percent. It is interesting to note that although the general considerations of Ternovskii[7] and Wright[8] suggest that the screening effect may be important,[9] in this experiment for pair energies less than 2 GeV the screening effect is small [see Eq. (1)]. Finally, we emphasize that the inelastic contribution is conspicuously important, accounting for almost one-half of the cross section for direct pair production. In conclusion, direct pair production from 360-GeV/c $\pi^- p$ interactions for pair energies between 40 and 2000 MeV is in good agreement with QED.

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

†Present address: Pfizer Medical Systems, Columbia, Md. 21045.

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$$\gamma \equiv \frac{m_e W}{\alpha E_+ E_-}\left(1+\frac{m_\pi{}^2}{E_1 E_2}\frac{E_+ E_-}{m_e{}^2}\right),$$

with E_1 and E_2 the lab energies of the incoming and outgoing pions. γ is actually the minimum of the quantity $(a_0{}^2 q^2)^{1/2}$ of Eq (2). In our case the minimum value of γ ranges from 9.33 to 0.22.

Radiative Decays of $\psi(3095)$ and $\psi(3684)$†

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,* V. Lüth, H. L. Lynch, R. J. Madaras, C. C. Morehouse,‡ H. K. Nguyen,§ J. M. Paterson, M. L. Perl, I. Peruzzi,¶ M. Piccolo,¶ F. M. Pierre,‖ T. P. Pun, R. Rapidis, B. Richter, B. Sadoulet,** R. H. Schindler, R. F. Schwitters, J. Siegrist, G. H. Trilling, F. Vannucci,†† 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

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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 ± 0.026. Evidence is presented for three intermediate states in the decay sequence $\psi(3684) \rightarrow \gamma\gamma\psi(3095)$ with masses of 3504, 3543, and 3455 or 3340 MeV.

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[1,2] and by their decays to $\gamma\psi$.[3,4] There is also evidence from DESY for a state below the ψ.[5] We present here the inclusive photon spectra from 142 000 ψ and 309 000 ψ' events observed in the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector at SPEAR; the detector and its trigger criteria have been described previously.[6] 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.[3]

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 length of material located 8 to 22 cm from the beam axis. The conversion products are tracked through the 4-kG magnetic field by

the two proportional chambers and by four double-gap spark chambers which cover the full azimuth and from 50° to 130° in polar angle θ. 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 that they are electrons) smaller than 0.0275 GeV are selected as photon conversions; this cut admits an ~20% accidental hadronic background as 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 inset in Fig. 1(a) shows the calculated photon detection efficiency ϵ_γ versus energy, including conversion probability and detector acceptance. An isotropic photon distribution is assumed; ϵ_γ drops by 16% for a $1+\cos^2\theta$ distribution.

The inclusive photon spectra for ψ and ψ' are presented in Figs. 1(a) and 1(b) in 4% energy bins. The line in Fig. 1(a) is the inclusive photon spectrum obtained from a simple phase-space Monte Carlo model of ψ events, normalized to the ψ data in the interval 0.30–0.35 GeV. The spectral 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.

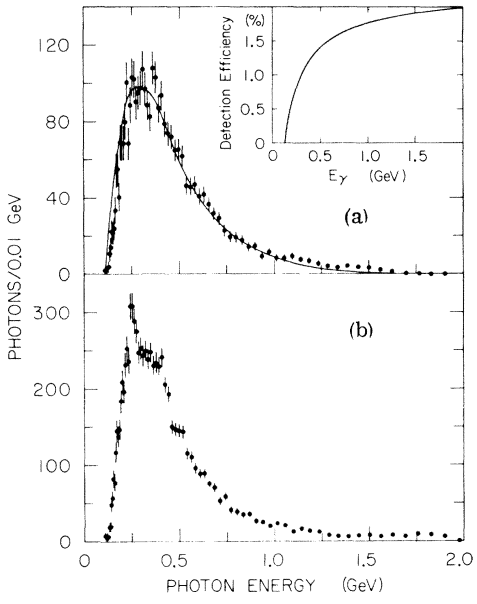

FIG. 1. The inclusive photon spectra in bins of 4% of the photon energy for (a) ψ and (b) ψ'. The smooth curve in (a) is the inclusive photon spectrum from a phase-space Monte Carlo model of ψ decays, normalized to the data in the region 0.30–0.35 GeV. The inset in (a) shows the photon detection efficiency vs energy.

