k is the available momentum and the coefficients are spin factors. With large errors the observed values are[1]:

$$
1.0 \quad : \quad 1.01 \quad : \quad 1.04 \quad . \qquad (7)
$$

Table I. Spin assignments of the χ states. The preferred assignments depend on assumptions discussed in the text.

State/J^P	0^-	0^+	1^+	2^+
$\chi(3550)$	excluded by $\chi \to \pi^+\pi^-$ or K^+K^- and by angular distribution in $\psi' \to \gamma\chi \to \gamma\gamma\psi$ hadrons	disfavored by angular distribution in $\psi' \to \gamma\chi \to \gamma\gamma\psi$ hadrons	excluded by $\chi \to \pi^+\pi^-$ or K^+K^-	preferred
$\chi(3510)$	excluded by angular distribution in $\psi' \to \gamma\chi \to \gamma\gamma\psi$	excluded by angular distribution in $\psi' \to \gamma\chi \to \gamma\gamma\psi$	preferred	disfavored by angular distribution in $\psi' \to \gamma\chi \to \gamma\gamma\psi$ if transitions are pure dipole
$\chi(3455)$	preferred			
$\chi(3415)$	excluded by $\chi \to \pi^+\pi^-$ or K^+K^-	preferred	excluded by $\chi \to \pi^+\pi^-$ or K^+K^-	

The $\chi(3510)$ has a larger branching fraction to $\gamma\psi$ than either the $\chi(3415)$ or $\chi(3550)$, presumably due to a suppression of $\chi(3510) \to$ hadrons. This behavior was expected for 1^+ P states in models in which C-even states decay to hadrons via two massless vector gluons.[18] Since a spin 1 particle cannot decay into two massless vector particles, these decays are suppressed.

The assignment of the $\chi(3455)$ as the η_c' appears to be in strong disagreement with models where it decays via two vector gluons. Chanowitz and Gilman[19] point out that the matrix element for $\psi' \to \gamma\eta_c$ is related to that for $\eta_c' \to \gamma\psi$. From this they conservatively deduce that the total decay width of the $\chi(3455)$ is at most a few tens of keV whereas one expects a width of several MeV in these models.

F. The X(2830)

Two experiments at DORIS have reported evidence for a state at about 2830 MeV/c^2 which is detected in the sequence $\psi \to \gamma X \to \gamma\gamma\gamma$.[20,21] Only the photon angles are measured and a one-constraint fit is performed. Backgrounds are $\psi \to \gamma\eta$, $\psi \to \gamma\eta'$, and radiative (nonresonant) two photon production.

The highest $\gamma\gamma$ invariant mass for each event is plotted in Fig. 11, along with a curve showing the expected events from radiative two photon production and reflections from $\gamma\eta$ and $\gamma\eta'$ decays.[20] The peak around

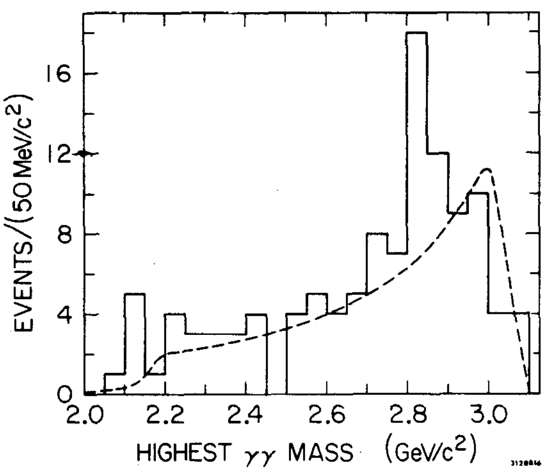

Fig. 11. The highest $\gamma\gamma$ mass combination for each event in $\psi \rightarrow 3\gamma$. The dashed curve is the expected contribution from radiative two photon production and reflections from $\gamma\eta$ and $\gamma\eta'$ decays.

