Observation of an Intermediate State in ψ(3684) Radiative Cascade Decay*

W. Tanenbaum, J. S. Whitaker, G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, G. J. Feldman, C. E. Friedberg, D. Fryberger, 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, G. H. Trilling, F. Vannucci,‖ F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 15 September 1975)

We present evidence for the existence of an intermediate state observed in the decay sequence $\psi(3684)\to\psi(3095)\gamma\gamma$. The mass of the state is either 3500 ± 10 or 3270 ± 10 MeV. The branching fraction of the sequence is $(3.6\pm0.7)\%$.

Since the discovery of the ψ particles[1] [$\psi(3095)\equiv\psi$ and $\psi(3684)\equiv\psi'$], there has been speculation on the existence of other narrow resonances which are not produced directly from e^+e^- annihilation. Some models[2] have predicted several such states with masses between those of the ψ and ψ'. We have previously presented evidence for the decay $\psi'\to\chi\gamma$ with at least two states χ which decay directly to hadrons.[3] Braunschweig *et al.* have recently observed the radiative cascade decay $\psi'\to P_c\gamma; P_c\to\psi\gamma$.[4] We here present evidence for this decay, confirming that observation, and we present a measurement of the branching fraction.

Our results come from the study of about 100 000 ψ' decays observed with the Stanford Linear Accelerator Center (SLAC)–Lawrence Berkeley Laboratory magnetic detector at the SLAC storage ring SPEAR.[5] The decay $\psi'\to\psi\gamma\gamma$ has been studied in three ways. In all approaches the ψ is detected by its decay into two muons, but the photon identification differs. In the first, the two photons are observed in the shower counters. In the second, one of the photons converts to an e^+e^- pair, allowing a one-constraint (1-C) fit to the event with better photon energy resolution than in method 1. In the third, the photons are not observed, but the two-photon branching fraction is deduced from a spectrum of the square of the missing mass (M_x^2) recoiling against the dimuon system, with greater precision than from either method 1 or 2.

We require the observed dimuon to have the square of its mass between 8.8 and 10.4 GeV^2,[6] 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. There is about an 8% contamination of the two-prong sample from the radiative tail of $\psi'\to\mu^+\mu^-$.

In the first approach described above, we search for photons in two-prong events by observing signals in the shower counters without an associated charged track. Signals in adjacent counters are considered to be from the same photon. Figure 1(a) shows M_x^2 as a function of the number of photons observed. For events with

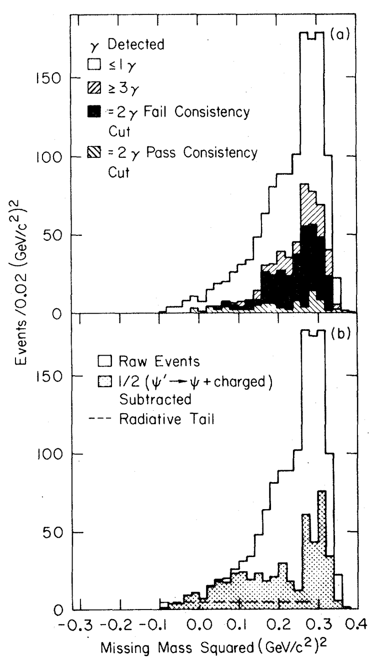

FIG. 1. (a) M_x^2 for two-prong events as a function of number of detected photons. (b) M_x^2 for two-prong events before and after subtraction of $\psi'\to\psi\pi\pi$.

three or more detected photons, the spectrum is consistent with that expected from $\psi' \to \psi\pi^0\pi^0$.[7] For events with no more than one detected photon, there is contamination from the radiative tail of $\psi' \to \mu^+\mu^-$. The dimuon mass constraint causes many of these events to have negative M_x^2. For events with exactly two detected photons, the radiative background is absent. We now use positional information from the shower counters to remove $\psi' \to \psi\pi^0\pi^0$ from the sample with two photons.

