DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 76/52
October 1976

New Particle Production in e^+e^- Colliding Beams

by

B. H. Wiik

[illegible]

2 HAMBURG 52 · NOTKESTIEG 1

New Particle Production in e^+e^- Colliding Beams

by

B.H.Wiik

Invited paper given at the XVIII International Conference on High Energy Physics - Tbilisi, USSR 15-21 July 1976

New Particle Production in e^+e^- Colliding Beams

by B.H.Wiik - DESY, Hamburg, Federal Republic of Germany

Introduction

The study of e^+e^- annihilation over the past two years[1] has led to new and exciting discoveries. Detailed measurements of the total cross section[2] have revealed a rich structure with two narrow resonances, the J/ψ and the ψ', and a threshold region between 4 GeV and 5 GeV with a complex structure containing further new vector mesons.

One attractive explanation of these observations introduces a new heavy quark Q with a new quantum number respected by the strong and the electromagnetic interactions. In this picture the J/ψ, the ψ' and the other new vector mesons are bound $Q\bar{Q}$ states and the step in the total cross section is interpreted as a threshold for production of a new class of hadrons obtained by combining an old and a new quark. Perhaps the most natural choice for Q is to identify it with the charmed quark, originally proposed to achieve symmetry between leptons and quarks[3] and later to explain the absence of strangeness changing neutral currents[4].

This picture has two major predictions:

1) More states of the type $Q\bar{Q}$ will exist[5,34], some with and others without the quantum numbers of a photon. These states should be SU(3) singlets and have isospin 0. These predictions, however, are not unique to the charm model, any new heavy quark with spin 1/2 will lead to similar predictions.

2) A new class of hadrons made from an old and a new quark must be found[6]. Such hadrons, carrying a new quantum number, can only decay weakly into normal hadrons. Their signature would therefore either be their semileptonic decays or extreme narrowness. Again, any new quark would give such a signature. The charm hypothesis can be identified by the preferred

decay of the charmed quark into a strange quark[4] $c \rightarrow -d\cdot\sin\theta_c + s\cdot\cos\theta$. This leads to properties specific to the charm hypothesis like correlations between electrons (muons) and kaons and apparently exotic decays [6].

States with positive charge conjugation between the ψ' and the J/ψ were found[7] last summer, confirming the $Q\bar{Q}$ picture. To this conference compelling evidence for the existence of a new class of hadrons with properties like those predicted by the charm model are reported. In addition new information on the properties of the J/ψ, the ψ' and related states has been submitted by groups working at ADONE, DORIS and SPEAR. Another important result is reported by the SLAC-LBL group. After sifting through the evidence on the $e\mu$-events they conclude that these events demonstrate the existence of new heavy leptons[8].

In this report I'll discuss the following topics:

- I Decays of the J/ψ, the ψ' and the status of the X(2.8).
- II New states with even charge conjugation.
- III Monochromatic photons observed above 4 GeV.
- IV Anomalous lepton events and evidence for new leptons and hadrons.

A discussion of the threshold region around 4 GeV including the data on the new vector mesons can be found in the talk [9] by Roy Schwitters. He will also discuss the new and exciting data [10] on the narrow resonances recently discovered at SPEAR.

I.) Decays of the J/ψ and the ψ'

Branching ratios and sundry comments

A large body of data now exists on various decay modes of the J/ψ and the ψ'. Updated values of the branching ratios are listed [11] in table 1 and 2.

1) Hadronic width of the ψ'

Last year, the width of the J/ψ could be accounted for by known decays, but some 20% to 30% of the ψ' seemed to be missing. These missing decays have now presumably been identified [27,30] as the ψ' decaying with the emission of monochromatic photons into states with even charge conjugation.

The width for the ψ' to decay directly into normal hadrons $\Gamma(\psi' \rightarrow \text{hadrons})$ can be obtained by subtracting from the total width of the ψ' the width observed for the following decay modes: hadronic cascade decay to J/ψ or via the intermediate $C=+1$ states, decays into pairs of electrons und muons and second order electromagnetic decays. This leads to $\Gamma(\psi' \rightarrow \text{hadrons}) \simeq 36$ keV with large errors caused by the uncertainties in the subtraction. This value is not inconsistent with the prediction

$$\Gamma(\psi' \rightarrow \text{hadrons}) = \Gamma(J/\psi \rightarrow \text{hadrons}) \cdot \frac{\Gamma^{\psi'}_{ee}}{\Gamma^{J/\psi}_{ee}} \simeq 22 \text{ keV}$$

based on the short range annihilation picture [34] of the $Q\bar{Q}$ system.

2) SU(3) classification of the J/ψ

The decays of the J/ψ into ordinary hadrons can be used to determine [35] its SU(3) classification provided the decay mechanism itself conserves SU(3). The pattern of the observed decay modes listed in table 1 and 2 favours assigning the J/ψ to an SU(3) singlet as required for the bound state of a pair of heavy quarks. The table shows that none of the decays forbidden by SU(3) like for example K^+K^- and $K^0_L K^0_S$ are seen above the level predicted from second order electromagnetic decays. The singlet assignment also predicts equalities between various decay modes like $p\bar{p}$ and $\Lambda\bar{\Lambda}$ and also between $\pi^{\pm}\rho^{\mp}$ and $K^{\pm}K^{*\mp}(892)$ Experimentally one observed $\Gamma(p\bar{p}) / \Gamma(\Lambda\bar{\Lambda}) = (1.38 \pm 0.7)$ and $\Gamma(\pi^-\rho^+) / \Gamma(K^-K^{*+}(892)) = (1.9 \pm 0.7)$ or 1.2 ± 0.6 and 1.6 ± 0.6 after applying a small phase space correction factor.

Table 1 - Decay modes of the $J/\psi(3095)$

Decay mode	Width (keV)	Fraction (%)	Ref.
total width	69 $\pm$ 15		12
e^+e^- $(\mu^+\mu^-)$	4.8 $\pm$ 0.6	6.9 $\pm$ 0.9	12
second order electromagnetic decays	12.0 $\pm$ 2	17 $\pm$ 3	12
direct to hadrons	47.4 $\pm$ 14	69 $\pm$ 4	12

Hadronic modes *)

Mode	Fraction %	Ref.	Mode	Fraction %	Ref.
$\pi^+\pi^-$	0.01 $\pm$ 0.007	13(a)	$\phi\pi\pi$	0.21 $\pm$ 0.09	19
$\pi^+\pi^-\pi^0$	1.6 $\pm$ 0.6	14	ωK^+K^-	0.03 $\pm$ 0.02	19
$2\pi^+2\pi^-$	0.4 $\pm$ 0.1	14(b)	ϕK^+K^-	0.09 $\pm$ 0.04	19
$2\pi^+2\pi^-\pi^0$	4.0 $\pm$ 1.0	14(c)	$\phi\eta$	0.07 $\pm$ 0.04	19
	4.4 $\pm$ 0.5	15	$\phi\eta'$	0.05 $\pm$ 0.04	19
			$\phi f'$	0.08 $\pm$ 0.05	19
$3\pi^+3\pi^-$	0.4 $\pm$ 0.2	14(b)	$p\bar{p}$	0.198 $\pm$ 0.015	21(h)
$3\pi^+3\pi^-\pi^0$	2.9 $\pm$ 0.7	14		0.23 $\pm$ 0.03	13(h)
$4\pi^+4\pi^-\pi^0$	0.9 $\pm$ 0.3	14		0.24 $\pm$ 0.09	22(h)
$\pi\rho$	1.3 $\pm$ 0.3	14	$p\bar{n}\pi^-$	0.38 $\pm$ 0.08	23
	1.2 $\pm$ 0.3	13	$p\bar{p}\pi^0$	0.10 $\pm$ 0.02	23
	1.0 $\pm$ 0.2	16	$p\bar{p}\eta$	0.19 $\pm$ 0.04	23
$A_2^\pm\pi^\mp$	< 0.43	13(b)	$p\bar{p}\pi^+\pi^-$	0.41 $\pm$ 0.08	23
			$p\bar{p}\pi^+\pi^-\pi^0$	0.11 $\pm$ 0.04	23
$\omega\pi\pi$	0.7 $\pm$ 0.2	15	$p\bar{p}\omega$	0.05 $\pm$ 0.01	23
K^+K^-	0.014 $\pm$ 0.014	13(d)	$\Lambda\bar{\Lambda}$	0.16 $\pm$ 0.08	20
K_SK_L	< 0.008	18(e)	$\gamma\gamma$	< 0.3	24(i)
$K^+K^-\pi^+\pi^-$	0.72 $\pm$ 0.23	19	$\gamma\pi^0$	< 0.016	25
$2K^+2K^-$	0.07 $\pm$ 0.03	19	$\gamma\eta$	0.1 $\pm$ 0.02 0.09 $\pm$ 0.04	25 16
$K^+K^-2\pi^+2\pi^-$	0.3 $\pm$ 0.1	20	$\gamma\eta'$	0.24 $\pm$ 0.7 0.25 $\pm$ 1.0	26 25
$K^+K^{-*}(892)$	0.32 $\pm$ 0.06	19			
	0.41 $\pm$ 0.12	13	$\gamma X(2.8)$	< 5	27
$K^0\bar{K}^{0*}$	0.27 $\pm$ 0.06	19	$\gamma X(2.8)\to 3\gamma$	0.015 $\pm$ 0.004	25
K^+K^{-**}	< 0.15	19		0.014 $\pm$ 0.008	16
$K^0\bar{K}^{0**}$	< 0.20	19	$\gamma X(2.8)\to\gamma p\bar{p}$	< 0.004	21
$K^{0*}\bar{K}^{0*}$	< 0.05	19		< 0.02	25
$K^{0*}\bar{K}^{0**}$	0.67 $\pm$ 0.26	19			
$K^{0**}\bar{K}^{0**}$	< 0.29	19			

*) The resonance contribution is included in the general mode - i.e. in $\rho\pi$ is included $\pi^+\pi^-\pi^0$. The branching ratio listed is the sum of the mode and its charge conjugate state. The limits refer to 90% confidence upper limits. $K(892) \equiv K^*$ $K(1420) \equiv K^{**}$.

Table 2 - Decay modes of the $\psi'(3684)$

Decay mode	Width (keV)	Fraction (%)	Ref.
total width	228 $\pm$ 56		28
$e^+e^-(\mu^+\mu^-)$	2.1 $\pm$ 0.3	0.93 $\pm$ 0.16	28
second order electromagnetic decays	6.6 $\pm$ 0.9	2.9 $\pm$ 0.4	28
direct decay to J/ψ	124 $\pm$ 30	54.4 $\pm$ 5	24,29(k)
direct decay to P_c/χ	~ 57	~ 25 $\pm$ 6	27,30
direct decay to hadrons	~ 36	~ 16	

Hadronic modes *)

Decay mode	Fraction %	Ref.	Decay mode	Fraction %	Ref.
$\pi^+\pi^- J/\psi$	32 $\pm$ 4	29	$\gamma\gamma$	< 0.5	33
	36 $\pm$ 6	24		< 0.8	24
$\pi^0\pi^0 J/\psi$	17 $\pm$ 2.9	29	$\gamma\pi^0$	< 0.7	33
	18 $\pm$ 6	24		< 1.0	24
$\eta J/\psi$	4.3 $\pm$ 0.8	31	$\gamma\eta$	< 0.13	24
	3.7 $\pm$ 1.5	24	$\gamma\eta'$	< 0.11	26
$\gamma J/\psi+\pi^0 J/\psi$	< 0.15	31	$\gamma X(2.8)$	< 1.1 < 5	30 27
$\pi^+\pi^-$	< 0.005	17	$\gamma X(2.8)\to\gamma\gamma\gamma$	<0.037	24
$2\pi^+2\pi^-$	0.08 $\pm$ 0.02	32			
$2\pi^+2\pi^-\pi^0$	0.35 $\pm$ 0.15	20	$\gamma\chi(3.41)$	10 $\pm$ 4	27(m)
$\rho\pi$	< 0.3	20		6.5 $\pm$ 2.2	30(m)
	< 0.1	26	$\gamma\chi(3.45)$	< 5	27(o)
K^+K^-	< 0.005	17	$\gamma P_c(3.51)$	9 $\pm$ 3	27(o)
$K^+K^-\pi^+\pi^-$	0.14 $\pm$ 0.04	32	$\gamma\chi(3.55)$	8 $\pm$ 3	27(o)
$p\bar{p}$	0.023 $\pm$ 0.007	17			

