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## RADIATIVE DECAYS OF $\psi(3095)$ AND $\psi(3684)^{\dagger}$

J. S. Whitaker, W. Tanenbaum, G. S. Abrams, M. S. Alam,
A. M. Boyarski, M. Breidenbach, W. Chinowsky, R. G. DeVoe,
G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber,
G. Hanson, J. A. Jaros, A. D. Johnson, J. A. Kadyk,
R. R. Larsen, D. Lüke,<sup>††</sup> V. Lüth, H. L. Lynch, R. J. Madaras,
C. C. Morehouse,<sup>†††</sup> H. K. Nguyen,<sup>‡</sup> J. M. Paterson, M. L. Perl,
I. Peruzzi,<sup>‡‡</sup> M. Piccolo,<sup>‡‡</sup> F. M. Pierre,<sup>‡‡‡</sup> T. P. Pun, P. Rapidis,
B. Richter, B. Sadoulet,<sup>\*</sup> R. H. Schindler, R. F. Schwitters,
J. Siegrist, G. H. Trilling, F. Vannucci,<sup>\*\*</sup> 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

## ABSTRACT

We present the inclusive photon spectra observed in  $\psi(3095)$ and  $\psi(3684)$  decays. The decay  $\psi(3684) \rightarrow \gamma \chi(3415)$  is observed with a branching fraction of  $0.075 \pm 0.026$ . Evidence is presented for three intermediate states in the decay sequence  $\psi(3684) \rightarrow$  $\gamma \gamma \psi(3095)$  with masses of 3504 MeV, 3543 MeV, and 3455 MeV or 3340 MeV.

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tt Fellow of	Deutsche	Forschungsgemeinschaft.
<sup>†††</sup> Permanent	address:	Varian Associates, Palo Alto, California.
<sup>‡</sup> Permanent	address:	LPNHE, Université Paris VI, Paris, France.
<sup>‡‡</sup> Permanent	address:	Laboratori Nazionali, Frascati (Rome), Italy.
<sup>‡‡‡</sup> Permanent	address:	DPhPE, Centre d'Etudes Nucléaires de Saclay, France.
*Permanent	address:	EP Division, CERN, Geneva, Switzerland.
**Permanent	address:	Institut de Physique Nucléaire, Orsay, France.

States of even charge conjugation intermediate in mass to  $\psi(3095) (\equiv \psi)$ and  $\psi(3684) (\equiv \psi')$  have been observed in radiative decays of  $\psi(3684)$  by their hadronic decays<sup>1,2</sup> and by their decays to  $\gamma\psi$ .<sup>3,4</sup> There is also evidence from DESY for a state below the  $\psi$ .<sup>5</sup> We present here the inclusive photon spectra from 142,000  $\psi$  and 309,000  $\psi'$  events observed in the SLAC-LBL magnetic detector<sup>6</sup> at SPEAR. We also present results on intermediate states in  $\psi' \rightarrow \gamma\gamma\psi$  decays based on a data sample three times larger than for our previous Letter.<sup>3</sup>

Photons are detected by their conversion to electron-positron pairs in material near the interaction region. The effective converter consists of the vacuum pipe, two scintillation counters, and two proportional chambers, a total of 0.052 radiation lengths of material located 8 to 22 cm from the beam axis. The conversion probability for normally incident photons is 0.030 at 0.15 GeV and rises to 0.039 at 2 GeV. The conversion products are tracked through the four-kilogauss magnetic field by the two proportional chambers and by four double-gap spark chambers which cover the full azimuth and from  $50^{\circ}$  to  $130^{\circ}$  in polar angle  $\theta$ . Particles must traverse at least the two inner spark chambers to be detected, implying a minimum transverse momentum per particle of 0.055 GeV/c.

