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$\psi(3684)$ Radiative Decays to High-Mass States*

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We present experimental evidence for the existence of the decay $\psi(3684)\to\gamma\chi$, $\chi\to 4\pi^\pm$, $6\pi^\pm$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-$, and K^+K^-. There is clear evidence for at least two χ states, one at 3.41 ± 0.01 GeV/c^2 and the other at 3.53 ± 0.02 GeV/c^2. The $\chi(3410)$ decays into $\pi\pi$ and KK and thus must have even spin and parity.

We present evidence for the existence of new high-mass even-C states. These states are observed in the decay sequence $\psi(3684)\to\gamma\chi$, $\chi\to 4\pi^\pm$, $6\pi^\pm$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-$, and K^+K^-. There is clear evidence for at least two χ states. One of these states may be the one reported by Braunschweig *et al.*[1,2] The existence of several even-C states in the mass region between the $\psi(3095)$ and the $\psi(3684)$ has been suggested theoretically by many authors.[3]

$\chi\to 4\pi^\pm$.—The data are obtained from approximately 100 000 $\psi(3684)$ decays measured in the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at SPEAR.[4] To search for $\chi\to 4\pi^\pm$, we select events detected with four charged particles of total charge zero. Events of the form $\psi(3684)\to\pi^+\pi^-\psi(3095)$, $\psi(3095)\to e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-\pi^0$[5] are eliminated by requiring that the mass recoiling against the low-momentum $\pi^+\pi^-$ pair be less than 2.95 GeV/c^2. We estimate that 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 distribution of the square of the missing mass, m_x^2, corresponding to $\psi(3684)\to 4\pi^\pm+x$. Figure 1(a) is a scatter plot of this distribution versus the missing momentum, p_x. Figure 1(b) shows the same quantities for the reaction $\psi(3095)\to 4\pi^\pm+x$. In $\psi(3095)$ decays, the band of events near $m_x^2\approx 0$ extends over the entire range of p_x, whereas in $\psi(3684)$ decays these events cluster primarily in the region $0.1<p_x<0.3$ GeV/c. In Figs. 2(a) and 2(b) the events from Figs. 1(a) and 1(b) in the range $0.1<p_x<0.3$ GeV/c have been projected on the m_x^2 axis. The comparisons between Figs. 2(a) and 2(b), and between the data in these figures and the resolution functions predicted by Monte Carlo simulations, lead us to the conclusion that the missing particle in this p_x region is predominately a π^0 in $\psi(3095)$ decays while it is predominately a γ in $\psi(3684)$ decays.

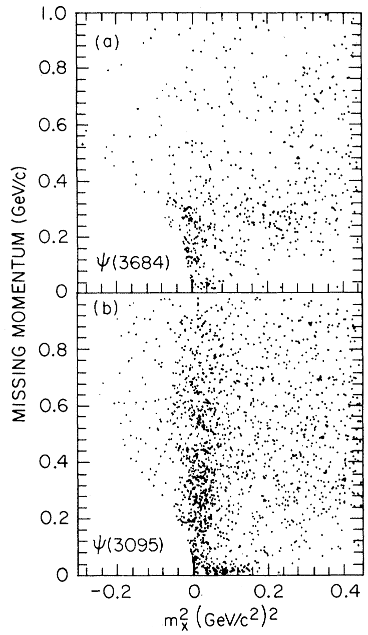

FIG. 1. Scatter plots of missing momentum versus square of the missing mass for four-prong events in (a) $\psi(3684)$ decays and (b) $\psi(3095)$ decays.

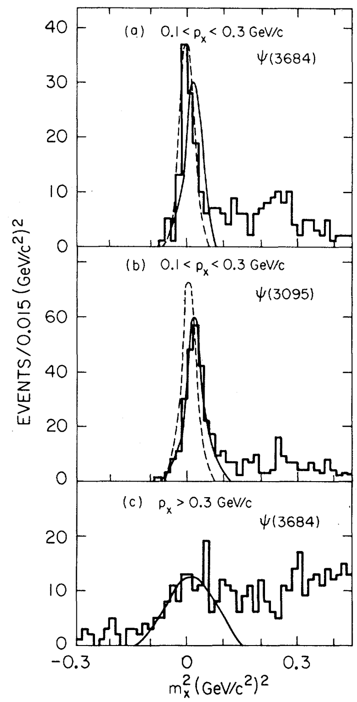

FIG. 2. The square of the missing mass for four-prong events. (a) $\psi(3684)$ decays with $0.1 < p_x < 0.3$ GeV/c. (b) $\psi(3095)$ decays with $0.1 < p_x < 0.3$ GeV/c. (c) $\psi(3684)$ decays with $p_x > 0.3$ GeV/c. The solid and dashed lines give the predicted resolution functions for a missing π^0 and γ, respectively.