*) See remarks to table 1

a) Two $\pi^+\pi^-$ pairs with an estimated background of 0.24 events were found. The decay violates isospin and proceeds presumably via a second-order electromagnetic interaction. With this assumption $|F_\pi(q^2=3.1\ GeV^2)|^2=(5.6\pm4.0)\times10^{-3}$.

b) Violates isospin and proceeds via a second order electromagnetic interaction.

c) 20% $\omega\pi\pi$, 30% $\rho\pi\pi\pi$.

d) One event observed. Forbidden for a SU(3) singlet state, this implies $|F_{K^\pm}(q^2=3.1^2GeV^2|^2<8.6\times10^{-3}$.

e) Forbidden for a SU(3) singlet state, this implies $|F_{K^0}(q^2=3.1^2GeV^2|^2<4.3\times10^{-3}$

f) Forbidden for a SU(3) singlet state.

h) A $(1+\cos^2\theta)$ angular distribution assumed consistent with the experimental results.

i) Forbidden for a spin 1 particle.

j) Two candidates for the decay $J/\psi\to p\bar{p}\gamma$ observed. These events might not result from the decay of an intermediate state.

k) Sum of the $\psi'\to\pi\pi J/\psi$ and the $\psi'\to\eta J/\psi$ decay mode.

l) The decay $\psi'\to\pi^0 J/\psi$ is forbidden by isospin, the decay $\psi'\to\gamma J/\psi$ by C-parity.

m) Angular distribution of $(1+\cos^2\theta)$ assumed.

o) Valid for an isotropic distribution of the photon. An $(1+\cos^2\theta)$ distribution would increase the quoted fraction by a factor 1.3

3) The three photon final state and evidence for X(2.8)

At the mass of the J/ψ and the ψ' a three photon final state might arise from:

a) the radiative decay of these resonances into a state with even charge conjugation and spin different from one which subsequently decays into two photons. Earlier data [24,36] showed some evidence for a new resonance with a mass around 2.8 GeV.

b) The direct decay of the J/ψ or the ψ' into three photons [37]. The branching ratio for this decay has been estimated and found to be small.

c) Hard photon correction to the e^+e^- annihilation into two photons, leading to a final state with three photons. The cross section for this QED reaction is large, however, it can be computed [38] and unlike the decay via a resonance, it will not lead to a peak in effective mass between any pair of photons.

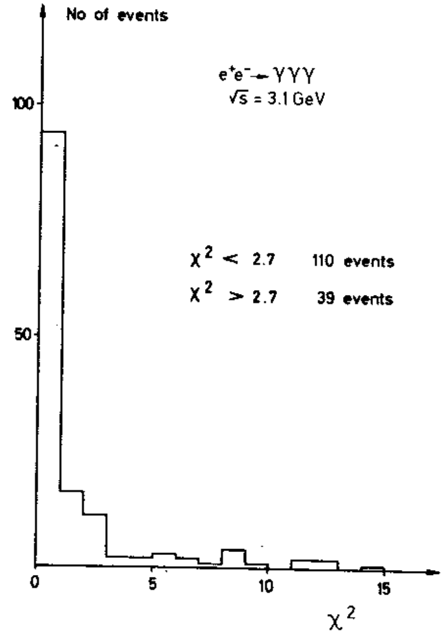


Fig. 1 - Number of apparent three photon events observed by the DASP group at the J/ψ resonance. The events are plotted as a function of χ^2 calculated from a fit to the hypothesis that the conversion points and the interaction point lie in a plane.

Experimental results are presented by the DESY-Heidelberg group [16] and by the DASP collaboration [25]. Both groups used non-magnetic detectors to select the three photon final state and to measure the directions of the photons. Demanding a three photon final state removes the background from beam-gas interactions, multihadron events or cosmic ray events. This is shown in Fig. 1 where the number of three photon candidates observed by the DASP group at the J/ψ resonance is plotted as a function of χ^2. The χ^2 is calculated from 1C fit to the hypothesis that the three conversion points and the interaction point lie in a plane. Events with missing

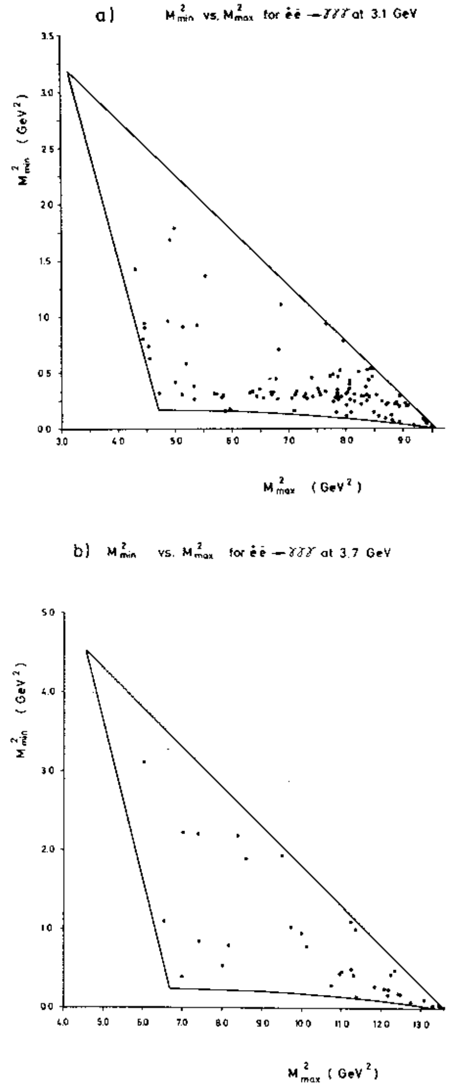


Fig. 2a,b - Dalitz plot of the three photon events observed by the DASP-group at the J/ψ(a) and the ψ'(b) resonance.

tracks will in general not be coplanar. The photon energies for the 110 events with a χ^2 less than 2.7 were computed from the measured directions of the three photons and the known cms energy. A Dalitz plot of the events is shown in Fig. 2a,b for events from the J/ψ and the ψ' respectively. Note the low mass boundary in the Dalitz plot which results from demanding an opening angle greater than 30° between any pair of photons. This cut effectively excludes $J/\psi \to \pi^0\gamma$. The data obtained at the J/ψ show a clear cluster at the mass of the η, a few events consistent with the η' and some events with a mass between 2.8 GeV and 2.9 GeV, which might result from the 2γ decay of a new heavy resonance. No clear clustering of events along any fixed mass line is observed at the ψ'. In Fig. 3a, the events at the J/ψ resonance are projected onto the high mass axis. A clear peak, superimposed on a smooth background, is observed between 2.8 GeV and 2.9 GeV. The width is

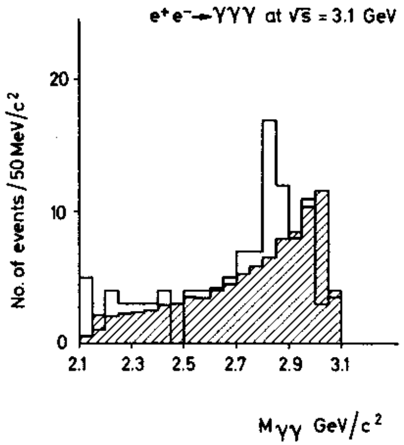


Fig. 3a - The three photon events from the Dalitz plot in Fig. 2a (J/ψ region) projected on to the high mass axis. The hatched area shows the background from QED and reflexions.

consistent with the experimental resolution. The sum of the contribution from the QED process and reflexions from $\eta\gamma$ and $\eta'\gamma$ are indicated by the hatched area. It is clear that the events outside the resonance region can be accounted for by these sources alone. Between 2.8 GeV and 2.9 GeV the DASP group observes 29 events compared to an expected background of 14 events. Assuming the observed enhancement to result from the decay of a narrow resonance they obtain M = (2.83 ± 0.05) GeV and $BR(J/\psi \to X\gamma) \cdot BR(X \to \gamma\gamma) = (1.5 \pm 0.4) \times 10^{-4}$.

The DESY-Heidelberg group [16], using the same method, finds an enhancement of 8 events above a background of 10 ± 4 events around a mass of 2.7 GeV. If this excess is attributed to a resonance they find:

$$BR(J/\psi \to \gamma X)\ BR(X \to \gamma\gamma) = (1.4 \pm 0.8) \times 10^{-4}.$$

These branching ratios agree well with earlier results reported [24,36] by both groups based on less than half the present luminosity.

At the Stanford meeting the DASP group reported [24] two candidates for the cascade decay $J/\psi \to \gamma X \to \gamma p\bar{p}$. Increasing the data by more than a factor of two failed to produce any new events and therefore only an upper limit $BR(J/\psi \to \gamma X)\ BR(X \to p\bar{p}) < 2 \cdot 10^{-4}$

can be given. The SLAC-LBL group [21] has also searched for events of this type. They find no signal; the 90% confidence upper limit is $BR(J/\psi \to \gamma X) \cdot BR(X \to p\bar{p}) < 4 \times 10^{-5}$).

In Fig. 3b the three photon events observed by the DASP group at the ψ' resonance are plotted as a function of the highest mass found in the event. The events observed above a mass of 2.9 GeV are consistent with the rate expected from QED alone, shown as the hatched area. Between 2.7 GeV and 2.9 GeV 5 events are found compared to a predicted QED background of 1.3 events. From these data a 90% confidence upper limit of 3.7×10^{-3} can be derived for the decay $\psi' \to \gamma X(2.8) \to \gamma\gamma\gamma$.

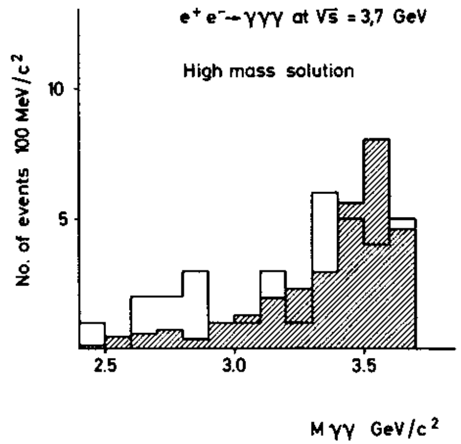


Fig. 3b - The three photon events from the Dalitz plot in Fig. 2b (ψ' region) projected on to the high mass axis. The hatched area shows the background from QED and reflexions.

In Fig. 4 the three photon events observed by the DASP group at the J/ψ resonance are plotted as a function of the lowest mass observed in the event. A clear peak at the mass of the η is observed, whose width of 30 MeV is consistent with the experimental resolution. The background from QED events and events from the kinematic reflexion of the X(2.8) is shown as the hatched area. From this data a $BR(J/\psi \to \eta\gamma) = (1.0 \pm 0.2) \times 10^{-3}$ was found, in good agreement with $(0.9 \pm 0.4) \times 10^{-3}$ obtained by the DESY Heidelberg group using a similar analysis. The few events consistent with $J/\psi \to \eta'\gamma$ correspond to $BR(J/\psi \to \eta'\gamma) = (1.5 \pm 0.9) \times 10^{-3}$. This is in agreement with a measurement [25,26] of this decay mode identifying η' by its decay $\eta' \to \rho\gamma$ as discussed below.

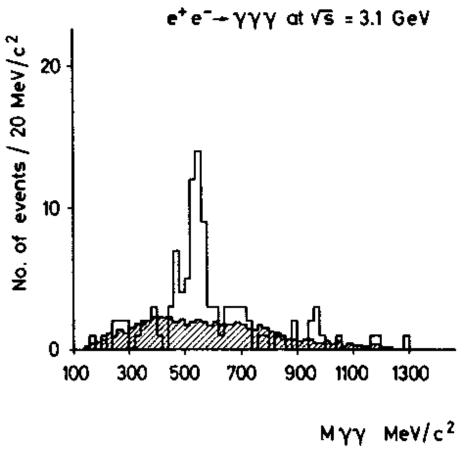


Fig. 4 - The three photon events from the Dalitz plot in Fig. 2a (J/ψ region) projected on to the low mass axis.

An analysis by the DASP group of the three photon final states with no cut on the minimum opening angle fail to find any evidence for the decay $J/\psi \to \pi^0\gamma$. The 90% confidence upper limit is $BR(J/\psi \to \pi^0\gamma) < 1.6\times10^{-4}$.

