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RADIATIVE TRANSITIONS FROM THE ψ(3095) TO ORDINARY HADRONS*

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ABSTRACT

Preliminary results from the Mark II and Crystal Ball experiments on radiative transitions from the ψ to ordinary hadrons are presented. In addition to the previously observed transitions to the η, η'(958), and f(1270), both groups observe a transition to a state which is tentatively identified as the E(1420).

I. INTRODUCTION

This talk is the second of two reviewing charmonium results from SPEAR. The first talk[1] reviewed the status of the η_c(2980) which has now been observed in radiative transitions from both the ψ(3095) and the ψ'(3684). In this talk, I will review the status of radiative transitions from the ψ to ordinary hadrons, where ordinary hadrons are defined to be those which, to first order, do not contain charmed quarks. As in the previous talk, results from both the Mark II[2] and Crystal Ball[3] experiments will be presented.

I will begin with a brief discussion of inclusive photon production at the ψ. This leads naturally into a discussion of the four exclusive radiative transitions which constitute the main part of this talk. Three of these transitions, to the η, η'(958), and f(1270), have been previously observed. The new results are in reasonable, but not perfect, agreement with the previous measurements. The fourth observed transition is to a state which is tentatively associated with the E(1420). This transition has not been previously observed. I will conclude with a review of some recent results on hadronic production of the E, along with an explanation for the relevance of this digression.

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II. INCLUSIVE PHOTON PRODUCTION

Measurements of inclusive photon production at the $\psi(3095)$ by the Mark II[4] and Lead-Glass Wall (LGW)[5] collaborations have shown that there is a sizable direct-photon component in the momentum spectrum. However, because of the relatively poor photon energy resolutions of the liquid argon (LA) shower counter system employed by the Mark II ($\delta E/E \approx 12\%/E^{1/2}$, E in GeV) and the lead-glass counters in the LGW ($\delta E/E \approx 9\%/E^{1/2}$), neither experiment was able to observe any narrow structure in the inclusive photon momentum distribution.

The Crystal Ball detector[6] was designed to provide good energy resolution for electromagnetic showers. The use of NaI(Tℓ) for shower detection presently allows a resolution of $\delta E/E \approx 2.8\%/E^{1/4}$ (E in GeV) to be obtained.

Figure 1 shows a preliminary measurement of the inclusive γ energy distribution at the ψ from the Crystal Ball.[7] It is plotted as a function of the logarithm of the γ energy (E_γ in MeV) so that the bin width is roughly proportional to the energy resolution at all energies. This distribution is based on a sample of approximately 900,000 events obtained during approximately two weeks of running near the peak of the ψ. Details of the analysis can be found in Ref. 6.

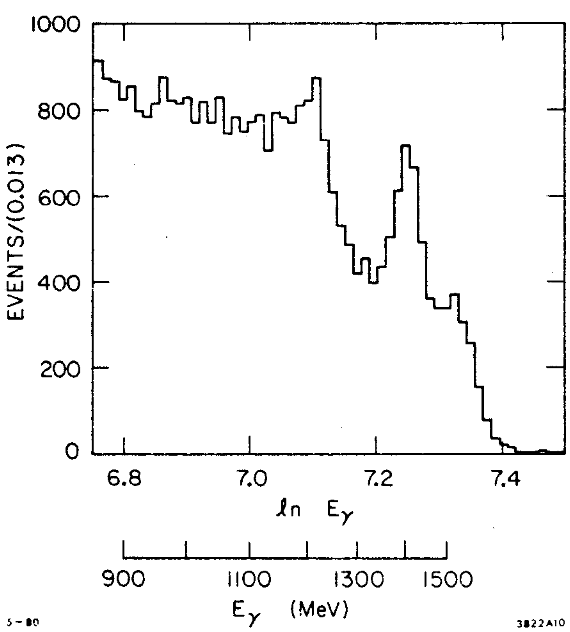

Fig. 1. Inclusive γ distribution at the ψ as a function of the logarithm of the γ energy (in MeV). (Crystal Ball)

The structure observed in Fig. 1 is evidence for exclusive processes of the type

$$\psi \rightarrow \gamma + X \ .$$

There is clear evidence for the radiative transitions to the η,[8-10] $\eta'(958)$,[8-11] and a new state which I will refer to as the E(1420) which has recently been observed by the Mark II collaboration.[12] [Although I refer to this state as the E(1420), this assignment is still in question.] An additional transition which has been previously observed is $\psi \to \gamma f(1270)$.[13,14] Because of the relatively small branching fraction for this transition, it is not observed in this inclusive distribution. Each of these four transitions will be discussed in turn in the following sections.

III. $\psi \to \gamma\eta, \gamma\eta'$

As the η and η' are members of the same SU(3) nonet, it makes sense to discuss the radiative transitions to these two states at the same time, along with the transition to the π°. I will take the extremely naive approach that it is possible to understand these processes in terms of leading-order QCD diagrams. Thus, one can imagine that the radiated photon is produced either from the outgoing quark line (assumed to be u, d, or s) as in Fig. 2(a) or from the initial charmed quark line as in Fig. 2(b). In the first case, the minimal coupling between the charmed quark line and the ordinary quark line requires three gluons. In the second case, two gluons is sufficient.

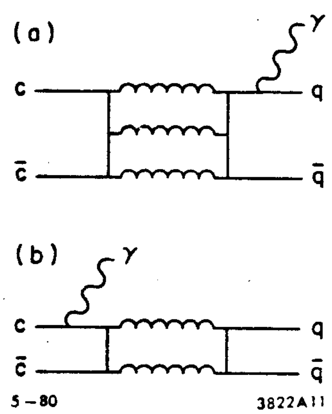

Fig. 2. Leading-order diagrams for radiative transitions from the ψ with (a) photon emission from the final-state quark line and (b) photon emission from the initial-state charmed quark line.

Let me first consider only the process shown in Fig. 2(a) and assume it is the dominant one. By invoking vector-meson dominance, I can relate the $\gamma\pi^\circ$ and $\rho^\circ\pi^\circ$ decay widths

$$\Gamma(\psi \to \gamma\pi^\circ) = (\alpha\pi/\gamma_\rho^{\,2})\,\Gamma(\psi \to \rho^\circ\pi^\circ) \ .$$

This leads to a prediction for the $\gamma\pi^\circ$ branching fraction $B(\psi \to \gamma\pi^\circ) \approx 2 \times 10^{-5}$ from the measured $\rho^\circ\pi^\circ$ branching fraction.[11,15,16] This is consistent with the experimental measurement[9] $B(\psi \to \gamma\pi^\circ) = (7 \pm 5) \times 10^{-5}$.

The next step is to relate the widths of the $\gamma\eta$ and $\gamma\eta'$ transitions to the width of the $\gamma\pi^\circ$ transition. The η and η' have the following SU(3) singlet and octet components

$$\eta = \eta_8 \cos\theta + \eta_1 \sin\theta$$

$$\eta' = -\eta_8 \sin\theta + \eta_1 \cos\theta \ ,$$

where θ is the standard octet-singlet mixing angle. If one assumes SU(3) invariance, only the octet components contribute to the process shown in Fig. 2(a) and one obtains (up to phase space corrections)

$$\Gamma(\psi \to \gamma\pi^\circ):\Gamma(\psi \to \gamma\eta):\Gamma(\psi \to \gamma\eta') = 3:\cos^2\theta:\sin^2\theta \ .$$

Using the experimentally determined mixing angle $\theta = -11^\circ$, one calculates

$$\Gamma(\psi \to \gamma\pi^\circ):\Gamma(\psi \to \gamma\eta):\Gamma(\psi \to \gamma\eta') = 3:0.96:0.04 \ ,$$

which grossly contradicts the experimental measurements.[8-11] The $\gamma\eta'$ branching fraction has been experimentally determined to be larger than the $\gamma\eta$ branching fraction, and both are at least an order of magnitude larger than the π° transition. The conclusion is that the process in Fig. 2(b) is the dominant one.

