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RADIATIVE DECAYS OF THE ψ AND ψ'*

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Abstract: The status of the η_c signal seen in the Crystal Ball data on ψ' and ψ radiative decay is presented. The η_c has a mass of (2981 ± 15) MeV, and a width of 20 ± 15 MeV. The decay mode $\eta_c \to \eta\pi\pi$ is observed by fitting to exclusive events. Data on other radiative decays of the ψ show evidence for the E(1420) meson.

On presente l'etat des donnees acquisest avec le detecteur 'Crystal Ball' dans la desintegration du ψ' et ψ. La resonance η_c a une masse de (2981 ± 15) MeV et une largeur de 20 ± 15 MeV. Le mode de desintegration $\eta_c \to \eta\pi\pi$ est observe. Les donnees de les autres modes de desintegration radiatives du ψ montrent l'existence du meson E(1420).

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Introduction

The existence of the η_c, the $^1S_0$ hyperfine partner of the ψ is crucial to all models which regard the ψ as composed of a spin 1/2 quark bound to a spin 1/2 antiquark. The η_c is expected to have quantum numbers $J^{PC} = 0^{-+}$ and can be reached by an M1 radiative transition from the ψ, or by a hindered M1 transition from the ψ', since in this latter case the wavefunctions of the ground state η_c and the radially excited ψ' do not overlap much. For such M1 transitions there is a factor of $(E_\gamma)^3$ in the transition rate, and so if the η_c lies close to the ψ the branching ratio $BR(\psi \to \gamma\eta_c)$ will be small. Within the framework of the charmonium picture[2,3] the η_c is expected to lie about 100 MeV below the ψ, and the branching ratio $BR(\psi \to \gamma\eta_c)$ is expected to be of the order of a few percent.

The Crystal Ball[1] is a non-magnetic detector consisting of a highly segmented array of sodium iodide crystals. It has good energy resolution for photons (a sigma of 0.28 $E^{3/4}$ GeV). It is described in detail by Oreglia[4] in the previous talk at this conference. The Crystal Ball is well-suited to the study of the η_c by measuring the low energy photons from the radiative decays of ψ and ψ'.

Status of the η_c Signal Seen in the Inclusive Radiative Decays of ψ and ψ'

Figure 1 shows the inclusive photon spectrum[5,6] from a sample of 800K ψ' decays. Photons from π^0 decay have been removed by a pairing algorithm, but a large background of photons from π^0 decay remains. The spectrum shows the three monochromatic photon peaks corresponding to the radiative decays of the ψ' to the three $^3P_1$ states, $\chi(3410)$, $\chi(3505)$ and $\chi(3550)$, and the Doppler-broadened photon peaks from the cascade decay of the χ-states to the ψ. In addition to this structure we see evidence for a monochromatic photon of energy 634 MeV,[7] which we interpret as evidence for the decay $\psi' \to \gamma\eta_c$. This photon energy corresponds to a η_c mass of 2983 MeV. Since we have not yet established the quantum numbers of the 2983 MeV state, we should at this stage strictly call it the "η_c candidate," but we may now begin to tentatively identify it as the η_c itself.

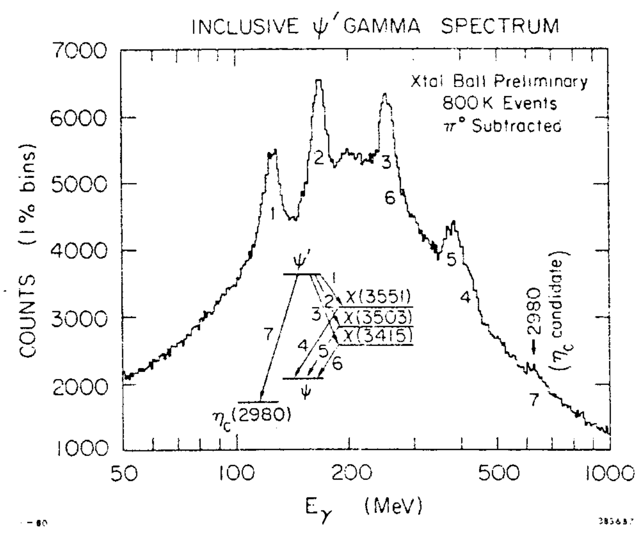

Fig. 1. Inclusive photon spectrum from 800k ψ' decays. The logarithmic energy scale is used since the experimental resolution $\Delta E/E$ varies only slowly with E.