The DESY-Heidelberg group has measured [16,26] the decay $J/\psi \to \eta'\gamma \to \rho\gamma\gamma \to \pi^+\pi^-\gamma\gamma$. The momenta of the final state particles are computed using the measured directions as an input to the energy and momentum equations assuming that the charged particles are pions. Events with negative energy solution, in general corresponding to events with unseen particles, were rejected. The decay $J/\psi \to \rho\pi$, feeding the same topology, has in all charge states a π^0 in the final state. This decay was therefore excluded by requiring the $\gamma\gamma$ effective mass to be greater than 0.35 GeV. In addition the $\pi^+\pi^-$ were required to have a mass between .55 GeV and 1.0 GeV, consistent with the mass of the ρ-meson. The resulting invariant mass spectrum for $\pi^+\pi^-\gamma$ is plotted in Fig. 5. A clear η' peak with a total of 57 ± 13 events is observed superimposed on a smooth background from kinematic reflexions. the branching ratio is $BR(J/\psi \to \eta'\gamma) = (2.4 \pm 0.7) \times 10^{-3}$. This is also in agreement with preliminary data [25]' from the DASP group using the $\eta' \to \rho\gamma$ decay to identify the η'.

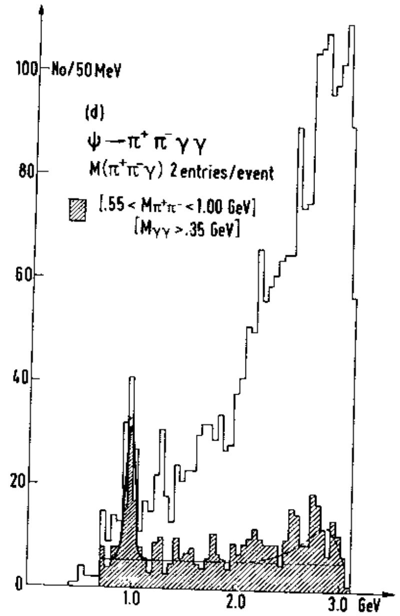


Fig. 5 - Invariant mass spectrum for $\pi^+\pi^-\gamma$ observed by the DESY-Heidelberg group in the decay $J/\psi \to \pi^+\pi^-\gamma\gamma$.

If the η and the η' contain only old quarks then the radiative decay [39] must proceed via the two graphs shown in Fig. 6a,b. The first graph predicts $\Gamma(\pi^o\gamma) > \Gamma(\eta\gamma) >> \Gamma(\eta'\gamma)$ in contradiction to the experimental findings. The second graph predicts $\Gamma(\pi^o\gamma) = 0$ and a ratio $(\Gamma(J/\psi \to \eta'\gamma) \,/\, \Gamma(J/\psi \to \eta\gamma))$ of the order of 25. Experimentally the

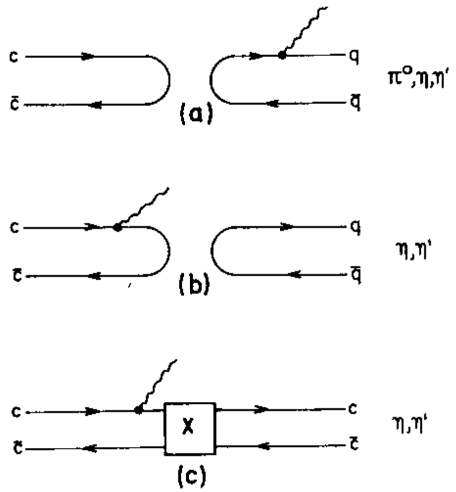


Fig. 6 - Feynman graphs for the radiative decays of the $J/\psi(\psi')$ into a meson.

ratio is (2.4 ± 0.7). If 6b is indeed the relevant graph then this would imply a large SU(3) breaking not seen in other decay modes. Also note that the absolute rates of these decays are comparable to the rate for strong decays like $J/\psi \to \rho^o\pi^o$ despite the factor of α present in the amplitude for the radiative decay.

As a possible solution to this problem it has been suggested [39,40] that the η,η' and the charm pseudoscalar states mix. Then the η and the η' would aquire a small $c\bar{c}$ component and the radiative decay could proceed as indicated in Fig. 6c without suppression from the OZI rule [41].

II.) New states with even charge conjugation

Nonrelativistic binding of a pair of heavy quarks $Q\bar{Q}$ in a steeply rising attractive potential [5,42] will lead to the schematic level scheme of Fig. 7. The levels are labeled by J^{PC} with $P = -(-)^L$ and $C = (-)^{L+S}$.

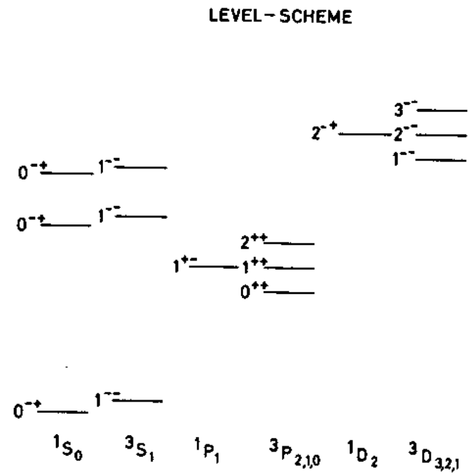


Fig. 7 - Level scheme predicted for two fermions bound in a steeply rising attractive potential

In this scheme the J/ψ and the ψ' are identified with the 1^3S_1 and 2^3S_1 levels, respectively.

The X(2.8) discussed earlier has $C = +1$ and $J \neq 1$ and might be assigned to the first pseudoscalar level, the 1^1S_o.

For any reasonable potential there should be several $C = +1$ states below the ψ'. These states might be observed by searching the ψ' decay debris for:

1) Monochromatic photons
2) The J/ψ together with one monochromatic and one nearly monochromatic photon.
3) A monochromatic photon together with hadrons.

1) Monochromatic photons

The SLAC-LBL group measures 30) the single photon spectrum produced in the decay of the J/ψ and the ψ' resonance by using the magnetic solenoid as a pair spectrometer. A photon converted in the material ($\sim$ 0.05 of an radiation length) mounted in front of the chambers is identified by demanding a pair of oppositely charged particles to have an invariant mass less than 0.0275 GeV. The photon energy is the sum of the measured electron and positron energies; the resulting resolution (rms) is 4%. The photon spectra so obtained are plotted in Fig. 8a,b for the J/ψ and the ψ' respectively. At the ψ' resonance the spectrum shows a clear peak centered at (261 $\pm$ 10) MeV corresponding to a mass for the intermediate state of (3413 $\pm$ 10) MeV. The observed width is consistent with the experimental resolution. The branching ratio is $(6.5 \pm 2.2) \times 10^{-2}$ assuming the photon to have a $(1+\cos^2\theta)$ angular distribution with respect to the beam axis, or $(5.5 \pm 1.9) \times 10^{-2}$ for an isotropic distribution. The other P_c or χ states give photons with energies below 250 MeV and are masked by the rapid variation of the photon detection efficiency at low energy. Photon lines from the decay of the intermediate states into the J/ψ plus a photon are not observed, presumably because of Doppler broadening.

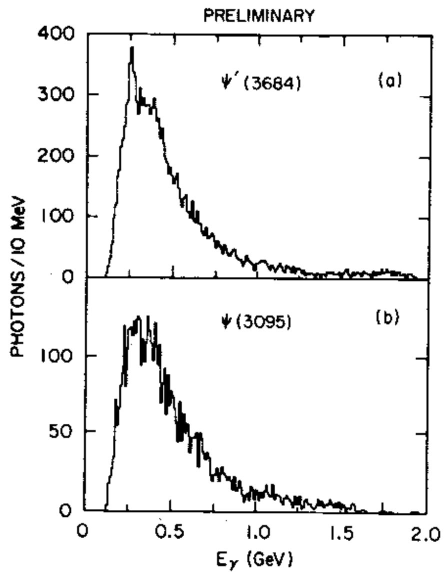


Fig. 8a,b - The raw photon spectrum observed in the decay of the J/ψ and the ψ' resonances by the SLAC-LBL group.

The decay of the ψ' into X(2.8) would lead to a monochromatic photon line at around 750 MeV. No such line is observed. The 90% confidence upper limit is 1.1%. No peak resulting from the decay $J/\psi \to \gamma X$ is found in the spectrum measured at the J/ψ resonance. However, note that the sensitivity for observing this decay depends strongly on the mass of

the X since the detection efficiency for low energy photons depends strongly on the photon energy.

The Maryland, Pavia, Princeton, UC San Diego, SLAC and Stanford Collaboration determines 27) the photon energy spectrum by measuring the energy deposited in two sets of segmented NaI(Tl) crystals mounted above and below the beam pipe. The energy resolution varied between 2.5% at 1500 MeV and 5% at 200 MeV. An event was recorded when two or more charged particles were registered in the tube chambers surrounding the interaction region and more than 110 MeV was deposited in any of the three NaI(Tl) arrays. Electronic threshold effects were eliminated by demanding that the measured photon should not be a part of the trigger. The resulting photon spectrum obtained at the J/ψ and the ψ' resonance is plotted in Fig. 9. The spectrum obtained at the ψ' resonance shows several bumps superimposed on a smoothly varying background in contrast to the structureless spectrum observed at the J/ψ resonance.

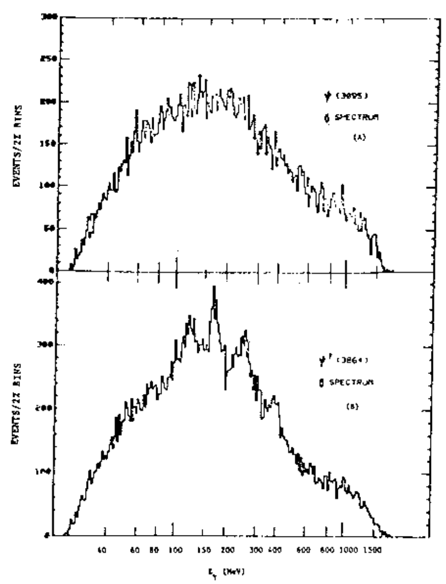


Fig. 9a, b - The raw photon spectrum observed in the decay of the J/ψ and the ψ' resonances by the Maryland, Pavia, Princeton, UC San Diego, SLAC and Stanford Collaboration.

Photon lines centered at 121 MeV, 168 MeV, 256 MeV and 383 MeV are observed in the debris of the ψ'. The three first transitions correspond to intermediate states with masses of 3561 MeV, 3512 MeV and 3418 MeV. This proves that the P_c states first observed at DESY in the $\gamma\gamma$ cascade are the same as the χ states observed at SPEAR. The peak at 383 MeV can be identified with the decay $P_c(3.51) \to \gamma\ J/\psi$.

There are two major problems in extracting a branching ratio for these transitions. Firstly, the observed widths of the three peaks corresponding to monochromatic photon lines are not the same. Whereas the 168 MeV peak has a width corresponding to the expected resolution, both the 121 MeV line and the 256 MeV line are wider than expected. Since these resonances should be narrow, this might indicate the presence of additional, as yet unresolved, photon lines or unknown experimental problems. The fit was made assuming a width (rms) of 7%, the maximum allowed for the 121 MeV and the 256 MeV transition. A second problem is the proper shape of the non-resonant photon spectrum at the ψ' resonance. As a temporary solution the authors assumed this to be similar to the spectrum observed at the J/ψ resonance. This can clearly only be an approximation since photons from the cascade decay $\psi' \to \pi^0\pi^0 J/\psi$ will make a large contribution to the ψ' spectrum. The result of the fit is shown in Fig. 10 and the branching ratios listed in table 2. The systematic uncertainties dominate the error. Note that the branching ratio observed for the decay $\psi' \to \gamma\chi(3.41)$ is substantially larger than the value observed by the SPEAR group. However, the value $P_c(3.51) \to \gamma J/\psi$ / $\psi' \to$ all of $(4 \pm 3) \times 10^{-2}$ is consistent with earlier measurements at DESY and SPEAR.