One can proceed with similar calculations for the second process [shown in Fig. 2(b)]. Assuming SU(3) invariance (now only the singlet components contribute) and ignoring phase space corrections, one obtains

$$\Gamma(\psi \to \gamma\pi^\circ):\Gamma(\psi \to \gamma\eta):\Gamma(\psi \to \gamma\eta') = 0:\sin^2\theta:\cos^2\theta \ .$$

This is qualitatively in better agreement with the data. However, the ratio $\Gamma(\psi \to \gamma\eta')/\Gamma(\psi \to \gamma\eta)$ is much larger than the experimentally measured ratio.

If one allows for SU(3) symmetry breaking, these results are modified. Fritzsch and Jackson[17] have calculated the relative widths of the $\gamma\eta$ and $\gamma\eta'$ transitions by considering gluon-mediated mixing between the three isoscalar states η, η', and $\eta_c(2980)$. Based on the experimental masses of these states, they find the following admixture of η and η' in the η_c:

$$\eta_c = \bar{c}c + \varepsilon\cdot\eta + \varepsilon'\cdot\eta' \quad ,$$

where $\varepsilon \approx 10^{-2}$ and $\varepsilon' \approx 2.2 \times 10^{-2}$. The decay widths (for M1 transitions) for $\gamma\eta$ and $\gamma\eta'$ are

$$\Gamma(\psi \to \gamma\eta) = \varepsilon^2 \frac{4\alpha}{3m_c^2} \left(\frac{2}{3}\right)^2 k^3 \, \Omega^2$$

$$\Gamma(\psi \to \gamma\eta') = (\varepsilon')^2 \frac{4\alpha}{3m_c^2} \left(\frac{2}{3}\right)^2 (k')^3 \, \Omega^2 ,$$

where m_c is the charmed quark mass, $k(k')$ is the momentum of the $\eta(\eta')$, and Ω is an overlap integral. If it is assumed that the overlap integral is the same for both the η and η' transitions, one finds for the ratio of the two partial widths

$$\frac{\Gamma(\psi \to \gamma\eta')}{\Gamma(\psi \to \gamma\eta)} = \left(\frac{k'}{k}\right)^3 \left(\frac{\varepsilon'}{\varepsilon}\right)^2 \approx 3.9 .$$

By estimating the overlap integral $\Omega^2 \approx 0.1$, Fritzsch and Jackson also make predictions for the absolute values of the widths, $\Gamma(\psi \to \gamma\eta) \approx 60$ eV and $\Gamma(\psi \to \gamma\eta') \approx 220$ eV.

Branching fractions for the transitions $\psi \to \gamma\eta$ and $\psi \to \gamma\eta'$ have recently been published by the Crystal Ball collaboration.[10] The measurements were based on a sample of decays $\psi \to 3\gamma$. Figure 3 shows the Dalitz plot for this sample of events. Two distinct bands associated

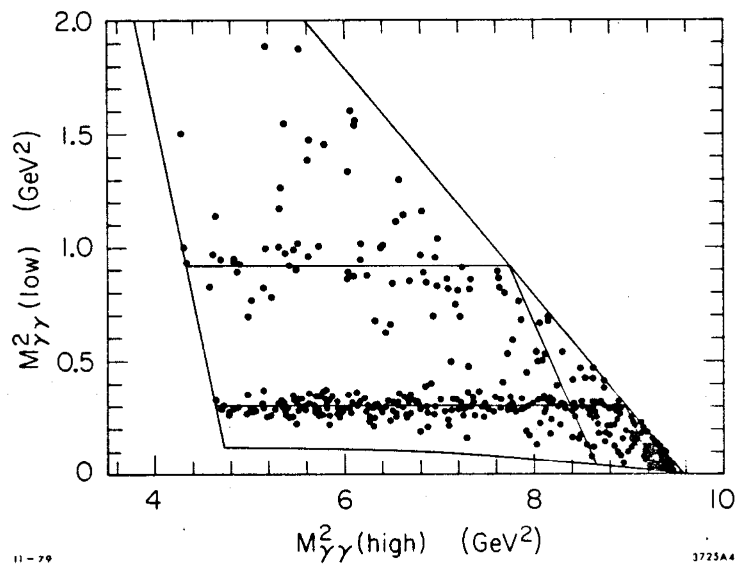

Fig. 3. Dalitz plot for $\psi \to 3\gamma$. Boundary includes effects of both kinematics and $\gamma\gamma$ opening angle cuts. (Crystal Ball)

with the $\gamma\eta$ and $\gamma\eta'$ transitions are observed.[18] The projection of the low-mass $\gamma\gamma$ combination, in Fig. 4, clearly shows peaks at the η and η' masses. The branching fractions for these transitions were determined from a fit to the Dalitz plot. They are $B(\psi \to \gamma\eta') = (6.9 \pm 1.7) \times 10^{-3}$ and $B(\psi \to \gamma\eta) = (1.2 \pm 0.2) \times 10^{-3}$.

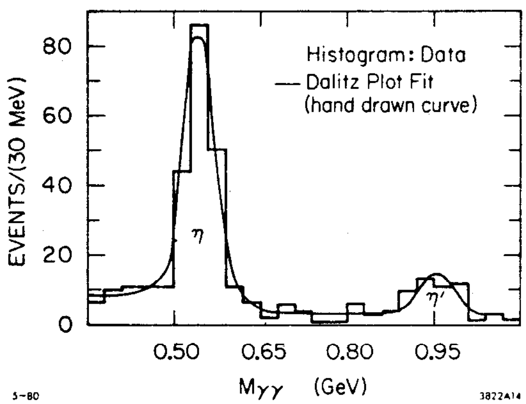

Fig. 4. Low-mass $\gamma\gamma$ invariant mass combinations for $\psi \to 3\gamma$ events. (Crystal Ball)

The Mark II has measured the branching fraction for the process[19]

$$\psi \to \gamma\eta' \ , \ \eta' \to \pi^+\pi^-\gamma \ .$$

The data sample used in the Mark II analyses discussed in this talk is basically the same as the Crystal Ball data sample, as both experiments were running at SPEAR simultaneously.[20] Previous publications can be referred to for details on the detector and the analysis.[4,21]

Events with two oppositely charged tracks identified as pions and two or more photons[22] observed in the LA shower counter modules were fit to the hypothesis

$$\psi \to \pi^+\pi^-\gamma\gamma \ . \qquad (1)$$

Events in which the fitted $\gamma\gamma$ invariant mass was between 0.12 and 0.15 GeV (i.e., consistent with the π° mass) were eliminated. The $\pi^+\pi^-\gamma$ invariant mass distribution for the events remaining after the χ^2 and π° cuts is shown in Fig. 5. From Monte Carlo calculations of the detection efficiency (which include an assumed $1 + \cos^2\theta$ dependence for the ψ decay, where θ is the angle between the photon and the beam direction), the Mark II measures the branching fraction $B(\psi \to \gamma\eta') = (3.4 \pm 0.7) \times 10^{-3}$.

