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OBSERVATION OF NEW PARTICLES IN e^+e^- ANNIHILATION AT SPEAR*

V. Lüth

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305 U. S. A.

1. Introduction

Among the many different ideas that were proposed to explain the narrow width of the high-mass states $\psi(3095)$ and $\psi'(3684)$ the simplest and most popular one is based on the quark model: In addition to the three "old" light quarks u, d, s (collectively denoted as q) there is a "new" heavy quark Q carrying a new quantum number, that is to be conserved in strong and electromagnetic interactions. Consequently one expects three types of mesons,

a. Ordinary $(q\bar{q})$ states,

b. High-mass $(Q\bar{Q})$ states,

c. New $(q\bar{Q})$ and $(\bar{Q}q)$ states.

The $\psi(3095)$ and the $\psi'(3684)$ are taken to be bound states of $(Q\bar{Q})$ and decay only to "ordinary" hadrons. Since such decays are forbidden by the Zweig-Iizuka rule[1] the strongly suppressed hadronic widths can be explained. This report will focus on the search for new hadrons produced in e^+e^- annihilation, both those possibly carrying a new quantum number and those without. It will summarize results that have been obtained from an extensive analysis of data that were recorded by the solenoidal magnetic detector at SPEAR. A considerable fraction of these results has not been published and is to be taken as preliminary.

2. Apparatus

The experiment is performed by a collaboration of physicists from SLAC and LBL[2] at the SLAC e^+e^- colliding beam facility SPEAR. The end view of the apparatus[3] is schematically shown in fig. 1. A solenoidal magnet provides a nearly uniform axial magnetic field of 4 kG in a volume 3 m long and 3 m in diameter. The detector inside covers a solid angle of 65% of 4π. The azimuthal acceptance is complete, and the subtended polar angle ranges from 50° to 130°. A particle leaving the interaction region in the center first traverses the 0.15 mm stainless steel vacuum pipe, then a pair of cylindrical scintillation counters and two proportional wire chambers that form an element of the trigger system. Continuing outwards, it enters 4 sets of cylindrical spark chambers, 2 gaps each, with magnetostrictive readout. Next, the trigger hodoscope provides time-of-flight measurement with a resolution of 0.4 nsec. Outside the 1 radiation length

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magnet coil an array of lead-scintillator shower counters (5 radiation lengths) identifies electrons. Most hadrons are absorbed in the 20 cm thick iron yoke and will not reach a set of spark chambers outside, which aids muon identification. The hardware trigger requires at least two particles with momenta above 200 MeV/c in coincidence with the beams. The data analysis reconstructs tracks and vertices (momentum resolution $\Delta p/p \simeq 0.015$ p (GeV/c)) from the wire chamber information and selects three classes of events, i.e., $e^+e^- \to$ hadrons, $e^+e^- \to e^+e^-$, and $e^+e^- \to \mu^+\mu^-$. A hadronic event is required to have 3 or more tracks or 2 tracks that are acoplanar by more than 20° and have momenta above 300 MeV/c.

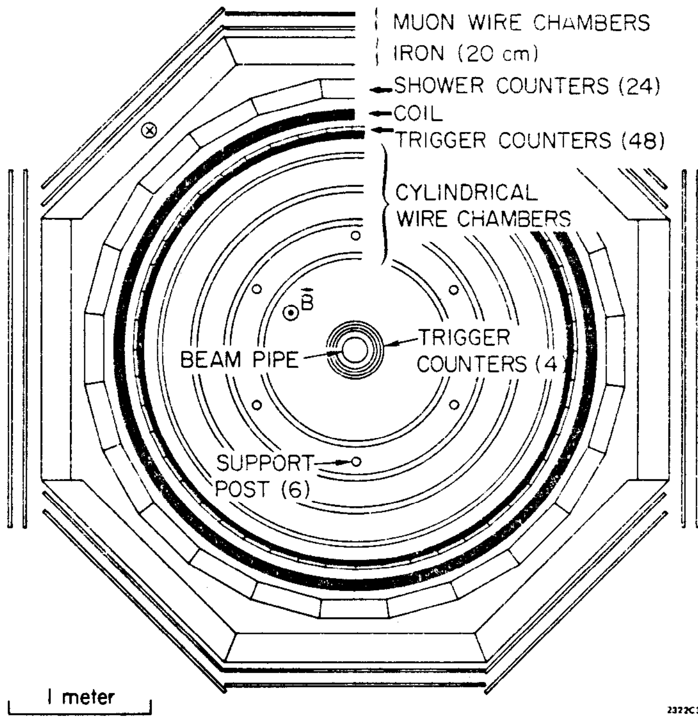

Fig. 1. Schematic diagram of the end view of the SLAC-LBL magnetic detector.

The efficiency for detecting hadronic final states is determined by Monte Carlo techniques. In addition to the properties of the apparatus a model of the final states is a necessary ingredient in the simulation. The parameters of the model are adjusted to obtain agreement with the observed multiplicity and the observed angular and momentum spectra. Still, the knowledge of the final state is imperfect and this leads to a systematic uncertainty in the overall efficiency of up to 15%. The average efficiency is assumed to be a smooth function of the c.m. energy; it varies from 40% at 2.5 GeV to 65% at 7 GeV.

3. Search for Other ψ States

The production of hadrons by e^+e^- annihilation proceeds mainly via a single time-like photon, i.e., a state with the quantum numbers $J^{PC} = 1^{--}$ and all additive quantum numbers equal to zero. Consequently any particle coupled to the photon with the same quantum numbers can be observed as an enhancement in the total hadronic cross section when the c.m. energy equals the mass of the particle. The "standard" vector mesons ρ, ω, and ϕ with masses up to 1 GeV have been known for some time, and e^+e^- annihilation was believed to have reached asymptopia above 2 GeV. The discovery of the two enormous, narrow resonances above 3 GeV destroyed this simple picture. It became imperative to perform a systematic search for other such states.

The complete measurement of the total hadronic cross section in e^+e^- annihilation over the whole c.m. energy range of the SPEAR machine from 2.4 GeV to 7.8 GeV was first presented at the 1975 Lepton-Photon Symposium.[4] Figure 2 shows the ratio R, the ratio of the total hadron cross section to the simple QED cross section for μ-pair production as a function of the c.m. energy W. Radiative corrections have been applied to remove the tails of the $\psi(3095)$ and $\psi(3684)$ resonances. The errors include statistical errors and the systematic point-to-point errors (8-10%). Below 3.5 GeV, R is approximately constant with a value around 2.5. Above 5 GeV, R is again roughly constant, but at a level approximately twice that of the lower energy region. In between, around 4 GeV, there is a rather complex structure which we are only beginning to resolve.

