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Measurement of $\gamma\gamma\psi$ Final States in ψ' Decay

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The decay mode $\psi' \to \gamma\gamma\psi$ has been studied with the Mark-II detector at SPEAR. New measurements of branching ratios for decays of the type $\psi' \to \gamma\chi$, $\chi \to \gamma\psi$ involving known χ states are presented. The existence of a χ state of mass near 3455 MeV/c^2 produced in this decay chain is not confirmed, and the upper limit (90% confidence level) of the product of branching ratios is measured to be 0.13%. A new decay mode, $\psi' \to \pi^0\psi$, which violates isospin conservation is observed with branching ratio (0.15 ± 0.06)%.

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The $\gamma\gamma\psi$ final states produced in $\psi'(3684)$ decays have previously been shown to arise from the two processes

$$\psi' \to \gamma\chi, \quad \chi \to \gamma\psi \tag{1}$$

and

$$\psi' \to \psi\eta, \quad \eta \to \gamma\gamma . \tag{2}$$

In addition to clear observations[1-4] of the $\chi(3510)$ and $\chi(3555)$ in Reaction (1), there have been indications of possible contributions from the well-established $\chi(3415)$ and from other candidate charmonium levels at 3455 MeV/c^2 (Refs. 2,4) and 3590 MeV/c^2 (Ref. 3). The $\psi\eta$ final state has been established both through observation[3,4] of Reaction (2) and through study[4,5] of the spectrum of missing mass recoiling against detected ψ.

We present here the results of a new high-statistics study of ψ' decays observed in the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory Mark-II magnetic detector at SPEAR. For this study, the SPEAR energy was set to within ± 0.15 MeV of the peak of the $\psi'(3684)$ resonance; and data were accumulated for approximately six weeks, yielding about 1 000 000 ψ' decays.

The detector has been described elsewhere,[6] and we confine ourselves here to a brief discussion of those elements used in the identification of the $\gamma\gamma\psi$ final state. The ψ was identified through its decay into lepton pairs. These decays triggered the apparatus over approximately 75% of 4π. The lepton momenta were measured with the drift chambers,[7] and the photons were observed in the lead–liquid-argon calorimeters.[8] Candidate events were required to have two oppositely charged particles with invariant mass between 2.8 and 3.4 GeV/c^2 and at least two photons detected in the calorimeter. Photons detected within 0.3 m of a charged track were not used. Events with more than two detected photons were retained because noise in the liquid argon preamplifiers occasionally caused the tracking program to find false photons.

The largest background in this data sample arises from the decay $\psi' \to \pi^0\pi^0\psi$. To reduce this background and improve the mass resolution of the signal, the events satisfying the above criteria have been fitted to the hypothesis $\psi' \to \gamma\gamma\psi$, $\psi \to e^+e^-$ or $\mu^+\mu^-$ with a kinematic fitting program. After removal of events for which the χ^2 confidence level corresponding to this five-constraint fit is less than 0.08, there remain a total of 688 events including an estimated 180 background events.

The $\gamma\gamma$ invariant-mass spectrum is presented in Fig. 1. The dominant sharp peak centered at 547.6 ± 0.2 MeV/c^2 comes from the $\eta\psi$ decay mode [Reaction (2)]. The width of the peak is consistent with the expected mass resolution of ± 1.7 MeV/c^2. Its position has a systematic error of ± 0.8 MeV/c^2 due to the uncertainty in the ψ'-ψ mass difference, and is therefore consistent with the world average η mass[9] of 548.8 ± 0.6 MeV/c^2. The narrow width of the signal results from the kinematic fit which makes precise measurement of the photon energies unnecessary.