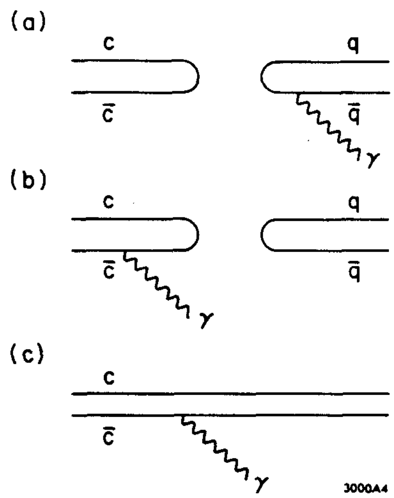

Fig. 12. Quark diagrams illustrating three mechanisms for $\psi \rightarrow \gamma\pi^0$, $\psi \rightarrow \gamma\eta$, and $\psi \rightarrow \gamma\eta'$ decays.

2.83 GeV/c^2 contains 30 events with 14 expected from backgrounds. This corresponds to about a four standard deviation effect. Although no new plots are available yet, I understand that there has been some additional data collected by the DASP group and that the signal has now become a five standard deviation effect.[10]

III. $c\bar{c}$ MIXING IN PSEUDOSCALAR STATES

We now turn to three topics which each have a bearing on the question of whether there is $c\bar{c}$ mixing into the ordinary pseudoscalar states, the η and η'.

A. ψ Radiative Decays

Recent data from DORIS[20,22] allow us to draw some interesting conclusions from ψ radiative decays to ordinary pseudoscalar mesons. The decay $\psi \rightarrow \gamma\pi^0$ has a very small branching fraction, $(7.3 \pm 4.7) \times 10^{-5}$. The decays $\psi \rightarrow \gamma\eta$ and $\psi \rightarrow \gamma\eta'$ have branching fractions which are around an order of magnitude larger, $(8.8 \pm 1.9) \times 10^{-4}$ and $(2.4 \pm 0.6) \times 10^{-3}$ respectively.

Three processes which could account for these decays are shown in Fig. 12. In Fig. 12a the photon is emitted from the light quarks. The SU(3) coupling here is a singlet going to a pair of octets. From SU(3) we would expect $\gamma\pi^0$ to be three times $\gamma\eta$. This clearly cannot be an important mechanism since the $\gamma\pi^0$ branching fraction is very small.

The second mechanism (Fig. 12b) is for the photon to be emitted from the charmed quark pair. This SU(3) coupling must be a singlet going to a pair of singlets. This diagram should be completely dominated by $\gamma\eta'$ since η' is almost a pure SU(3) singlet, while the η is almost pure octet. If this diagram is to account for all of the radiative decays, it is hard to understand why the η to η' ratio is so large, although SU(3) breaking effects could be quite important.[23]

This brings us to an interesting suggestion.[24,25] If there is a small amount of $c\bar{c}$ mixing in the η and η' (there can be no mixing in the π^0 by isospin conservation), then the radiative decays can occur without OZI suppression, as shown in Fig. 12c. The data on radiative decays give support to this suggestion.

B. $\psi' \rightarrow \psi\eta$ Decay

There is nothing new to report about this decay. Its magnitude is well established having been measured by two laboratories.[9,26] However, what I want to emphasize here is that its branching fraction, $4.1 \pm 0.7\%$,[1] is surprisingly large since it has everything working against it:

(1) There is little phase space; the Q value is only 40 MeV.
(2) This is a p-wave decay, so there is an angular momentum barrier.
(3) The decay is SU(3) forbidden in the limit that the η is pure octet.

However, if there is some $c\bar{c}$ mixing in the η, $\psi' \rightarrow \psi\eta$ is no longer OZI suppressed and its large branching fraction can easily be understood.

C. Inclusive η Production in ψ Decays

In view of these first two indications of possible $c\bar{c}$ mixing in the η and η', it would be interesting to study inclusive η and η' production in ψ decays.[25] Unfortunately, no detector has yet had the sensitivity to do this directly. However, we have accumulated sufficient measurements of other decay modes to estimate all modes except those involving η or η' production. We can then obtain a first guess at η and η' production by subtraction.

In doing this it is important to avoid double counting of decay modes and to proceed in an objective manner. Thus, we employ a statistical model to uniquely predict branching fractions for all charge states of a channel given the observation of one charge state of that channel.[27,28] We assume that isospin is conserved in ψ decays so that the final state has I=0. The only exceptions are states consisting solely of even numbers of pions. These decays proceed via a second-order electromagnetic interaction and we assume that I=1 for these states.