Figure 2 shows the inclusive photon spectrum from 900k ψ decays. The radiative transition of the ψ to an η_c of mass 2980 MeV would yield a monochromatic photon of energy 113 MeV; indeed the spectrum does exhibit a very slight but not very convincing bulge at this energy. We should bear in mind that the resolution of sodium iodide for a 110 MeV photon has a full width at half maximum (FWHM) of 14 MeV; that the η_c state itself may be broad (of the order of 10 or 20 MeV); and that the line shape will be distorted by the $(E_\gamma)^3$ factor. A proper extraction of this signal should take all of these effects into account, and will require a full understanding of the background shape based on Monte Carlo simulation. Work in this direction is in progress. Meanwhile a simple fit using a linear plus quadratic background has been performed. The ψ' spectrum shows a signal of greater than 5 σ significance at an energy of (634 ± 13) MeV, corresponding to the mass of the η_c state being (2983 ± 16) MeV. The ψ spectrum shows a broad signal at an energy of 112 MeV, corresponding to an η_c mass of 2981 MeV.

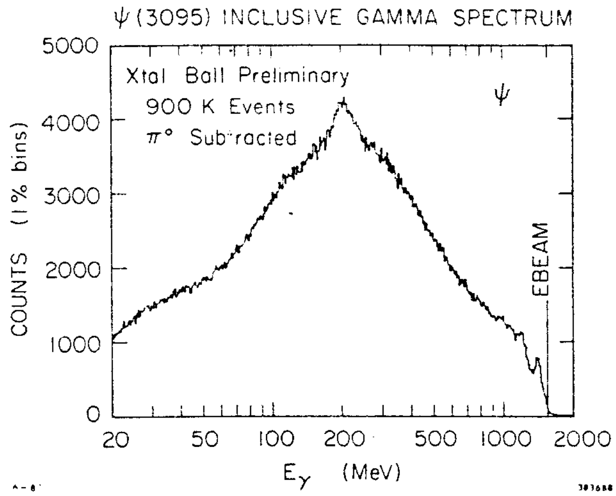

Fig. 2. Inclusive photon spectrum from 900k ψ decays.

In order to extract the best information possible regarding the mass and Γ, the natural width, of the η_c, a 9 parameter fit was simultaneously made to the ψ' and ψ inclusive spectra in the region of the state. The 9 fit parameters are: 3 for a background quadratic for the ψ' near 634 MeV, 3 for a background quadratic for ψ near 112 MeV, the amplitude for a Breit-Wigner folded with a gaussian resolution of 43 MeV (FWHM) at the ψ', the amplitude for a Breit-Wigner folded with a gaussian resolution of 11 MeV (FWHM) at the ψ, and the mass of the assumed resonance. The natural line width, Γ, of the Breit-Wigner shape was also varied externally to the fit and the dependence of χ^2 on Γ was determined.

Figure 3 shows the common best fit with M = 2981 (±15) MeV and $\Gamma = 20\binom{+16}{-11}$ MeV (χ^2 = 53.2 for 66 degrees of freedom) overplotted on the data for the ψ and ψ' inclusive photon spectra respectively. The error on the mass of ±15 MeV is predominantly systematic. The error on Γ, however, is purely statistical. No attempt has yet been made to realistically estimate the systematic errors on Γ.

Figure 4 shows $\chi^2(\Gamma)$ and $A(\Gamma)$ where $A(\Gamma)$ is the number of counts in the extracted signal at the ψ as a function of Γ. A broad minimum in χ^2 is seen centered at Γ = 20 MeV. However, the 1 σ limits ($\chi^2_\pm = \chi^2$ min ± 1) of Γ are +16