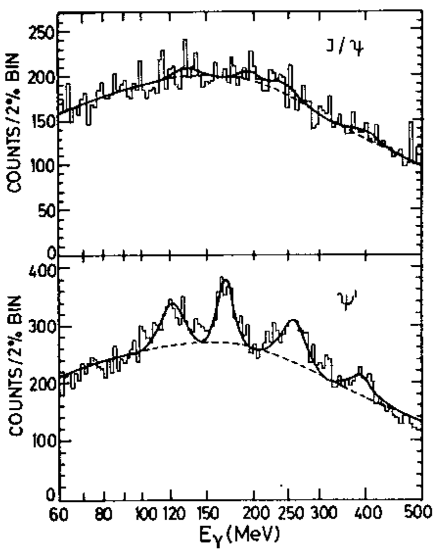


Fig. 10a, b - The results of a fit to the photon spectrum shown in Fig. 9a,b.

No significant structure in the photon spectrum is observed at the J/ψ resonance. A 90% confidence upper limit of 5% is found for the decay $J/\psi \to \gamma X(2.8)$.

2) The $\gamma\gamma$ cascade

The cascade decay $\psi' \to \gamma P_c \to \gamma\gamma\, J/\psi$ was first observed by the DASP group [7] at DESY and later by the SLAC-LBL group [43] at SPEAR.

The DASP group searched for events of the type $\psi' \to \gamma\gamma\mu\mu$ with the two muons detected in the magnetic arms of the spectrometer and the two photons observed with the inner detector. A 3C fit was made to the 34 events satisfying the selection criteria assuming they all resulted from a $\gamma\gamma$ cascade via an intermediate state. Of the 11 events with an acceptable χ^2 of 8 or less, 3 events had a $\gamma\gamma$ effective mass greater than 0.27 $(\mathrm{GeV}/c^2)^2$ and were attributed to the decay $\psi' \to J/\psi\, \eta$. The remaining events are plotted in Fig.11 as a function of the low mass solution versus the high mass solution. A clear cluster of events with a mass around 3.5 GeV is seen with three single events. A background of 0.6 events is expected in the sample. The location of resonances observed by other decay modes is shown by the arrows line.

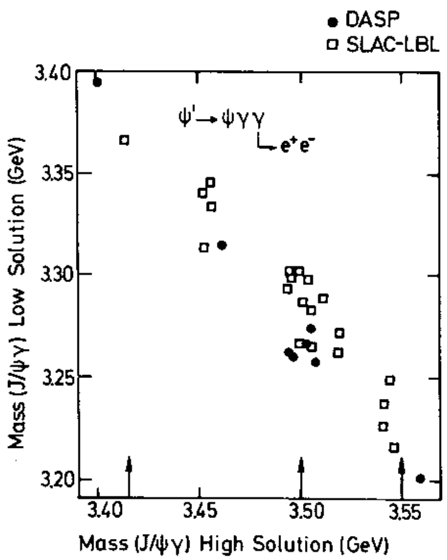


Fig. 11 - The decay $\psi' \to \gamma\, P_c/\chi \to \gamma\gamma\, J/\psi$. The events obtained by the DASP group and the SLAC-LBL collaboration are plotted as a function of the low mass solution versus the high mass solution. The position of the resonances as determined by other methods are indicated.

The SLAC-LBL group [43] selected events of the type $\psi' \to \gamma\, J/\psi + X$ with the photon converted in front of the chambers and the J/ψ identified by its characteristic decay into a pair of leptons. Demanding an opening angle between the electron and the positron of less than 177.5° and a collinearity angle between the photon and either of the electron greater than 10° led to a sample of 54 events. Of these, 27 events had a missing mass squared recoiling against the $J/\psi\ \gamma$ system between -0.03 $(\mathrm{GeV}/c^2)^2$ and $+0.03$ $(\mathrm{GeV}/c^2)^2$ as expected for a $\gamma\gamma$ cascade. The $\psi' \to J/\psi\ \eta$ were excluded by a cut in the $\gamma\gamma$ effective mass leading to a final sample of 21 events with an estimated background of 1 event. These events are also plotted in Fig. 11. Besides a clear cluster of events around 3.500 GeV there are 4 events clustered around 3.455 GeV and 3.545 GeV and a single event at 3.41 GeV. Note that the single events from the DASP experiment more or less agree with these latter SPEAR events. The branching ratios

$$\frac{P_c\ /\ \chi \to \gamma\ J/\psi}{P_c\ /\ \chi \to \text{all}}$$

are listed in table 3. Note that the decay of the 3.41 GeV state is based on only one event from each experiment.

The resonance at 3.455 GeV (or at 3.331 GeV) is not observed in any other decay mode. Although the existence of this state needs to be confirmed, note that the background in these experiments is rather low and hence the observation of five events might well be significant. The upper limit of 5% set on the decay $\psi' \to \gamma\ \chi(3.45)$ can be used to obtain a lower limit of 24% on the decay $\chi(3.45) \to \gamma\ J/\psi$.

The DESY-Heidelberg group [16] has used a non-magnetic detector to measure the angular distribution with respect to the beam axis of the photons emitted in the cascade decay

$$\psi' \to \gamma\ P_c(3.51) \to \gamma\gamma\ J/\psi$$

The J/ψ is identified by its decay into a pair of electrons or muons. The kinematics of the event are fully determined by the directions of the four final state particles. A total of 77 events with an estimated background of 8 events satisfied the selection criteria. The resolution is not sufficient to separate the transitions from the closely spaced intermediate states, However, the DASP and the SLAC-LBL data show that the cascade transition via the $P_c(3.51)$ state is the most prominent one. This transition is further enhanced by demanding the higher energy photon to have an energy between 350 MeV and 450 MeV. A total of 60 events with an estimated background of 3 events satisfied this condition. The angular distribution with respect to the beam axis of the higher and lower energy photons is plotted in Fig. 12. A fit to the angular distribution of the lower energy photons of the form $1 + \alpha \cos^2\theta$ gives $\alpha = -(1.1 \pm 0.3)$

Table 3 - Properties of the Intermediate States

Mass(P_c/χ) (GeV)	α $(1+\cos^2\theta)$	Decay	$BR(\psi' \to \gamma P_c/\chi)$ $BR(P_c/\chi$ decay) $\cdot 10^{-3}$	Fraction $o\pi^+\pi^-/2\pi^+2\pi^-$ $K^* K^\pm\pi^\mp/\pi^+\pi^-K^+K^-$	$BR(P_c/\chi$ decay)[a] $\cdot 10^{-2}$	Ref.
3.414 ± 4	1.4 ± 0.4 [32]	$\pi^+\pi^-$	0.7 ± 0.2		1.0 ± 0.3	32
		K^+K^-	0.7 ± 0.2		1.0 ± 0.3	32
		$2\pi^+2\pi^-$	3.2 ± 0.6	0.39 ± 0.12	4.4 ± 0.8	32
		$\pi^+\pi^-K^+K^-$	2.7 ± 0.7	0.41 ± 0.10	3.7 ± 1.0	32
		$3\pi^+3\pi^-$	1.4 ± 0.5		1.9 ± 0.7	32
		$\gamma\ J/\psi$	(3)		(4)	30b
			(10)		(14)	24b
3.454 ± 7		$\pi^+\pi^-$	< 0.3			32
		K^+K^-	< 0.3			32
		$\pi^+\pi^-K^+K^-$	< 0.5			32
		$2\pi^+2\pi^-$	< 0.4			32
		$3\pi^+3\pi^-$	< 0.7			32
		$\gamma\ J/\psi$	12 ± 6		> 24	30
			(10)			24b
3.508 ± 4		$\pi^+\pi^- + K^+K^-$	< 0.15		< 0.17	32
	0.26 ± 0.5 [32]	$2\pi^+2\pi^-$	1.1 ± 0.3	0.24 ± 0.20	1.2 ± 0.4	32
		$\pi^+\pi^-K^+K^-$	0.6 ± 0.3	0.35 ± 0.18	0.67 ± 0.33	32
	-1.1 ± 0.3 [16]	$3\pi^+3\pi^-$	1.25± 0.4		∿ 1.4	32c
		$\gamma\ J/\psi$	37 ± 11		42 ± 12	30
			40 ± 20			24
			40 ± 30			26
		$\gamma\gamma$	< 0.013		< 0.014	24d
3.552 ± 6		$\pi^+\pi^- + K^+K^-$	0.23 ± 12		0.29 ± 0.15	32
		$2\pi^+2\pi^-$	1.6 ± 0.4	0.31 ± 0.17	2.0 ± 0.5	32
		$\pi^+\pi^-K^+K^-$	1.4 ± 0.4	0.25 ± 0.13	1.8 ± 0.5	32
	0.22 ± 0.4 [32]	$3\pi^+3\pi^-$	1.25 ± 0.4		∿ 1.6	32c
		$\gamma\ J/\psi$	12 ± 6		15 ± 8	30
			(10)			24b

a) The values listed in table 2 for the decay $\psi' \to \gamma\ P_c/\chi$ were used to extract the branching ratios for the various P_c/χ decays. An average value of 7.3% was used for the $BR(\psi' \to \gamma\chi(3.41))$

b) The numbers in bracket correspond to only 1 event

c) Only the sum $\chi(3.55) + P_c(3.51) \to 3\pi^+3\pi^-$ is measured. In the table the observed $3\pi^+3\pi^-$ yield is divided evenly on the two states.

d) Forbidden for a state with spin 1

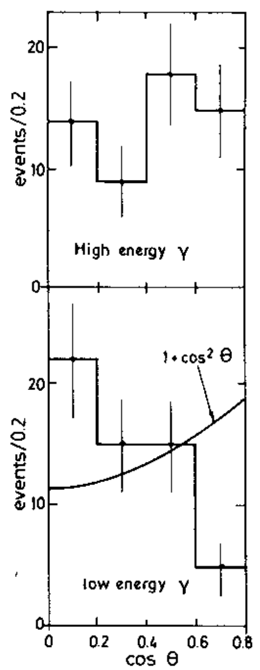


Fig. 12 - The angular distribution with respect to the beam axis of photons from the decay $\psi' \to \gamma P_c \to \gamma\gamma J/\psi$. The data were obtained by the DESY-Heidelberg group.

whereas $\alpha = +1$ for a spin 0 state. This measurement therefore excludes spin 0 for the $P_c(3.51)$ state.

3) Hadronic decays of the intermediate states

New exciting data [32] on the decay $\psi' \to \gamma\, \chi \to \gamma$ + charged hadrons are reported by the SLAC-LBL collaboration. The criteria used to select these events and evidence for the decay modes

$$\begin{aligned} \chi &\to \pi^+\pi^-\pi^+\pi^- \\ &\to \pi^+\pi^-\,K^+K^- \\ &\to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^- \\ &\to \pi^+\pi^-,\ K^+K^- \end{aligned}$$

have been reported earlier [7]. This analysis is based on a substantially

larger data sample. Furthermore, a careful study of systematic effects has increased the precision of the geometrical reconstruction, resulting in an improved mass resolution. This is seen in Fig. 13, where the fitted spectra corresponding to the decay modes listed above are plotted as a function of mass. The $2\pi^+2\pi^-$ and the $\pi^+\pi^-K^+K^-$ spectra now show clear evidence for three peaks centered at 3415 MeV, 3500 MeV and 3550 MeV with an uncertainty of ± 10 MeV in addition to the peak resulting from the direct decay of the ψ'. The two upper states are not yet resolved in the $3\pi^+3\pi^-$ mode, however, the uniform distribution of the events as a function of mass in this region indicate similar contributions from both. There is a very clear $\pi^+\pi^-$ and K^+K^- signal in the decay of the 3415 MeV state. A significant signal of eight events is also observed in the decay of the 3550 MeV state. The few events with an effective mass around 3500 MeV might result from the decay of the upper state. Note that none of these decay modes shows any evidence for the 3454 MeV state seen in the $\gamma\gamma$ cascade.

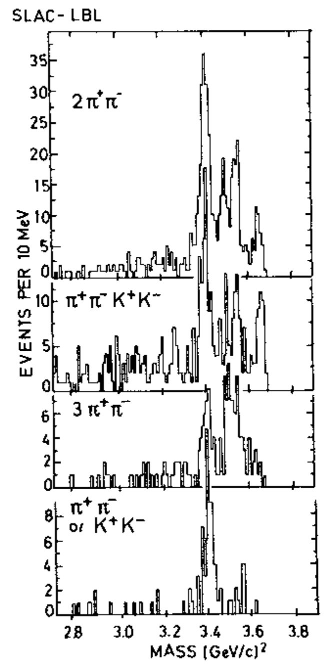


Fig. 13 - Effective mass spectra observed by the SLAC-LBL group in the decay of the ψ' into a single photon and charged hadrons.

