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ψ RADIATIVE DECAYS*

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Abstract: Inclusive and exclusive measurements of ψ radiative decay are presented. The magnitude of hard inclusive radiative decay is comparable to the prediction of first order QCD, but the measured spectrum is considerably softer. In addition to measurements of radiative decays to the known pseudoscalar and tensor mesons, a sizable decay to a resonance of mass 1440 $^{+10}_{-15}$ MeV/c^2 in the $K\bar{K}\pi$ mode is observed. This may be the E(1420) meson. Supporting evidence is presented for the existence of the η_c at a mass of 2980 MeV/c^2.

Resumé: Nous présentons des mesures de modes de désintégration radiatifs, inclusif et exclusifs du ψ. L'intensité de la production inclusive de photons énergiques dans la désintégration du ψ est comparable à la prédiction au premier ordre de chromodynamique quantique mais l'énergie des photons est significativement plus basse. En plus des modes de désintégration radiatives du ψ en mesons pseudoscalaire et tenseur, nous avons observé une désintégration importante du ψ en une resonance de masse 1440 $^{+10}_{-15}$ MeV/c^2 se désintégrant en $K\bar{K}\pi$. C'est peut-être le E(1420 MeV/c^2). Nous présentons aussi une observation grandement en faveur de l'existence du η_c à la masse de 2980 MeV/c^2.

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Introduction

Within the context of QCD, bound states of heavy quarks, such as the ψ and Υ, are unique in that they decay to a pure state of gluonic or gluonic and photonic matter. These two possibilities are illustrated in Fig. 1. Figure 1(a) shows the production and decay of the ψ to a hadronic state through three gluons, while Fig. 1(b) shows the radiative decay in which one of the gluons is replaced by a photon. The latter decay will be the focus of this talk. In particular, we will address two questions: First, to what extent do radiative decays resemble the predictions of first order QCD? And, second, what simple hadronic states are produced by the two gluons in Fig. 1(b)? Of special interest will be the question: Do the two gluons ever form a glueball, that is, a state which has no quark content? One final topic which I will treat briefly at the end of the talk is evidence for η_c production in ψ' radiative decays. This has a little to do with the main theme of the talk, but is nonetheless of some interest.

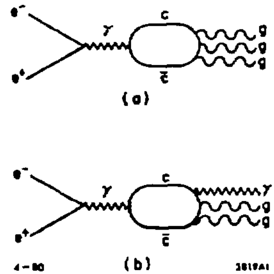

Fig. 1. Diagrams of ψ production and decay to (a) hadrons through three gluons and (b) a photon and hadrons through two gluons.

The data I will discuss all come from the Mark II detector at SPEAR which is operated by a collaboration from SLAC and LBL.[1)] A schematic drawing of the detector is shown in Fig. 2. Charged particles are detected and momentum analyzed by a 16 layer drift chamber[2)] embedded in a 4 kG solenoid magnetic field. In the low energy range relevant to these data the rms momentum resolution is dominated by multiple coulomb scattering and is approximately 1.5%. Time of flight counters at a radius of 1.5 m with an rms resolution of about 300 ps generally allow unambiguous separation of pions from kaons in ψ decays.

Photons are detected primarily by lead-liquid argon shower counters.[3)] These counters provide about 12% rms energy resolution and between 3 and 8 mr angular resolution. The latter is particularly important in the detection of exclusive states. If four or fewer photons occur in the final state, energy and momentum conservation can be used in a constrained fit to effectively replace the relatively poor photon energy resolution with the much better angular resolution.

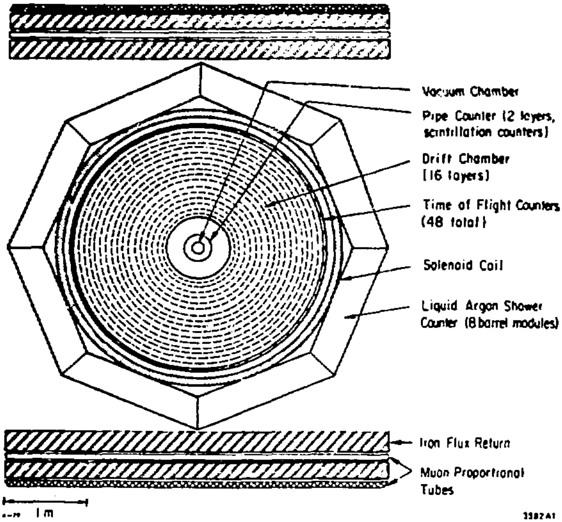

Fig. 2. A schematic drawing of the Mark II detector.