The ψ' spectrum shows a $>5\sigma$ peak at ~260 MeV, having a width consistent with the resolution. With 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 with the $\chi(3415)$ observed in hadronic channels.[1,2]

The branching fraction for the transition $\psi' \to \gamma\chi(3415)$ is calculated[7] as

$$B=\frac{(\text{No. of signal events})/\epsilon_\gamma R\epsilon_{tr}^{\,s}}{(\text{No. of total events})/\epsilon_{tr}^{\,all}}.$$

Here R, calculated to be ~0.8, is a correction for events lost from the peak as a result of radiation by the electron or the positron, $\epsilon_{tr}^{\,all}$ is the average trigger efficiency for all events, and $\epsilon_{tr}^{\,s}$ is the trigger efficiency for signal events, which include a ~260-MeV photon conversion; $\epsilon_{tr}^{\,s}$ is taken to be equal to $\epsilon_{tr}^{\,all}$ enhanced by the contribution from the converted photon—this *assumes* that the $\chi(3415)$ has multibody decays similar to ψ or ψ'. The ratio $\epsilon_{tr}^{\,all}/\epsilon_{tr}^{\,s}$, determined by counting the fraction of events in which the photon conversion was essential to the trigger, is 0.74 ± 0.07. There is a further 7% correction to the branching ratio to account for internal conversions which contribute to the signal.[8] The branching fraction is 0.063 ± 0.022 for an isotropic photon distribution and 0.075 ± 0.026 for a $1+\cos^2\theta$ distribution (which is favored by the data[2]). The 35% relative error is the sum in quadrature of the 17% statistical error and 30% estimated systematic errors. This result is in good agreement with the preliminary results of the SPEAR collaboration of Badtke *et al.*[9] and slightly larger than the upper limits found by the experiment of Simpson *et al.*[10] at SPEAR.

There are no other clear monochromatic signals in the ψ or ψ' spectra above 250 MeV; below 250 MeV the small and rapidly varying photon detection efficiency makes monochromatic signals difficult to observe. Table I gives 90%-confidence-level upper limits for branching fractions for monochromatic photon lines, separated from other lines by at least the full width at half-maximum energy resolution, for representative energies above 250 MeV at ψ and ψ'. The question of additional signals in the ψ' spectrum is compli-

TABLE I. 90%-confidence-level branching fraction limits for monochromatic photon production above 0.250 GeV at ψ and ψ'.

ψ		ψ'	
E_γ (GeV)	Limit	E_γ (GeV)	Limit
0.26	0.039	0.40	0.028[a]
0.37	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		

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

cated by the Doppler broadening of the photons from intermediate states χ, $\chi \to \gamma\psi$, due to the motion of the χ state. The broadening is sufficient to more than double the expected width and to merge together the contributions from the various χ states, making the background beneath any possible signal in the 300–400-MeV region difficult to estimate.

Photon conversions enable us to identify $\psi' \to \gamma\gamma\psi$ events, where one of the photons converts and the ψ 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 then constrained to the ψ mass. Electron pair events are rejected when the angle between the electron and the positron is greater than 177.5°, eliminating more than 95% of the radiative background from $\psi' \to e^+e^-$ but only ~8% of real $\psi' \to \gamma\gamma\psi$, $\psi \to e^+e^-$ 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.

Figure 2 shows the square of the missing mass, 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 $\psi' \to \gamma\gamma\psi$ events and a broad background from $\psi' \to \psi\pi^0\pi^0$ where a photon from a π^0 converted. The shading in Fig. 2 flags the detection of additional photons in the shower counters: Darkly shaded events have a shower counter signal consistent[11] 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 $\psi' \to \pi^0\pi^0\psi$ events). The high correlation of shading with small M_x^2 corroborates the identification

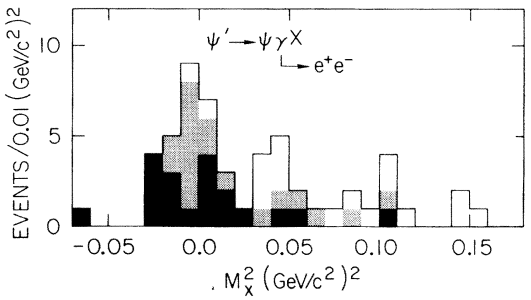

FIG. 2. $\psi\gamma$ events vs square of the missing mass, M_x^2. The shading is explained in the text.

of events with small M_x^2 as $\psi' \to \gamma\gamma\psi$ events.

The 27 shaded events with -0.03 (GeV/c^2)^2 $< M_x^2 < 0.03$ (GeV/c^2)^2 are kept. The unconverted photon is detected in the shower counters in fifteen of these events, consistent with detector acceptance and efficiency. Six events with the square of the missing mass recoiling against the ψ greater than 0.27 (GeV/c^2)^2 are removed as possible $\psi' \to \psi\eta$, $\eta \to \gamma\gamma$ events (four such events are expected). The remaining 21 events are constrained to fit $\psi' \to \gamma\gamma\psi$. 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 ~8 MeV; the masses of the