The product of the branching ratios for the various decay channels are listed in table 3, column 4, together with 90% confidence upper limits for the decay of the 3455 MeV state. The $2\pi^+2\pi^-$ and the $\pi^+\pi^-K^+K^-$ branching ratios are nearly the same for all the observed states. These decay modes proceed partly via ρ^0 and K^* production respectively as seen in Fig. 14, where the effective $\pi^+\pi^-(\pi^\mp K^\pm)$ mass spectra are plotted for the two decay modes

$$\chi \to \rho^0\pi^+\pi^- \to \pi^+\pi^-\pi^+\pi^-$$
$$\to K^*K^\mp\pi^\pm \to \pi^+\pi^-K^+K^-.$$

The fractional contributions are listed in table 1 column 5.

A ratio of $\rho^{o}\pi^{+}\pi^{-}/K^{*+}K^{\mp}\pi^{\pm} = 9/8$ is predicted assuming the intermediate states to be SU(3) singlets and neglecting effects arising from the mass difference. The experimental results, obtained by multiplying column 4 and 5, are in agreement with this prediction.

The distribution [44] in θ, the angle of the photon with respect to the beam axis, has been obtained by summing over the various decay channels. The result is shown in Fig. 15. Only spin 0 leads to a unique angular distribution $1+\cos^2\theta$. Higher spins could lead to a more isotropic distribution. The values of the coefficient α determined from fitting the data to $1+\alpha\cos^2\theta$ are listed in table 3, column 2. Note that the value of α obtained for the decay to $P_c(3.51)$ disagrees with the value found by the DESY-Heidelberg group.

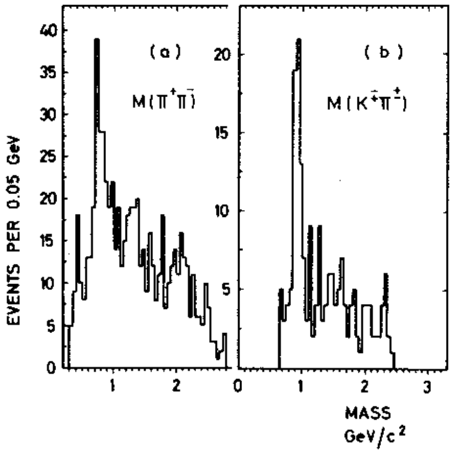


Fig. 14a,b - Effective mass spectra of $\pi^+\pi^-$(a) and $K^{\mp}\pi^{\pm}$(b) observed in the decay of the χ(3.41) into $2\pi^+2\pi^-$ and $K^+K^-\pi^+\pi^-$.

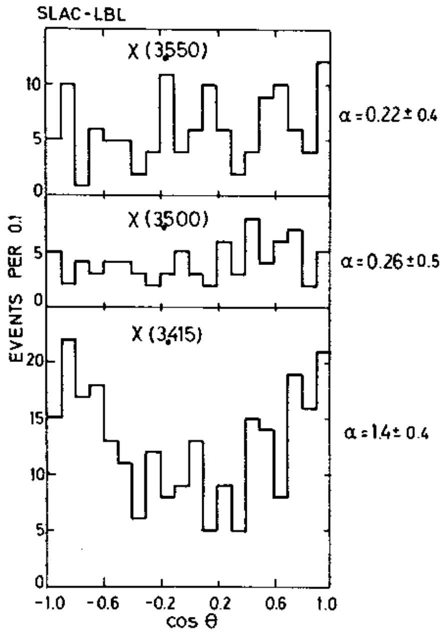


Fig. 15 - The angular distribution with respect to the beam axis of the photon from the decay $\psi' \to \gamma P_c/\chi \to \gamma$ charged hadrons. The data were obtained by the SLAC-LBL group.

In the level scheme depicted in Fig. 7 there are four levels with even charge conjugation between the J/ψ and the ψ', one pseudoscalar ^1S_o with $J^{PC} = 0^{-+}$ and three ^3P states with $J^{PC} = 2^{++}, 1^{++}, 0^{++}$. Are the levels found consistent with such quantum numbers ?

3.414 GeV It follows from the observed decay into both $\pi^+\pi^-$ and K^+K^- that the state must have natural spin-parity and be an isoscalar. The angular distribution is consistent with J = 0. We can therefore safely assign this state to $J^{PC} = 0^{++}$.

3.454 GeV Presumably for real, but needs to be confirmed.

3.508 GeV The absence of $\pi^+\pi^-$ and K^+K^- decays are consistent with the state belonging to an unnatural spin-parity sequence. $0^-, 1^+, \ldots$. The SLAC-LBL group and the DESY-Heidelberg group disagree on the value for α. However, they both require J ≠ 0.

3.552 GeV This level must belong to an natural spin parity sequence (based on the $\pi^+\pi^-$ + K^+K^- events), and the observed value of α indicate J ≠ 0.

This is all that can be deduced from the data alone. However, comparing the available information with the levels available according to Fig. 7, one is lead to a unique assignment by the following reasoning. The 3.414 GeV level must be the 0^{++} state. This leaves only one natural spin parity level, the $3P_2(2^{++})$ which then must be associated with the 3.552 GeV level. The 3.508 GeV level has J ≠ 0 and must therefore be the $^3P_1(1^{++})$ level. This assignment is also consistent with the fact that it is not seen to decay into $\pi^+\pi^-$ or K^+K^- pairs. The only level left according to Fig. 7 is the pseudoscalar 0^{-+} which then must be identified with the 3.454 GeV level. This assignment has been suggested earlier by Chanowitz and Gilman [45].
Does this picture lead to contradictions ?
For the assigned P states the situation seems to be rather satisfactory. The absolute and the relative rates computed for $\psi' \to \gamma P_c/\chi$ assumung electric dipole transitions are now in good agreement with the data [46,47]. The relative splittings observed between the P levels are in disagreement with general bounds computed [42] in a non relativistic model.
However, satisfactory agreement with the data has been

obtained both in a relativistic calculation [47] and in a model by Schnitzer [48] which introduces a long-range spin dependence.

The short range picture of the decays of the $Q\bar{Q}$ state predicts that the total width of the 0^{++} should be larger than the total width of the 1^{++} state. This is in qualitative agreement with the data as evidenced by the large branching ratio observed for the decay $P_c(3.51) \to \gamma\, J/\psi$.

However, identifying the 3.454 GeV level with the $2\,^1S_o$ state leads to a serious contradiction with the expectations based on the charmonium model and the standard short range picture of the decays. According to standard lore, the $^3S_1$ and ^1S_o states have similar wave functions while those for $2\,^3S_1$ and $1\,^3S_1$ or $2\,^1S_o$ and $1\,^1S_o$ should be nearly orthogonal. This is certainly consistent with $BR(\psi' \to \gamma X(2.8)) < 1.1\%$ despite the large phase space. Naively, we therefore expect $2\,^1S_o \to 1\,^3S_1 + \gamma$ to be similarly suppressed, contradicting the lower limit $BR(3.454 \to J/\psi + \gamma) > 24\%$. Furthermore, using this limit and the relation

$$\Gamma(2\,^1S_o \to 1\,^3S_1 + \gamma) \lesssim (2\,^3S_1 \to 1\,^1S_o + \gamma) < 2.5 \text{ keV}$$

we find $\Gamma(2\,^1S_o \to \text{all}) < 10$ keV. This is in strong disagreement with the standard short range picture which predicts a width of about 2 MeV.

It is important to note that the level assignments are based on the assumption that there are only four levels with even charge conjugation between J/ψ and the ψ'. Recently [49] it has been pointed out that the large singlet-triplet splitting obtained by identifying $1\,^1S_o$ with the X(2.8) could also lead to the $^1D_2(J^{PC} = 2^{-+})$ level being located below the ψ'. Then we expect five levels with (C+1) between the J/ψ and the ψ', and a complete assignment of levels in the framework of a $Q\bar{Q}$ model is no longer possible with present information.

III. Monochromatic photons observed above 4 GeV

The Maryland, Pavia, Princeton, UC San Diego, Stanford, SLAC-Collaboration reports [50] evidence in the inclusive photon spectrum obtained at cms energies above 4.2 GeV for monochromatic photons with an apparant energy of 55 MeV. The photons are produced in association with at least two charged tracks.

The observed spectrum is plotted in Fig. 16. The signal is statistically significant, however, the analysis is still preliminary. If it survives further analysis unchanged it presumably indicates the production of new particles or the decay between the narrow states recently observed [9,10] at SPEAR.

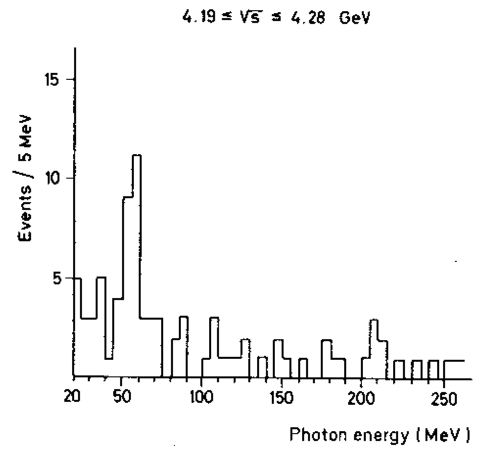


Fig. 16 - Single photon spectrum observed by the Maryland, Pavia, Princeton, UC San Diego, SLAC and Stanford Collaboration on e^+e^- collisions at cms energies between 4.14 GeV and 4.28 GeV.

IV.) Anomalous lepton events and evidence for new leptons and hadrons

The pair production in e^+e^- annihilation of new objects with large leptonic or semileptonic decay modes will lead to mixed final states containing electrons and muons or leptons and hadrons. The observation of such final states at a level above the background expected from higher order electromagnetic interactions and semileptonic pion or kaon decays is direct evidence for the production of new particles. A heavy sequential [8] lepton or a hadron with a new quantum number conserved by the strong and the electromagnetic interactions are two examples of such particles. The anticipated features of a new lepton and a new hadron are summarized in table 4.

The low multiplicity expected for the decay of a pair of heavy leptons into a final state with an electron (muon) plus hadrons arises as follows. In the decay $L \to \nu_L$ + hadrons, the hadrons come from a low mass current. If the multiplicity is comparable to that from a virtual photon of the same mass, it will be small. Specific calculations [51] support this conjecture. The leptonic decay of its partner L contributes only one charged track. Inelastic production i.e. $e^+e^- \to L\bar{L}$ + hadrons is negligible. The high multiplicity expected in the decay of a pair of heavy hadrons arises as follows: the weak decay of the new hadron into ordinary hadrons will presumably lead to a multiplicity comparable to that observed in the decay of an ordinary hadron of the same mass i.e. on the average 2 to 3 charged particles plus 2 to 3 photons. From the semileptonic decay of its partner we expect roughly 2 charged particles and 2 photons. At higher energies inelastic production is expected to be dominant, contributing additional hadrons.

Table 4 – Properties of heavy sequential leptons and new hadrons

	L	H
Production	$e^+e^- \to L\bar{L}$ (point cross section) $e^+e^- \to L\bar{L}$ + hadrons (Negligible. Less than α^2 of elastic production)	$e^+e^- \to H^+\bar{H}^-$ (damped by form factor) $e^+e^- \to H\bar{H}$ + hadrons (dominant at higher energies)
Decay modes:	$L \to \ell\, \bar{\nu}_\ell \nu_L$ $\to \nu_L \cdot$ hadrons	$H \to \ell\, \bar{\nu}_\ell$ (suppressed if H has spin = 0) $\to \ell\, \bar{\nu}_e \cdot$ hadrons $\to$ hadrons
Final states:		
eμ + neutrinos	important, clear signature (e(μ) from threebody decay)	negligible (e(μ) from twobody decay)
eμ + neutrinos + hadrons	negligible (order α^2)	large, e(μ) from a multibody decay)
e(μ) + neutrino + hadron	large, lepton spectrum computable and "hard" low multiplicity $<n_{ch}> \sim <n_\gamma> \sim 2\text{-}3$	large, lepton spectrum might be soft high multiplicity $<n_{ch}> \sim <n_\gamma> \sim 4\text{-}6$

1) eμ-events as evidence for a new lepton

As is well known the SLAC-LBL group at SPEAR has found [8] events of the type

$$e^+e^- \to e^\mp\mu^\pm + \text{"nothing"}.$$

These events were selected using the following criteria:

1) Only two charged tracks with opposite charge and no photons.