Inclusive ψ Radiative Decays

In first order QCD the ratio of radiative decays, Fig. 1(b), to normal hadronic decays, Fig. 1(a), is[4)]

$$R_\gamma = \frac{\Gamma(\psi \to \gamma gg)}{\Gamma(\psi \to ggg)} = \frac{36}{5}\ \frac{\alpha Q^2}{\alpha_s} \qquad (1)$$

where 35/5 is a color SU(3) factor, α is the electromagnetic coupling constant, Q is quark charge in units of e, and α_s is the strong coupling constant. If we use the ratio of the hadronic to the leptonic width of the ψ to estimate α_s, we obtain $\alpha_s = 0.185$ and $R_\gamma = 8.6\%$.[5)]

The energy spectrum of these photons is predicted in first order QCD to be approximately triangular, that is,

$$\frac{dE_\gamma}{dx} \approx 2x \qquad (2)$$

where $x = 2p/m_\psi$. This distribution is mostly due to three body phase for massless particles. For the experimenter it is a fortunate distribution for it implies that most of the photons should occur at high x where the backgrounds will be smallest.

At the outset we should note that there are reasons to suspect that the first order QCD calculation may not be totally reliable. First, the calculation deals with massless gluons which must emerge in the real world as massive hadrons. The ψ mass is not high enough to allow one to ignore these hadronic masses. Second, there is no reason to believe the perturbation series expansion is good. In a related process, the decay of the η_c to two gluons, it was shown that the second order term was larger than the first order term.[6] No second order calculation had been done for ψ decay. Nevertheless, realizing that Eqs. (1) and (2) may only be approximate, we address the question of whether there is any evidence of these underlying processes.

The analysis technique is to measure the photon, π^0, and η spectra, then to generate in software the photon spectrum from π^0 and η decay, and to subtract it from the raw photon spectrum to obtain the direct photon spectrum. This process involves the subtraction of comparable numbers in some regions of x and is thus sensitive to systematic effects. As a check on our understanding of these effects, the analysis has been done with three independent sets of data which are sensitive to different systematic effects. The first method, which has been recently published,[7] uses ψ data with photons detected by the lead-liquid argon shower counters. The second method also uses ψ data, but photons are detected by their conversion to electron pairs in the beam pipe and the scintillation counters surrounding the beam pipe. The third method uses $\psi' \to \pi^+\pi^-\psi$ decays with photons detected in the shower counters. The characteristics of these three methods are summarized in Table I.

TABLE I

Characteristics of the different methods of measuring inclusive ψ radiative decays

	I	II	III
Data Set	ψ	ψ	$\psi' \to \pi^+\pi^-\psi$
Photon detection	LA Shower counters	Photon conversion	LA Shower counters
Effective number of produced ψ decays	435k	22k	92k
Photon resolution	$.12/\sqrt{E}$	~.02	$.12/\sqrt{E}$
Special problems	Trigger efficiency correction required	2-γ QFD background subtraction required	non-ψ decay background and Lorentz transformation required

The systematic effects that are most important for one method are often non-existent for another method. For example, the first method has the best statistics but requires a correction for trigger efficiency. The detector is triggered by two charged particles, so that ψ decays which contain no charged particles or in which the charged particles are at small angles to the beams will not be detected. In the other two methods two charged particles are always detected and no correction is necessary which depends on the nature of particles in the ψ decays other than the photon. Another example is that the second method almost completely avoids the use of the liquid argon shower counters and thus systematic uncertainties in their efficiencies. The only exception is that in this method π^0's are detected by observing one converted photon and one photon in a shower counter.

Figure 3 shows the $\gamma\gamma$ mass spectrum (using method I) for several x regions. For $x > 0.5$, the π^0's are clearly delineated with relatively little background. We will only need to use the π^0's in this higher x region. Only in the $x > 0.8$ region are η's clearly discernible from the background. In this region the ratio of 2-γ final states from η's to that from π^0's is 0.16 ± 0.06. At lower x the ratio is less than 0.10.

Comparisons between the measured photon spectra and the predicted photon spectra from π^0 and η decay are shown for each of the three methods in Fig. 4. The error bars on the latter spectra include the relative systematic uncertainty between the measured and predicted spectra. For $x < 0.4$, the measured spectra are consistent with the predicted spectra, but at larger x there is a large excess of measured photons indicating the presence of radiative decays. The direct photon spectra obtained by subtracting the π^0 and η decay spectra from the measured spectra are shown in Fig. 5. For $x > 0.6$ the direct photon spectra are measured with reasonable precision and the three methods agree quite well. The first order QCD predictions folded with the appropriate experimental resolutions are also shown in Fig. 5.