The remaining portion of the $\gamma\gamma$ invariant-mass spectrum arises mainly from the χ intermediate states [Reaction (1)] plus the estimated $\pi^0\pi^0\psi$ background shown as the smooth curve in Fig. 1. This background is estimated by a Monte Carlo simulation which has the same momentum and angular distributions as those observed in the $\pi^+\pi^-\psi$ final state. The number of events within the η peak is determined to be 166 ± 14 after subtraction of the small contributions from both Reaction (1) and the $\pi^0\pi^0\psi$ background. This number, combined with a Monte Carlo calculation of the acceptance and with a determination of the total ψ' decay population based on detection of the $\pi^+\pi^-\psi$ final state, gives a branching ratio for Reaction (2) of $2.5 \pm 0.6\%$. The quoted error includes systematic uncertainties to which the primary contribution is the uncertainty in the photon detection efficiency.[9] Our present measurement is somewhat lower than previously reported values,[3-5] but is in good agreement with a recent result from the Crystal Ball Collaboration.[10]

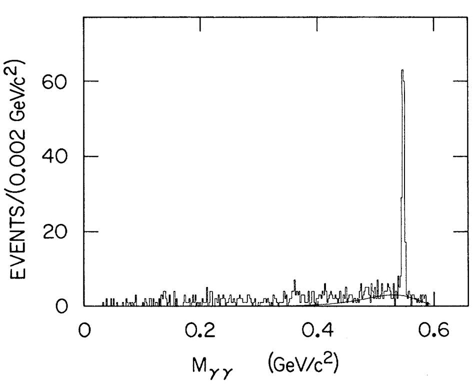

FIG. 1. $\gamma\gamma$ mass distribution. The smooth curve is the background expected from $\psi' \to \pi^0\pi^0\psi$.

For the study of Reaction (1), events in which the $\gamma\gamma$ mass lies between 540 and 556 MeV/c^2 are removed. The two possible values of the $\gamma\psi$ invariant mass for the remaining sample are presented in the scatter plot of Fig. 2. The high-mass projection of these data clearly shows the well-established $\chi(3510)$ and $\chi(3555)$ states. Kinematic reflections of these peaks arising from combination of the ψ with the initially emitted photon dominate the low mass projection.

There is no clear evidence in Fig. 2 for additional intermediate states. The sensitivity decreases rapidly for states of mass greater than 3570 MeV/c^2 because of the steeply falling detection efficiency for photons of energy less than 100 MeV. Previous indications of a state at 3455 MeV/c^2 are not confirmed by these data. There is some suggestion of a signal at 3415 MeV/c^2, but this evidence is not compelling, particularly if one takes account of the fact that the reduction in population for masses less than 3400 MeV/c^2 is in part due to the effect of the scatter plot boundary. For this reason we quote only a branching ratio upper limit for the $\chi(3415)$.

To determine branching ratios, the data of Fig. 2 were fitted by a function describing expected

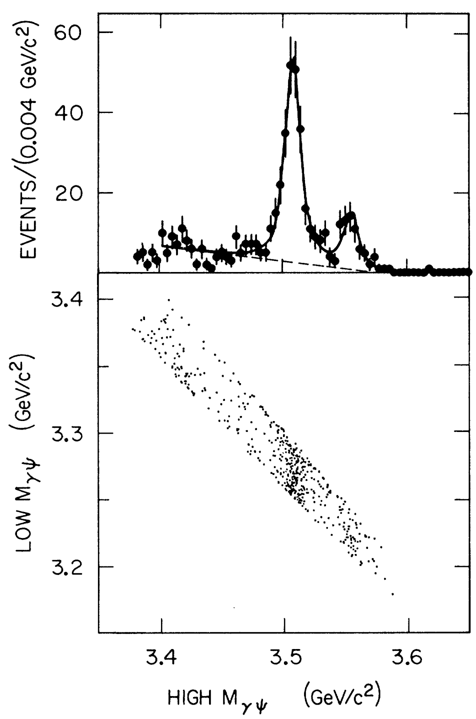

FIG. 2. Scatter plot of the higher $\gamma\psi$ mass vs the lower $\gamma\psi$ mass. The fit is explained in the text.