During the last year a considerable effort was made to obtain a more detailed picture of this transition region (fig. 3).[5] What at first looked like a broad enhancement at 4.15 GeV, has now been resolved into a resonance at 4.4 GeV, a broad shoulder near 3.95 GeV, an extremely sharp rise just above 4.0 GeV and possibly several narrow peaks near 4.1 GeV. Though there exist more data now, considerably more will be required to determine the details of this threshold region. For a number of reasons it is very difficult to tell the number of states and obtain the widths and integrated cross sections. First, the shape of the

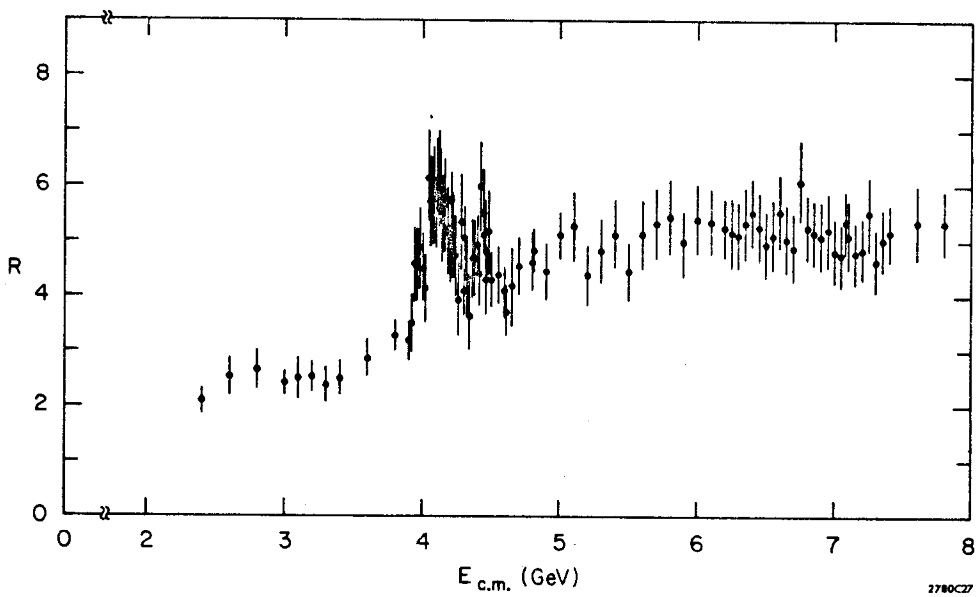

Fig. 2. R versus c.m. energy W. The radiative tails of the $\psi(3095)$ and $\psi'(3684)$ have been subtracted.

nonresonant background is not known and there may be interference with this background. Secondly, the resonances may strongly interfere with each other, and thirdly, in the transition region between the low and the high energy plateaus threshold production of new particles may badly distort the Breit-Wigner shapes. The masses, widths, and couplings to the e^+e^- system for the ψ states are summarized in Table I. The 4.1 region is most likely not a single state and has therefore not been listed. Considering the leptonic width of the ψ(4414) and the sensitivity of the overall scan, it becomes obvious that resonances comparable to this state could exist elsewhere and could have escaped detection up to now.

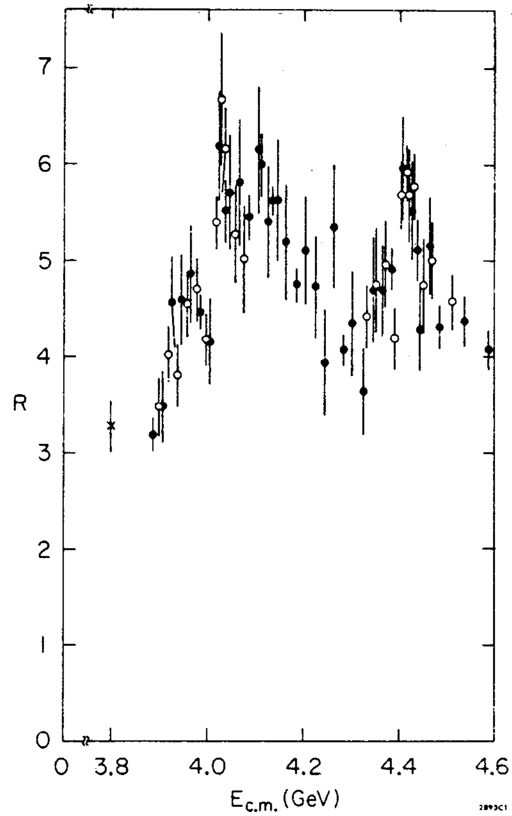

Fig. 3. R versus c.m. energy including more recent data.

Shortly after the discovery of the ψ(3095) a systematic search for other narrow resonances in e^+e^- annihilation was performed. A scanning procedure was developed whereby the c.m. energy could be automatically increased by approximately 2 MeV every few minutes, allowing for an average of two or three hadronic events per step. During the first run of this search, the ψ'(3684) was discovered. Since then the scan has been completed to cover the range from 3.2 GeV to 7.6 GeV. Aside from the ψ(3095) and ψ(3684), no other narrow resonances were discovered. Upper limits on the integrated cross section of a possible narrow resonance have been published.[6]

Table I. Resonances observed in e^+e^--annihilation above 3 GeV. Γ is the full width, Γ_e the partial width to electron pairs.

State	Mass (MeV)	Γ (MeV)	Γ_e (keV)
ψ(3095)[9]	3096 ± 4	0.069 ± 0.015	4.8 ± 0.6
ψ(3684)[10]	3684 ± 5	0.228 ± 0.056	2.1 ± 0.3
ψ(4414)[5]	4414 ± 7	33 ± 10	0.44 ± 0.14

The sensitivity of the scan depends on the width of the resonance and on its mass, because the c.m. energy resolution depends on the energy. It is roughly 1 MeV at 3 GeV and increases to ~4 MeV at 6 GeV. Thus, for resonances having widths of the order of 1 MeV or less the above scan sets limits on the integrated area that are small fractions (8%) of the $\psi(3095)$ resonance. This means, their partial widths into lepton pairs must be less than 1 keV.

Recently, the observation of high mass e^+e^- pairs in high energy p-Be interactions, and possible new resonances at 6.0 GeV and 7.2 GeV were reported.[7] In order to investigate these new states in e^+e^- annihilation a more precise scan was performed between 5.65 and 6.64 GeV and between 6.95 and 7.45 GeV. The step size was chosen to be 4 MeV to match the energy resolution. On the average 60 or more hadronic events were recorded per step. The preliminary result is given in fig. 4, showing no sign of a narrow peak in any of the two energy intervals. Quantitatively these measurements can be translated to a leptonic width of $\Gamma_e \lesssim 150$ eV for a narrow state, or to a leptonic branching ratio of $B_e \lesssim 10^{-5}$ for a resonance wide enough to be resolved. These limits are rather stringent for vector mesons which typically have leptonic widths of several keV. The $\psi(4414)$, however, has $\Gamma_e = 440$ eV, indicating that such small coupling to leptons is not unthinkable. On the other hand, the limit of $B_e \lesssim 10^{-5}$ and the quoted value of $(\sigma \cdot B_e) = (5.2 \pm 2.0) \times 10^{-36}$ cm^2 per nucleon for the product of the hadronic production cross section and the branching ratio to electrons leads to the production cross section of about 5×10^{-31} cm^2. This is more than three times the ψ production measured in the same experiment.[8] A rather surprising result!