The results are given in Table II. By using present measurements and the statistical model, we can account for $52.4 \pm 3.4\%$ of ψ decays. Other than decays involving η and η' production, two types of decays have not been included in Table II because there are no measurements of them: (a) decays with higher multiplicities, and (b) decays involving photons (other than $\gamma\pi^0$, $\gamma\eta$, and $\gamma\eta'$). By using smooth multiplicity curves we can estimate the first class to contribute about 6%. The decay $\psi \rightarrow \gamma\chi(2830)$, contributes less than 1.7%[11] and radiative decays to ordinary hadrons should not contribute more than an additional 2%. Adding all these contributions together, we can account for no more than 62% of the ψ decays. This leaves 38% of all decays (or 44% of hadronic decays) which can be accounted for only if they contain an η or η'.

Additional evidence for a substantial fraction of ψ decays containing η's comes from an old measurement at Adone.[29] They have determined the

Table II. ψ decay modes using the statistical model. All final states are assumed to have I=0 except $n\pi$ states with n even, for which I=1 is assumed. See Ref. 1 for references on the branching fractions.

Observed Mode	General Mode	$\frac{\Gamma(\text{observed})}{\Gamma(\text{general})}$	Branching Fraction (general)%
e^+e^-	e^+e^-	1	7.3 ± 0.5
$\mu^+\mu^-$	$\mu^+\mu^-$	1	7.5 ± 0.5
$\pi^+\pi^-$	2π	1	0.011 ± 0.006
$\pi^+\pi^-\pi^0$	3π	1	1.6 ± 0.6
$2\pi^+2\pi^-$	4π	2/5	1.0 ± 0.25
$2\pi^+2\pi^-\pi^0$	5π	2/3	6.45 ± 0.75
$3\pi^+3\pi^-$	6π	5/28	2.2 ± 1.1
$3\pi^+3\pi^-\pi^0$	7π	5/12	7.0 ± 1.7
$4\pi^+4\pi^-\pi^0$	9π	7/29	3.7 ± 1.2
$K^+K^- + K_SK_L$	$K\bar{K}$	1	0.017 ± 0.011
$K^0K^-\pi^+$ + cc	$K\bar{K}\pi$	2/3	0.78 ± 0.21
$K^+K^-\pi^+\pi^-$	$K\bar{K}2\pi$	1/4	2.9 ± 0.9
$K^+K^-\pi^+\pi^-\pi^0$	$K\bar{K}3\pi$	9/40	5.3 ± 1.3
$K^+K^-2\pi^+2\pi^-$	$K\bar{K}4\pi$	1/9	2.8 ± 1.2
$2K^+2K^-$	$2K2\bar{K}$	1/6	0.42 ± 0.18
$p\bar{p}$	$N\bar{N}$	1/2	0.42 ± 0.04
$p\bar{p}\pi^0$, $p\bar{n}\pi^-$, $\bar{p}n\pi^+$	$N\bar{N}\pi$	5/6	0.58 ± 0.10
$p\bar{p}\pi^+\pi^-$	$N\bar{N}2\pi$	1/4	1.64 ± 0.32
$p\bar{p}\pi^+\pi^-\pi^0$	$N\bar{N}3\pi$	9/40	0.49 ± 0.18
$\Lambda\bar{\Lambda}$	$\Lambda\bar{\Lambda}$	1	0.16 ± 0.07
$\Xi^-\bar{\Xi}^-$	$\Xi\bar{\Xi}$	1/2	0.08 ± 0.08
$\gamma\pi^0$	$\gamma\pi^0$	1	0.007 ± 0.005
		TOTAL	52.4 ± 3.4

average number of charged particles in ψ decays to be 3.8 ± 0.3 and the average number of photons to be 6.2 ± 1.6. Since the ψ has I=0, there should only be 3.8 photons per decay from direct π^0's. If we assign the excess 2.4 ± 1.6 photons per event to η production, there are an average of 0.9 ± 0.6 η's per decay.

Detectors with high resolution photon detection will be operational soon and be able to measure η production directly.

IV. TESTS OF THE OZI RULE

The ψ is narrow because all of its decays are suppressed by the OZI rule. The decays $\psi \to \omega\pi\pi$ and $\psi \to \phi\pi\pi$ allow the examination of this phenomenological rule further since the $\phi\pi\pi$ decay corresponds to a doubly disconnected diagram as illustrated in Fig. 13b.