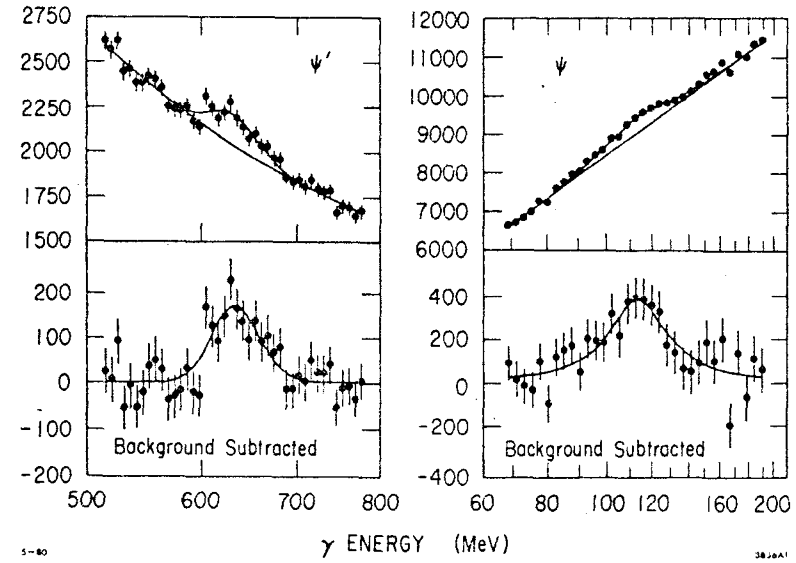

Fig. 3. Expanded regions of inclusive photon spectrum from ψ and ψ' in region of η_c signal. Results of a fit described in the text (Γ = 20 MeV) are overplotted.

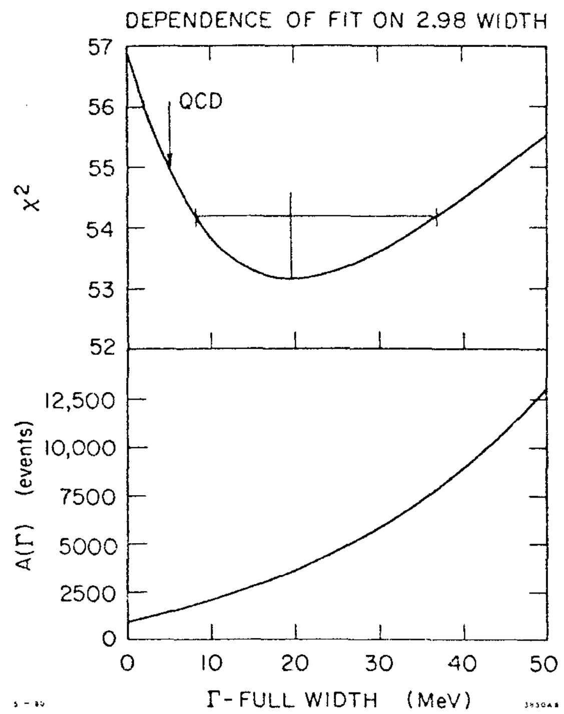

Fig. 4. Dependence of best χ^2 and number of counts in the inclusive photon spectrum from ψ as a function of the separately varied width Γ.

and -11 MeV. Thus, the expected quantum chromodynamics value[1)] of ~5 MeV for the width of the standard η_c is only about 1.5 σ away from the preferred value of 20 MeV. Indeed, Γ = 0 is less than 2 σ from the preferred value.

Uncertainty in the form of the background for the fits to the ψ inclusive spectrum will clearly influence the derived Γ.

Without a detailed Monte Carlo calculation of the photon detection efficiency, it is difficult to quote branching ratios for the inclusive radiative decays to the η_c. Also, in the case of $\psi \to \gamma\eta_c$, it is clear that the transition rate is strongly coupled to the total width. At present, our best estimates for the branching ratios are

$$BR(\psi' \to \gamma\eta_c) = 0.2 \text{ to } 0.5\%$$

$$BR(\psi \to \gamma\eta_c) = 1\%$$

Another feature of the ψ spectrum is an apparent excess of photons at low energy. This region has been examined, using Monte Carlo simulation and it is found that much of the photon signal below 50 MeV is due to hadronic energy from hadronic interactions in the NaI(Tℓ) sodium iodide. This energy has separated from the main hadronic track and is erroneously identified as photons by the analysis software. We expect that in the near future, using Monte Carlo codes, we will be able to subtract this background and find the true photon spectrum at low energy. This hadronic "split off" energy also causes some problems in the Crystal Ball when exclusive states are considered.

Exclusive Hadronic Decays in the Crystal Ball

The Crystal Ball detector measures both the energy and angle of electromagnetically showering particles such as electrons and photons; for charged hadrons only the angles are measured. The charged hadrons either interact in the one radiation length of sodium iodide, or deposit minimum ionizing energy as they traverse the ball. In both cases only a fraction of the hadron energy is seen. A reaction such as $\psi \to \gamma\gamma\pi^+\pi^-$ can be kinematically fitted with two constraints, since lack of knowledge of the energies of the two charged hadrons reduces the four energy-momentum constraints to two. The measurement error (sigma) on the energy of a photon is $\Delta E = 0.3\ E^{3/4}$ (E in GeV) and the error on the space angle is $\Delta\alpha = 34$ milliradian. This angle does have a slow dependence on the photon energy, but has been taken as constant for the present analysis. The error on the angle of the charged particles which are tracked by the central wire spark and proportional chambers is $\Delta\phi = 20$ milliradian and $\Delta\theta = 40$ milliradian. The fitting of events with charged hadrons is complicated by secondary interactions of the hadrons in the sodium iodide, which often lead to a region of hadronic energy deposition distinct from that region pointed to by the tracking chambers. This 'split-off' hadronic energy is not recognized correctly as such by the software algorithms, and appears as extra fake low-energy photons, thereby confusing the topological classification of the event. This lowers the efficiency for the detection of the hadronic exclusive final state. We can measure this effect by fitting a reaction with a known branching ratio, and have done this using the reaction