signals and backgrounds. The shapes of signal peaks were fixed to the resolution function determined by application of the kinematic fitting program to Monte Carlo–simulated events, and only the masses and amplitudes were allowed to vary. The calculated background from $\pi^0\pi^0\psi$ decays is shown by the dashed line in the high-mass projection of Fig. 2. The solid line is the fit to the spectrum including the background and the peaks corresponding to the two observed χ states. The acceptance was calculated by Monte Carlo methods for which the main source of systematic error is as before the uncertainty in the photon detection efficiency. The results of these fits are presented in Table I. Of the two errors given for the masses of the observed χ states the first is the statistical error and the second is the systematic error due to the uncertainties in the ψ and ψ' mass values.[12] Other systematic errors are smaller than the statistical errors. Our branching ratios for the $\chi(3510)$ and $\chi(3555)$ states are in good agreement with the results of other experiments.[2-4,10] Table I also presents branching-ratio upper limits for the well-established $\chi(3415)$ and for a state of mass 3455 MeV/c^2. In the determination of these limits, appropriate side bands are used for the background estimation. The stringent limit (a factor of 6 below the previously reported branching ratio[2]) near 3455 MeV/c^2 implies that there is no compelling evidence for a state in this mass range. Previous experiments have published less stringent upper limits on this branching ratio.[3,4] Recent results from the Crystal Ball Collaboration[10] give even smaller upper limits.

To search for the isospin-nonconserving decay mode $\psi' \to \pi^0\psi$, we have reduced the background in Fig. 1 by removing all events for which the high $\gamma\psi$ mass lies above 3488 MeV/c^2 [which are candidates for Reaction (1)]. The resulting $\gamma\gamma$ mass spectrum, shown in Fig. 3(a), exhibits an enhancement as the π^0 mass. The expected resolution from the kinematic fit for $\gamma\gamma$ mass near the π^0 is expected to be ± 4 MeV/c^2. The background has been further reduced by the imposition of the following four additional cuts. First, only photons with measured energy greater than 140 MeV are used. This cut reduces background from false photons without significantly reducing the π^0 detection efficiency. Second, events for which the azimuthal angle between the directions of the leptons is greater than 178.5° are removed to re-

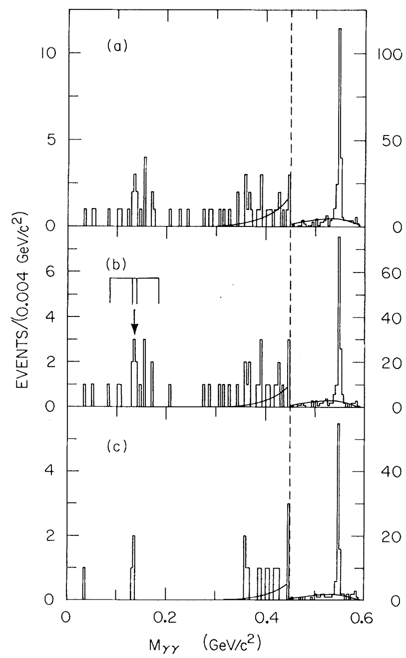

FIG. 3. $\gamma\gamma$ mass distributions with χ events removed. The cuts used for the histograms (a), (b), and (c) are explained in the text. The curve is the expected $\psi\pi^0\pi^0$ background. The three intervals indicated above the histogram (b) are the signal and background regions used for the branching-ratio determination, and the arrow shows the accepted π^0 mass. Note that the η peak is scaled down by a factor of 10.

TABLE I. Branching ratios for the decay $\psi' \to \gamma\chi \to \gamma\gamma\psi$.