2) Each track should have a momentum greater than 650 MeV/c.

3) One prong is identified as an electron by the pulseheight in the shower counter, the other as a muon by range. The probability of misidentifying a hadron as an electron or as a muon is respectively 18% or 20%.

4) The coplanarity angle between the planes defined by the electron and the beam direction and the muon and the beam direction must be greater than 20°.

A total of 139 events produced at cms energies between 3.8 GeV and 7.8 GeV satisfied these criteria with an estimated background of 34 events. The signal of 105 events is statistically significant and might represent the production and decay of new particles. To verify the production of new particles and to study their properties the SLAC-LBL group has investigated the following features:

1) Threshold behaviour.
2) Angular correlation between the e and the μ.
3) Does the e(μ) result from a threebody or a twobody decay ?
4) Mass of undetected particles.
5) Limits on unseen hadrons accompanying the eμ events.

Their findings are:

1) The cross section plotted in Fig. 17 as a function of energy suggests a threshold for eμ-production at or below 4 GeV. This would seem to limit the mass of the new particle to 2 GeV or less. A stringent mass limit is difficult to derive from these data because of the background and the small number of events observed below 4.4 GeV. The energy dependence of the cross section is consistent with the behaviour expected for a heavy lepton. However, a reasonable fit can also be obtained assuming production of new hadrons.

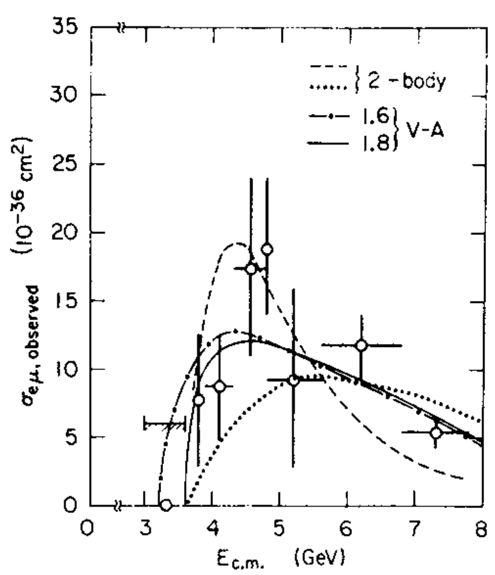


Fig. 17 - The observed cross section for eμ-production, corrected for background. The cross hatched line indicate the 90% confidence upper limit for the background. The solid and dash-dot curves are the expected cross section for the production of heavy leptons of mass 1.6 GeV/c^2 and 1.8 GeV/c^2. The dashed and the dotted curve are for a boson of mass 1.8 GeV with a two-body leptonic decay mode. These latter curves are strongly model dependent.

2) At high cms energies the electron and the muon are preferentially emitted in opposite directions since they result from the decay of heavy particles produced back to back. From the threshold behaviour and the collinearity distribution the SLAC-LBL group determines the mass of the new particles to be between 1.6 GeV/c^2 and 2.0 GeV/c^2.

They argue that the observation of a threshold and the strong angular correlations between the electron and the muon demonstrates that new particles are produced.

3) The observed momentum distribution of the electrons (muons) exclude a two-body decay mode as the sole source. The three-body decay mode required by the data is necessary for a heavy lepton, but might also be the preferred mode for the semileptonic decay of a heavy hadron.

Note that the experimental observations discussed above cannot be used to disentangle the production of a heavy lepton from the production of new hadrons. These possibilities might be separated either by a measurement of the mass of the third particle in the decay or by excluding unobserved hadrons.

4) The electron (muon) spectrum is plotted in Fig. 18 as a function of the normalized momentum

$$\rho = \left(\frac{P - 0.65\ \mathrm{GeV/c}}{P_{max} - 0.65\ \mathrm{GeV/c}} \right).$$

The momentum distribution of the electron (muon) expected from the decay of a heavy particle into 3 particles, two of which are massless, is also plotted as a function of the mass of the third particle. The curves - all except one - are evaluated for a V-A current. A particle with the mass of the neutron is clearly excluded. However, an acceptable fit is obtained if the third particle has a mass of 0.5 GeV or less.

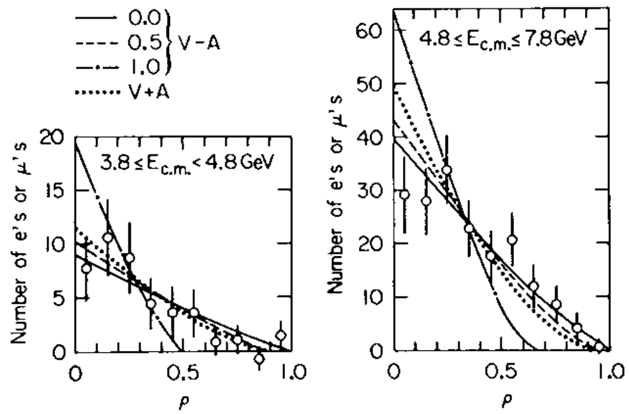


Fig. 18 - The electron and the muons plotted as a function of the normalized momentum ρ The solid, the dashed and the dashed-dotted curve show the distribution expected from the (V-A) decay of a lepton with mass 1.8 GeV for various values of the neutrino mass. The dotted curves are for a massless neutrino, and a (V+A) current.

5) The SLAC-LBL group has made a careful evaluation of the possibility that the eμ events are accompanied by undetected hadrons. They conclude with 90% confidence that no more than 39% of all the eμ-events can contain additional charged particles or photons.

They argue that if the eμ events are to be explained by a single source they must arise from the production and the leptonic decay of a new sequential lepton. From the observed eμ cross section and the production cross section for a pair of point particles with a mass of 1.8 GeV/c^2 they find

$$BR\ (U \rightarrow \nu_U\ \ell\ \bar{\nu}_\ell) \ = \ (0.17\ {}^{+\,0.06}_{-\,0.03}\ )$$

This was derived assuming equal decay rates to the e and the μ modes, V-A coupling and a massless neutrino.

All the data published by the SLAC-LBL group point to a new heavy lepton as the source of the observed eμ-events. However, it seems crucial and prudent to verify such an important discovery by an independent method, for example by a measurement of the hadronic decay modes of the heavy lepton. Such information might be obtained from a measurement of single electrons or muons produced in $e^+e^- \rightarrow U\bar{U} \rightarrow \ell$ + anything. The observed lepton originating in the leptonic or the semileptonic decay of one of the pairproduced new objects is used to tag the event, imposing no constraint on the other member of the pair. Thus heavy leptons and new hadrons might be identified by the momentum distribution of the observed lepton and the observed multiplicity.

2) Inclusive muons and the new lepton

Two groups have submitted results on inclusive muon production in e^+e^- collisions.

The Maryland, Pavia, Princeton group [52] measure the momentum of charged particles with a single arm magnetic spectrometer which is centered at 90° and covers a solid angle of 0.1 sterad. Muons are identified as minimum ionizing particles that penetrate 69 cm of iron. Thus only muons with momenta greater than 1.05 GeV/c are detected. Charged tracks are identified in 99% of 4π with cylindrical proportional chambers surrounding the interaction region. Data collected at 3.8 GeV and 4.8 GeV were divided into two groups according to the observed multiplicity:

$$e^+e^- \rightarrow \mu^\pm + 1 \text{ charged track} + \gamma\text{'s (acoplanarity angle} \geq 20^\circ)$$
$$\rightarrow \mu^\pm + \geq 2 \text{ charged tracks} + \gamma\text{'s.}$$

The data and the estimated background are listed in table 5.

Table 5 - Data on muon inclusive reactions

Energy (GeV)	Group	Luminosity (nb^{-1})	$n_{ch} = 2$ events	background	$n_{ch} \geq 3$ events	background
3.8	MP^2	- a)	3	1.3	4	2.4
4.8	MP^2	3840	13	4	2	5.3
4.0-4.45	PLUTO	957	98	87	43	36

a) No luminosity quoted.

Only in the two prong events at 4.8 GeV is a significant signal observed. Here 13 events are observed as compared to 4 estimated background events, one from punch through and decay, and 3 from $e^+e^- \rightarrow \mu\,\mu\,\gamma$. The resulting cross section assuming an isotropic angular distribution of the muon is listed in table 6.

The DESY, Hamburg, Siegen and Wuppertal collaboration has measured inclusive muon spectra [15] using the superconducting solenoid PLUTO [22]. The magnetic field, parallel to the beam axis, has a strength of 2 Tesla in a field volume 1.05 m long and 1.4 m in diameter. Charged tracks are measured over 86% of 4π using the information from 14 cylindrical proportional chambers. Lead converters with thicknesses 0.44 and 1.7 of a radiation length respectively, are inserted at radii of 37.5 and 59.4 cm. The chambers mounted behind these converters are used for photon and electron identification. Muons are identified in 55% of 4π as charged tracks penetrating at least 65 cm of iron. This corresponds to a cut-off momentum of 1.0 GeV/c. Measurements at the J/ψ resonance showed that a hadron with momentum between 1.0 GeV/c and 1.5 GeV/c is misidentified as a muon with a probability of (3.5 ± 0.5)%.

Data were collected between 4.0 GeV and 4.45 GeV with 75% of the data between 4.0 GeV and 4.2 GeV. The events were divided into two groups according to multiplicity. The results are also summarized in table 5.

In the multiprong class ($n \geq 3$) 43 events were found. A background of 29 events was estimated from the number of charged tracks pointing towards the muon identifiers. Processes of the type $e^+e^- \rightarrow e^+e^-\gamma \rightarrow \psi'\gamma$ followed by $\psi' \rightarrow J/\psi$ anything $\rightarrow \mu^+\mu^-$ anything can account for 7 events. After background subtractions (7 ± 7) events remain. The 90% confidence upper limit on the total cross section is listed in table 6 assuming the muons to be isotropic.

The two prong events were selected as follows:

1) at least one track with a momentum greater than 1.0 GeV/c penetrating the iron and firing a muon chamber
2) acoplanarity angle greater than 18^{o}
3) the two tracks should have opposite charge
4) no restriction on the number of photons.

A total of 98 events satisfying these criteria were found including four candidates for eμ-events. A background of 87 events was estimated from misidentified hadrons and radiative muon pairs of the type $e^+e^- \rightarrow \mu^+\mu^-\gamma$. The bulk of the background, 75 events, were of the latter type and was determined experimentally. The number of such events and their distributions are in good agreement with theoretical predictions. After excluding 4 eμ-candidates there remain (7 ± 6) events of the type μ + hadron + (photons). The 90% confidence upper limit is listed in table 6 again assuming an isotropic distribution.

Table 6 - Cross section for muon inclusive reactions

Group	Energy (GeV)	L (nb^{-1})	σ(n = 2) (pb)	σ(n ≥ 3) (pb)
MP^2	4.8	3840	$(285 {+151 \atop -113})$	< 95
PLUTO	4.0-4.45	957	< 80	< 70

The branching ratio for the decay $L \rightarrow \mu\, \bar{\nu}_\mu\, \nu_L$ can be extracted from the events observed by the MPP group assuming they originate in the decay of a heavy lepton. Using the point cross section for the production and neglecting the decay into final states with more than two charged prongs they find:

$$\frac{L \rightarrow \mu\, \bar{\nu}_\mu . \nu}{L \rightarrow \text{all}} = 0.20 {+0.10 \atop -0.08} .$$

The negative result found by the PLUTO group might be used to set a lower limit on the mass of a heavy lepton. The 90% confidence limits quoted in table 6 correspond to the cross section expected from the production of a point lepton with mass of 1.95 GeV and a 17% branching ratio into muons.

The results of the PLUTO group and the MP^2-group can also be compared directly neglecting the difference in energy. Accounting for the trigger efficiency, the luminosity and the solid angle for muon detection we find that PLUTO should observe a factor of 7.2 more events than the MP^2 experiment. This is in good agreement with the experimental results of 98 events versus 13 events observed in the two experiments. However, there seems to be a discrepancy in the number of radiative muon pairs. PLUTO's 75 μμγ events scale down to 10.4 for MP^2, compared to 3 events estimated by the MP^2 group. This discrepancy cannot be accounted for by the difference in energy or other parameters.

From the present muon inclusive data there is no convincing evidence for the production of a new heavy lepton. However, this might easily be due to lack of statistics in the case of the MP^2 experiment and to a threshold effect in the case of PLUTO.