The 24 shower counters divide the azimuthal angle into 24 equal bins. The shower counters and associated trigger counters have phototubes at both ends, and the relative pulse heights and/or pulse arrival times provide an rms longitudinal (z) position resolution of 20 cm at a radius of 1.82 m. This crude positional information twice overconstrains $\psi' \to \psi\gamma\gamma$. We reconstruct each event ignoring the z-position information, and compare the measured and reconstructed z positions as a consistency check. We discard all events that have a χ^2 per degree of freedom >2 or that have no physical solutions. Figure 1(a) also shows M_x^2 for the surviving events. The distribution is approximately flat. We require M_x^2 to be less than 0.27 GeV^2 to eliminate $\psi' \to \psi\eta$ events.[8] By studying events with ≥ 3 photons, a pure sample of $\pi^0\pi^0$ 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 twofold 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 $\psi' \to \psi\gamma\gamma$ decay with no intermediate state. The solid curve is the predicted distribution for a narrow intermediate state of mass either 3270 or 3500 MeV. The rms mass resolution for both the data and the Monte Carlo calculation 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 3270 ± 10 or 3500 ± 10 MeV.

In the second approach, we obtain better resolution by detecting events where a photon has converted either in the beam vacuum pipe or in the surrounding ~0.03-radiation-length scintillation counters. We find eleven dimuon events that have

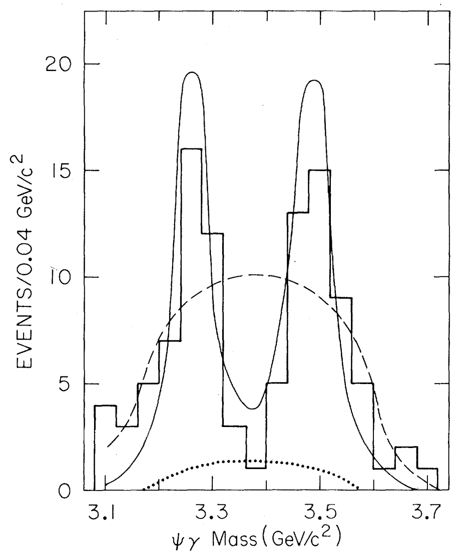

FIG. 2. The reconstructed mass of intermediate states in $\psi' \to \psi\gamma\gamma$. The smooth curves are explained in the text.

an additional oppositely charged pair with an opening angle of less than 10 deg. The $\pi\pi$ opening angle from $\psi' \to \psi\pi^+\pi^-$ is so strongly peaked at large angles[7] that the background from pion pairs is negligible. We remove events where the converted photon comes from final-state radiation from 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 square of missing mass in the interval -0.02 to $+0.02$ GeV^2 as $\psi' \to \psi\gamma\gamma$. There is a relative absence of detected photon conversions from $\psi' \to \psi\pi^0\pi^0$ 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 $\psi' \to \psi\eta, \eta \to \gamma\gamma$,[8] 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 3 shows the two solutions for each event. The clustering indicates the presence of

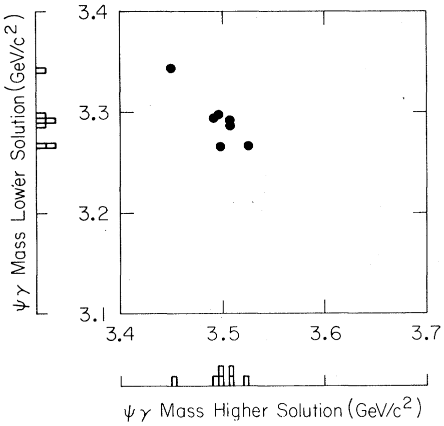

FIG. 3. Scatter plot of the two solutions for the mass of intermediate states in $\psi' \to \psi\gamma\gamma$ events with a converted photon.

an intermediate state with a mass of 3283 ± 10 or 3504 ± 8 MeV, consistent with our resolution for a narrow state.