Due to the bias imposed by the trigger requirement,[23] the Mark II is unable to observe the reaction

$$e^+e^- \to \psi \to 3\gamma \ .$$

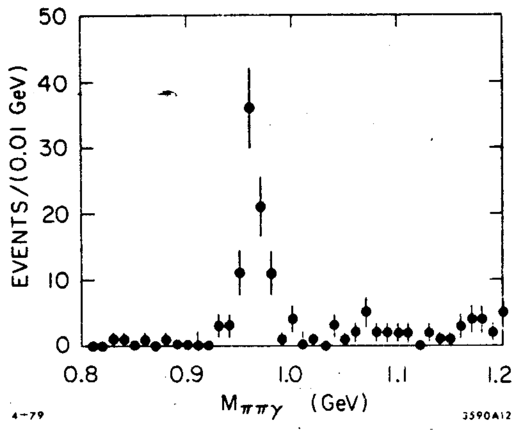

Fig. 5. $\pi^+\pi^-\gamma$ invariant mass distribution for events satisfying (1) with π° combinations eliminated. (Mark II)

In order to measure the $\gamma\eta$ branching fraction, it was necessary to analyze the more complicated process[24]

$$\psi' \to \pi^+\pi^- \psi \ , \ \psi \to 3\gamma \ . \qquad (2)$$

The $\pi^+\pi^-$ from the ψ' cascade decay provided the trigger. Figure 6 shows the invariant mass of the low-mass $\gamma\gamma$ combinations for the 10 events satisfying fits to (2). Eight are peaked at the η mass. From this, the branching fraction $B(\psi \to \gamma\eta) = (0.9 \pm 0.4) \times 10^{-3}$ is obtained.

In Table I is a compilation of the Mark II and Crystal Ball results, along with the previous experimental results, for the $\gamma\eta$ and $\gamma\eta'$ branching fractions. The Mark II measurement of the $\gamma\eta'$ branching fraction is somewhat larger, but still consistent with the previous measurements. The Crystal Ball finds a branching fraction that is twice that of the Mark II. This discrepancy is not totally understood. However, it should be noted that the two measurements are based on different decay modes of the η', and at least part of the discrepancy may come from the uncertainty in the relative branching fractions of the two decay modes. On the other hand, all four determinations of the branching fraction to $\gamma\eta$ are consistent. Also shown in Table I are the theoretical predictions calculated by Fritzsch and Jackson.[17] The excellent agreement between theory and experiment is better than one has a right to expect because of the uncertainties in the calculations.

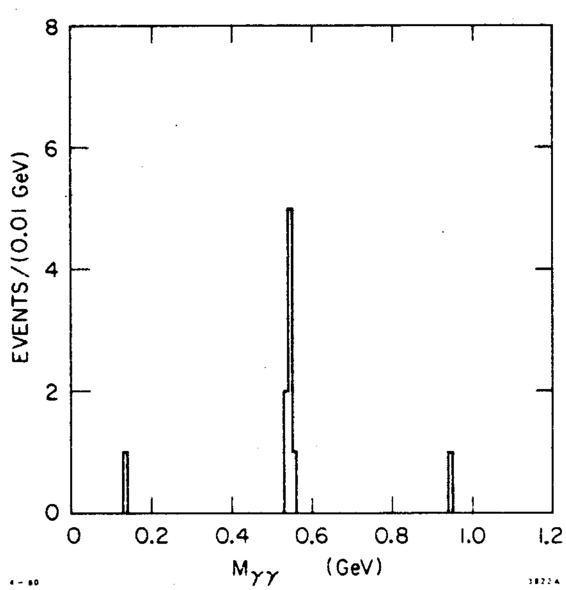

Fig. 6. Low-mass $\gamma\gamma$ invariant mass combinations for events satisfying (2). (Mark II)

Table I. Branching fractions for radiative transitions from the ψ to the η and η'.

decay	mode	branching fraction	experiment
$\psi \to \gamma\eta'$	$\rho^\circ\gamma$	$(3.4 \pm 0.7) \times 10^{-3}$	Mark II
	$\gamma\gamma$	$(6.9 \pm 1.7) \times 10^{-3}$	Crystal Ball
	$\gamma\gamma$	$(2.2 \pm 1.7) \times 10^{-3}$	DASP[a)]
	$\rho^\circ\gamma$	$(2.4 \pm 0.7) \times 10^{-3}$	DESY-Heidelberg[b)]
		3.3×10^{-3}	theory[c)]
$\psi \to \gamma\eta$	$\gamma\gamma$	$(0.9 \pm 0.4) \times 10^{-3}$	Mark II
	$\gamma\gamma$	$(1.2 \pm 0.2) \times 10^{-3}$	Crystal Ball
	$\gamma\gamma$	$(0.8 \pm 0.2) \times 10^{-3}$	DASP[a)]
	$\gamma\gamma$	$(1.3 \pm 0.4) \times 10^{-3}$	DESY-Heidelberg[b)]
		0.9×10^{-3}	theory[c)]

[a)] Ref. 9
[b)] Refs. 8, 11
[c)] Ref. 17

Table II summarizes the measurement of the ratio $B(\psi \to \gamma\eta')/B(\psi \to \gamma\eta)$. The measured values range from approximately 2 to 6, and the theoretical prediction is 3.9. Thus, I think it is fair to say that we have a reasonable understanding of the M1 transitions from the ψ to the ordinary pseudoscalar meson states.

In order to further explore the properties of the charmonium system, the Crystal Ball and Mark II collaborations have begun similar studies of radiative transitions from the ψ'. Naively, one would expect these branching fractions to be approximately an order of magnitude smaller than the corresponding branching fractions at the ψ.[25] Presently, no evidence for $\gamma\eta$ or $\gamma\eta'$ production from the ψ' has been observed, with preliminary 90% confidence level upper limits from the Crystal Ball of $B(\psi' \to \gamma\eta') < 8 \times 10^{-4}$ and $B(\psi' \to \gamma\eta) < 10^{-4}$. As these limits are

Table II. $B(\psi \rightarrow \gamma\eta')/B(\psi \rightarrow \gamma\eta)$.

ratio	experiment
3.8 ± 1.9	Mark II
5.9 ± 1.5	Crystal Ball
2.8 ± 2.3	DASP[a)]
1.8 ± 0.8	DESY-Heidelberg[b)]
3.9	theory[c)]

a) Ref. 9
b) Refs. 8, 11
c) Ref. 17

only a factor of eight below the measured ψ branching fractions, there is no reason to worry about the absence of these signals at this time.

IV. $\psi \rightarrow \gamma f(1270)$

In order to understand the radiative transition to the f(1270), I will once more consider the two processes shown in Fig. 2. The measured branching fraction for the process $\psi \rightarrow \omega f$ is approximately 3×10^{-3}.[26] Invoking VMD for the process shown in Fig. 2(a), one is led to expect a rate for the γf transition which is considerably less than the measured value.[13,14] Thus, even in this case, where the final state has $J^P = 2^+$ rather than 0^-, it appears that the process in Fig. 2(b) is dominant.