The magnitudes of the predictions and measurements are comparable. In the region $x > 0.6$, the first order QCD prediction is a branching ratio $(\psi \to \gamma + \text{anything}/\psi \to \text{all}) = 5.0\%$.

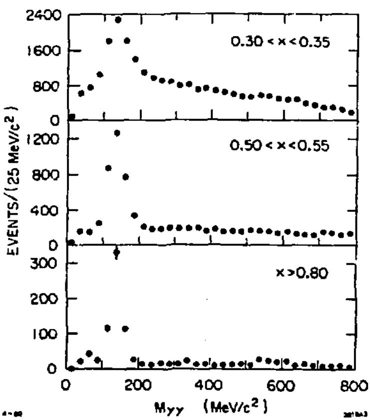

Fig. 3. Diphoton invariant mass for three x ranges.

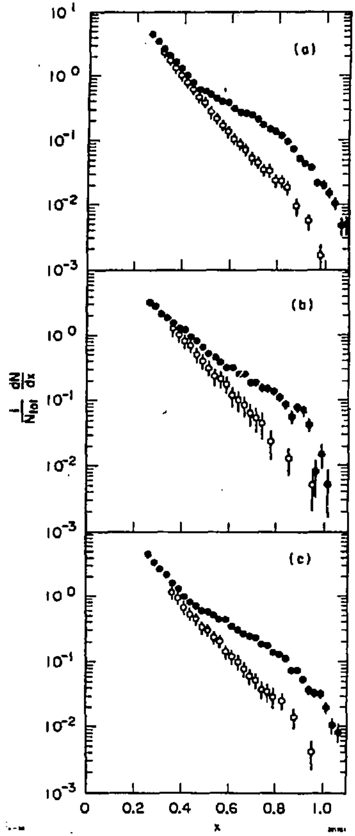

Fig. 4. Inclusive photon momentum spectra for each of the three methods. The solid points represent the measured spectra and the open points represent the predicted spectra from measurements of π^0 and η distributions. Relative systematic errors are included in the error bars on the open points, but a possible overall scale error of ±20% is not included.

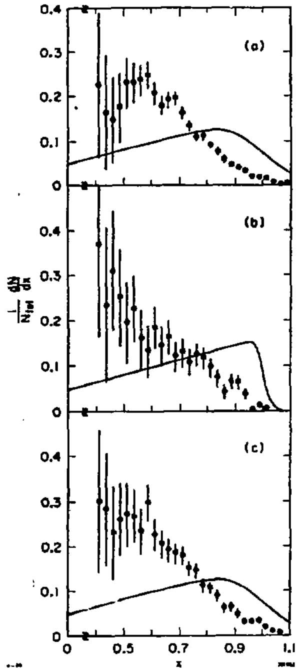

Fig. 5. Direct photon momentum spectra for each of the three methods. A possible overall scale error of ±20% is not included in the error bars.

The three methods yield measurements of branching ratios of $(4.1 \pm 0.8)\%$, $(3.9 \pm 1.2)\%$, and $(4.4 \pm 1.0)\%$, respectively, for this x region. A lower statistics measurement done with the lead-glass wall addition to the Mark I detector yielded measurements in the range 1.1 to 4.3%.[8)]

However, the shape of the measured spectra and the predictions of first order QCD are not consistent. The experimental spectra are much softer at high x than the predictions. Perhaps second order QCD effects can explain this discrepancy but the needed calculations have not yet been done.

Exclusive ψ Radiative Decays

Now that we have established the existence of radiative decays, it is natural to ask what final states are formed. In the language of QCD, what states do two gluons form? Radiative decays to pseudoscalar and tensor mesons have been studied by several groups over the past few years. Using Mark II data we have measured or set limits on all of these decays.[9)] I do not have time in this short talk to discuss these measurements, but I have listed our preliminary branching ratio determinations in Table II along with the results of other groups.[10-13)]

TABLE II

Branching fractions for $\psi \to \gamma x$. The values are in per cent and upper limits are at the 90% confidence level. The upper limits on the f' mode assume that $K\bar{K}$ is the sole f' decay mode.