Pairs of oppositely-charged particles with invariant mass (assuming electron masses) smaller than 0.0275 GeV are selected as photon conversions; this cut admits ~ 20% accidental hadronic background (estimated from like-charged pairs). The photon energy is calculated as the sum of the energies of the two particles. Charged particle momentum resolution and energy loss by ionization or radiation after conversion lead to an rms photon energy resolution of 2-4% from 0.2 to 2 GeV. The insert in Fig. la shows the calculated photon detection efficiency  $\epsilon_{\gamma}$  versus energy; conversion probability, detector angular acceptance, and the transverse momentum cutoff are included. An isotropic photon distribution is assumed;  $\epsilon_{\gamma}$  drops by 16% for a  $1 + \cos^2 \theta$  distribution.

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The inclusive photon spectra for  $\psi$  and  $\psi$ ' are presented in Figs. la,b in 4% energy bins. The line in Fig. la is the inclusive photon spectrum obtained from a simple phase space Monte-Carlo model of  $\psi$  events, normalized to the data in the 0.30-0.35 GeV interval. The spectra shapes of the Monte-Carlo results and the data agree well above ~ 0.2 GeV; the Monte-Carlo photon conversion yield per event agrees with the data within the ~ 10% systematic uncertainties of the model.

The  $\psi'$  spectrum shows a > 5 $\sigma$  peak at ~ 260 MeV, having a width consistent with the resolution. The peak position and width are not affected by an increase in the charged particle transverse momentum cutoff, indicating the peak is not shaped by the acceptance. After a correction for mean energy loss by ionization the peak is at 261±10 MeV, corresponding to a state of mass 3413±11 MeV; we identify this as the X(3415) observed in hadronic channels.<sup>1,2</sup>

The branching fraction for the transition  $\psi' \rightarrow \gamma X(3415)$  is calculated as

$$BF = \frac{(\text{No. of signal evts.})/(\epsilon_{\gamma} \cdot RC \cdot \epsilon_{\text{tr}}^{s})}{(\text{No. of total evts.})/\epsilon_{\text{tr}}^{\text{all}}}$$

Here RC, calculated to be ~ 0.8, is a correction for radiative losses,  $\epsilon_{tr}^{all}$  is the average trigger efficiency for all events, and  $\epsilon_{tr}^{s}$  is the trigger efficiency for signal events;  $\epsilon_{tr}^{s}$  is taken to be equal to  $\epsilon_{tr}^{all}$  enhanced by the contribution from the converted photon -- this <u>assumes</u> the X(3415) has multibody decays similar to  $\psi$  or  $\psi'$ . The ratio  $\epsilon_{tr}^{all}/\epsilon_{tr}^{s}$ , determined by counting the fraction of events in which the photon conversion was essential to trigger, is 0.74±0.07. There is a further 7% correction to the branching ratio to account for internal conversions.<sup>7</sup> The branching fraction is 0.063±0.022 for an isotropic photon distribution and 0.075±0.026 for a 1+cos<sup>2</sup>  $\theta$  distribution (which is favored by the data<sup>2</sup>). The 35% relative error is the sum in quadrature of the 17% statistical error and estimated systematic errors of 20%

in the background subtraction, 20% in the photon detection efficiency, 10% in the  $\epsilon_{\rm tr}^{\rm all}/\epsilon_{\rm tr}^{\rm s}$  calculation, and 5% in the radiative correction. This result is in good agreement with the preliminary results of the SPEAR SP-27 collaboration<sup>8</sup> and slightly larger than the upper limits found by the HEPL experiment at SPEAR.<sup>9</sup>

There are no other clear monochromatic signals in the  $\psi$  or  $\psi$ ' spectra above 250 MeV; below 250 MeV the small and rapidly varying photon detection efficiency makes monochromatic signals difficult to observe. Upper limits for monochromatic signals were calculated by replacing the number of signal events in the branching fraction calculation by the excess over the smooth background plus twice the error on the total within the FWHM photon energy resolution; allowing for systematic errors, these should be interpreted as 90% confidence level upper limits. Table I gives upper limits for monochromatic photon lines, separated from other lines by at least the FWHM energy resolution, for representative energies above 250 MeV at  $\psi$  and  $\psi$ '. The question of additional signals in the  $\psi$ ' spectrum is complicated by the Doppler broadening of the photons from intermediate states X, X  $\rightarrow \gamma \psi$ , due to the motion of the X state. The broadening is sufficient to more than double the expected width and to merge together the contributions from the various X states, making the background beneath any possible signal in the 300-400 MeV region difficult to estimate.