Mass (GeV/c^2)	Events	$B(\psi' \to \gamma\chi)B(\chi \to \gamma\psi)$	$B(\chi \to \gamma\psi)$ [a]
3.415	<40	$<5.6\times10^{-3}$(90% C.L.)	<0.08
3.455	<11	$<1.3\times10^{-3}$(90% C.L.)	···
3.5081 ± 0.0006 ± 0.004	254 ± 31	$(2.4\pm0.6)\times10^{-2}$	0.34 ± 0.13
3.555 ± 0.001 ± 0.004	69 ± 11	$(1.1\pm0.3)\times10^{-2}$	0.16 ± 0.06

[a]To obtain the $B(\chi \to \gamma\psi)$ values, we use the $B(\psi' \to \gamma\chi)$ measurements of Biddick *et al.* (Ref. 11), namely, 0.07 ± 0.02 for all three established χ states.

duce background from Bhabha scattering. Third, photons which derive part of their liquid argon signal from a strip also struck by a charged particle are removed. Finally, events with a photon of energy greater than 175 MeV in addition to the two photons used in the kinematic fit are eliminated. The resulting $\gamma\gamma$ mass spectrum presented in Fig. 3(b) shows the same π^0 signal but a somewhat reduced background. There are 7 events in the 12-MeV-wide signal region centered on the π^0 mass. We use 48-MeV-wide control regions on both sides of the π^0 to estimate a background of 1.1 events in the signal region. Our Monte Carlo studies predict a smooth background of 1.1 events in the signal region. Our Monte Carlo studies predict a smooth background shape in the above control regions. The probability that this background could fluctuate to seven or more events is about 2×10^{-4}. Furthermore, the correct position of the π^0 peak resulting from the five-constraint kinematic fit rules out the possibility of missing particles of energy greater than about 25 MeV. In particular, the $\pi^0\pi^0\psi$ decay mode with both photons from one π^0 used is not a background because of the large (> 135 MeV) missing energy. Most of the remaining events in Fig. 3(b) at low $\gamma\gamma$ mass arise from $\chi(3510)$ in the low-mass tail of the peak. Removal of all events for which the high $\gamma\psi$ mass is greater than 3448 MeV/c^2 leads to the $\gamma\gamma$ spectrum shown in Fig. 3(c). Three signal events remain with essentially no background. The branching ratio for the decay mode $\psi' \to \pi^0\psi$ is determined from the data of Fig. 3(b) to be $(0.15 \pm 0.06)\%$. This result is slightly above the previous upper limit of 0.1%,[3] and is 0.06 ± 0.03 of the $\psi' \to \eta\psi$ branching ratio. It agrees within its rather large uncertainty with the Crystal Ball Collaboration result.[10]

Several papers have made theoretical predictions of the $\psi' \to \pi^0\psi$ branching ratio.[13] The calculations involve the mixing of SU(2) and SU(3) eigenstates to form the physical π^0, η, and η' states and consider also the effects of SU(2) and SU(3) symmetry breaking in the decay amplitudes. Recent calculations[14] lead to branching ratio values in the neighborhood of 0.1%, compatible with the results of this experiment.

In summary, we have observed that the $\psi' \to \gamma\gamma\psi$ decay mode is dominated by the intermediate states $\gamma\chi(3510)$, $\gamma\chi(3555)$, and $\eta\psi$. We have also detected a small but significant contribution from the decay $\psi' \to \pi^0\psi$. We have found no evidence for any χ state of mass in the vicinity of 3455 MeV/c^2.

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[9]We also include in all quoted branching-ratio errors the uncertainty in our determination of the total number of ψ' decays. We take the branching ratio for the $\pi^+\pi^-\psi$ decay mode on which our normalization is based to be 0.33 ± 0.03.

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[12]The kinematic fits actually determine the quantity $A \equiv [m(\chi) - m(\psi)]/[m(\psi') - m(\psi)]$. The masses $m(\chi)$ quoted in Table I are based on the values $m(\psi') = 3684$ MeV/c^2, $m(\psi) = 3095$ MeV/c^2. For different ψ and ψ' mass values, the appropriate χ mass is obtained by keeping A fixed.

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