Mode	Mark II	Crystal Ball[10]	DASP[11]	PLUTO[12]	DESY-Heidelberg[13]
π^0	0.004 ± 0.004		0.0073 ± 0.0047		< 0.0055
η	0.075 ± 0.035	0.117 ± 0.017	0.080 ± 0.018		0.13 ± 0.04
η'	0.30 ± 0.06	0.687 ± 0.171	0.22 ± 0.17		0.24 ± 0.07
A_2	< 0.05				
f	0.13 ± 0.03		0.12 ± 0.06	0.20 ± 0.07	
f'	< 0.04		< 0.034	< 0.023	

Recently, an additional radiative decay was found in the $\gamma K_S K^{\mp}\pi^{\pm}$ final state. The analysis technique was first to select events of the proper topology: a photon, three charged pions, and one charged kaon, where the pions and kaon were identified by the time-of-flight system. Then the events were subjected to a five constraint fit to the hypothesis $\psi \to \gamma K_S K^{\mp}\pi^{\pm}$, $K_S \to \pi^+\pi^-$ and events with $\chi^2 < 15$ were retained. The $K_S K^{\mp}\pi^{\pm}$ mass spectrum is shown in Fig. 6(a). A clear peak is seen near 1.4 GeV/c^2.

The only major source of background could be $\psi \to K_S K^{\mp}\pi^{\pm}\pi^0$ decays in which a low energy γ from the π^0 decay was not observed. We measured these decays and determined that less than one event from this source was expected in the $K_S K^{\mp}\pi^{\pm}$ mass region below 1.6 GeV/c^2. We took advantage of this lack of background by expanding the data sample to include two constraint fits to events in which the photon was not detected.[14] The resulting mass spectrum is shown in Fig. 6(b). A Breit-Wigner fit gives a mass of $1440 {}^{+10}_{-15}$ MeV/c^2 and a full width of $50 {}^{+30}_{-20}$ MeV/c^2. The branching ratio to this state in the $K\bar{K}\pi$ mode is of the order of 3 or 4×10^{-3}. This is a sizable branching ratio; in this single decay mode it is comparable to the branching ratio to the η', the largest of the previously known exclusive radiative decays.

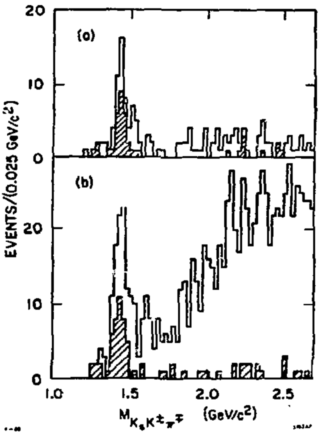

Fig. 6. $K_S K^{\pm}\pi^{\mp}$ invariant mass in $\psi \to \gamma K_S K^{\pm}\pi^{\mp}$ for (a) 5-c fits and (b) 2-c fits. The shaded region shows the mass distributions for events in which the $K_S K^{\mp}$ mass is less than 1.05 GeV/c^2.

The Dalitz plot of the events from Fig. 6(b) in the mass region 1375 to 1500 MeV/c^2 is shown in Fig. 7. The Dalitz plot shows a strong enhancement in the region of low $K\bar{K}$ mass, as is shown more clearly in Fig. 8. A fit to the Dalitz plot indicates that this enhancement is more likely to be due to a $\delta\pi$ state rather than the constructive interference of two KK^* bands.

It is tempting to identify this resonance with the E(1420) meson seen in hadronic interactions. The E was first observed in $p\bar{p}$ annihilation at rest.[15] In this experiment spin zero was preferred over spin one. More recently a πp interaction experiment studied the E with high statistics.[16] This experiment determined the E mass and width to be 1426 ± 6 MeV/c^2 and 40 ± 15 MeV/c^2. Spin one was strongly preferred. The Dalitz plot also had a low $K\bar{K}$ mass enhancement, but fits determined that it was largely KK^* rather than $\delta\pi$.

The pressing question is the spin of the resonance seen in ψ decay. If it is spin one then it is presumably to be identified with the E(1420) seen in πp interactions. It has a natural place in the quark model as the isospin zero

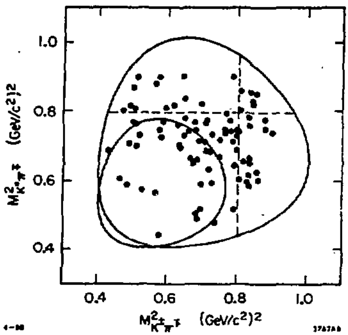

Fig. 7. Dalitz plot for events in Fig. 6(b) between 1.375 and 1.500 GeV/c^2. Solid curves represent low and high mass boundary limits. Dashed lines show K* central mass values.