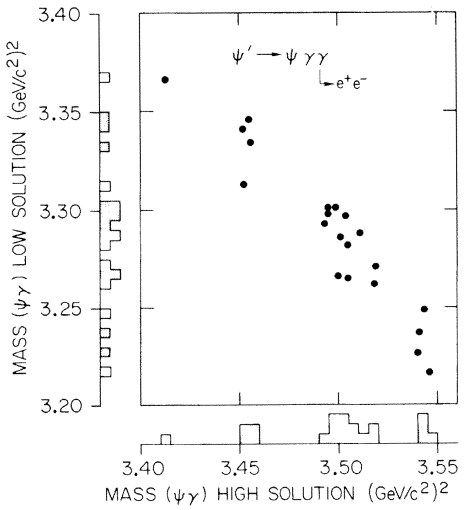

FIG. 3. Scatter plot of the two solutions for the mass of intermediate states in $\psi' \to \gamma\gamma\psi$ events.

three possible states are 3543 ± 10, 3504 ± 10, and 3454 ± 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 $\lesssim 0.025$ 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[2]; however, there is no evidence in hadronic channels for a state at 3455 or 3340 MeV, and such a state awaits confirmation. Correcting for ψ branching ratios and photon detection efficiency, we calculate the branching ratio products for $\psi' \to \gamma\chi$, $\chi \to \gamma\psi$ 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 from background; if it is taken as signal, the branching ratio is $(0.2 \pm 0.2)\%$.

In conclusion, the transition $\psi' \to \gamma\chi(3415)$ has been observed in the ψ' 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 ψ or ψ' inclusive photon spectra, with 90%-confidence-level upper limits of 1–4% for the branching fractions. If we identify $\chi(3415)$ with the $^3P_0$ charmonium state, the observed branching fraction is a factor of 2 smaller than the prediction of Eichten *et al.*[12] Also, the 90%-confidence-level upper limit of ~1% for transitions from ψ' to a state[5] near 2.8 GeV is a factor of 4 smaller than their prediction if we assume that the 2.8-GeV state is the pseudoscalar partner of the ψ.

From studying the $\psi\gamma$ masses in $\psi' \to \gamma\gamma\psi$ events, we find evidence for two states χ at 3504 ± 10 and 3543 ± 10 MeV with branching fraction products for $\psi' \to \gamma\chi$, $\chi \to \gamma\psi$ of $(2.4 \pm 0.8)\%$ and $(1.0 \pm 0.6)\%$, respectively. There is also an indication of a state at 3455 or 3340 MeV with branching fraction product of ~0.8%. The established states at 3415, 3505, and 3545 MeV are candidates for the predicted triplet ***P***-wave states of charmonium. However, there is serious disagreement between theoretical prediction and experiment for the branching fraction product for $\psi' \to \gamma\chi(3455)$, $\chi(3455) \to \gamma\psi$ if the $\chi(3455)$ is identified with the pseudoscalar partner of the ψ'.[13] While such issues remain to be resolved, there is now an emerging picture of ψ and χ spectroscopy in qualitative agreement with the charmonium picture.

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*Fellow of Deutsche Forschungsgemeinschaft.

‡Permanent address: Varian Associates, Palo Alto, Calif. 94302.

§Permanent address: Laboratoire de Physique Nucléaire et Hautes Energies, Université Paris VI, Paris, France.

¶Permanent address: Laboratori Nazionali, Frascati (Rome), Italy.

‖Permanent address: Départment de Physique des Particles Elémentaires, Centre d'Etudes Nucléaires de Saclay, France.

**Permanent address: EP Division, CERN, Geneva, Switzerland.

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

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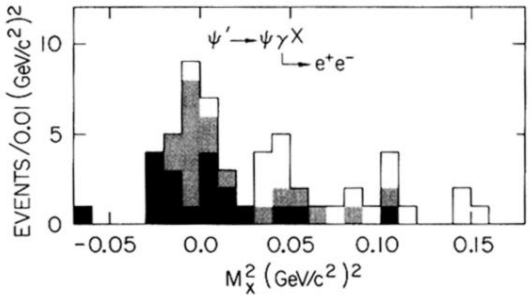

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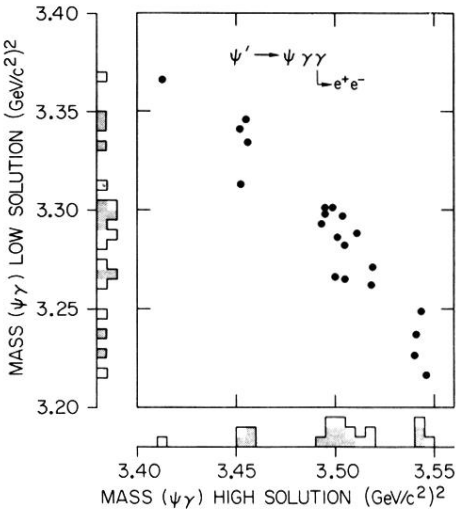

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