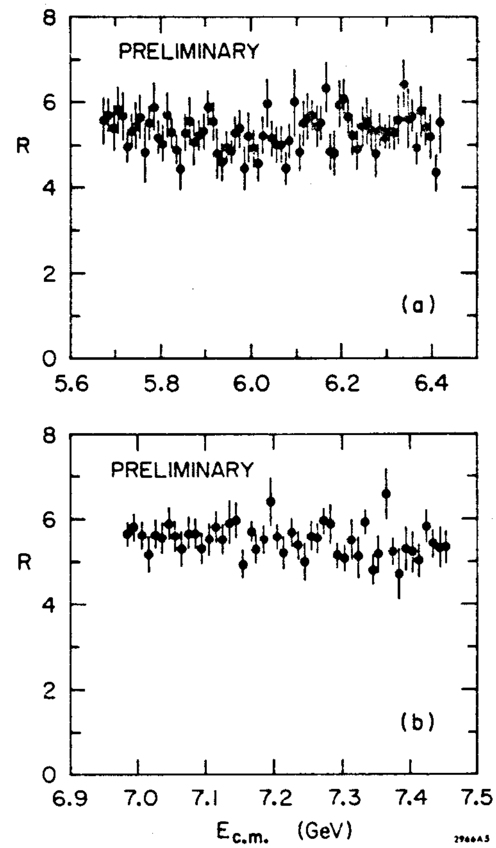

Fig. 4. Search for the Υ in e^+e^- annihilation, preliminary analysis of R vs. c.m. energy.

4. New States in Radiative Decays of the ψ States

If one accepts the hypothesis that the $\psi(3095)$ as well as the $\psi'(3684)$ are bound states of a pair of new heavy quarks ($Q\bar{Q}$) then in analogy to the usual quark model one expects a whole family of such states. The lowest mass states would have zero orbital momentum (L) between the quark and antiquark, and hence be $J^{PC}=0^{-+}$ and 1^{--} states. The L=1 states, triplet 0^{++}, 1^{++}, 2^{++} and singlet 1^{+-}, should be several hundred MeV higher. At even higher masses would be L=2 states and radially excited L=0 and L=1 states.

The $\psi(3095)$ with $J^{PC}=1^{--}$ is associated with the L=0, S=1 ground state, the $\psi'(3684)$ is assumed to be the first radial excitation, with the same spin configuration. Likewise the broader structures above 4.0 GeV, which are directly formed in e^+e^- annihilation, have most likely the quantum number of the photon and could be interpreted as higher radial excitations. In addition to these states, others should exist that could be reached by radiative transitions from $\psi(3095)$ and from $\psi'(3684)$ as indicated in fig. 5. In the following these C-even states will be referred to by the generic name χ. These new states could be either pseudoscalar or P-wave states, and they could decay into $\psi(3095)$ by the emission of a second photon or they could decay directly to ordinary hadrons. Some 150,000 decays of the $\psi(3095)$ and some 350,000 decays of the $\psi'(3684)$ have been analyzed.

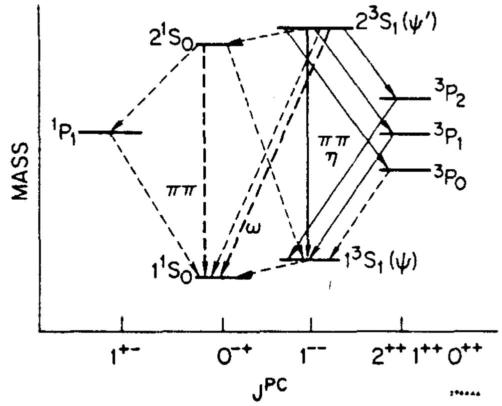

Fig. 5. Expected radiative and hadronic transitions in the spectroscopy of $(Q\bar{Q})$ states.

4.1 Inclusive photon spectra

The most direct way to look for C=+1 states among the decay products of $\psi(3095)$ and $\psi'(3684)$ is to study the energy spectrum of photons observed in their decays.[11] Photons are detected by their conversion to e^+e^- pairs in the 5% radiation length material of the vacuum pipe and the surrounding scintillation counters. Though the conversion rates are very low and lead to a detection efficiency of the order of 1%, the rms energy resolution of 3-4% is very good. The shape of the inclusive photon spectra as shown in fig. 6 is largely given by production and subsequent decay of neutral pions.

The γ spectrum of the $\psi'(3684)$, however, has a 5σ peak at 261 ± 5 MeV with a width consistent with the resolution. This photon line identifies the decay $\psi'(3684) \rightarrow \gamma\, \chi(3415)$. The branching fraction for this decay is 0.055 ± 0.019 for an isotropic angular distribution and 0.065 ± 0.022 for a distribution $f(\theta) \sim 1+\cos^2\theta$ of the polar angle θ (compare section 4.3). The relatively large error is dominated by systematics.

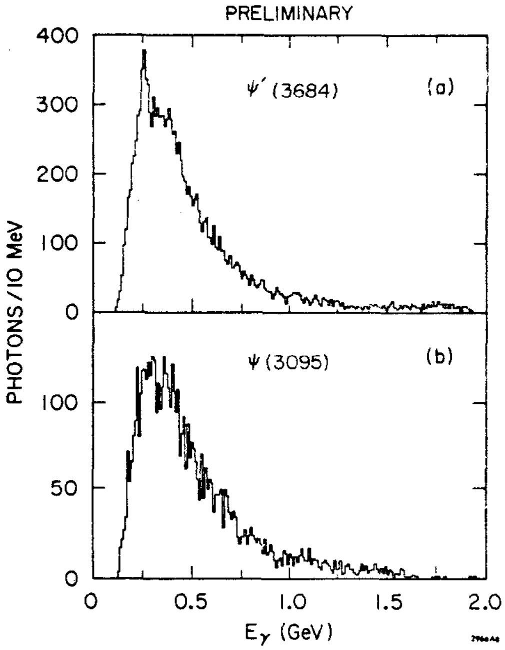

Fig. 6. Inclusive photon spectra measured at $\psi(3095)$ and $\psi'(3684)$.

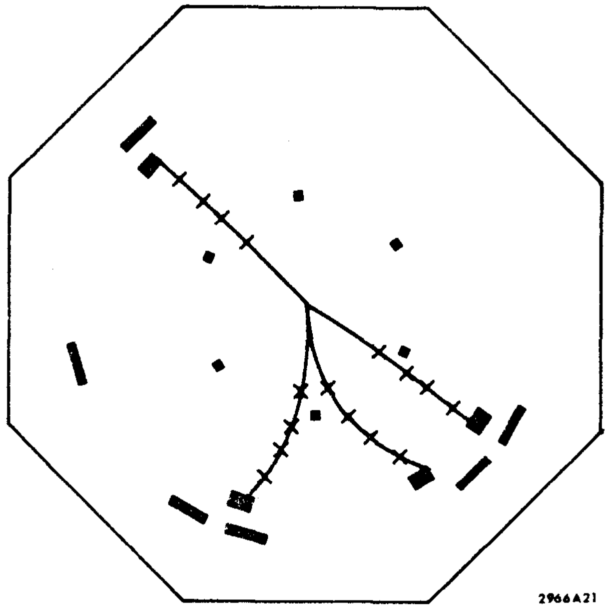

Fig. 7. Reconstructed tracks for an example of the reaction $\psi' \to \psi + \gamma\gamma$, $\psi \to \mu^+\mu^-$, $\gamma \to e^+e^-$

There are no other significant monochromatic signals in either of the two spectra. Below 250 MeV, the small and rapidly varying acceptance makes it extremely difficult to find a signal. At higher energies the lines are expected to be broadened due to the motion of the decaying state. This Doppler broadening enlarges the widths by more than a factor of two and may cause an overlap of different lines. Upper limits have been evaluated under the assumption that the photon lines are well separated. They are typically about 4% at 400 MeV and 1% at 1 GeV (90% C.L.). These results are in agreement with preliminary results reported by other groups at SPEAR[12] and DORIS.[13]

