SLAC-PUB-1659
LBL-4293
September 1975
(T/E)

RADIATIVE DECAYS OF THE ψ(3684) TO NEW HIGH MASS STATES*

G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G. J. Feldman, C. E. Friedberg, G. Goldhaber, G. Hanson, D. L. Hartill†, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke††, B. A. Lulu, V. Lüth, H. L. Lynch, C. C. Morehouse, J. M. Paterson, M. L. Perl, F. M. Pierre, T. P. Pun, P. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci, J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, California 94720

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Presented by W. Tanenbaum

ABSTRACT

We present experimental evidence for the existence of the decay $\psi(3684)\to\gamma\chi$, $\chi\to 4\pi^{\pm}$, $\pi^+\pi^-$, K^+K^-, and also $\gamma\psi(3095)$. There is clear evidence for at least two χ states decaying to hadrons, one at 3.41 ± 0.01 GeV and the other at 3.53 ± 0.02 GeV. The $\chi(3410)$ decays into $\pi\pi$ and KK and thus must have even spin and parity. There is also evidence for one state decaying to $\psi\gamma$ at a mass of either 3.50 ± 0.01 GeV or 3.27 ± 0.01 GeV. The data, taken together, indicate the existence of at least three χ states.

We present evidence for the existence of new high mass even-C states.[1] These states are observed in the decay sequence $\psi(3684)\to\gamma\chi$, $\chi\to4\pi^{\pm}$, $\pi^+\pi^-$, K^+K^-, and $\gamma\psi(3095)$.[2] There is clear evidence for at least three χ states. One of these states has been observed by the DASP Collaboration.[3] The existence of several even-C states in the mass region between the $\psi(3095)$ ($\equiv\psi$) and the $\psi(3684)$ ($\equiv\psi'$) has been suggested theoretically by many authors.[4] The data are obtained from approximately 100,000 ψ' decays measured in the SLAC-LBL magnetic detector at SPEAR.[5]

<u>$\chi\to4\pi^{\pm}$</u>. We select events with four charged particles detected of total charge zero. Events of the form $\psi'\to\pi^+\pi^-\psi$, $\psi\to e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-\pi^0$ are eliminated by requiring that the mass recoiling against the low momentum $\pi^+\pi^-$ pair be less than 2.95 GeV. The residual contamination from such events is less than 10%; such events should not preferentially populate any particular mass region.

Assuming that all the charged particles are pions, we can calculate the missing mass squared, m_X^2, distribution corresponding to $\psi'\to4\pi^{\pm}+x$, and compare to that of $\psi\to4\pi^{\pm}+x$. In ψ decays, the band of events near $m_X^2\approx0$ extends over the entire range of p_X, whereas in ψ' decays these events cluster primarily in the region $0.1<p_X<0.3$ GeV/c. In addition, the m_X^2 distribution in ψ' decay peaks at zero, while in ψ decays it peaks at the π^0 mass. From the absence of any large π^0 contribution for events with $p_X>0.3$ GeV/c and the assumption that the π^0 momentum distribution in $4\pi^{\pm}\pi^0$ is similar at ψ' to that

*Supported by the U.S. Energy Research and Development Administration.
†Alfred P. Sloan Fellow.
††Fellow of Deutsche Forschungsgemeinschaft.
(Presented at the Annual Meeting of the Division of Particles and Fields, American Physical Society, Seattle, Washington, August 27-29, 1975.)

at ψ, we estimate that only 15 ± 8 $4\pi^{\pm}\pi^{0}$ events contribute to the 96 ψ' decays with $-0.03 < m_X^2 < 0.03$ GeV^2.

The mass distribution of the 4π events with $|m_X^2| < 0.03$ GeV^2, calculated with the constraint that $m_X^2 = 0$, is shown in Fig. 1a. The rms mass resolution is estimated to be about 0.025 GeV. There is clear evidence for at least two states, one at 3.41 ± 0.01 GeV and the other at 3.53 ± 0.02 GeV.