New measurements of the γf transition have been made by the Mark II.[27] Figure 7 shows the $\pi^+\pi^-$ invariant mass distribution (data points with error bars) for events which satisfy a fit to the hypothesis

$$\psi \rightarrow \pi^+\pi^-\gamma \tag{3}$$

with $\chi^2 < 15$. Two structures are evident in the mass distribution, one at the ρ mass and the other at the f(1270) mass. Since the decay $\psi \rightarrow \rho^\circ\gamma$ does not conserve charge conjugation parity (C-parity), it is assumed that the events in the ρ° mass region resulted from $\rho^\circ\pi^\circ$ decays

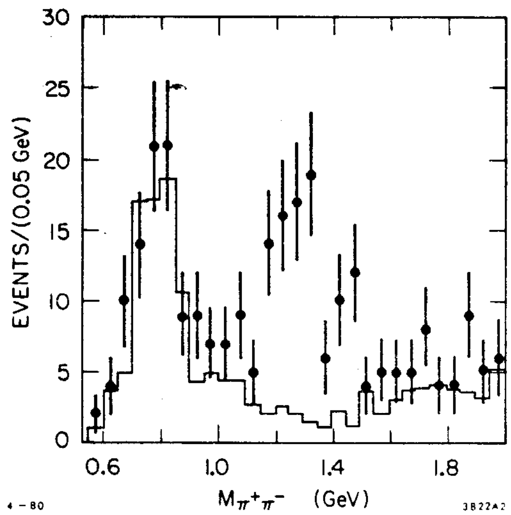

Fig. 7. $\pi^+\pi^-$ invariant mass distribution for events satisfying (3). Histogram shows the expected feeddown from the $\pi^+\pi^-\pi^\circ$ final state as determined by Monte Carlo. (Mark II)

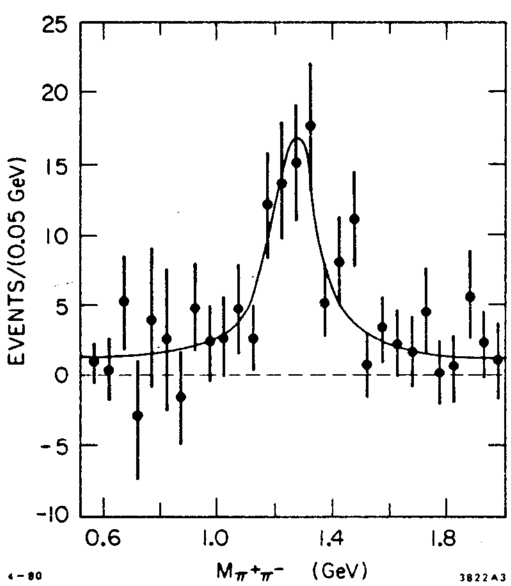

Fig. 8. $\pi^+\pi^-$ invariant mass distribution after subtraction of $\pi^+\pi^-\pi^\circ$ feeddown. Curve is described in text. (Mark II)

in which an asymmetric decay of the π° led to an acceptable fit to (3). A Monte Carlo was used to determine the $\pi^+\pi^-\pi^\circ$ feeddown into the $\pi^+\pi^-\gamma$ channel. The resulting distribution (including production of both $\rho^\circ\pi^\circ$ and $\rho^\pm\pi^\mp$) is compared with the data in Fig. 7 and can clearly account for the observed ρ° peak.

Figure 8 shows the $\pi^+\pi^-$ mass distribution after subtraction of the $\pi^+\pi^-\pi^\circ$ background. The distribution is dominated by the f. An expression consisting of a Breit-Wigner resonance term plus a flat background term was fitted to this distribution. The curve in Fig. 8 shows the best fit which gave $M = 1280$ MeV and $\Gamma = 180$ MeV for the resonance parameters. The branching fraction for (3) was found to be $B(\psi \to \gamma f) = (1.3 \pm 0.3) \times 10^{-3}$. This branching fraction is consistent with the previously measured values of $B(\psi \to \gamma f) = (2.0 \pm 0.3) \times 10^{-3}$ from PLUTO[13] and $B(\psi \to \gamma f)$ between $(0.9 \pm 0.3) \times 10^{-3}$ and $(1.5 \pm 0.4) \times 10^{-3}$ (depending on the helicity of the f in the final state) from DASP.[14]

As pointed out in the previous section, we seem to have a fairly good understanding of the transitions to the $I_z = 0$ members of the

$J^P = 0^-$ nonet. If measurements of the radiative transitions to the f' and A_2° could be made, we would have an additional check on the theoretical ideas discussed previously. The Mark II has preliminary results which show no evidence for transitions to either of these two states. They give 90% confidence level upper limits of $B(\psi \to \gamma f') \times B(f' \to K\bar{K}) < 10^{-3}$ and $B(\psi \to \gamma A_2^\circ) < 10^{-3}$. Unfortunately, these limits are not yet small enough to provide meaningful constraints on models. As in the case of the $\gamma\pi^\circ$ transition, one expects to see a very small branching fraction for γA_2° because of isospin conservation. However, the $\gamma f'$ transition should be observable. Based on a naive calculation assuming SU(3) invariance (similar to the η-η' calculation described earlier),[28] one expects

$$\frac{B(\psi \to \gamma f')}{B(\psi \to \gamma f)} = \frac{1}{2} \ .$$

The Mark II limit is not yet inconsistent with this prediction.

V. $\psi \to \gamma E(1420)$

As the E(1420) is a fairly obscure resonance, I will briefly review what was known about the E as of the last (1978) Particle Data Group tables[29] before discussing the results on the γE radiative transition. The E is a fairly narrow resonance with width estimates ranging from 40 to 80 MeV. Measurements of the mass lie between 1400 and 1440 MeV. None of the quantum numbers of the E have been firmly established. The isospin is believed to be zero as no charged E has ever been observed; the C-parity is believed to be even; and analyses of the decay Dalitz plot favor an abnormal spin-parity assignment. $J^P = 0^-$ and 1^+ are the preferred values. The principally observed decay mode is $K\bar{K}\pi$, but there is some evidence for an $\eta\pi\pi$ decay mode. Finally, up until 1978, the best signals for the E were observed in $p\bar{p}$ annihilations at rest. I will mention only one of these experiments here. Baillon et al.[30] studied a sample of $p\bar{p}$ annihilations in the CERN 81-cm hydrogen bubble chamber. They did a spin-parity analysis of the E observed in the reaction $p\bar{p} \to E\pi\pi$ and determined $J^P = 0^-$.

The Mark II sees evidence for the process[12]

$$\psi \to \gamma E \ , \ E \to K_S K^\pm \pi^\mp \ . \qquad (4)$$

Observation of this transition establishes C = + for the E. Figure 9(a) shows the $K_S K^{\pm}\pi^{\mp}$ invariant mass for events satisfying the 5-constraint (5C) fit to (4) with $\chi^2 < 15$.[31] The constraints are the normal ones of energy-momentum conservation with an additional constraint for the K_S mass. A peak is seen near the mass of the E(1420). One is not compelled to interpret this structure as the E(1420), but due to the similar characteristics of this structure and the previously observed E, I will make this tentative assignment.