4.2 Radiative decays of the χ states

The χ states intermediate in mass to the $\psi(3095)$ and $\psi'(3684)$ can decay to $\gamma\, \psi(3095)$. The final state is characterized by the very distinct pattern of tracks in the detector (fig. 7). The $\psi(3095)$ is recognized by its decay to lepton pairs, one of the photons is required to convert. There are two principle sources of background, namely, $\psi' \to \psi\pi^0\pi^0$ and $\psi' \to \psi\eta$. The latter is easily removed by a cut on mass recoiling against the $\psi(3095)$, the former can be studied with the help of the shower counters that cover ~65% of the solid angle and provide a rough measurement of the azimuthal angle. In fig. 8 the square of the missing mass is plotted: the darkly shaded events have a shower counter signal consistent with the direction of the missing photon, the lightly shaded events have no photon signal in the shower counter, and the unshaded events have shower bits inconsistent with

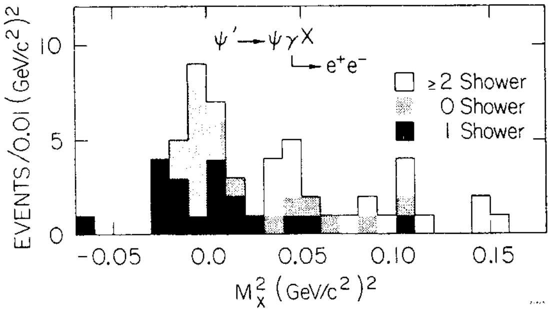

Fig. 8. Missing mass squared M_X^2 for events of the type $\psi' \to \psi\gamma x$.

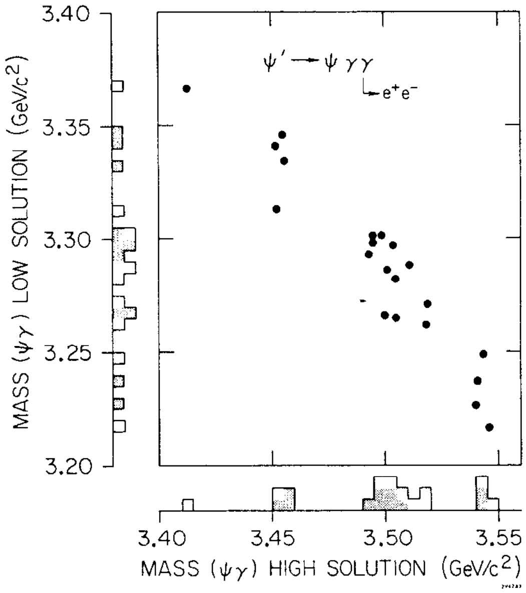

Fig. 9. Scatter plot of the two solutions for the mass of intermediate states in decays $\psi' \to \psi\gamma\gamma$.

the $\psi\gamma\gamma$ hypothesis (most likely $\psi\pi^o\pi^o$ states). A cut at $M_X^2 = 0.03$ (GeV/c^2)^2 eliminates practically all contamination.

The remaining 21 candidates containing no more than one background event are kinematically constrained to the hypothesis $\psi\gamma\gamma$. For each event there are two solutions for the mass of the intermediate state, as one does not know a priori which γ was emitted first. These masses are plotted in fig. 9. The expected resolution is about 8 MeV. There is clear support for a state at 3.50 GeV, four events cluster at 3.45 GeV and another four at 3.55 GeV. There is no other mass assignment for three states that fits the data. The branching ratio products for the decay sequence $\psi' \to \gamma\chi$, $\chi \to \gamma\psi$ are $(1.2 \pm 0.6)\%$, $(3.7 \pm 1.1)\%$, and $(1.2 \pm 0.6)\%$ for the $\chi(3450)$, $\chi(3500)$ and $\chi(3550)$, respectively. These rather small transition rates are compatible with the observed inclusive photon spectra. Furthermore, they agree with the previously published data.[14, 15] There is only one event compatible with the decay of the $\chi(3415)$. As the detection efficiency does not change rapidly, its branching ratio to $\psi\gamma$ seems to be considerably smaller than for the neighboring χ states.

4.3 Hadronic decays of the χ states

It was the hadronic decay modes of the χ particles that first provided evidence for the existence of several states, intermediate in mass to the $\psi(3095)$ and the $\psi'(3684)$.[16] The data sample for this study consists of 2-, 4- and 6-prong events with total charge zero, recorded at the $\psi'(3684)$. The photon in the final state is undetected, its presence being inferred from the measurement of the missing energy and the missing momentum. To illustrate this, the square of the missing mass in 4-prong events is compared for decays of the $\psi(3095)$ and the $\psi(3684)$ in fig. 10. In the case of the $\psi(3095)$, the distribution is consistent with the missing π^o, but inconsistent with the missing γ. For the $\psi'(3684)$ the opposite is the case —the missing neutral is not a π^o, but it is consistent with being a photon. The case can actually be proven with the help of the shower counter information. In the rest system of the missing particle the angular distribution of the photons observed in the shower hodoscope is strongly peaked in forward direction, whereas for a π^o this distribution should be flat. Events compatible with the hypothesis $\psi'(3684) \to \gamma\chi$ and the subsequent decays

$$\chi \to \pi^+\pi^+\pi^-\pi^- , \quad \chi \to \pi^+\pi^+\pi^+\pi^-\pi^-\pi^- , \quad \chi \to \pi^+\pi^+K^+K^- , \quad \chi \to \pi^+\pi^- \text{ or } K^+K^-$$

are selected and submitted to a kinematic fitting procedure. Additional cuts are applied to remove background from the "cascade" decays $\psi' \to \psi\pi^+\pi^-$ and to isolate the various decay modes. The shower counters and the muon chambers are used to suppress the enormous potential background in the two-body decays due to radiative electron or muon pairs. The invariant masses of all hadrons in the final states are presented in fig. 11

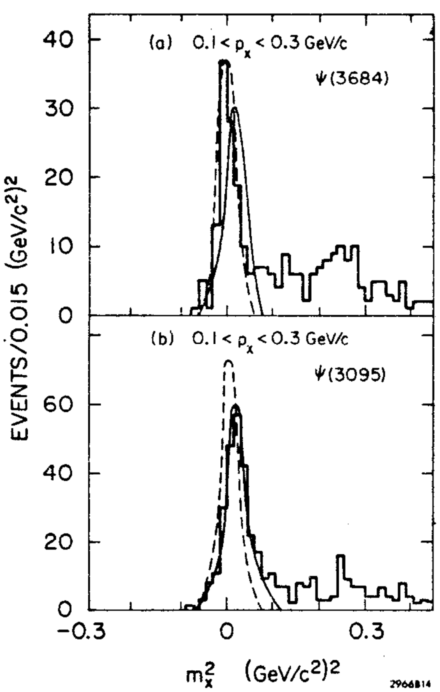

Fig. 10. The square of the missing mass for 4-prong events with missing momentum $0.1<p_X<0.3$ GeV/c (a) for $\psi'(3684)$ and (b) for $\psi(3095)$. The solid and the dashed lines give the resolution functions for a missing π^o and γ, respectively.