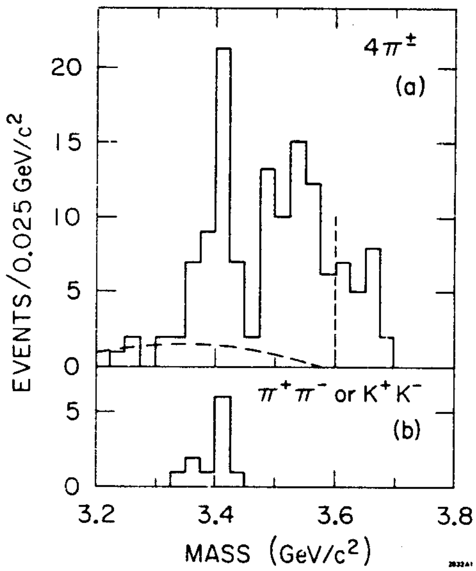

Fig. 1. Invariant mass distributions after applying the constraint $m_X^2 = 0$ for the modes (a) $4\pi^{\pm}$, and (b) the sum of $\pi^+\pi^-$ and K^+K^-. No missing momentum cut has been made. Events above 3.60 GeV in (a) are mainly events having no missing neutral and thus were fitted to the wrong hypothesis. The dashed line is the estimated background from $4\pi^{\pm}\pi^{0}$.

<u>$\chi \to \pi^+\pi^-$ and $\chi \to K^+K^-$</u>. We search for these reactions by looking at events with two prongs. The major potential background is $\psi(3684) \to e^+e^-\gamma$ or $\mu^+\mu^-\gamma$. To eliminate electron pairs we require that both particles pass through the active areas of the shower counters and give low pulse heights in these counters. This requirement gives a rejection of 5×10^{-5} against electron pairs. We similarly require that both particles point towards an active area of the muon spark chambers and fail to penetrate the 20 cm iron hadron filter. This yields a rejection of 7×10^{-4} against muon pairs.

We require that $|m_X^2| < 0.1$ GeV^2 for either the $\pi\pi$ or $K\bar{K}$ hypothesis. Fifteen events were found, four of which had two or more photons detected in the shower counters and were thus inconsistent with $\psi(3684) \to \gamma\pi\pi$ or γKK. With our m_X^2 rms resolution of 0.04 GeV^2, it is not possible to distinguish which is the proper hypothesis for every event. However, the most likely hypothesis for each event is about equally divided between the two possibilities and it is quite improbable that they are all pion pairs or all kaon pairs. There are no events at $m_X^2 \approx 0$ and $p_X \approx 0$ where we expect 0.9 event background from $\psi' \to e^+e^-$ or $\mu^+\mu^-$.

The pair mass for the remaining eleven events after applying the constraint $m_X^2 = 0$ and using the most likely mass hypothesis is shown in Fig. 1b. The background from $ee\gamma$ and $\mu\mu\gamma$ is estimated to be less than 0.05 events. The events cluster at 3.40 ± 0.01 GeV with an rms width of 0.022 GeV consistent with our expected resolution.

<u>$P_c \to \gamma\psi$</u>. The ψ is detected by its decay into two muons. We require the observed dimuon to have a mass squared between 8.8 GeV^2 and 10.4 GeV^2, and then constrain the dimuon mass to be equal to the ψ mass to improve our resolution. Events without (with) additional observed charged tracks are called two-prong (multiprong) events.

We first search for photons in two-prong events by observing signals in the shower counters without an associated charged track. We consider only events with exactly two detected photons. The crude photon positional information twice overconstrains $\psi' \to \psi\gamma\gamma$. We discard all events that have a

χ^2/d.o.f. > 2. We require the missing mass squared recoiling against the dimuon system to be less than 0.27 GeV^2 to eliminate $\psi' \rightarrow \psi\eta$ events. By studying events with ≥ 3 photons, a pure sample $\psi' \rightarrow \psi\pi^0\pi^0$ events, and comparing with the two photon events, we determine that the 51 surviving events have a $\pi^0\pi^0$ contamination of less than 10%.