In Fig. 2(c) the events from Fig. 1(a) with $p_x > 0.3$ GeV/c are plotted versus m_x^2 along with the π^0 mass resolution predicted by a Monte Carlo simulation.[6] From the absence of any large π^0 contribution in Fig. 2(c) and the assumption that the π^0 momentum distribution in $4\pi^\pm\pi^0$ is similar at $\psi(3684)$ to that at $\psi(3095)$, we estimate that only 15 ± 8 $4\pi^\pm\pi^0$ events contribute to the 96 events shown in Fig. 2(a) with $-0.03 < m_x^2 < 0.03$ (GeV/$c^2)^2$.

The mass distribution of the $4\pi^\pm$ events with $|m_x^2| < 0.03$ (GeV/$c^2)^2$, calculated with the constraint that $m_x^2 = 0$, is shown in Fig. 3(a). [Since the constrained fit required that $m_{4\pi} \leq m_{\psi(3684)}$, events corresponding to $\psi(3684) \to 4\pi^\pm$ lie between about 3.60 and 3.684 GeV/c^2.] The rms mass resolution is estimated to be about 0.025 GeV/c^2. There is clear evidence for at least two states, one at 3.41 ± 0.01 GeV/c^2 and the other at 3.53 ± 0.02 GeV/c^2.[7]

$\chi \to 6\pi^\pm$.—A similar analysis has been performed with six-prong events. Again an accumulation is found at low missing momentum. Although the statistics are low, the mass spectrum of Fig. 3(b) is consistent with the behavior observed with 4π.

$\chi \to \pi^+\pi^-K^+K^-$.—To study this reaction it is necessary to use both kinematic fitting and time-of-flight information to distinguish kaons from pions. The invariant mass of $\pi^+\pi^-K^+K^-$ with $-0.03 < m_x^2 < 0.03$ (GeV/$c^2)^2$ is shown in Fig. 3(c). The structures in this figure are similar to those observed in the multipion decays. The enhancement just below the mass of the $\psi(3684)$ is interpreted as $\psi(3684) \to \pi^+\pi^-K^+K^-$.

$\chi \to \pi^+\pi^-$ *and* $\chi \to K^+K^-$.—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.

The square of the missing mass was calculated for all two-prong events which satisfied the above

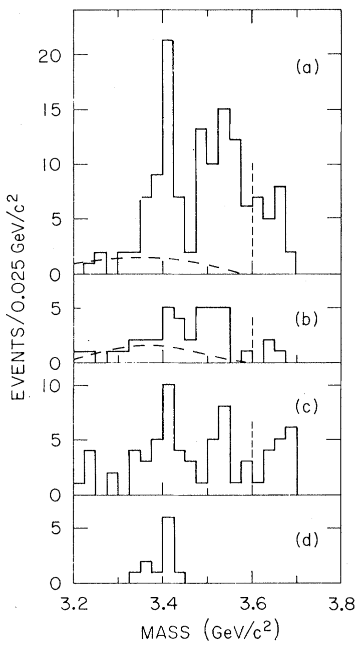

FIG. 3. Invariant-mass distributions after applying the constraint $m_x^2=0$ for the modes (a) $4\pi^\pm$, (b) $6\pi^\pm$, (c) $\pi^+\pi^-K^+K^-$, and (d) the sum of $\pi^+\pi^-$ and K^+K^-. No missing-momentum cut has been made. Events above 3.60-GeV/c^2 in (a)–(c) are mainly events having no missing neutral and thus were fitted by the wrong hypothesis. The dashed line is the estimated background from (a) $4\pi^\pm\pi^0$ and (b) $6\pi^\pm\pi^0$.

requirements. Figure 4 shows a scatter plot of p_x versus m_x^2 for both the $\pi\pi$ and KK hypotheses for events with $|m_x^2|<0.1$ (GeV/c^2)^2 for either hypothesis. Fifteen events were found, four of which (shown with dashed lines) had two or more photons detected in the shower counters and were thus inconsistent with the hypothesis $\psi(3684)\to\gamma\pi\pi$ or γKK. With our m_x^2 rms resolution of 0.4 (GeV/c^2)^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 $m_x^2\approx0$ and $p_x\approx0$ where we expect 0.9-event background from $\psi(3684)\to e^+e^-$ or $\mu^+\mu^-$.[8]

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. 3(d). 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/c^2 with an rms width of 0.022

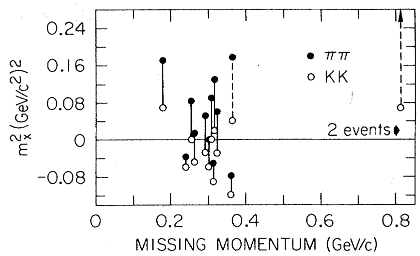

FIG. 4. Scatter plot of missing momentum versus square of the missing mass for two-prong events calculated for both the $\pi\pi$ and KK hypothesis. Events with a dashed line (including both events which are off the right-hand side of the graph) contain evidence of two missing photons.

GeV/c^2 consistent with our expected resolution.