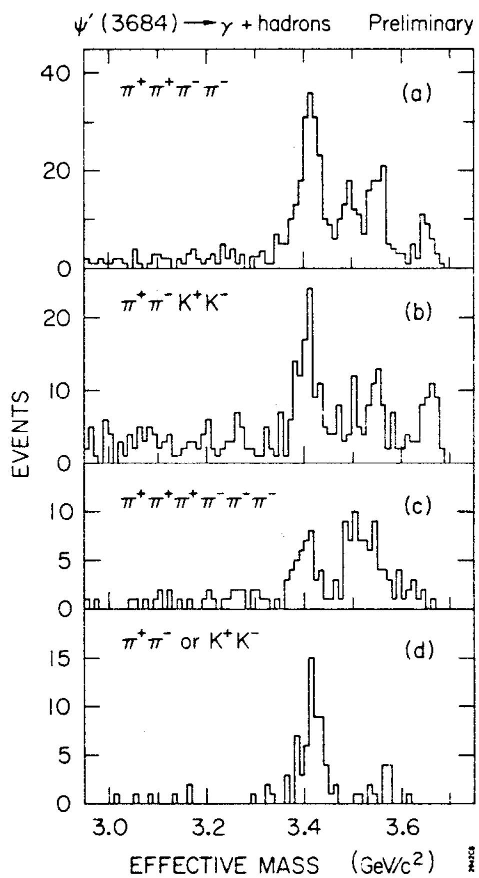

Fig. 11. Invariant mass spectra for events constraint to fit the reactions $\psi' \to \gamma$ + hadrons for various hadronic decay modes.

for all decay modes under study. The four-body spectra show three clearly separated peaks at masses of 3415, 3500, and 3550 MeV/c^2 plus a fourth above 3600 MeV/c^2 corresponding to the nonradiative decays $\psi' \to 4\pi$ and $\psi' \to \pi\pi KK$. Except for the fortuitously narrow spike in $\pi^+\pi^-K^+K^-$ at 3.50 GeV/c^2, the observed widths are all similar and consistent with the experimental resolution. The 6π data appear to have a slightly worse resolution than the 4-prong data, and the two higher mass states are not resolved. The interpretation of the populations above 3.45 GeV/c^2 in terms of two distinct states is, however, supported by the analysis of the radiative decays discussed above.

For 2-prong events, the distinction between the $\pi^+\pi^-$ and K^+K^- final state has been made on the basis of the lowest χ^2 in the kinematic fit. These decays into two pseudoscalar mesons are particularly interesting because such a state has natural spin and parity and therefore only χ states with even spin and parity can decay to this mode. The strong signal at 3415 MeV/c^2 and a considerably weaker signal at 3550 MeV/c^2 confirm the earlier result.[16] Ignoring a couple of events near 3500 MeV/c^2, this distribution is consistent with the possible interpretation of the three states as the L=1 triplet with $J^{PC}=0^{++}$, 1^{++}, 2^{++} expected from the $Q\bar{Q}$ spectroscopy.

In order to obtain some more information on the spin of the χ states, the angular distributions of the photon relative to the incident positron beam have been studied. In general, this distribution is of the form $1+a\cos^2\theta$; for spin zero a=1, while predictions of a for other spins are not unique. The data for the three χ states are presented in fig. 12. The distribution for $\chi(3415)$ suggests a J=0 assignment, the two other distributions are consistent with isotropy, but the statistical errors are too large to allow any conclusions (compare last column of Table II). The DESY-Heidelberg group at DORIS has demonstrated that the $\chi(3500)$ has nonzero spin.[18]

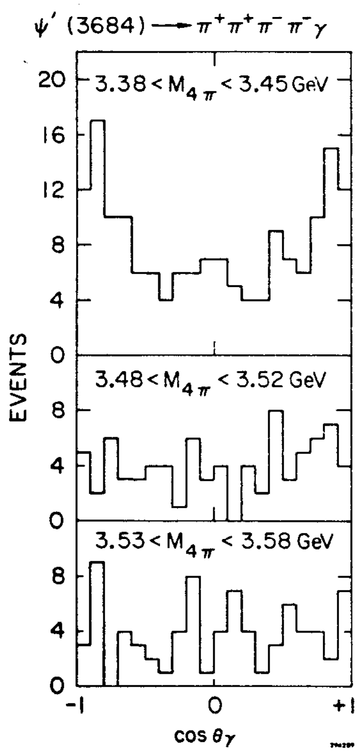

Fig. 12. Distribution of cos θ for 3 different bins of the 4π invariant mass. θ is the angle between the direction of the photon and the positron beam direction.

A summary of the branching ratio products $B(\psi' \to \chi\gamma) \times B(\chi \to \text{hadrons})$ of various decay modes of the different states is given in Table II.[17] The data have been corrected for losses due to limited geometrical acceptance and cuts, as well as for decay in flight of $K^{\pm}$ mesons. The errors quoted reflect both statistical and systematic uncertainties. One can use the branching ratio for $\psi'(3684) \to \chi(3415)\gamma$ as obtained from the inclusive photon spectrum, namely $(6.5 \pm 2.2)\%$, to calculate the actual branching fractions of the $\chi(3415)$. There is no evidence for a hadronic decay mode of a state at 3450 MeV/c^2 that has only been seen in the study of $\psi' \to \psi\gamma\gamma$.[11] Upper limits at 90% confidence level are given in Table II.

4.4 Search for the $\chi(2850)$

At the Lepton-Photon Symposium last summer, two experiments at DORIS[19,20] reported evidence for a new state with a mass of 2.85 GeV/c^2 decaying into two photons. The existence of this state has been reinforced by new data from DASP presented at this Conference.[13] Although $J \neq 1$ and $C=+1$ is all that is known so far, this state has generally been interpreted as the pseudoscalar state with $J^{PC} = 0^{-+}$. From this assignment one would expect large decay rates for $\psi'(3684) \to \omega\chi(2850)$. This decay can be detected via the electromagnetic decay $\omega \to \pi^+\pi^-$, which occurs with a small branching ratio of 1.3%. A crude upper limit of 8.6% (90% C.L.) has been derived from the data presently available.

Extensive searches for hadronic decay modes of the $\chi(2850)$ in radiative decays of the $\psi(3095)$ have so far not been successful. Special emphasis was placed on the decay $\chi(2850) \to p\bar{p}$, since some candidate events were reported last year.[19] In fig. 13, the effective mass $M(p\bar{p})$ is plotted for events compatible with the reaction $\psi(3095) \to p\bar{p}X$ with $M_X \equiv 0$. The resolution does not allow a distinction between a missing π^0 or γ. A study of the shower counter information, however, clearly proves that the signal is dominantly $p\bar{p}\pi^0$. The angular distribution of the detected photon is completely flat in the rest system of the missing particle, as expected from π^0 decay. The data compare well to the phase-space distribution for the decay $\psi(3095) \to p\bar{p}\pi^0$. A rather stringent limit for the existence of a state with a mass in the range 2.75-2.85 GeV decaying to $p\bar{p}$ can be derived from these data; $B(\psi \to \chi\gamma) \times B(\chi \to p\bar{p}) < 4 \times 10^{-5}$.