$$\begin{array}{l} \psi \to \gamma\eta' \\ \qquad \hookrightarrow \rho\gamma \\ \qquad\quad \hookrightarrow \pi^+\pi^- \end{array}$$

All ψ decays with the topology of 2-photons 2-charged tracks were fitted to the two-constraint hypothesis $\psi \to \gamma\gamma\pi^+\pi^-$ using the kinematic fitting computer code SQUAW.[8] Figure 5 shows the $M_{\pi^+\pi^-\gamma}$ distribution for events which pass the fit with $P(\chi^2) > 0.10$. The $\eta'(958)$ is seen as expected. The background comes mainly for the reaction $\psi \to \pi^+\pi^-\pi^0$ and peaks near the ψ mass. The $M_{\pi^+\pi^-}$ distribution shown in Figure 6 shows a signal at the $\rho(770)$. Figure 7a shows the energy

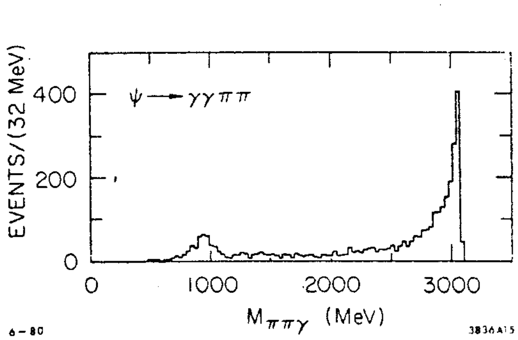

Fig. 5. $M_{\pi^+\pi^-\gamma}$ distribution for events fitting $\psi \rightarrow \gamma\gamma\pi^+\pi^-$. A peak due to $\eta'(958)$ is visible.

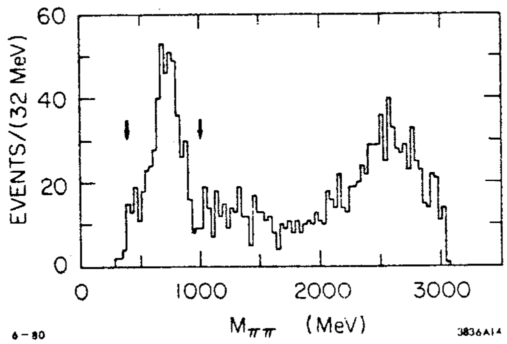

Fig. 6. $M_{\pi^+\pi^-}$ distribution for events fitting $\psi \rightarrow \gamma\gamma\pi^+\pi^-$ showing a ρ peak at $M_{\pi\pi}$ = 770 MeV. Arrows indicate cuts used to select events with a ρ meson.

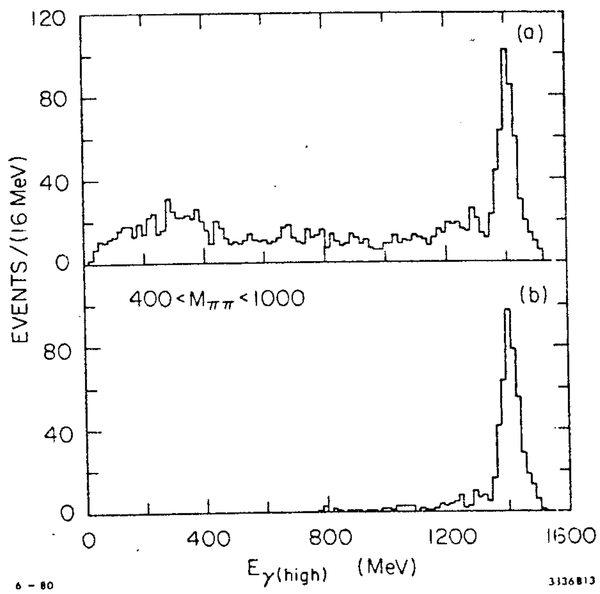

Fig. 7. Energy spectrum of higher energy photon in events fitting $\psi \rightarrow \gamma\gamma\pi\pi$ for a) all events, b) events with $M_{\pi\pi} \approx M\rho$.