In the third approach, the $\psi' \to \psi\gamma\gamma$ branching fraction is determined most precisely from M_x^2 for two-prong events, shown in Fig. 1(b). The rms resolution ranges from 0.01 GeV^2 at high M_x^2 to 0.02 GeV^2 at low M_x^2. The events include $\psi' \to \psi\eta$, $\psi' \to \psi\pi\pi$, and the radiative tail of $\psi' \to \mu^+\mu^-$ as background.

We consider only the interval 0.0 to 0.27 GeV^2, thus excluding $\psi' \to \psi\eta$.[8] We determine the spectrum for $\psi' \to \psi\pi^+\pi^-$ from the multiprong events, and we assume that the spectrum for $\psi' \to \psi\pi^0\pi^0$ has the same shape. We further assume that the pions are in an $I = 0$ state,[6] in which case $(\psi' \to \psi\pi^0\pi^0)/(\psi' \to \psi\pi^+\pi^-) = 0.5$. The $\psi' \to \psi\pi\pi$ contribution is then subtracted. The M_x^2 spectrum of the radiative tail of $\psi' \to \mu^+\mu^-$ is flat over the interval considered. Its contribution is determined by observing the interval from -0.09 to -0.01 GeV^2 and then is subtracted. The results are shown in Fig. 1(b). The resultant branching fraction for $\psi' \to \psi\gamma\gamma$ over the square of missing mass range 0.0 to 0.27 GeV^2 is $(3.6 \pm 0.7)\%$.[9,10] If we assume *a priori* that the M_x^2 spectrum for $\psi' \to \psi\gamma\gamma$ is flat, we can, without the $I = 0$ assumption, fit the data by a sum of $\psi' \to \psi\gamma\gamma$ and $\psi' \to \psi\pi\pi$. The branching ratio thus obtained is $(3.4 \pm 0.7)\%$, consistent with that obtained assuming $I = 0$. The branching ratios obtained from the observed events in methods 1 and 2 are also consistent, being $(3 \pm 1.5)\%$ and $(6 \pm 3)\%$, respectively.

We have observed $\psi' \to P_c\gamma, P_c \to \psi\gamma$, where the state P_c has a mass of either 3500 ± 10 or 3270 ± 10 MeV. We have previously observed[3] $\psi' \to \chi\gamma$, $\chi \to$ hadrons, with χ states at 3410 ± 10 and 3530 ± 20 MeV. The absence of $\chi(3410)$ in the radiative cascade decay suggests that for this state the ratio $\Gamma(\chi \to \text{hadrons})/\Gamma(\chi \to \gamma\psi)$ is substantially larger than for the P_c. From the data in Fig. 2, we can put a 90% confidence level upper limit on the product of the branching ratios $\psi' \to \gamma\chi(3410)$, $\chi(3410) \to \gamma\psi$ at 0.5%.

It seems natural to identify the P_c with the $\chi(3530)$ reported in Ref. 3. However, a single state of mass 3500 ± 10 MeV is not easily reconciled with the broad mass spectrum, centered on 3530 MeV, observed[3] in the decay $\chi \to 2\pi^+2\pi^-$. This comparison suggests that the $\chi(3530)$ either 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 $\gamma\psi$.

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

*Work supported by the U. S. Energy Research and Development Administration.

†Alfred P. Sloan Fellow.

‡Fellow of Deutsche Forschungsgemeinschaft.

§Permanent address: Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.

‖Permanent address: Institut de Physique Nucléaire, Orsay, France.

[1] J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[2] T. Appelquist *et al.*, Phys. Rev. Lett. 34, 365 (1975); E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975).

[3] G. J. Feldman *et al.*, Phys. Rev. Lett. 35, 821 (1975). As in this reference, we use χ as a generic name for new C-even states and P_c for the specific state seen decaying into $\psi\gamma$.