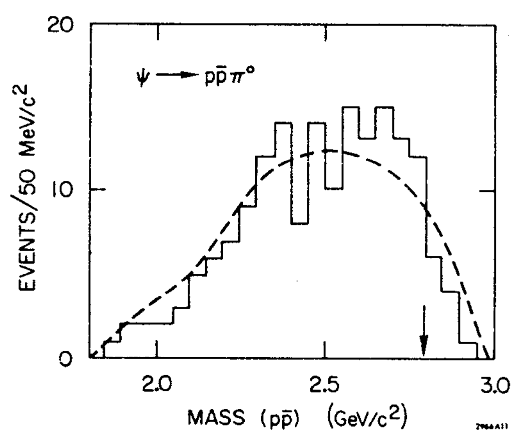

Fig. 13. Effective mass $M(p\bar{p})$ for events compatible with the decays $\psi(3095) \to p\bar{p}\pi^0$.

Table II. Summary of the hadronic decay modes of the χ states.

State	Decay mode f	$BR(\psi' \to \chi\gamma) \times BR(\chi \to f)$	$BR(\chi \to f)$	Coefficient a in $(1 + a \cos^2 \theta)$
$\chi(3415)$	$\pi^+\pi^-\pi^+\pi^-$	$(3.2 \pm 0.6) \times 10^{-3}$	0.05 ± 0.02	1.4 ± 0.4
	$\pi^+\pi^-K^+K^-$	$(2.7 \pm 0.7) \times 10^{-3}$	0.04 ± 0.02	
	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(1.4 \pm 0.5) \times 10^{-3}$	0.02 ± 0.01	
	$\pi^+\pi^-$	$(0.7 \pm 0.2) \times 10^{-3}$	0.01 ± 0.005	
	K^+K^-	$(0.7 \pm 0.2) \times 10^{-3}$	0.01 ± 0.005	
$\chi(3500)$	$\pi^+\pi^-\pi^+\pi^-$	$(1.1 \pm 0.4) \times 10^{-3}$		0.25 ± 0.5
	$\pi^+\pi^-K^+K^-$	$(0.6 \pm 0.3) \times 10^{-3}$		
	$\pi^+\pi^- + K^+K^-$	$< (0.15 \times 10^{-3})$		
$\chi(3500) + \chi(3550)$	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(2.5 \pm 0.8) \times 10^{-3}$		
$\chi(3550)$	$\pi^+\pi^-\pi^+\pi^-$	$(1.6 \pm 0.4) \times 10^{-3}$		0.2 ± 0.4
	$\pi^+\pi^-K^+K^-$	$(1.4 \pm 0.4) \times 10^{-3}$		
	$\pi^+\pi^- + K^+K^-$	$(0.23 \pm 0.12) \times 10^{-3}$		
$\chi(3450)$*	$\pi^+\pi^-\pi^+\pi^-$	$< 4 \times 10^{-4}$		
	$\pi^+\pi^-K^+K^-$	$< 5 \times 10^{-4}$		
	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$< 7 \times 10^{-4}$		
	$\pi^+\pi^- + K^+K^-$	$< 3 \times 10^{-4}$		

*90% confidence level.

4.5 The ψ spectroscopy

A summary of all new states and their decay modes is presented schematically in fig. 14. This diagram clearly resembles the picture (fig. 5) drawn from the idea that the new mesons are bound states of a new quark and its antiquark.[21] There are at least three C-even states between $\psi(3095)$ and $\psi'(3684)$, namely $\chi(3415)$, $\chi(3500)$, and $\chi(3550)$. The relatively strong decays to $\pi^+\pi^-$ and K^+K^- and the angular distribution of the $\chi(3415)$ highly suggest the quantum number assignment $J^{PC}=0^{++}$. The much weaker decay of the $\chi(3550)$ to the same two-body states is consistent with $J^{PC}=2^{++}$. There may be a fourth state $\chi(3445)$. It is seen to decay to $\psi(3095)\gamma$, but no hadronic modes have been observed. Similarly, there is no evidence for hadronic decays of the $\chi(2850)$ which is usually taken to be the pseudoscalar partner of the $\psi(3095)$. Could this be a hint to the fact that the $\psi(3445)$ is the pseudoscalar partner of the $\psi(3684)$?

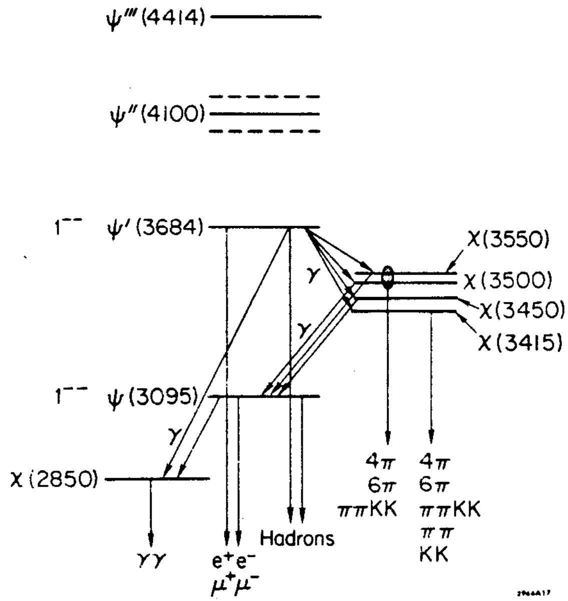

Fig. 14. Energy level diagram and decay modes of the new states.

While the number of observed χ states is so far in agreement with the hypothesis of $Q\bar{Q}$ bound states, some difficulties may arise if the 4.1 GeV enhancement turns out to be split into several substates. Furthermore, the exact mass splitting of the states near 3.5 GeV cannot be explained by a simple, nonrelativistic ansatz of the quark-antiquark potential.[22] A comparison between the measured radiative decay rate of the χ states and theoretical calculations is even more contradictory.[21, 22]

The observation of radiative decays of the $\psi'(3684)$ to C-even states has greatly augmented our knowledge of the $\psi'(3684)$ decay modes. The following account can be made up for the known and inferred decays:

$\psi'(3684)$	$\rightarrow \psi(3095)$ + anything	57%
	$\rightarrow \gamma_V \rightarrow$ anything	5%
	$\rightarrow$ "direct" hadrons	10%
	$\rightarrow \gamma + \chi$	10–20%

The limit of 10% for direct decays refers to an estimate derived from all $\psi(3095)$ decays other than those proceeding via an intermediate photon. This estimate is based on the observation that for any specific hadronic decay the measured partial width for the $\psi'(3684)$ is about a factor 3 smaller than for the $\psi(3095)$.[23] The estimate of 10-20% for radiative transitions to known χ states is an extrapolation from their observed hadronic decays. There remain 10-20% of all decays of the $\psi'(3684)$ unaccounted for. This discrepancy cannot be entirely due to a single radiative transition to a hitherto unobserved state or to the pseudoscalar partners of the $\psi(3095)$ and $\psi'(3684)$, since the limits derived from the inclusive photon spectra[11,24] are rather stringent. However, if there are several states with several percent branching ratio each the problem may be reduced to the uncertainties in the estimate for the radiative decays.

5. Search for Charmed Mesons

The most serious difficulty the addition of a new heavy quark to the basic constituents has encountered so far is the lack of evidence for the existence of particles carrying a new quantum number. It is only in the search for such mesons that the specific characteristics of the new quark play a role. If the behavior of the hadronic cross section near 4 GeV is somehow related to the threshold for the production of new mesons, their mass should lie between 1.84 GeV and 1.95 GeV. The lower limit is set by the narrow width of the $\psi'(3684)$ while the upper limit is given by the rise in R near 3.9 GeV.