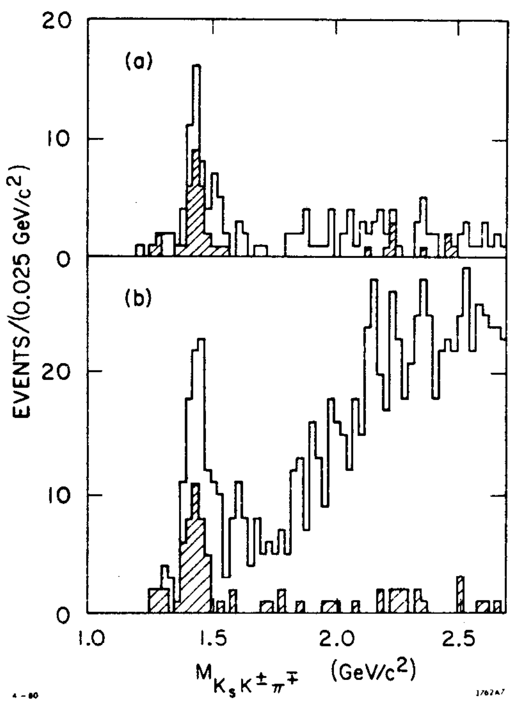

Fig. 9. $K_S K^{\pm}\pi^{\mp}$ invariant mass distributions for events satisfying (a) 5C fits and (b) 2C fits (i.e., observation of the photon is not required) to (4). Shaded regions have the additional requirement $M_{K\overline{K}} < 1.05$ GeV. (Mark II)

The parameters of the resonance were obtained by fitting the invariant mass distribution to a Breit-Wigner[32] plus a smooth background. The Mark II finds $M = 1.44^{+0.01}_{-0.015}$ GeV and $\Gamma = 0.05^{+0.03}_{-0.02}$ GeV. These errors include systematic uncertainties due to the functional form used in the fit. The branching fraction product, based on 47 ± 12 observed events, is $B(\psi \to \gamma E) \times B(E \to K_S K^{\pm}\pi^{\mp}) = (1.2 \pm 0.5) \times 10^{-3}$.[33] With the assumptions that the E is an isoscalar and that K_S and K_L production are equal in the decay of the E, one can relate the $K^+K^-\pi^\circ$, $K^\circ\overline{K}^\circ\pi^\circ$, and $K^\circ K^{\pm}\pi^{\mp}$ branching fractions and determine the branching fraction product $B(\psi \to \gamma E) \times B(E \to K\overline{K}\pi) = (3.6 \pm 1.4) \times 10^{-3}$.

Previous experiments[29] have found the decay of the E to be associated with a low mass $K\overline{K}$ enhancement which is also observed by the Mark II. If a cut requiring $M_{K\overline{K}} < 1.05$ GeV is imposed on the data, the shaded region in Fig. 9(a) is obtained.

Since the signal is quite clean, it is possible to relax the requirement that the photon be observed. The resulting 2C fit to (4) is shown in Fig. 9(b). Although there is an improvement in statistics,[34] there is also an increase in the background level. However, as shown by the shaded region, the $K\overline{K}$ mass cut again substantially reduces the background.

The Dalitz plot for the sample of events shown in Fig. 9(b) with masses between 1.375 and 1.500 GeV (the signal region) is shown in Fig. 10. The curves show the low-mass and high-mass kinematic boundaries and the dashed lines show the nominal K*(890) mass values. The points are plotted as functions of the $(K\pi)^\circ$ invariant mass squared vs. the $(K\pi)^\pm$ invariant mass squared. The $K\overline{K}$ axis, if it were shown, would be at an angle approximately bisecting the two $K\pi$ axes. One sees an excess of events in the upper right-hand corner of the Dalitz plot.[35] It is not clear whether these events correspond to a low-mass $K\overline{K}$ enhancement (spread out by the movement of the kinematic boundary as the $K\overline{K}\pi$ mass changes), or to constructive interference where the K^* bands overlap.

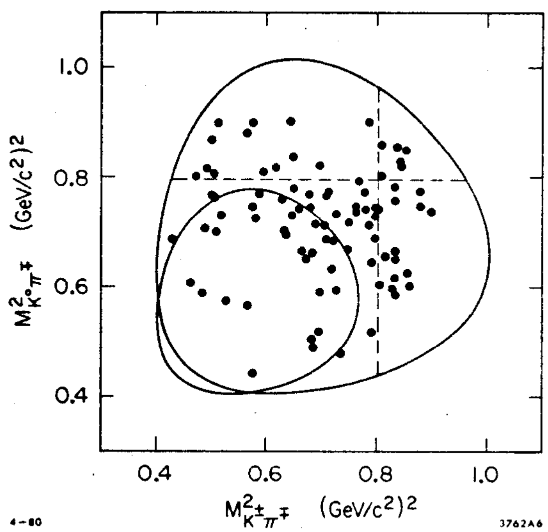

Fig. 10. Dalitz plot for events with $1.375 \le M_{K\overline{K}\pi} < 1.500$ GeV. Curves show low-mass and high-mass kinematic boundaries. Dashed lines show nominal K^* mass values. (Mark II)

Figure 11(a) shows the $K_S K^\pm$ invariant mass distribution for events in the signal region and Fig. 11(b) shows the corresponding distribution for events outside the signal region. There is evidence for a low-mass $K\overline{K}$ enhancement for events in the signal region which is absent for events outside the signal region. One possible interpretation of this enhancement is the $\delta(980)$.

In an attempt to understand the decay mechanism of the E, fits were made to the Dalitz plot which included $K^*\overline{K}$ (the inclusion of both this state and the charge conjugate state are implied by this notation), $\delta\pi$, and phase space contributions. These three contributions

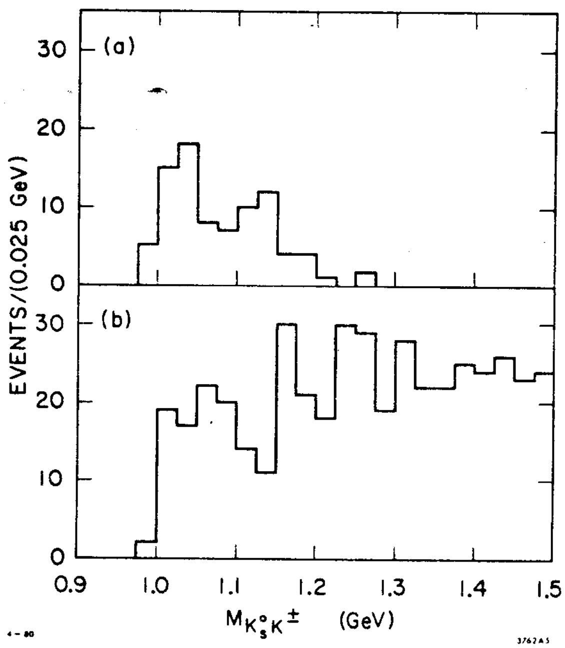

Fig. 11. $K_SK^\pm$ invariant mass distributions for events (a) in the signal region and (b) outside of the signal region. (Mark II)

were added incoherently, but the $K^*\bar{K}$ contribution included components from both the charged and neutral K^* states, which were assumed to interfere constructively where they cross on the Dalitz plot (as demanded by the even C-parity of the E). The best fit favors $\delta\pi$ as the primary component of the decay with

$$\frac{B(E \to \delta\pi) \times B(\delta \to K\bar{K})}{B(E \to K\bar{K}\pi)} = 0.8 \pm 0.2$$

The quoted error does not include possible systematic errors. One has to be careful in interpreting this result, as the best fit to the Dalitz plot does not completely simulate the $K\bar{K}$ invariant mass distribution. This indicates that the decay mechanism is not completely understood.