When we reconstruct the masses of intermediate states, we have a two-fold ambiguity since we do not know which photon is emitted in the first decay. Figure 2 shows both solutions, with each event plotted twice. The two solutions for a given event are approximately symmetric around a mean of about 3380 MeV. The dashed curve represents the phase space distribution for direct $\psi' \rightarrow \psi\gamma\gamma$ decay with no intermediate state. The solid curve is the predicted distribution for a narrow intermediate state of mass either 3270 MeV or 3500 MeV. The rms mass resolution for both the data and the Monte Carlo is 35 MeV. The solid curve includes the expected contribution of the $\pi^0\pi^0$ background, shown separately as the dotted curve. The data suggest a state of mass 3.27 ± 0.01 GeV or 3.50 ± 0.01 GeV.

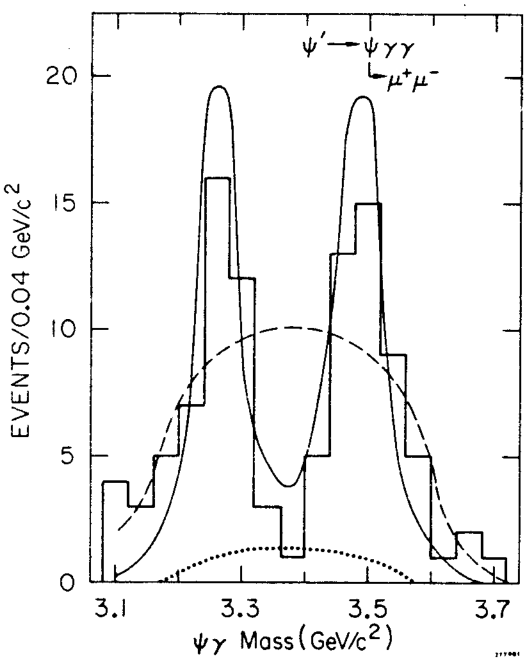

Fig. 2. The reconstructed mass of intermediate states in $\psi' \rightarrow \psi\gamma\gamma$. The smooth curves are explained in the text.

We can obtain better mass resolution by detecting photons in a different manner. We detect events where a photon has converted either in the beam vacuum pipe or in the surrounding ~0.03 radiation length scintillation counters. We find 11 dimuon events that have an additional oppositely charged pair with an opening angle of less than 10 degrees. The $\pi\pi$ opening angle from $\psi' \rightarrow \psi\pi^+\pi^-$ is so strongly peaked at large angles that the background from pion pairs is negligible. We remove events where the converted photon comes from final state radiation by one of the muons by eliminating those two events where the converted pair is collinear with one of the muons. The efficiency for converting and detecting photons of a given energy is negligible below 170 MeV, 0.25% at 200 MeV, 0.9% at 300 MeV, and 1.2% at 400 MeV.

From the nine events remaining, we select the eight with missing mass squared in the interval -0.02 to +0.02 GeV^2 as $\psi' \rightarrow \psi\gamma\gamma$. There is a relative absence of detected photon conversions from $\psi' \rightarrow \psi\pi^0\pi^0$ because the typical photon from this decay has an energy of 150 MeV, too small to be detected. Four of the eight events have an extra shower counter that fired, presumably from the missing photon. In all four cases, the reconstructed missing photon points to the correct counter. Only one of the eight events fits the hypothesis $\psi' \rightarrow \psi\eta$; $\eta \rightarrow \gamma\gamma$, and it is discarded.

We perform a 1-C fit on the remaining seven events and calculate the masses of intermediate states. As before, there is an ambiguity from not knowing which photon is emitted in the first decay. Figure 5 shows the two solutions for each event. The clustering indicates the presence of an intermediate state with a mass of 3.283 ± 0.01 or 3.504 ± 0.008 GeV, consistent with our resolution for a narrow state.

Branching fractions. We have estimated branching fractions $B_f = \psi' \to \gamma\chi;\ \chi \to f/\psi' \to$ all for each of the χ states. The results are given in Table I.

Conclusions. We have presented evidence for the existence of at least two χ states decaying to hadrons. In the case of the 4π decay modes there is strong evidence that the χ's are formed by the radiative decay of the $\psi(3684)$. All the other channels are consistent with this hypothesis. One of the χ's is at a mass of 3.41 ± 0.01 GeV and the other is at a mass of 3.53 ± 0.02 GeV. In the $4\pi^{\pm}$ decay mode the $\chi(3530)$ appears wider than the $\chi(3410)$, and wider than what we would expect from our estimated mass resolution. This suggests the possibility that this state may be broad or consist of two or more unresolved states.