spectrum of the photon with the higher energy, and Figure 7b shows the same distribution for events which satisfy a ρ cut (i.e., $400 < M_{\pi\pi} < 1000$ MeV). A clear peak is seen at E_γ = 1400 MeV due to the $\psi \rightarrow \gamma\eta'$ events. After subtraction of a small background, there are 365 ± 30 events in this peak. Using the value for the branching ratio measured earlier by the Crystal Ball $BR(\psi \rightarrow \gamma\eta') = (6.9 \pm 1.8)10^{-3}$[9] and the known branching ratio $BR(\eta' \rightarrow \rho\gamma)$ = 0.30 ± 0.02,[10] together with a Monte Carlo estimate of 0.53 ± 0.10 for our geometric acceptance, we expect 905 ± 120 η' events from our data sample of 850k ψ decays. For this we estimate the efficiency for correctly identifying and fitting the 2-charged topology as $\varepsilon = 0.4 \pm 0.1$. We hope to improve this efficiency in the future once we have learned to deal with the hadronic 'split-off' events.

Exclusive Hadronic Decays of the ψ

Having gained some confidence in our ability to detect exclusive hadronic final states in the Crystal Ball, we search now for decays of the ψ into states with photons and two charged hadrons, such as $\psi \rightarrow \gamma\eta\pi^+\pi^-$ and $\psi \rightarrow \gamma K^+K^-\pi^0$. From our sample of 850k ψ decays we select hadronic events on the basis of total energy and energy asymmetry. Those events with the correct 3-photon 2-charged topology and with the energy of each photon above 20 MeV are subject to the kinematic fit.

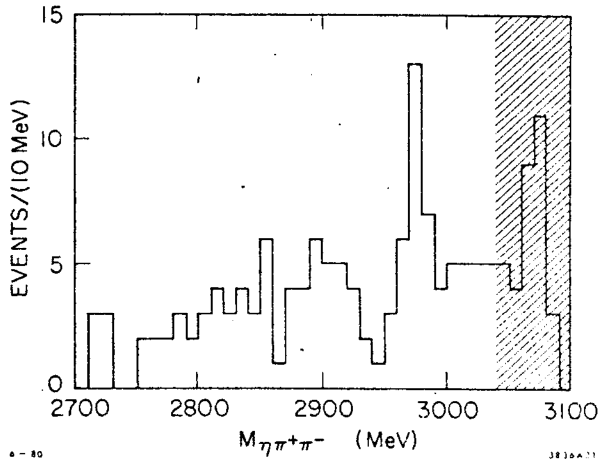

Fig. 8. $M_{\eta\pi^+\pi^-}$ distribution in fitted $\psi \to \gamma\eta\pi^+\pi^-$ events showing an η_c signal at mass 2972 ± 15 MeV. The region where the topology is confused by hadronic 'split-off' events is shaded.

Figure 8 shows the mass distribution $M_{\eta\pi^+\pi^-}$ in events which pass the 3-constraint fit to the hypothesis

$$\psi \to \gamma\eta\pi^+\pi^-$$
$$\hookrightarrow \gamma\gamma$$

with $P(\chi^2) > 0.1$. A clear signal is seen at a mass $M_{\eta\pi^+\pi^-} = (2972 \pm 15)$ MeV. The error on the mass comes mainly from the poor statistics. This mass agrees excellently with the mass of the η_c as determined from the ψ and ψ' inclusive spectra. The width of the η_c in this channel appears to be of the order of 20 MeV, and again the contribution to the width from the sodium iodide resolution is 14 MeV, since here the error in the mass determination is due almost totally to the error in the measurement of the low energy photon. We have not yet made a detailed analysis of the intrinsic width of the η_c from these few fitted events, but it is clear that the width could lie anywhere between 0 and 20 MeV. Notice that in Figure 8 events in the shaded region arise mainly from the 2-photon 2-charged topology with an hadronic 'split-off' faking the extra low energy photon. The signal at 2972 MeV consists of 14 ± 6 events above background. Using the previously estimated efficiency $\varepsilon = 0.4 \pm 0.1$ and an estimated geometric acceptance of 0.4 ± 0.2 for the $\eta\pi^+\pi^-$ final state, we calculate a preliminary product branching ratio

$$BR(\psi \to \gamma\eta_c) \cdot BR(\eta_c \to \eta\pi^+\pi^-) = (2.7 \pm 1.5) \times 10^{-4}$$

Using our crude estimate of $BR(\psi \to \gamma\eta_c) = 0.01$ we see that the branching ratio of the $\eta_c \to \eta\pi^+\pi^-$ mode is of the order of 0.03.