An attempt has been made to determine the spin of the E by analysis of the double decay angular distribution for events consistent with

$$\psi \to \gamma E \ , \ E \to \delta\pi \ .$$

However, the limited statistics do not allow a statistically significant determination of the spin.

Preliminary results from the Crystal Ball also show evidence for the transition $\psi \to \gamma E$.[7] Figure 12 shows the $K^+K^-\pi^\circ$ invariant mass distribution[36] for events which satisfy the 2C fit to

$$\psi \to \gamma K^+K^-\pi^\circ \ , \tag{5}$$

with $M_{K\bar{K}} < 1.1$ GeV. Although the Crystal Ball detector has excellent energy resolution for photons, the absence of a magnetic field does not allow a momentum measurement for charged particles. This reduces the constraint class for (5) from 4 to 2. Evidence for an E signal is seen in this distribution.

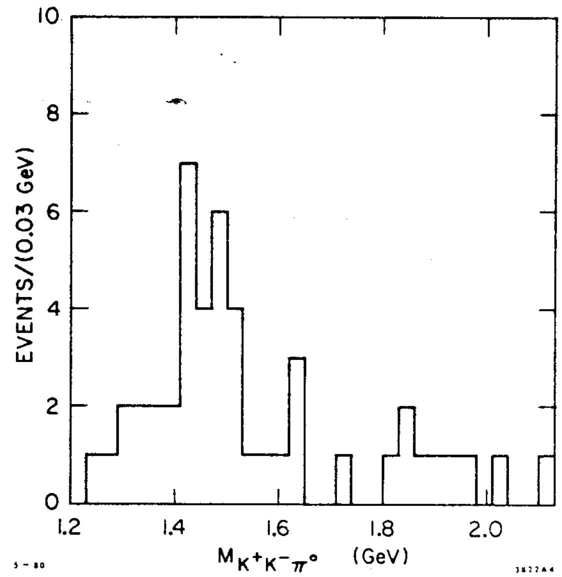

Fig. 12. $K^+K^-\pi^\circ$ invariant mass distribution for events satisfying (5) with $M_{K\bar{K}} < 1.1$ GeV. (Crystal Ball)

As the Crystal Ball efficiency calculations are still in a very preliminary state, estimates of the branching fraction are only good to a factor of two at best. When corrections are made for the K^+K^- mass cut[37] and the unobserved decay modes of the E, they find $B(\psi \to \gamma E) \times B(E \to K\bar{K}\pi) \approx 2 \times 10^{-3}$.

As was mentioned earlier, there is some evidence for the decay of the E into $\eta\pi^+\pi^-$. Fig. 13 shows the $\eta\pi^+\pi^-$ invariant mass distribution (from the Crystal Ball) for events satisfying fits to

$$\psi \to \gamma\eta\pi^+\pi^- \quad . \tag{6}$$

In addition to the η' signal, there is evidence for a peak in the E mass region. A preliminary estimate of the branching fraction product $B(\psi \to \gamma E) \times B(E \to \eta\pi\pi)$ finds it to be smaller than the corresponding number for $K\bar{K}\pi$, but a firm number will have to wait until calculations of the efficiencies are made.

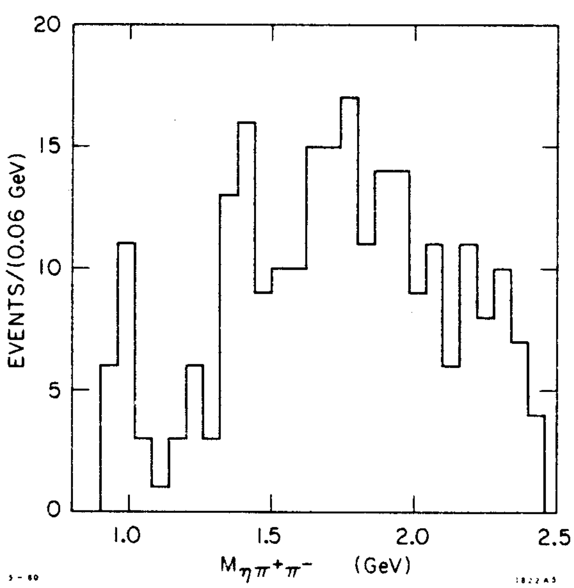

Fig. 13. $\eta\pi^+\pi^-$ invariant mass distribution for events satisfying (6). (Crystal Ball)

In summary, the E is observed very strongly in radiative transitions from the ψ. The only other transition that has been observed with a comparable branching fraction is the $\gamma\eta'$ transition. The possible significance of this will be discussed in the next section. Observation of this transition has established the C-parity of the E as even. Unfortunately, a determination of the spin is impossible with the present statistics. Finally, the Mark II finds the $K\bar{K}\pi$ decay mode of the E to be predominantly $\delta\pi$. The consequences of this will also be discussed in the next section.

VI. REVIEW OF THE STATUS OF THE E(1420)

I was asked by the organizers of this conference to include a review of the status of the E(1420) in my talk. Although this is somewhat outside the original scope of the talk, namely charmonium studies, I agreed as I think an understanding of the E could have important consequences in regard to understanding the charmonium system. As I have already given a brief introduction to the status of the E as of 1978, I will confine my discussion to two recent hadronic experiments which observe the E, and a comparison of their results with those of the Mark II.

The first results are from a high statistics (90 events/μb) bubble chamber experiment in which the reaction

$$\pi^- p \rightarrow K_S K^\pm \pi^\mp n \qquad (7)$$

was studied at 3.95 GeV/c.[38] Figure 14 shows the $K_S K^\pm \pi^\mp$ invariant mass for events which satisfy the 1C fit (the neutron was not observed) to (7). Evidence is seen for both D(1285) and E(1420) production. A fit to the $K_S K^\pm \pi^\mp$ invariant mass distribution yields values for the E mass and width of $M = 1426 \pm 6$ MeV and $\Gamma = 40 \pm 15$ MeV.[39] These errors are statistical only.

The Dalitz plot for events in the region $1.39 \leq M_{K\bar{K}\pi} \leq 1.47$ GeV is shown in Fig. 15. As was observed in the Mark II data, there is evidence for an enhancement in the upper right-hand corner of the Dalitz plot. However, in this case, there is also clear evidence for $K^*(890)$ production. A partial-wave analysis of the data determined the spin-parity of the E to be $J^P = 1^+$, and also determined the branching fraction ratio

$$\frac{B(E \rightarrow K^*\bar{K})}{B(E \rightarrow K^*\bar{K} + \delta\pi)} = 0.86 \pm 0.12 \; .$$

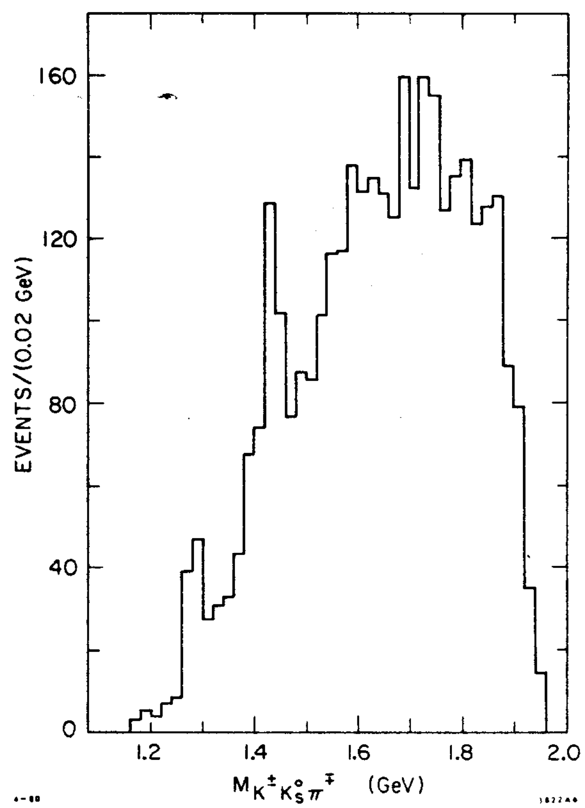

Fig. 14. $K_SK^{\pm}\pi^{\mp}$ invariant mass distribution for events satisfying (7). Data is from Ref. 38.