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

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

[6] G. S. Abrams *et al.*, Phys. Rev. Lett. 34, 1181 (1975).

[7] J. A. Kadyk *et al.*, LBL Report No. LBL-3687, 1975 (unpublished).

[8] $\psi' \to \psi\eta$ will be discussed in a future paper. The level of $\psi' \to \psi\eta$ background removed is consistent in all three methods.

[9]Assuming the muons are isotropic. For $1+\cos^2\theta$, the result is $(4.2 \pm 0.8)\%$; for $1-\cos^2\theta$, $(2.9 \pm 0.6)\%$.

[10]See J. W. Simpson *et al.*, Phys. Rev. Lett. 35, 699 (1975). This reference sets 99% confidence level upper limits on monochromatic photons from ψ' decay which are at or somewhat above this measured value.

Separation of Compound and Direct Reaction Processes by the Crystal Blocking Technique*

E. P. Kanter, Y. Hashimoto,† I. Leuca, G. M. Temmer, and K. R. Alvar‡
Department of Physics, Rutgers University, New Brunswick, New Jersey 08903

and

W. M. Gibson
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 18 August 1975)

The crystal blocking effect was used to study the time distribution of 5-MeV protons elastically scattered from a germanium crystal. The time delay associated with compound-elastic scattering is estimated and used to separate the direct and compound-nuclear contributions to the elastic cross section.

We have been able to observe directly the time delay associated with compound-elastic scattering (CES) relative to shape-elastic scattering by application of the crystal blocking technique, previously used only for the study of inelastic scattering and compound-nuclear reactions.[1] Briefly, this technique consists of comparing the relative suppression of the yields of charged particles emitted along a crystallographic axis or plane. The angular distribution of such particles measured near an axis will display a characteristic "dip" due to the "shadow" cast by the atomic row. If the scattering is a "prompt" ($\lesssim 10^{-18}$ sec) event, then the emission originates from the normal site of the target nucleus in the crystal lattice. If, however, the projectile "sticks" and the resultant compound nucleus recoils away from this lattice site before re-emission of a charged particle, then the observed dip will be filled in somewhat. Thus longer lifetimes imply shallower dips, there being a one-to-one, monotonically varying correspondence between dip depth (χ_{min}) and the compound-nucleus recoil distance ($v_\perp\tau$) perpendicular to the atomic row. The formulation of a quantitative relationship between the shapes of these axial dips and the actual recoil distance requires detailed computer calculations to take account of such effects as thermal vibrations, multiple scattering, flux peaking, and dechanneling. Such calculations have been carried out for the case studied here by Hashimoto, Barrett, and Gibson,[2] whose work forms the basis for the lifetimes derived in our earlier measurements.[3] It should be noted, however, that the separation of compound and direct processes as outlined below is independent of such calculations.

The most fundamental distinction between direct reaction (DR) processes and the reactions proceeding through a compound nucleus (CN) is that of the time delay involved in the latter. Because this time delay is extremely short ($\sim 10^{-17}$ sec), it had not been possible to make direct measurements; hence the separation of these processes had relied on time-independent measurements such as characteristic angular distributions, and are therefore dependent upon reaction-model calculations. Because the crystal blocking effect is sensitive to events which occur on the time scale of the compound-nucleus period ($h/D \sim 10^{-17}$ sec), it offers a unique opportunity to distinguish reaction mechanisms solely on the basis of time delay. It is the purpose of this Letter to describe such a measurement and to describe the separation into CN and DR processes.

In our experiments[4] a 1.5-μm-thick natural germanium crystal was oriented such that the surface normal $\langle 110\rangle$ crystal axis was directed toward two position-sensitive detectors located at $+35°$ in transmission and at $-145°$ in reflection geometry in the reaction plane (see Fig. 1). Incident proton beams of 4.950, 5.035, and 8.000 MeV, were used, and angular distributions covering $\sim 2°$ near the crystal axis were obtained for the elastically scattered particles. Because both