3) $e^+e^- \rightarrow e^\pm X$ and new hadrons

Using the double arm spectrometer at DORIS the DASP collaboration (Aachen, DESY, Hamburg, MPI-München, and Tokyo) has observed [25,53] final states containing electron and hadrons.

The DASP detector [24] consists of two identical magnetic spectrometer arms which are positioned symmetrically with respect to the interaction point and covers a solid angle of 0.9 sr. A large aperture non-magnetic detector, capable of identifying electrons, photons and hadrons is mounted between the arms of the spectrometer. Electrons passing through the arms of the spectrometer were identified independently by a signal from a threshold Cerenkov counter mounted before the magnet and the pulse height in the shower counters mounted in the rear.

An electron event was defined as follows:

1) A minimum ionizing particle with momentum greater than 200 MeV/c originating at the interaction point.
2) The particle fired the Cerenkov counter.
3) The particle produced a large pulse height in the shower counter, consistent with that of a showering particle.
4) At least one additional particle was observed in the inner detector which did not cause a shower.

Data were collected at energies between 3.6 GeV and 4.414 GeV as listed in table 7. The events were classified by multiplicity depending on whether the total number of charged tracks (including the electron) plus photons was greater than 3 or not.

The results are listed in table 7.

Table 7 - Data on electron inclusive reactions

Energy (GeV)	luminosity (nb^{-1})	number of events $n \leq 3$	$n \geq 4$
3.6-3.68	266	2	1
$\psi(3.68)$	54	2	3
4.0-4.2	670	6	22
$\psi(4.414)$	450	4	7

The following sources for background events were considered:

1) Dalitz decays of $\pi^0(\eta^0)$ or pair conversions of photons.
2) Hadrons mislabeled as electrons.
3) Beam-gas interactions.
4) Compton scattering in the material mounted before the Cerenkov counters.
5) Semileptonic decays of pions and kaons.
6) $e^+e^- \rightarrow e^+e^- +$ hadrons.
7) Cascade decay through an intermediate state.

Of the 28 events observed between 4.0 GeV and 4.2 GeV at most 7 events can be accounted for by these sources, whereas the number of events observed be-

low 3.68 GeV are consistent with background only. The DASP group therefore conclude that they have observed the production of a new particle which can only decay via the weak interactions. From the observed threshold behaviour they conclude that the mass of the new particle must be between 1.8 GeV and 2.0 GeV.

It is not possible to ascribe all the observed events to the decay of pairs of heavy sequential leptons. In Fig. 19 the spectrum of the number of detected particle tracks per event is plotted. The distribution peaks at 5 tracks per event and only six events have multiplicity less than four. For comparison the result of a Monte Carlo calculation for a heavy lepton as seen by the DASP detector is shown in Fig. 20.

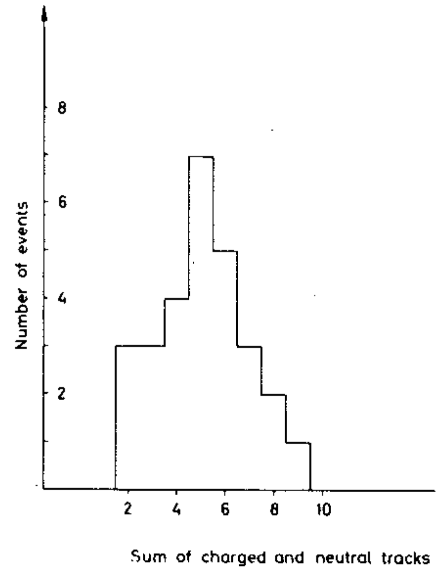


Fig. 19 - Number of tracks per event in the reaction $e^+e^- \rightarrow e^- +$ minimum ionizing track + anything observed by the DASP group above 4.0 GeV. The electron and the minimum ionizing track count as tracks.

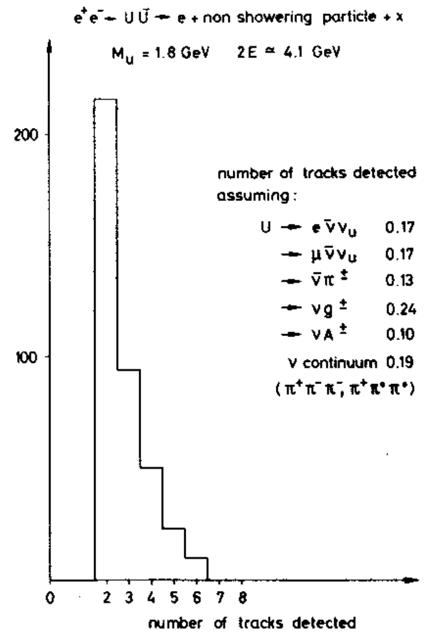


Fig. 20 - The number of tracks per event predicted from the decay of a pair of heavy leptons for the trigger conditions defined in the text.

Additional evidence comes from the momentum spectrum of the electrons. The acceptance corrected momentum spectrum for events with $n \geq 4$ is plotted in Fig. 21. Note that the spectrum is very soft with no events having electrons with momenta above 700 MeV/c. For comparison the expected distributions for electrons resulting from the (V-A) decay of a heavy lepton of mass 1.9 GeV assuming a massless neutrino is shown as the dashed curve. The distribution is clearly inconsistent with the data. If the computed curve is normalized to the events observed with electron momenta below 700 MeV/c it predicts 28 events with electron momenta above 700 MeV/c where none is seen.

The DASP group therefore excludes a heavy sequential lepton as the sole source of the events. Both the soft electron spectrum and the large multiplicity associated with the events is expected to occur in the decay of new heavy hadrons. Therefore the most likely interpretation of the data is that the bulk of the events come from the semileptonic decay mode of a hadron with a new quantum number which is respected by the strong and the electromagnetic interaction. It seems reasonable to associate these hadrons with the narrow states recently observed [9,10] at SPEAR.

The relative cross section for the production of inclusive electron events with large multiplicities ($n \geq 4$) is plotted in Fig. 22 as a function of energy.

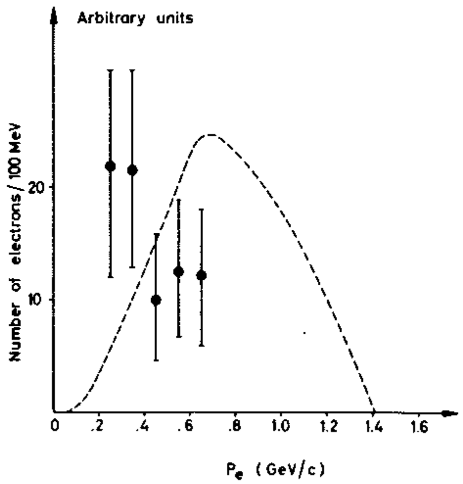


Fig. 21 - Acceptence corrected electron momentum distribution for events with 4 or more tracks. The curve was calculated for a leptonic decay of a heavy lepton of mass 1.9 GeV assuming a massless neutrino and a (V-A) current. The curve is normalized to the events observed between 0.2 GeV/c and 0.7 GeV/c.

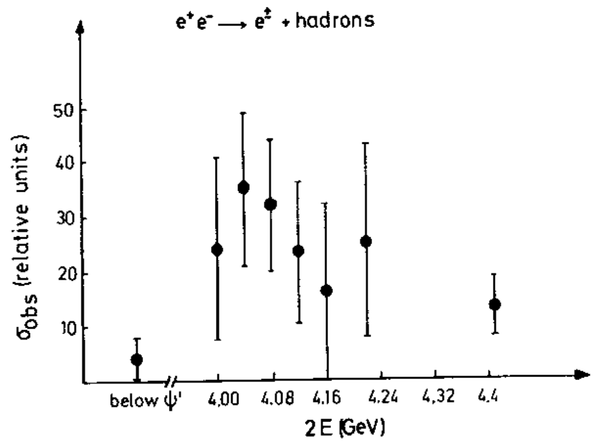


Fig. 22 - The observed cross section for electron inclusive events with large multiplicities are plotted as a function of the cms energy.

Note that the threshold for producing these new particles coincides with the step observed in the total cross section around 4 GeV. Averaged over the 4.0 - 4.2 GeV region DASP quotes a lower limit on the production of inclusive electrons and hadrons:

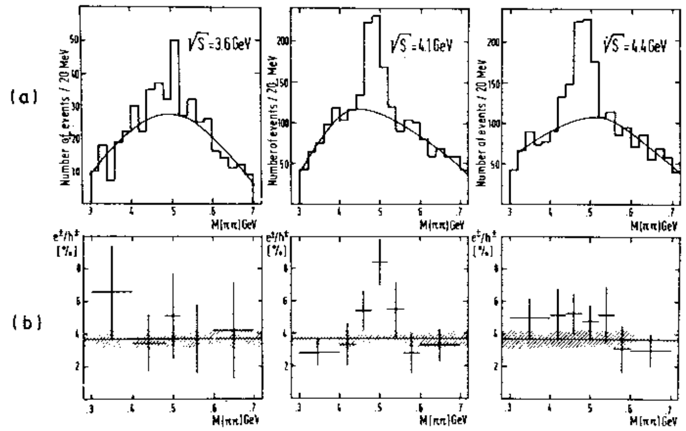
$$\sigma(e^+e^- \rightarrow e^\pm + \text{hadrons}) \quad = \quad 2B(H \rightarrow e^\pm + X)\cdot(e^+e^- \rightarrow H\bar{H}) > 1 \text{ nb}.$$

Decays of the type observed by DASP group may not have been seen by the Maryland, Pavia, Princeton group or by the PLUTO group because of the high cut off momenta required for the detection of a muon.

4) Ke correlations

According to the quark model, the new hadrons are combinations of an old and a new quark. If the new quark is indeed the charmed quark then one expects in the semileptonic decays of these hadrons to find a strong correlation between kaons and electrons but not between electrons and pions.

The PLUTO group [54] has observed correlations between electrons and neutral kaons. The K^o_s were identified by the decay $K^o_s \rightarrow \pi^+\pi^-$. A search for K^o_s was made in the multihadron events by computing the effective mass of oppositely charged tracks originating at a minimum distance of 5 mm (geometrical average) from the interaction point. The reconstructed momentum vector of the parent particle had to point towards the interaction point. Effective $\pi^+\pi^-$ mass distributions were obtained at 3.6 GeV, 4.1 GeV and 4.4 GeV and the results are plotted in Fig. 23a. A clear K_s^o signal is seen at all three energies.



Fi. 23a - Invariant mass spectra for selected $\pi^+\pi^-$ pairs obtained by the PLUTO group for three different cms energies. The background is indicated by the solid lines.

Fig. 23b - $e^{\pm}$/hadron ratio for the $\pi^+\pi^-$ pairs shown above. The shaded area shows the estimated background.

The $\pi^+\pi^-$ events so selected were then examined for electrons. The electrons were defined as charged tracks with a momentum greater than 0.3 GeV/c originating at the interaction point and producing a shower after penetrating a radiator, 1.7 of a radiation length thick. Data obtained at the J/ψ resonance show that with this definition a hadron has less than a 3% chance to be misidentified as an electron. Confusing a hadron with an electron will lead to an apparant K_s^o e correlation proportional to the number of $\pi^+\pi^-$ pairs observed.

The result of the search is shown in Fig. 23b. Plotted is the number of $(e^{\pm}\pi^+\pi^-)$ events, normalized to the number of hadron tracks within the electron

acceptance, as a function of the $\pi^+\pi^-$ effective mass. Between 4.0 GeV and 4.3 GeV a clear enhancement is observed at the mass of the K_s^o. This demonstrates the existence of a strong eK_s^o correlation in this energy range. Note the absence of a clear K_s^oe signal at 4.4 GeV.

The visible cross section for K_s^oe production is plotted in Fig. 24 as a function of cms energy. This cross section was obtained by using events with $.46 < m_{\pi\pi} < 0.54$ GeV/c^2. The cross section shows a sharp peak around 4.05 GeV. After background subtraction and correction for acceptence, branching ratio and unobserved K_L^o mesons they find $\sigma(e^+e^- \to e\ K^o + \text{anything}) = 3$ nb with a systematic uncertainty of a factor of two. Such a strong K_s^oe correlation suggests that the observed events result from the decay of a charmed meson. An average charged multiplicity of 2.5 extra tracks are found in the K_s^oe events. The electrons have in general momenta below 700 MeV/c. Both observations are in agreement with the properties of the electron inclusive events observed by the DASP group.