Photon conversions enable us to identify  $\psi' \rightarrow \gamma \gamma \psi$  events, where one of the photons converts and the  $\psi$  is detected by its lepton pair decay. The observed lepton pair mass is required to lie between 2.97 and 3.22 GeV and is the constrained to the  $\psi$  mass. Electron pair events are rejected when the angle between the electron and the positron is  $> 177.5^{\circ}$ , eliminating > 95%of the radiative background from  $\psi' \rightarrow e^+e^-$  but only  $\sim 8\%$  of real  $\psi' \rightarrow \gamma \gamma \psi$ ,  $\psi \rightarrow e^+e^-$  events. Radiative events were further reduced by rejecting events if the converted photon was collinear within 10° with one of the leptons; five events were rejected by this cut. Background from  $\psi' \rightarrow \pi^+\pi^-\psi$  where the  $\pi^+\pi^-$ 

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simulate a converted photon is negligible, since the  $\pi^+\pi^-$  mass peaks strongly at large values.<sup>10</sup>

Figure 2 shows the missing-mass-squared,  $M_X^2$ , recoiling against the  $\psi\gamma$ system for the 54 events surviving the selection cuts. There is a peak at zero  $M_X^2$  corresponding to true  $\psi' \rightarrow \gamma\gamma\psi$  events and a broad background from  $\psi' \rightarrow \psi\pi^0\pi^0$  where a photon from a  $\pi^0$  converted. Additional photons may be detected in the shower counters, which cover  $\sim 65\%$  of  $4\pi$  and have resolution of  $\sim 10^0$ in azimuthal angle. The shading in Fig. 2 flags the detection of additional photons: darkly shaded events have a shower counter signal consistent<sup>11</sup> with the missing photon direction assuming a  $\psi\gamma\gamma$  decay, lightly shaded events have no unconverted photons detected, and unshaded events have one or more photons detected in counters inconsistent with the missing photon direction (as expected for  $\psi' \rightarrow \pi^0\pi^0\psi$  events). The high correlation of shading with small  $M_X^2$ corroborates the identification of events with small  $M_X^2$  as  $\psi' \rightarrow \gamma\gamma\psi$  events.

The 27 shaded events with  $-0.03 (\text{GeV/c}^2)^2 < M_X^2 < 0.03 (\text{GeV/c}^2)^2$  are kept. The unconverted photon is detected in 15 of these events, consistent with detector acceptance and efficiency. Six events with missing-mass-squared recoiling against the  $\psi$  greater than 0.27  $(\text{GeV/c}^2)^2$  are removed as possible  $\psi' \rightarrow \psi\eta, \eta \rightarrow \gamma\gamma$  events (four such events are expected). The remaining 21 events are constrained to fit  $\psi' \rightarrow \gamma\gamma\psi$ . There are two values of the  $\psi\gamma$  mass for each event; these are plotted against one another in Fig. 3. The shaded events in Fig. 3 have the unconverted photon detected in the proper counter. The expected background is one event.

There are three main clusters of events in Fig. 3. The mass spread of the high mass projection of each cluster is consistent with the expected rms resolution of  $\sim 8$  MeV; the masses of the three possible states are  $3543 \pm 10$ MeV,  $3504 \pm 10$  MeV, and  $3454 \pm 10$  MeV. The mass spread of the low mass projections of each of the clusters is consistent with the expected Doppler-broadened resolution of ~ 14 MeV; each cluster has a confidence level of  $\leq 0.025$  for the low mass projection assuming the 8 MeV unbroadened resolution. However, the events at 3454 MeV in the high mass projection could be interpreted as a state at 3340 MeV with three events and one background event. The states  $\chi(3545)$  and  $\chi(3505)$  have been observed through hadronic decays<sup>2</sup>; however, there is no evidence in hadronic channels for a state at 3455 MeV or 3340 MeV, and such a state awaits confirmation. Correcting for  $\psi$  branching ratios and photon detection efficiency, we calculate the branching ratio products for  $\psi' \rightarrow \gamma \chi$ ,  $\chi \rightarrow \gamma \psi$  to be  $0.8 \pm 0.4\%$ ,  $2.4 \pm 0.8\%$ , and  $1.0 \pm 0.6\%$  for the  $\chi(3455)$ ,  $\chi(3505)$ , and  $\chi(3545)$  respectively. The single event at 3413 MeV is either from the  $\chi(3415)^{1,2}$  or background. If it is taken as signal, the branching ratio is  $0.2 \pm 0.2\%$ .