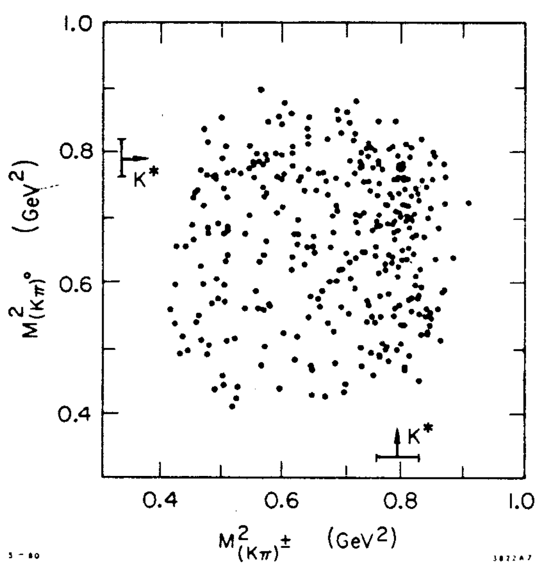

Fig. 15. Dalitz plot for events with $1.39 \leq M_{K\overline{K}\pi} \leq 1.47$ GeV. Data is from Ref. 38.

However, it should be pointed out that the E signal is over a relatively large background which has a significant $K^*\overline{K}$ component, so that one should regard this result with caution.

In another experiment, the reaction

$$\pi^- p \rightarrow K_S K^{\pm}\pi^{\mp} + X \qquad (8)$$

was studied at 50 and 100 GeV/c.[40] The $K_SK^{\pm}\pi^{\mp}$ invariant mass distribution for this sample of events, in Fig. 16, shows no evidence for an E signal. However, if a δ cut is applied, $M_{K\overline{K}} < 1.04$ GeV, both the D and the E become quite prominent, as shown in Fig. 17. If instead of a δ cut, a cut is applied requiring one of the $K\pi$ invariant mass combinations to be in the K^* mass region ($0.84 < M_{K\pi} < 0.94$ GeV), one still sees an E signal, but with considerably worse background. A fit to the $K_SK^{\pm}\pi^{\mp}$ mass distribution in Fig. 17 yielded values of the resonance parameters of $M = 1440 \pm 6$ MeV and $\Gamma = 110 \pm 27$ MeV. (The curve in Fig. 17 represents the best fit to the data.) The errors are statistical only. The systematic errors, especially for the

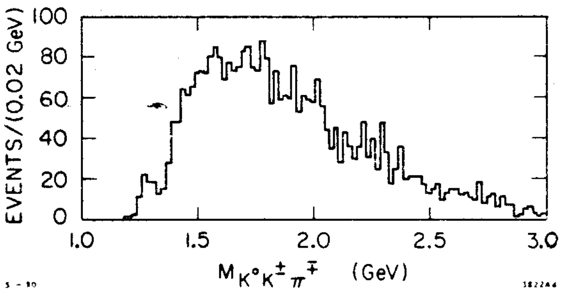

Fig. 16. $K_S K^\pm \pi^\mp$ invariant mass distribution for events satisfying (8). Data is from Ref. 40.

width, are probably large. Another fit made to a similar spectrum (after subtraction of the estimated background due to K-π misidentification) yielded M = 1440 ± 5 MeV and Γ = 62 ± 14 MeV. On the surface, this data seems to indicate a preference for the $\delta\pi$ decay mode of the E over the $K^*\overline{K}$ decay mode. However, questions of kinematic overlap in the Dalitz plot and phase space boundaries have not been considered in detail. Thus, this preference should be considered only as an indication until a more sophisticated analysis is done.

Despite all the new information on the E from recent experiments, the situation is not much clearer than it was in 1978. One point of controversy is whether the E decays predominantly into $\delta\pi$ or $K^*\overline{K}$. The Mark II (and possibly also the Fermilab experiment of Bromberg et al.[40]) seem to favor the decay E $\rightarrow$ $\delta\pi$. On the other hand, Dionisi et al.[38] see little evidence for $\delta\pi$ and find the predominant decay of the E is into $K^*\overline{K}$. As for the spin, Dionisi et al. find $J^P = 1^+$ which agrees with some earlier results, but disagrees with others. However, their determination of the spin goes hand-in-hand with the determination of the predominance of the $K^*\overline{K}$ decay mode. Since this predominance is not firmly established,

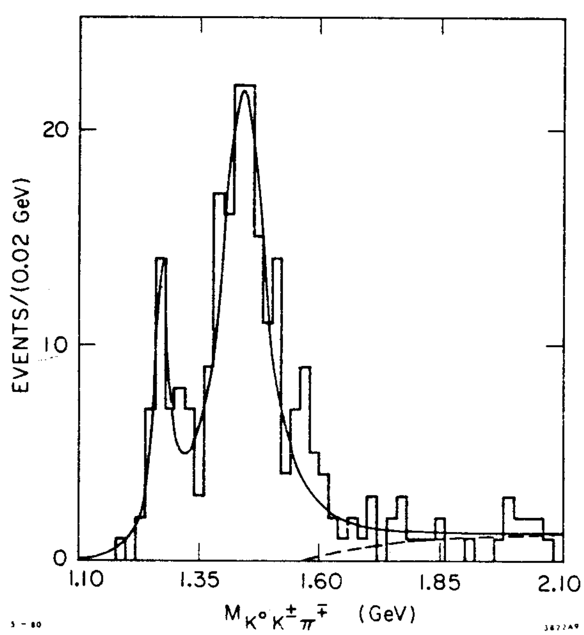

Fig. 17. $K_S K^\pm \pi^\mp$ invariant mass distribution with $M_{K\overline{K}} < 1.04$ GeV. Solid curve shows fit to mass spectrum. Dashed curve shows background distribution determined from fit. Data is from Ref. 40.

I think that one should still consider the spin of the E to be an open question until the decay mechanism is understood better.[41]

To understand my reasons for this excessive interest in the quantum numbers of the E, let me refer for the last time to Fig. 2(b). As discussed yesterday by Donoghue,[42] if gluonium states[43] exist, the process shown in Fig. 2(b), after elimination of the outgoing quark lines, would be an ideal process for production of such states. I would like to suggest the possibility that the E might be such a gluonium state, rather than an ordinary $q\bar{q}$ resonance. Although there is certainly no real evidence for this hypothesis, there are a few peculiarities associated with the γE radiative transition from the ψ which I would like to point out.

First, the branching fraction for $\psi \to \gamma E$ is larger than the corresponding branching fractions for transitions to other ordinary hadrons, with the possible exception of the η'. This is in contrast to hadronic experiments where E production is in general small compared to the production of other resonances. This would lead one to infer a connection between the E and the 2-gluon intermediate state in Fig. 2(b). Whereas the production of gluonium states is expected to be significant in ψ radiative transitions, there is no reason to expect significant production of such states in hadronic reactions.