In order to search for inclusive production of 'new' mesons searches for narrow peaks in invariant mass plots of two, three, and four body systems were performed using some 29,000 hadronic events collected at center-of-mass energies between 3.90 and 4.60 GeV. A significant signal appears in invariant mass spectra for all possible neutral combinations of two charged particles assuming both π and K masses for the particles as was done in our previous search for narrow peaks at 4.8 GeV.[25] Through kinematic reflections, the signal appears near 1.74 GeV/c^2 for the $\pi^+\pi^-$ hypothesis (fig. 16a), at 1.87 GeV/c^2 for $K^+\pi^-$ or $K^-\pi^+$ (fig. 16b), and at 1.98 GeV/c^2 for K^+K^- (fig. 16c).

To establish the correct choice of final-state particles associated with these peaks the flight time information (fig. 15) is used. Since the typical difference in flight time between a π and a K in the $K\pi$ signal is only about 0.5 ns compared to a resolution of 0.4 ns, the following technique is applied to extract maximal information on particle identity. Each track is assigned weights proportional to the probabilities that it is a π or K. These weights are determined from the measured momentum and time of flight assuming a Gaussian distribution with standard

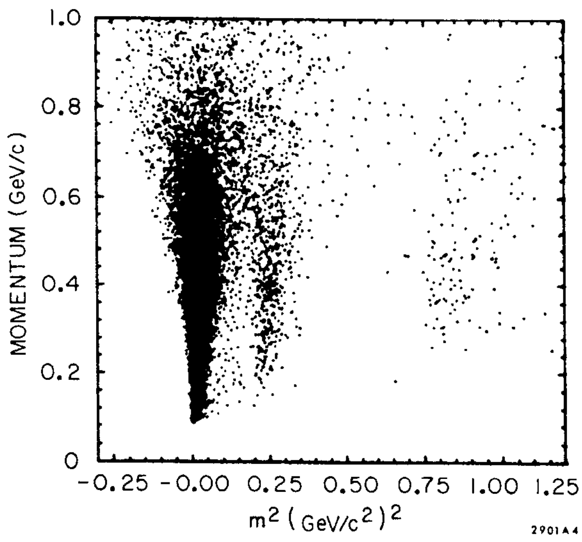

Fig. 15. Square of the particle mass as derived from the time of flight as a function of the particle momentum.

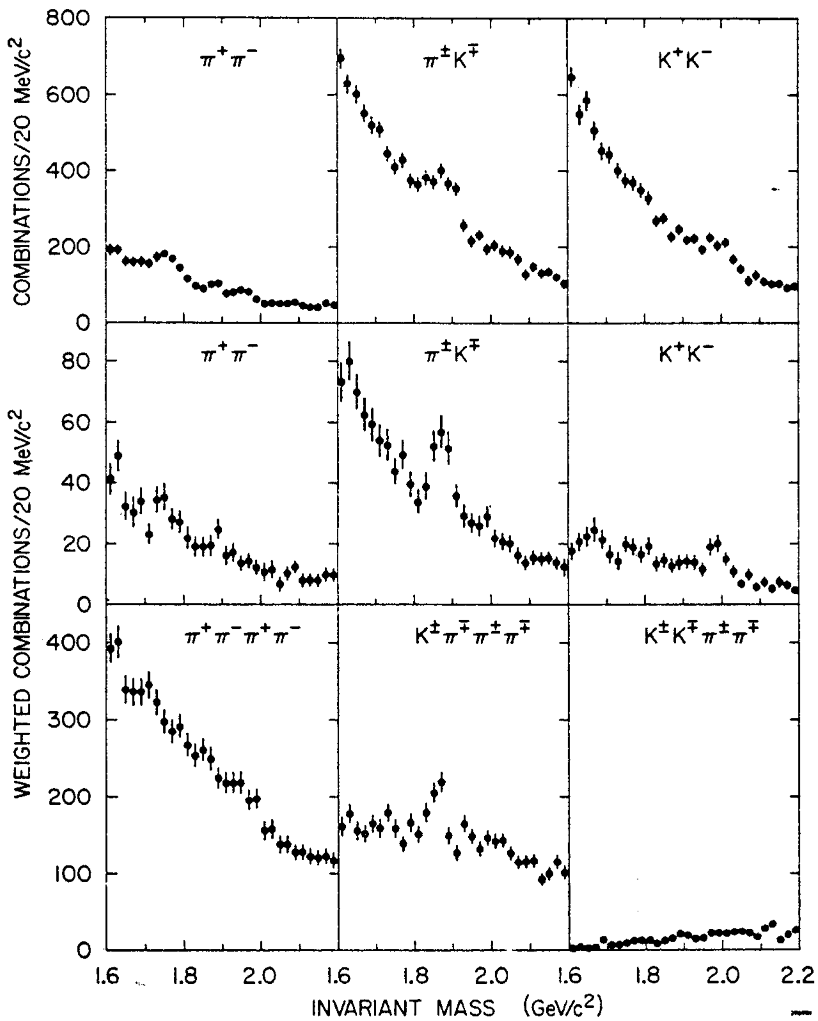

Fig. 16. Invariant mass spectra for neutral combinations of two, and four charged particles (a-c) arbitrary assignment of masses to both tracks; (d-f) same as above, but each pair is weighted by the probability for the particular mass assignment; (g-h) weighted four-particle masses.

deviation 0.4 ns. The relative π-K weights are normalized so that their sum is unity, and two-particle combinations are weighted by the joint probability that the particles satisfy the particular π or K hypothesis assigned to them. In this way, the total weight assigned to all $\pi\pi$, $K\pi$, and KK combinations equals the number of two-body combinations and no double-counting occurs.

Invariant mass spectra weighted by the above procedure are presented in fig. 16d-f. The $K\pi$ hypothesis with a peak at 1.87 GeV/c^2 is clearly preferred over either $\pi^+\pi^-$ or K^+K^-. The areas under the small peaks in the $\pi^+\pi^-$ and K^+K^- channels are consistent with the entire signal being $K\pi$ and the resulting misidentification expected from our flight time measurement. The estimated confidence level for the signal to arise only from $\pi^+\pi^-$ or K^+K^- is less than 1%. Summing the signal events in fig. 16d-f, there is a total of 110 ± 15 decays of a new state; the significance of the peak in fig. 16e alone is greater than 5 standard deviations. No signal occurs in the corresponding doubly charged channels.

Evidence for the decay of this state to neutral combinations of a charged K and three charged π's is presented in fig. 16g-i. Again, the weighting technique is employed. As can be seen in fig. 16h, a clear signal is obtained in the $K3\pi$ system at a mass near 1.86 GeV/c^2. No corresponding signal is evident at this mass or the appropriately shifted masses for either the $\pi^+\pi^-\pi^+\pi^-$ or $K^+K^-\pi^+\pi^-$ systems. The number of $K3\pi$ decays in the 1.86 GeV/c^2 peak is 124 ± 21, again more than 5 standard deviations. There is no signal in the corresponding doubly charged channel.