In conclusion, the transition  $\psi' \rightarrow \gamma X(3415)$  has been observed in the  $\psi'$  inclusive photon spectrum with branching fraction 0.075±0.026, assuming a  $1 + \cos^2 \theta$  angular distribution. No other monochromatic signals are observed above 250 MeV in the  $\psi$  or  $\psi'$  inclusive photon spectra, with 90% confidence level upper limits of 1 - 4% for the branching fractions. Identifying X(3415) with the  ${}^{3}P_{0}$  charmonium state, the observed branching fraction is a factor of 2 smaller than the prediction of Eichten et al.<sup>12</sup> Also, the 90% confidence level upper limit of ~ 1% for transitions from  $\psi'$  to a state<sup>5</sup> near 2.8 GeV is a factor of four smaller than their prediction if we assume the 2.8 GeV state is the pseudoscalar partner of the  $\psi$ .

From studying the  $\psi\gamma$  masses in  $\psi' \rightarrow \gamma\gamma\psi$  events we find evidence for two states X at 3504 ± 10 MeV and 3543 ± 10 MeV with branching fraction products for  $\psi' \rightarrow \gamma X$ , X  $\rightarrow \gamma \psi$  of 2.4 ± 0.8% and 1.0 ± 0.6% respectively. There is also an indication of a state at 3455 MeV or 3340 MeV with branching fraction product of ~ 0.8%; this state awaits corroboration. The established states at 3415, 3505, and 3545 MeV are candidates for the predicted triplet P wave states of

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charmonium. However, there is serious disagreement between theoretical prediction and experiment for the branching fraction product  $\psi' \rightarrow \gamma \chi(3455)$ ,  $\chi(3455) \rightarrow \gamma \psi$  if the  $\chi(3455)$  is identified with the pseudoscalar partner of the  $\psi'$ .<sup>13</sup> While such issues remain to be resolved, there is now an emerging picture of  $\psi$  and  $\chi$  spectroscopy in qualitative agreement with the charmonium picture.

ψ		ψ <b>"</b>	ψ <sup>†</sup>		
E <sub>γ</sub> (GeV)	Limit	$E_{\gamma}$ (GeV)	Limit		
0.26	0.039	0.40	o.028*		
o. 37	0.038	0,50	0.022		
0.51	0.024	0.74	0.011		
0.80	0.014	1.05	0.010		
1.10	0.008				

Table I. 90% confidence level branching fraction limits for monochromatic photon production above 0.250 GeV at  $\psi$  and  $\psi'.$ 

\*Limit for a narrow peak. See text for a discussion of complications due to the cascade photons.

## FOOTNOTES AND REFERENCES

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## FIGURE CAPTIONS

- Fig. 1. The inclusive photon spectra in 4% bins of the photon energy for (a)  $\psi$ and (b)  $\psi$ '. The smooth curve in (a) is the inclusive photon spectrum from a phase space Monte-Carlo model of  $\psi$  decays, normalized to the data in the region 0.30-0.35 GeV. The insert in (a) shows the photon detection efficiency versus energy.
- Fig. 2. Missing-mass-squared  $M_X^2$  against  $\psi\gamma$ ; the shading is explained in the text.
- Fig. 3. Scatter plot of the two solutions for the mass of intermediate states in  $\psi' \rightarrow \gamma \gamma \psi$  events.









Fig. 3