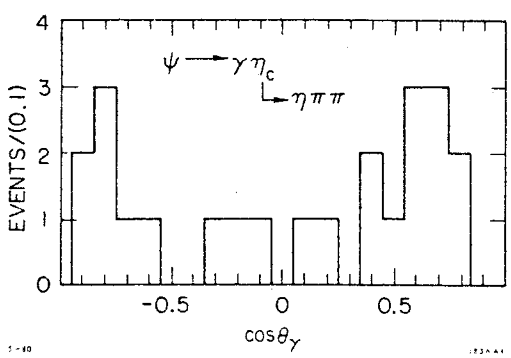

Fig. 9. Angular distribution of the radiated photon in events $\psi \to \gamma\eta\pi^+\pi^-$ with $M_{\eta\pi^+\pi^-} \approx M_{\eta_c}$.

Figure 9 shows the angular distribution of the 121 MeV monochromatic photon for the events in the peak ($2960 < M_{\eta\pi\pi} < 2990$ MeV). Since the statistics are very poor, the angular distribution in $\cos\theta$ where θ is the angle of the photon with respect to the e^+e^- beam axis, is consistent both with being isotropic, and with being of the form $1 + \cos^2\theta$ expected for a pseudoscalar η_c.

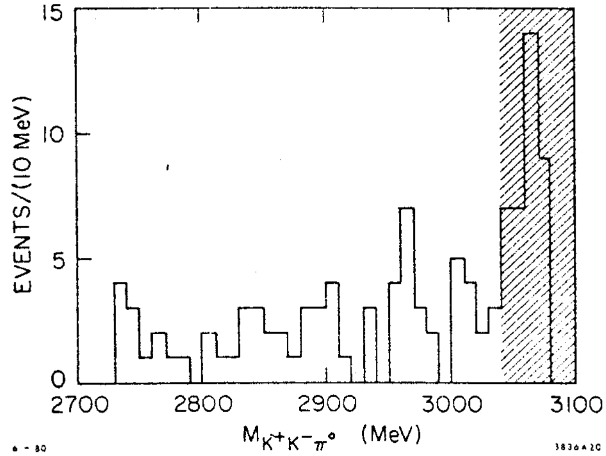

Fig. 10. $M_{K^+K^-\pi^0}$ distribution fitted $\psi \to \gamma K^+K^-\pi^0$ events. The region where the topology is confused by hadronic 'split-off' events is shaded.

We have also looked for the decay mode $\eta_c \to K^+K^-\pi^0$ by fitting events to the 3-constraint hypothesis

$$\psi \to \gamma K^+K^-\pi^0 \quad \pi^0 \to \gamma\gamma$$

By isospin symmetry, this mode is a factor of two smaller than the $K_S^0K^{\pm}\pi^{\mp}$ mode in which evidence for a state at 2980 MeV has been seen by the Mark II group at Spear.[11]

Figure 10 shows the $M_{K^+K^-\pi^0}$ distribution. Only a very weak signal is seen, so we set a preliminary 90% confidence level upper limit on the product branching ratio

$$BR(\psi \to \gamma\eta_c) \cdot BR(\eta_c \to K^+K^-\pi^0) < 1.5 \times 10^{-4}$$

This upper limit is consistent with the reported Mark II signal.

We are able to look for other decay modes of the η_c such as $\pi^+\pi^-\pi^0\pi^0$ and $K^+K^-\pi^0\pi^0$ and work in this direction is in progress.

Other Radiative Decays of the ψ

Figure 11 shows the high energy part of the inclusive photon spectrum from ψ decays. The two photons from high energy π^0 decay will appear merged into one region of energy deposition in the ball, and thus appear as a single photon, but generally the pattern of energy deposition for these π^0 photons will be fatter than that for a single photon. A cut based on the pattern of these collapsed photons has been used to remove some of the high energy π^0 background. Visible in the spectrum is a peak at E_γ = 1500 MeV from the $\psi \to \gamma\eta(548)$ decay; one at E_γ = 1401 MeV from the $\psi \to \gamma\eta'(958)$ and a structure at E_γ = 1220 MeV apparently due to the radiative decay of the ψ to a state of mass 1420 MeV. There exists a meson state of this mass, the E(1420). It has been seen before in a high statistics bubble chamber experiment[12] as a $K_SK^{\pm}\pi^{\mp}$ resonance in the