Current measurements[1] give

$$\frac{\Gamma(\phi\pi\pi)}{\Gamma(\omega\pi\pi)} = 0.26 \pm 0.12 \tag{10}$$

which gives an overall suppression factor of about four. However, this overall factor is quite misleading. To understand the dynamics better, we want to study the ratio in Eq. (10) as a function of $\pi\pi$ mass, which is plotted in Fig. 14.[28] Above 1100 MeV/c^2, there is only one observed $\phi\pi\pi$ event

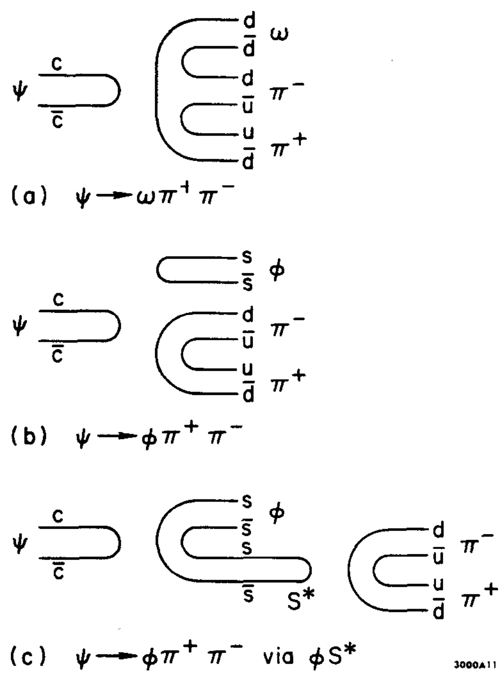

Fig. 13. Quark diagrams illustrating (a) $\psi \to \omega\pi^+\pi^-$, (b) $\psi \to \phi\pi^+\pi^-$, (c) $\psi \to \phi S^* \to \phi\pi^+\pi^-$.

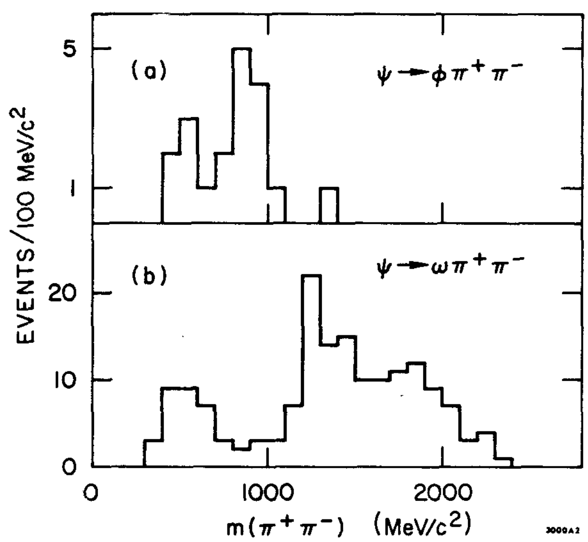

Fig. 14. Invariant mass of $\pi^+\pi^-$ in (a) $\psi \to \phi\pi^+\pi^-$, and (b) $\psi \to \omega\pi^+\pi^-$.

and the suppression factor is of order 70. But below 1100 MeV/c^2, there does not appear to be any suppression.

One way this could occur is shown in Fig. 13c.[28] Two pair of $s\bar{s}$ quarks could be formed with only single OZI suppression. One pair forms a ϕ, the other a $s\bar{s}$ state near or below threshold for K pairs, for example the S*(993). Because of phase space this state will be forced to decay into pions rather than kaons.

Additional striking evidence for the OZI rule in ψ decays comes from the decays into ωf, ϕf, ωf' and ϕf'. The decays ωf and ϕf' are observed, while the similar decays ωf' and ϕf are not. We find[1]

$$\frac{\Gamma(\psi \to \omega f)}{\Gamma(\psi \to \omega f')} \gtrsim 17 \quad , \tag{11}$$

and

$$\frac{\Gamma(\psi \to \phi f')}{\Gamma(\psi \to \phi f)} \gtrsim 2 \quad . \tag{12}$$

Assuming ideal mixing, the ω and f are made up of nonstrange quarks and the ϕ and f' are made up of strange quarks. Thus the decays $\psi \to \omega f'$ and $\psi \to \phi f$ are doubly disconnected while the decays $\psi \to \omega f$ and $\psi \to \phi f'$ are only singly disconnected.

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