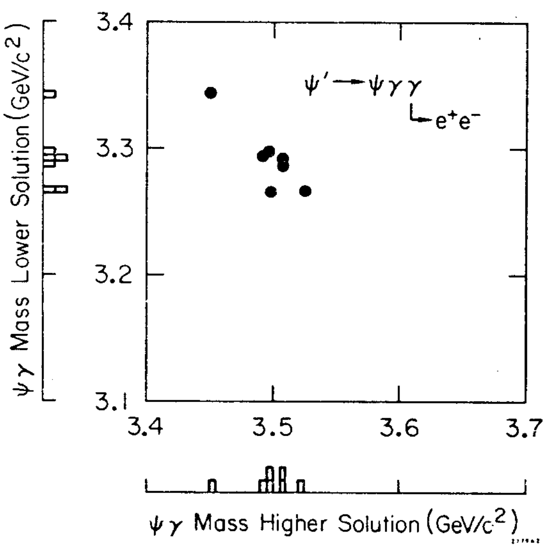

Fig. 3. Scatterplot of the two solutions for the mass of intermediate states in $\psi' \to \psi\gamma\gamma$ events with a converted photon.

Table I Branching fractions in percent

f	$\chi(3410)$	$\chi(3530)$	P_c
$4\pi^{\pm}$	0.14 ± 0.07	0.20 ± 0.10	?
$6\pi^{\pm}$	~ 0.1	~ 0.2	?
$\pi^+\pi^-K^+K^-$	~ 0.07	~ 0.05	?
$\pi^+\pi^-$ or K^+K^-	0.13 ± 0.05	< 0.027	< 0.027
$\gamma\psi$	< 0.5	?	3.6 ± 0.7

We have observed $\psi' \to P_c\gamma;\ P_c \to \psi\gamma$, where the state P_c has a mass of either 3.50 ± 0.01 or 3.27 ± 0.01 GeV. It seems natural to identify the P_c with the $\chi(3530)$. However a single narrow state of mass 3.50 ± 0.01 GeV/c^2 is not easily reconciled with the broad $\chi(3530)$. This comparison further suggests that either the $\chi(3530)$ is a broad state or is composed of at least two states, only one of which decays significantly to $\gamma\psi$. In either case, there must be at least three χ states. If the correct mass of the P_c is 3270 MeV there must still exist at least three χ states with only the P_c decaying significantly to $\gamma\psi$.

All χ states must have C=+1 since the $\psi(3684)$ has been shown to have C=−1.[6] The $\chi(3410)$ must be an even spin and parity state since it decays into two pseudoscalars. Most theoretical models[4] would assign it to the spin-parity state $J^{PC}=0^{++}$ or 2^{++}.

We wish to thank F. Gilman for his invaluable contributions.

REFERENCES

1. We have previously submitted these results for publication. See G. J. Feldman, B. Jean-Marie, B. Sadoulet, F. Vannucci et al., Phys. Rev. Letters 35, 821 (1975); and W. Tanenbaum, J. S. Whitaker et al., SLAC-PUB-1644, LBL-4253, submitted to Phys. Rev. Letters.
2. The χ decay modes $6\pi^{\pm}$ and $\pi^+\pi^-K^+K^-$ have also been reported by us in Ref. 1.
3. W. Braunschweig et al., Phys. Letters 57B, 407 (1975). We use χ as a generic name for new states which are radiatively coupled to ψ particles, reserving the name P_c, suggested by the DASP Collaboration, for the state which has been identified to have a major decay mode into $\gamma\psi(3095)$.
4. T. Appelquist et al., Phys. Rev. Letters 34, 365 (1975); E. Eichten et al., Phys. Rev. Letters 34, 369 (1975).
5. J.-E. Augustin et al., Phys. Rev. Letters 34, 233 (1975).
6. V. Lüth, A. M. Boyarski, H. L. Lynch et al., SLAC-PUB-1617, LBL-4211 (1975), submitted to Phys. Rev. Letters.