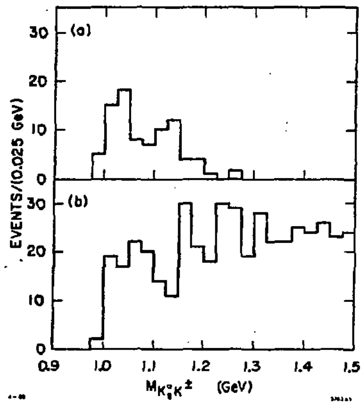

Fig. 8. $K_sK^\pm$ invariant mass (a) for events in the 1.375 to 1.500 GeV/c^2 $K_sK^\pm\pi^\mp$ mass region and (b) for events outside this region.

partner of the D(1285). The preference for the ψ to decay to the E rather than D would imply that the E is more of an SU(3) singlet than the D.[17]

However, if it is spin zero then its similarity to the E(1420) in mass, width, and decay modes is presumably accidental. A new pseudoscalar meson does not fit well into the standard quark model since the nine ground state mesons are all known. It could be a radial excitation or an exotic such as a four quark state. There is also the interesting possibility that it is a glueball mixing with the η'. Bag model calculations indicate that there should be such a state in this mass range.[18]

In principle, the spin of this state can be determined uniquely in e^+e^- annihilation. However, we do not have sufficient statistics to do this with our data. This question should receive high priority in any future study of ψ decay.

Evidence for $\psi' \to \gamma\eta_c$

After the Crystal Ball announced evidence for the η_c state at 2980 MeV/c^2,[19] we reviewed our data to see if we could find corroborating evidence. The technique was to first find ψ' decays with four charged tracks and a photon. The charged tracks are identified by time-of-flight and a fit is made to the proper hypothesis, either $\psi' \to \gamma\pi^+\pi^-\pi^+\pi^-$, $\gamma\pi^+\pi^-K^+K^-$, $\gamma K_sK^\pm\pi^\mp$, or $\gamma\pi^+\pi^-p\bar{p}$. Events with four-charged-particle invariant mass above 3.35 GeV/c^2 are removed from the sample to eliminate the well known χ states.[20]

The major background in these events will be ψ' decays in which the photon comes from a π^0 decay, and the second photon is not detected. To remove as much of this background as possible and to show that radiative ψ' decays exist in this mass range, we perform the following test. We form the missing momentum direction from the four charged tracks and construct the square of the photon momentum transverse to this direction. A plot of this quantity is given in Fig. 9. If all events contained a π^0, the distribution would be rather flat. The sharp peak at $p_T^2 < 0.001$ GeV/c^2 is evidence for radiative decays.

Taking only those events with $p_T^2 < 0.001$ GeV/c^2, we plot the four-charged-particle mass in Fig. 10. In the two bins about 2980 MeV/c^2 there are 17 events with 5.5 events expected from background. With binominal statistics the probability that this is a fluctuation is about 4×10^{-4}. This corresponds to less than a four standard deviation effect and we would certainly not claim a new particle on the basis of it. However, once the Crystal Ball has told us the mass, the coincidence of a peak at this identical mass is strong supporting evidence.

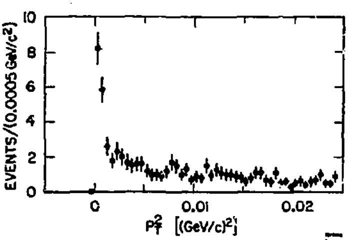

Fig. 9. p_T^2 distribution for $\psi' \to \gamma(4h^\pm)$ for $4h^\pm$ mass less than 3.35 GeV/c^2. The variable p_T^2 is explained in the text.

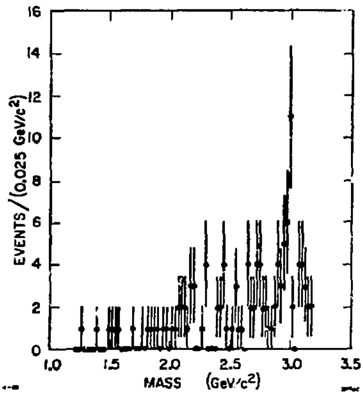

Fig. 10. Invariant mass distribution of 4 charged particles $(4h^\pm)$ in $\psi' \to \gamma(4h^\pm)$.

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