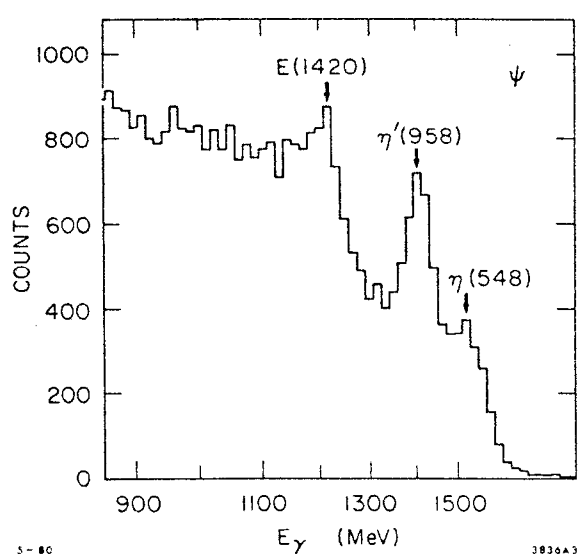

Fig. 11. High energy section of the inclusive photon spectrum from 850k ψ decays. A cut based on the pattern of energy distribution has been used to suppress some of the high energy π^0 background.

reaction $\pi^- p \to K_S K^\pm \pi\, n$ at 3.95 GeV/c incident π^- momentum. A partial wave analysis favors the assignment $J^P = 1^+$.

While it is too early for us to make a reliable estimate of the branching ratio for $\psi \to \gamma E(1420)$, it is clear that this radiative transition is fairly large, being of the order of half of the branching ratio of the $\psi \to \gamma\eta'$ transition. This is interesting, as such a large branching ratio raises the possibility that the E(1420) may have some gluonium component in addition to the normal quark-antiquark component. Radiative transitions from the ψ are thought to be a good way to reach gluonium states, as shown in Figure 12, where the monochromatic photon recoils against two gluons which are bound into the gluonium state.

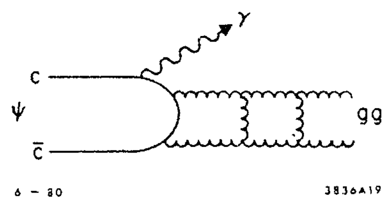

Fig. 12. Spacetime diagram for decay of a $c\bar{c}$ state (ψ) into a photon and two gluons, which form a bound gluonium state.

We have also looked for the E(1420) in exclusive channels. Figure 13a shows the $M_{K^+K^-\pi^0}$ distribution in a 3-constraint fit to the hypothesis

$$\psi \to \gamma K^+K^-\pi^0$$
$$\quad\quad\quad\quad \hookrightarrow \gamma\gamma$$

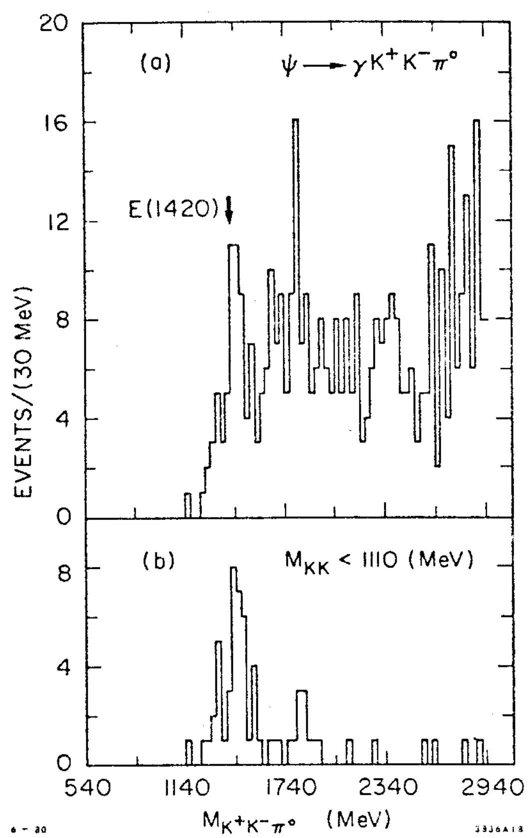

Fig. 13. $M_{K^+K^-\pi^0}$ distribution in events fitted to $\psi \to \gamma K^+K^-\pi^0$ for a) all events, b) events with $M_{K^+K^-} < 1110$ MeV. A peak due to the E(1420) is evident.