Branching fractions.—We have estimated branching fractions,

$$B_f=\frac{\psi(3684)\to\gamma\chi,\chi\to f}{\psi(3684)\to\text{all}},$$

for each of the two χ states. $B_{4\pi^\pm}$, $B_{6\pi^\pm}$, and $B_{\pi^+\pi^-K^+K^-}$ are of order 10^{-3} for each χ state. The sum of $B_{\pi^+\pi^-}$ and $B_{K^+K^-}$ is $(0.13\pm0.05)\%$ for the $\chi(3410)$ and has a 90%-confidence-level upper limit of 0.027% for the $\chi(3530)$.

In conclusion, we have presented evidence for the existence of at least two χ states. 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/c^2 and the other is at a mass of 3.53 ± 0.02 GeV/c^2. 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.

All χ states must have $C=+1$ since the $\psi(3684)$ has been shown to have $C=-1$.[9] The $\chi(3410)$ must be an even spin-and-parity state since it decays into two pseudoscalars. Most theoretical models[3] would assign it to the spin-and-parity state $J^{PC}=0^{++}$ or 2^{++}.

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[1]W. Braunschweig *et al.*, Phys. Lett. 57B, 407 (1975).

[2]We use χ as a generic name for new states which are radiatively coupled to ψ particles, reserving the name P_c, suggested by W. Braunschweig *et al.*, for the state which has been identified to have a major decay mode into $\gamma\psi(3095)$ (see Ref. 1). There is currently a twofold ambiguity in the determination of the P_c mass (3.52 or 3.26 GeV/c^2). The 3.53 GeV/c^2 state found here may or may not be the same as P_c.

[3]C. G. Callan *et al.*, Phys. Rev. Lett. 34, 52 (1975); T. Appelquist *et al.*, Phys. Rev. Lett. 34, 365 (1975); E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975); B. J. Harrington *et al.*, Phys. Rev. Lett. 34, 706 (1975); O. W. Greenberg, University of Maryland Technical Report No. 76-012, 1975 (unpublished); also see O. W. Greenberg, University of Maryland Technical Report No. 75-064, 1975 (unpublished), and references therein.

[4]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[5]G. S. Abrams *et al.*, Phys. Rev. Lett. 34, 1181 (1975); A. M. Boyarski *et al.*, Phys. Rev. Lett. 34, 1357 (1975); V. Lüth *et al.*, SLAC Report No. SLAC-PUB-1599, 1975 (unpublished), and Lawrence Berkeley Laboratory Report No. LBL-3897, 1975 (unpublished).

[6]In this region, the resolution of the square of the missing mass is approximately proportional to the missing energy. Hence the resolution shown for a missing π^0 is much broader in Fig. 2(c) than in Fig. 2(a).

[7]For the reasons discussed in Ref. 6 the reliability of separation of γ's from π^0's is somewhat less at 3.41 than at 3.53 GeV/c^2. However there is an additional argument to show that we are observing $\psi(3864) \rightarrow \gamma\chi(3410)$ rather than $\psi(3684) \rightarrow \pi^0\chi(3410)$. If the latter were to proceed through an interaction which conserves isospin, then the decays $\psi(3684) \rightarrow \pi^+\chi^-$ and $\pi^-\chi^+$ would occur at an equal rate. They are not observed at the level of 0.7 of the expected rate.

[8]From the absence of events in this region we can set upper limits on the branching fraction for the decays $\psi(3684) \rightarrow \pi^+\pi^-$ and $\psi(3684) \rightarrow K^+K^-$ at 1.9×10^{-4} and 2.3×10^{-4}, respectively, at the 90% confidence level.

[9]V. Lüth *et al.*, SLAC Report No. SLAC-PUB-1617, 1975 (unpublished), and Lawrence Berkeley Laboratory Report No. LBL-4211, 1975 (unpublished).

Search for Structure in the γ-Ray Spectra from $\bar{p}d$ and $\bar{p}p$ Annihilations at Rest*†

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The γ-ray spectra from annihilations at rest have been measured with a 10-in.×10-in.-diam NaI(Tl) detector. The resolution of the system was ~15% for γ-ray energies between 50 and 200 MeV. No clear evidence is found for monoenergetic γ rays with intensities greater than 1 per 30 annihilations.

The possibility of the existence of bound states of the nucleon-antinucleon system has been discussed by many authors.[1] Strong attractive forces between the nucleon and antinucleon could result in binding of several hundred MeV. Such states are expected to be short lived because of the annihilation process; however, the theoretical studies suggest that the widths may be less than several MeV for selected states. Thus "capture γ rays" or interstate γ transitions might compete with annihilation.[2]

In a recent publication,[3] the possible observation of such γ-ray transitions was reported. An incident beam of antiprotons was stopped in a deuterium bubble chamber. Approximately one thousand γ rays from annihilation events, producing pairs in the chamber, were observed and the energy spectrum measured. The observed rate of γ rays was about 25% in excess of that expected from π^0 decay, assuming charge independence in the annihilation process. Furthermore, the data suggested that the spectrum of this excess could be in the form of several narrow lines with energies between 80 and 300 MeV and intensities as large as 3% of the total. There was also some indication that certain lines could be en-