To determine the masses and widths of the peaks in the $K\pi$ and $K3\pi$ mass spectra, the data were fitted to a Gaussian for the peak and linear and quadratic background terms under various conditions of bin size, event selection criteria, and kinematic cuts. Masses for the $K\pi$ signal center at 1870 MeV/c^2; those for the $K3\pi$ signal center at 1860 MeV/c^2. The spread in central mass values for the various fits is ± 3 to 4 MeV/c^2, the widths obtained by these fits agree with those expected from experimental resolution alone. From Monte Carlo calculations one expects a rms mass resolution of 25 MeV/c^2 for the $K\pi$ system and 13 MeV/c^2 for the $K3\pi$ system. Systematic errors in momentum measurement are estimated to contribute a ± 10 MeV/c^2 uncertainty in the absolute mass determination, and can account for the 10 MeV/c^2 mass difference between the $K\pi$ and $K3\pi$ systems; thus, both signals are consistent with being decays of the same state. The mass resolution leads to a 90% confidence level upper limit of 40 MeV/c^2 for the decay width of this state.

In fig. 17, the weighted spectra of masses recoiling against neutral $K\pi$ and $K3\pi$ systems are shown for the signal region. Background estimates are obtained from the recoil spectra for the mass bands on either side of the signal. There is no evidence for the production of recoil systems with masses less than or equal to 1.87 GeV/c^2 in either spectrum. The $K\pi$ data show a large signal for recoil masses in the range 1.96 GeV/c^2 to 2.20 GeV/c^2. The $K3\pi$ spectrum has more background but appears to be consistent with the $K\pi$ spectrum. This suggests that the $K\pi$ and $K3\pi$ systems are produced with thresholds occurring above 3.7 c.m. energy.

As a further test of this apparent threshold behavior, 150,000 multihadronic events collected at the ψ(3095) and 350,000 events at the ψ'(3684) were examined. Because of the large cascade decay rate of the ψ'(3684) and the large second-order electromagnetic decay rate of the ψ, the resonance events contain 72,000 examples of hadron production by a virtual photon of c.m. energy 3.1 GeV. From fits to invariant mass spectra near 1.87 GeV/c^2 no $K\pi$ signal larger than 0.3 standard deviations and no $K3\pi$ signal larger than 1.2 standard deviation was found in this large sample of events. The upper limits (90% C.L.) are 60 events for the $K\pi$ signal and 200 events for the $K3\pi$ signal.

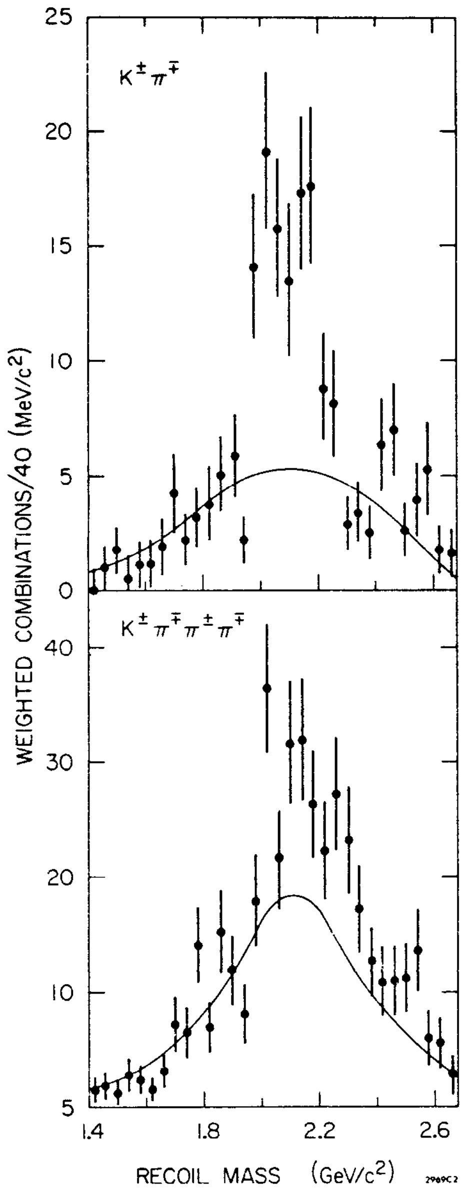

Fig. 17. Recoil mass spectra for combinations in the $K^{+}\pi^{-}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ mass peaks. The smooth curves represent estimates of the background obtained from data with invariant masses on either side of the signal.

Monte Carlo calculations have been performed to roughly estimate detection efficiencies for the two modes. The cross section times branching ratio averaged over the 3.9 GeV - 4.6 GeV data is 0.20 ± 0.10 nb for the $K\pi$ mode and 0.67 ± 0.35 nb for the $K3\pi$ mode. These are to be compared with the average total hadronic cross section in this energy region of 27 ± 3 nb. In the previous search for the production of narrow peaks at 4.8 GeV, there was a small $K\pi$ signal at 1.87 GeV/c^2 corresponding to 0.10 ± 0.07 nb. The hadronic cross section at 4.8 GeV is 18 ± 2 nb.

In summary, significant peaks in the invariant mass spectra of $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ have been observed. The two signals are consistent with being decays of a state of mass 1865 ± 15 MeV/c^2 and width less than 40 MeV/c^2. The recoil mass spectra indicate that this state is produced in association with systems of comparable or larger mass. This leads to a threshold energy for the production of this new state just below the broad structures in the total hadronic cross section near 4 GeV, but above the narrow ψ'(3684) resonance. This argues against the interpretation of the signal as being a conventional K* resonance. The narrow width of this state, its production in association with systems of even higher masses, and the fact that it decays into states of strangeness $S = \pm 1$ are properties that would be expected for a state possessing the proposed[26] new quantum number charm.

6. Summary and Conclusions

The search for new particles produced in e^+e^- annihilation at SPEAR has proven to be highly successful during the last year or two. In the energy range from 2.4 GeV to 7.6 GeV, there are two extremely narrow state with $J^{PC} = 1^{--}$, ψ(3095) and ψ'(3684), and there are two scaling regions, below 3.5 GeV and above 5 GeV, characterized by a constant value of R. The transition region near 4 GeV shows rather complicated structure with several broad enhancements in hadron production. Radiative decays of the ψ'(3684) have led to the discovery of at least three, more likely four, C-even states with masses between 3.40 GeV and 3.55 GeV. The DASP group at DESY observed a fifth state with a mass of 2.85 GeV decaying to two photons.

The present spectrum of states is consistent with the number of states expected from the hypothesis of one new quark bound to its antiquark. In particular the ψ(3095) and χ(2850) could be taken as L=0 ground states, while the χ states near 3.5 GeV are good candidates for L=1 states. In order to understand the structure near 4 GeV, one would probably need a more complicated configuration of quarks. Present limits for the production of additional states which couple directly to the virtual photon are rather stringent for very narrow states only; they do not exclude broader states with leptonic widths comparable to that of the ψ(4414).

The narrow state at 1.865 ± 15 MeV decaying to $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ has the properties expected for a meson carrying the new quantum number charm. So far, however, very little is known; two decay modes involving K mesons, the narrow width, and the association with systems of high recoil mass. If this new state is taken to be the charmed pseudoscalar D^o or the charmed vector D^{o*} it must have a charged partner $D^{\pm}$ or $D^{\pm *}$.[27] In order to prove that the new state carries a new hadronic quantum number one has to show that it decays weakly.

The SLAC-LBL collaboration is presently taking more data. The increased statistics should help in the search for other decay modes and other narrow states with similar properties. In particular, one would try to analyze the recoil mass spectra[28] and understand the production processes. We are all looking forward to the next few months.

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