The $M_{K^+K^-}$ invariant mass peaks slightly towards low masses, as shown in Figure 14; if we cut on $M_{K^+K^-} < 1110$ MeV we get the $M_{K^+K^-\pi^0}$ distribution in Figure 13b. A peak at (1430 ± 20) MeV is evident. We have not yet shown whether the low mass KK enhancement is due to $E \to \delta\pi$ or to overlap of K^* bands in the $E \to K^+K^-\pi^0$ Dalitz plots when the decay is $E \to K^*K$. If we assume the decay is all $\delta\pi$, then we can form a preliminary estimate of the product branching ratio

$$BR(\psi \to \gamma E) \cdot BR(E \to K^+K^-\pi^0) = (3.4 \pm 2.0) \times 10^{-4}$$

There is also some evidence for the decay $E \to \eta\pi^+\pi^-$. Figure 15 shows the $M_{\eta\pi^+\pi^-}$ distribution for events that fit the 3-constraint hypothesis. Apart from the η' signal, there is evidence for an enhancement in $M_{\eta\pi^+\pi^-}$ near 1420 MeV. A cut requiring the $M_{\eta\pi}$ mass to be close to M_δ, i.e., $900 < M_{\eta\pi^\pm} < 1050$ MeV does not significantly strengthen the signal.

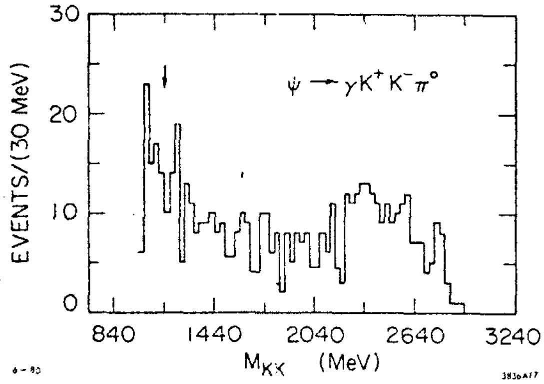

Fig. 14. $M_{K^+K^-}$ distribution in events fitted to $\psi \to \gamma K^+K^-\pi^0$. An enhancement at low $M_{K^+K^-}$ is seen.

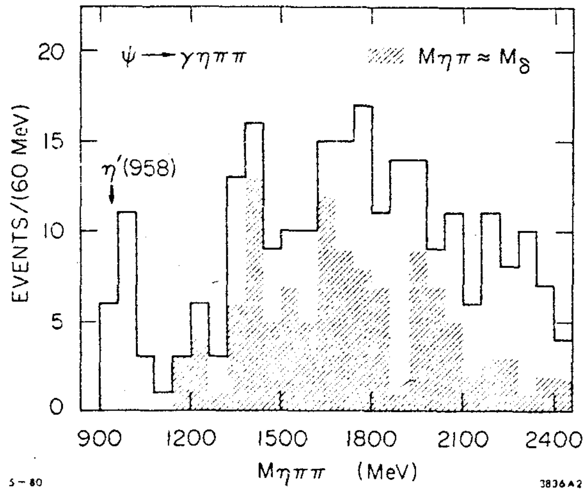

Fig. 15. $M_{\eta\pi^+\pi^-}$ distribution for events fitted to $\psi \to \gamma\eta\pi^+\pi^-$ for all events and, shaded, those events for which $M_{\eta\pi^\pm} \approx M_\delta$.

No other narrow structure is seen in either the $K^+K^-\pi^0$ or the $\eta\pi^+\pi^-$ mass spectra which could be interpreted as gluonium. In the mass range 900 to 3000 MeV we can set a 90% confidence level upper limit of 10^{-3} on the product branching ratio $BR(\psi \to \gamma X) \cdot BR(X \to K^+K^-\pi^0$ or $\eta\pi^+\pi^-)$ for a state X with width less than 50 MeV.

Summary

1) The Crystal Ball has seen evidence for the existence of the state η_c with mass 2981 ± 15 MeV in inclusive radiative decays from ψ and ψ'. The J^P quantum numbers are not yet established.

2) We have identified the decay mode $\eta_c \to \eta\pi^+\pi^-$ with a branching ratio of a few percent.

3) The E(1420) meson has been seen in the radiative decays of the ψ both inclusively and in the exclusive channels $E \to K^+K^-\pi^0$ and $E \to \eta\pi^+\pi^-$.

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