Second, whereas in most hadronic experiments in which an E is observed to decay into $K\bar{K}\pi$, one observes roughly comparable D(1285) production, neither the Mark II nor the Crystal Ball see much evidence for D production. The Mark II gives an upper limit for D production of $B(\psi \to \gamma D) \times B(D \to K\bar{K}\pi) < 0.7 \times 10^{-3}$ at the 90% confidence level. This might be taken as strong evidence for a difference in the production mechanisms involved in the two different processes, and hence an indication of a large gluonium component in the E. However, if one assumes that the D and E are both members of the standard $J^{PC} = 1^{++}$ nonet, and the E is the primarily singlet state and the D is the primarily octet state,[44] one would expect D production to be suppressed relative to E production because of SU(3) symmetry arguments. Thus, this suppression may not be relevant to the gluonium question at all.

In my opinion, the most important question which should be resolved regarding the E is its spin. If the E can be firmly established as an axial vector state, there is no reason not to make the standard $q\bar{q}$ meson interpretation and put it in the same nonet as the D(1285), A_1, and Q_A. If, on the other hand, the E is finally established as a pseudoscalar, it is difficult to interpret it within the standard quark model. The $J^P = 0^-$ nonet is complete, and one would have to consider the existence of another 0^- nonet, possibly a radial excitation of the ground state, in order to accommodate the E. However, I think it is equally plausible to interpret the E as a gluonium state.

VII. CONCLUSIONS

The first part of this talk dealt with radiative transitions from the ψ to the η, η', and f. The new results from the Mark II and Crystal Ball collaborations are basically compatible with previous results (ignoring minor factor-of-two problems with the η'). I tried to emphasize that these transitions can be understood in terms of minimal gluon-coupling ideas, with mixing between the different isoscalar states. Further work is being done to extend our understanding of these processes. The Mark II is in the process of studying the radiative transitions to the other tensor states, the f' and A_2°. Another direction which is being pursued by both the Mark II and the Crystal Ball collaborations is an analysis of similar radiative transitions from the ψ'. As mentioned previously, these transitions are expected to have branching fractions approximately an order of magnitude smaller than the corresponding ψ transitions. This should be verified, and may lead to surprises.

The rest of the talk dealt with the E(1420). As I discussed in detail in the previous section, it is interesting to entertain the possibility that the E is a gluonium state. If this were true, it would open up a whole new field of spectroscopy. However, let me emphasize that even if the spin-parity of the E were determined to be 0^-, there would be no compelling reason to believe that it is a gluonium state.

Although it was not emphasized during the talk, there has been some effort by the Mark II collaboration to look for other radiative transitions from the ψ. All states with reasonable acceptance in the Mark II detector (i.e., states decaying into combinations of $\pi^{\pm}$, $K^{\pm}$, K_S, p, and $\bar{p}$), and even some with poor acceptance (e.g., states with π°'s or η's in the final state), have been considered. No statistically significant signals aside from those shown today have been observed. Thus, if the E is not a gluonium state, neither the Mark II nor the Crystal Ball has any evidence for such a state.[45]

Let me conclude by remarking that in addition to the understanding of the charmonium system that can be gained by studying ψ decays (in particular, radiative transitions), there is also the possibility of being able to study ordinary (i.e., non-charmed) hadrons in a cleaner environment than can be obtained in typical hadronic interactions.

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18. Because of the six-fold symmetry of the final state, the Dalitz plot has been folded. This results in the observed folding of the η and η' bands at the boundary.
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20. However, due to problems with the Mark II liquid argon shower counter system, there was no photon detection for approximately half of the running time. Thus, any analyses which required photon detection were based on half of the total data sample.

21. G. S. Abrams et al., Phys. Rev. Lett. 43, 477 (1979); G. S. Abrams et al., Phys. Rev. Lett. 43, 481 (1979); G. S. Abrams et al., Phys. Rev. Lett. 43, 1555 (1979).

22. Due to noise in the LA electronics, spurious photons were occasionally reconstructed by the tracking program. In order not to lose good events, extra photons were allowed in candidate events. When analyzing these events, separate fits were attempted for each two-photon combination.

23. In general, two or more charged tracks were required to trigger the detector.

24. Approximately one million ψ' events were taken. From this sample 92,000 ψ decays were identified by missing mass from the $\pi^+\pi^-$ system.

25. This ratio is expected to be roughly the same as the ratio of the leptonic branching fractions of the ψ' and ψ.

26. J. Burmester et al., Phys. Lett. 72B, 135 (1977); F. Vanucci et al., Phys. Rev. D 15, 1814 (1977).

27. C. Zaiser et al., in preparation.

28. It is expected that the mixing due to gluon exchange will not affect this ratio as severely as in the case of the pseudoscalar nonet.

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31. This distribution includes a few additional events corresponding to the process $\psi' \to \pi^+\pi^-\psi$, $\psi \to \gamma E$. Details can be found in Ref. 12.

32. The mass resolution of these constrained events is considerably smaller than the natural line width of the resonance and is ignored in the fit.

33. The efficiency used in the determination of this branching fraction was based on a Monte Carlo analysis which assumed all decay distributions were isotropic. If the spin-parity of the E were 0^-, which results in a $1 + \cos^2\theta$ distribution for the angle of the photon with respect to the beam axis, the branching ratio product should be increased by 19%.
34. The increase in sample size arises principally from the fact that the sample of data in which the LA system was not operational could be used.
35. Monte Carlo analysis shows the acceptance to be roughly flat over the entire Dalitz plot. Hence, the observed structure is not the result of variations in the acceptance.
36. This decay mode is expected to be half the $K_S K^\pm \pi^\mp$ mode by isospin conservation.
37. The correction was based on the $K_S K^\pm$ mass distribution for the sample of $E \to K_S K^\pm \pi^\mp$ events from the Mark II.
38. C. Dionisi et al., CERN Report No. CERN/EP 80-1 (1980), submitted to Nucl. Phys. B.
39. The actual fit was made to a distribution which required at least one $K\pi$ combination within the K^* mass region, with some additional kinematic cuts to reduce the background.
40. The data are from experiment E110 using the Fermilab multiparticle spectrometer [C. Bromberg et al., California Institute of Technology Report No. CALT-68-747 (1980)].
41. It has been suggested that the resonance seen in hadronic experiments and known as the E(1420) is not the same state that has been observed by the Mark II in radiative transitions from the ψ. However, because of the consistency of the parameters of the states seen in these two processes and the outward similarity of the Dalitz plots, I think it is logical to consider them to be the same state until some evidence to the contrary is produced.
42. J. Donoghue, invited talk this conference.
43. A gluonium state is a bound state of two or more gluons.
44. Unfortunately, the masses of the other members of the nonet (the A_1 and the Q_A) are not well enough known to provide a reliable estimate of the mixing angle.

45. This does not mean that none exist. Neither the masses nor the widths are well defined theoretically, and the decay modes expected for such states are often such that their detection by the Mark II would be difficult. For a brief but excellent review of the possibilities, see J. D. Bjorken, Stanford Linear Accelerator Center Report No. SLAC-PUB-2366, to be published in the Proceedings of the 1979 EPS High Energy Physics Conference, Geneva, Switzerland, June 27-July 4, 1979.