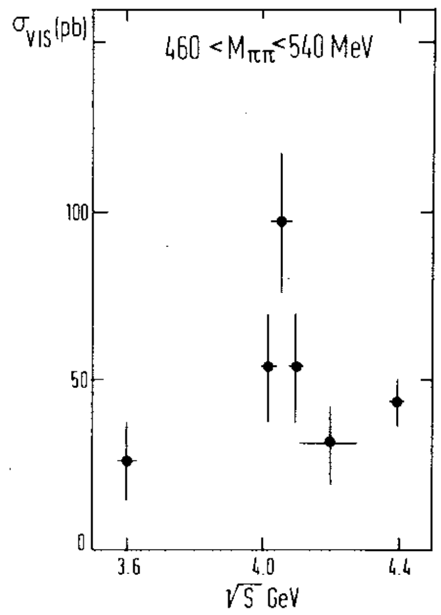


Fig. 24 - The visible cross section for K_s^oe-production versus cms energy. Note that the background is not subtracted.

The DASP group has searched for correlations between charged particles and electrons. Pions and kaons with momenta between 0.5 GeV/c and 1.3 GeV/c passing through the spectrometer were identified by time of flight. Electrons with energies above 0.25 GeV were identified by their showers in the inner detector. Preliminary results obtained on $(\pi^{\pm}e)$ correlations are shown in Fig. 25a. Plotted is the number of $(\pi^{\pm}e)$ events normalized to the number of charged pions passing through the spectrometer as a function of energy. The events observed below the ψ'-mass are a measure of the background from electron misidentifications in the inner detector.

The $\pi^{\pm}e$ yield observed above 4 GeV is larger than this background indicating the production of genuine $\pi^{\pm}e$ events. The dashed line shows the $\pi^{\pm}e$ yield expected if the electrons and the pions were uncorrelated. This was estimated as $\sigma(e^+e^- \to e + \text{anything}) / \sigma(e^+e^- \to \text{hadrons}) \cdot$ (number of charged pions passing through the acceptance of the spectrometer).

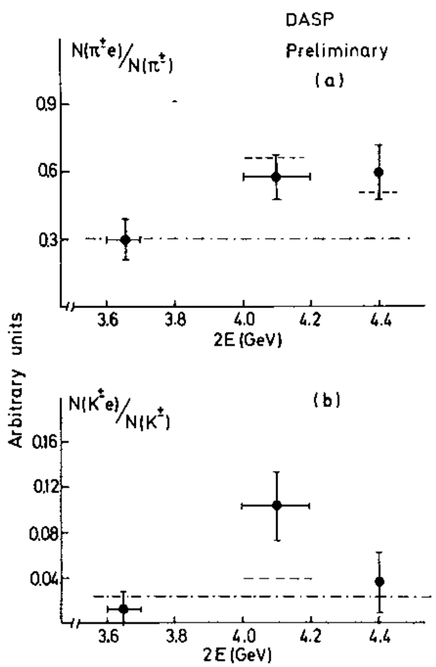


Fig. 25 a)Number of events with pions and electrons normalized to the events with pions as a function of energy. The pions were identified using the outer detector, the electrons by their showers using the inner detector.

Fig. 25 b - The same plot as above for kaons.

The observed $(K^{\pm}e)$ yield is plotted in Fig.25b. The dashed-dotted line indicates the background due to misidentifications and the dashed line the uncorrelated cross section. Between 4.0 and 4.2 GeV there seems to be a genuine correlation - i.e. requiring an electron in the inner detector enhances the probability of finding a charged kaon in the spectrometer. Note that this is only a two standard deviation effect and more data are needed. However, it is just the behaviour predicted by the charm model [3,4] and agrees with the finding of the PLUTO group for the $(K^oe^{\pm})$ correlations. No $K^{\pm}e$ correlation is observed at 4.414 GeV in agreement with the observation of the PLUTO group. If these results are confirmed they show that the

$\psi(4.414)$ is at least partly decaying into particles not directly related to the new hadrons observed between 4.0 GeV and 4.2 GeV.

Conclusion

All the data now available on new hadrons observed in e^+e^- collisions can be explained [53] by introducing a new heavy quark with properties similar to those conjectured by S.L.Glashow, J.Iliopoulos and L.Maiani for the charmed quark.

Acknowledgement

My thanks are due to the scientific secretaries Drs. Ya.I.Azimov, I.V.Bogulavsky, V.A.Khoze, Y.G.Serbo and S.I.Serednyakov for many discussions and for their efforts in making my stay a pleasent one.
I'm also grateful to Drs. D.L.Kreinick and T.Walsh and to Profs. H.Meyer and E.Lohrmann for discussions and help during the writing of this talk.

References:

1) For reviews of the experimental status at the end of 1975 see the Proceedings of the 7th International Symposium on Lepton and Photon Interactions at High Energies. Stanford, USA, August 21-27, 1975

2) J.E.Augustin et al., Phys.Rev.Lett. 34, 764 (1975)
J.Siegrist et al., Phys.Rev.Lett. 36, 700 (1975)

3) Y.Hara, Phys.Rev. B 134, 701 (1964)
J.D.Bjorken and S.L.Glashow, Phys.Lett. 11, 255 (1964)

4) S.L.Glashow, J.Iliopoulos and L.Maiani, Phys.Rev. D2, 1285 (1970)

5) S.L.Glashow and A.DeRujula, Phys.Rev.Lett. 34, 46 (1975)
T.Appelquist et al., Phys.Rev.Lett. 34, 365 (1975)
E.Eichten et al., Phys.Rev.Lett. 34, 369 (1975)

6) For an excellent review of the expected properties of the new particles see M.K.Gaillard, B.W.Lee and J.L.Rosner, Rev.Mod.Phys. 47, 277 (1975)

7) W.Braunschweig et al., Phys.Lett. 57B, 407 (1975)
G.J.Feldman et al., Phys.Rev.Lett 35, 821 (1975)

8) M.L.Perl, Phys.Rev.Lett. 35, 1489 (1975)
M.L.Perl, Phys.Lett. 63B, 466 (1976)

9) R.Schwitters in the Proceedings of the 18th International Conference on High Energy Physics . Tbilisi, USSR, July 15-21, 1976

10) G.Goldhaber et al., Phys.Rev.Lett. 37, 255 (1976)
I.Peruzzi et al., Phys.Rev.Lett. 37, 569 (1976)
F.M.Pierre et al., Contribution to the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976

11) A similar table has been prepared by G.Feldman for the SLAC Summer Institute on Particle Physics - August 2-13, 1976

12) A.M.Boyarski et al., Phys.Rev.Lett. 34, 1357 (1975)

13) W.Braunschweig et al., Phys.Lett. 63B, 487 (1975)

14) B.Jean-Marie et al., Phys.Rev.Lett. 36, 291 (1976)

15) J.Burmester et al., Contribution to the 18th International Conference on High Energy Physics, Tbilisi USSR, July 15-21, 1976

16) W.Bartel et al., Contribution to the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976

17) G.Feldman, private communication

18) F.Vannucci et al., SLAC-PUB-1724 (1976)

19) F.Vannucci et al., to be published

20) G.S.Abrams in the Proceedings of the 7th International Symposium on Lepton and Photon Interactions at High Energies, Stanford, USA, August 21-27, 1975

21) G.Goldhaber, LBL report LBL-4884 (1976)

22) L.Criegee et al., DESY report 75/32 (1975)

23) I.Peruzzi and M.Piccolo et al., to be published

24) B.H.Wiik in the Proceedings of the 7th International Symposium on Lepton and Photon Interactions at High Energies, Stanford, USA, August 21-27, 1975

25) Data from the DASP collaboration, H.U.Martyn, Contribution to the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976

26) W.Bartel et al., DESY-report 76/40

27) D.H.Badtke et al., Contribution to the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976
W.Vernon, private communication

28) V.Lüth et al., Phys.Rev.Lett. 35, 1124 (1975)

29) G.S.Abrams et al., Phys.Rev.Lett. 34, 1181, 1975

30) J.S.Whitaker, W.Tannenbaum et al., to be published.

31) W.Tannenbaum et al., Phys.Rev.Letters 36, 402 (1976)

32) F.M.Pierre, Contribution to the 18th International Conference on High energy Physics, Tbilisi, USSR, July 15-21, 1976
G.H.Trilling et al., to be published

33) E.B.Hughes et al., Phys.Rev.Lett. 36, 76 (1976)

34) T.Appelquist and H.D.Politzer, Phys.Rev.Lett. 34, 43 (1975)

35) V.Gupta and R.Kögerler, Phys.Lett. 56B, 473, (1975)
F.Gilman - Invited paper to the VI International Conference on High Energy Physics and Nuclear Structure, Santa Fe, New Mexico, June 9-13, 1975 - AIP Conference Proceedings No. 26, 33, 1975

36) J.Heintze in the Proceedings of the 7th International Symposium on Lepton and Photon Interactions at High Energies, Stanford, USA, August 21-27, 1975

37) H.Fritzsch and P.Minkowski - Nuovo Cimento 30A, 393 (1975)
E.Pelaquier and F.M.Renard, Nuovo Cimento 32A, 421 (1976)

38) F.A.Berends and R.Gastman, Nucl.Phys. B 61, 414 (1973)

39) T.F.Walsh, Nuovo Cimento Lett. 14, 290 (1975)
R.N.Cahn and M.S.Chanowitz, Phys.Lett. 59B, 277 (1975)
J.Ellis, Schladming Lectures 1975, CERN TH 1996, 1975
A.Kazi, G.Kramer and D.H.Schiller, Nuovo Cimento Lett. 15, 120 (1976)

40) H.Harari, Phys.Lett. 60B, 172 (1976)

41) S.Okubo, Phys.Lett. 5, 105 (1963)
G.Zweig, CERN report TH 401, 412(1964) unpublished
J.Iizuka, K.Okada and O.Shito, Prog.Theo.Phys. 35, 1061 (1966)

42) J.Pumplin, W.Repko and A.Sato, Phys.Rev.Lett. 35, 1538 (1975)
H.J.Schnitzer, Phys.Rev.Lett, 35, 1540 (1975)
H.J.Schnitzer, Phys.Rev. D13, 74 (1976)

43) W.Tannenbaum et al., Phys.Rev.Lett. 35, 1323 (1975)

44) L.S.Brown and R.N.Cahn, Phys.Rev. D13, 1195 (1976)
G.Karl, S.Meshkov and J.L.Rosner, Phys.Rev.D 13, 1203 (1976)
P.K.Kabir and A.J.G.Hey, Phys.Rev. D 13, 3161 (1976)
H.B.Thacker and P.Hoyer, LBL report LBL-4606

45) M.S.Chanowitz and F.J.Gilman, SLAC-PUB 1746, 1976

46) R.Barbieri, R.Gatto and R.Kögerler, Phys.Lett. 60B, 183 (1976)
E.Eichten et al., Phys.Rev.Lett. 36, 500 (1976)

47) A.B.Henriques, B.H.Kellett, R.G.Moorhouse, Phys.Lett. 64B, 85 (1976)

48) H.J.Schnitzer, Preprint Brandeis University, Waltham, Massachusetts 02159, July 1976

49) H.Harari, CERN Preprint TH-2222

50) D.Badtke et al., Contribution to the 18th International Conference on High Energy Physics, Tbilisi, 15-21 July 1976 (Post deadline paper)

51) Y.S.Tsai, Phys.Rev.D4, 2821 (1971)
J.D.Bjorken and C.H.Llewellyn-Smith, Phys.Rev.D7, 887 (1973)
K.Fujikawa and N.Kawamoto - DESY Preprint 76/01
K.J.F.Gaemers and R.Raito - SLAC-PUB-1727 (1976)

For a niece discussion on the properties of heavy leptons and how to observe them in e^+e^- collisions see
Ya.I.Azimov, L.L.Frankfurt and V.A.Khoze, Leningrad Nuclear Physics Institute, Preprint 245, June 1976

52) M.Cavalli-Sforza et al., Phys.Rev.Lett. 36, 558 (1976)
T.L.Atwood et al., Contribution to the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976

53) W.Braunschweig et al., Phys.Lett. 64 B, 471 (1976)

54) J.Burmester et al., DESY report 76/50

55) A.De Rujula in the Proceedings of the 18th International Conference on High Energy Physics, Tbilisi, USSR, July 15-21, 1976