Charmonium Production in Photon-Photon Collisions

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We have searched for the two-photon production of the η_c, χ_0, and χ_2 charmonium states at the SLAC e^+e^- collider PEP in the channels $\gamma\gamma \to K^{\pm}K^0_S\pi^{\mp}$, $\gamma\gamma \to K^+K^-\pi^+\pi^-$, $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$, and $\gamma\gamma \to K^+K^-K^+K^-$. We identify four η_c candidates in the $K^+K^-K^+K^-$ channel on a negligible background; the one $\phi\phi$ event among them implies a 95%-confidence-level (C.L.) lower limit for $\Gamma_{\gamma\gamma}(\eta_c)$ of 1.7 keV. In the other channels we find no evidence for any of the three states. We establish 95%-C.L. upper limits $\Gamma_{\gamma\gamma}(\eta_c) < 15.5$ keV, $\Gamma_{\gamma\gamma}(\chi_0) < 17.0$ keV, and $\Gamma_{\gamma\gamma}(\chi_2) < 4.2$ keV. From all channels combined, we obtain the value $\Gamma_{\gamma\gamma}(\eta_c) = 6.4^{+5.0}_{-3.4}$ keV.

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The two-photon widths $\Gamma_{\gamma\gamma}$ of the η_c, χ_0, and χ_2 are of interest for understanding the dynamics of charmonium states. In a nonrelativistic potential model,[1] one considers the η_c as a $c\bar{c}$ $^1S_0$ bound state with the same radial wave function as the J/ψ; the electromagnetic width of the J/ψ then implies $\Gamma_{\gamma\gamma}(\eta_c) \approx 6.7$ keV. Such a model also gives relations between electromagnetic and hadronic widths, leading to predictions of $\Gamma_{\gamma\gamma}$ for the ^3P_J states χ_0 and χ_2, though with larger uncertainties. Calculations of $\Gamma_{\gamma\gamma}$ have also been made in relativistic potential models[2] and in dispersion-relation models based upon QCD,[3,4] yielding values in the 3-6-keV range for η_c. Predictions for χ_0 and χ_2 have ranged from 4 to 8 keV and from 1 to 2 keV, respectively.

The experimental observation of charmonium states in photon-photon collisions is difficult because the two-photon luminosity at these relatively high masses is low and because the charmonium states have no dominant decay modes. The decays are thought to proceed via two intermediate gluons; consequently, branching fractions in the most common hadronic final states are only a few percent.[5] Among photon-photon collision experiments, several[6-8] have obtained only upper limits on $\Gamma_{\gamma\gamma}(\eta_c)$, while Berger *et al.*, the PLUTO Collaboration,[9] have reported a signal in the $K^{\pm}K^0_S\pi^{\mp}$ ($K^0_S \to \pi^+\pi^-$) channel. A value has also been reported from the reaction $p\bar{p} \to \gamma\gamma$ at the CERN ISR.[10] Two-photon widths of χ states have been reported from radiative ψ' decay[11] and from $p\bar{p}$ annihilation.[10]

We report here a measurement of the two-photon reaction $e^+e^- \to e^+e^-R$ (where R stands for η_c, χ_0, or χ_2) with the TPC/Two-Gamma facility[12] at the SLAC e^+e^- storage ring PEP, with incident e^+ and e^- energies of 14.5 GeV. Using the particle-identification capabilities of the Time Projection Chamber (TPC), we have studied four final states: $K^\pm K^0_S\pi^\mp$ ($K^0_S \to \pi^+\pi^-$), $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, and $K^+K^-K^+K^-$. The sums of known branching fractions[13,14] to these final states are 4.5%, 6.7%, and 4.1% for η_c, χ_0, and χ_2, respectively.

The data described here correspond to an integrated luminosity of 69 pb^{-1}. The TPC tracked charged particles in a 13.25-kG solenoidal magnetic field with a momentum resolution at large angles of $(\sigma_p/p)^2 \approx (1.5\%)^2 + (0.65\% \times p)^2$, with p in gigaelectronvolts. The TPC also sampled energy loss (dE/dx) along particle trajectories, with a typical resolution of 3.5%. Two proportional-mode pole-tip calorimeters and a hexagonal Geiger-mode calorimeter covered polar angles above 260 mrad. For some events, the detection of a scattered $e^\pm$ tagged one of the virtual photons (with four-momentum q_1 or q_2). These "tags" were detected in two arrays of NaI crystals in the polar-angle range 25–90 mrad and lead-scintillator shower counters from 100 to 180 mrad, and in two arrays of fifteen drift chamber planes in front of these detectors.

The trigger required at least two charged tracks in the TPC, each with polar angle $\theta > 26°$ and projecting back to the interaction point within 20 cm along the beam axis. Tracks with $\theta > 45°$ were required to be in coincidence with hits in a drift chamber outside the coil of the solenoid.

In this four-prong analysis, we selected events with two positively and two negatively charged tracks coming from the vertex. Two tracks were required to have $\theta > 30°$. Minimum momenta of 100 and 300 MeV were required for pions and kaons, respectively, with momentum uncertainty less than 30%. For particle identification, the measured dE/dx (defined as the average of the lowest 65% of the samples) and momentum were compared to empirically determined curves for the various particle types (e,μ,π,K,p). A confidence level was calculated for each of the four final states of interest, and in addition for the background states $p\bar{p}\pi^+\pi^-$, $e^+e^-e^+e^-$, and $\pi^+\pi^-\gamma$ and $K^+K^-\gamma$ where the photon converts to an e^+e^- pair. We required the confidence level for a final state to be about 10%. Additional requirements were imposed on the differences between the confidence level and those for other possible final states. For the $K^\pm K^0_S\pi^\mp$ channel, two oppositely charged pions had to have an effective mass within 40 MeV of the K^0_S mass. Events with photon candidates having energy depositions larger than 150 MeV in the hexagonal Geiger-mode calorimeter or larger than 300 MeV in the pole-tip-calorimeters were rejected. We required the summed transverse momentum squared, $P_\perp^2$, for the four charged particles and the tag (if present) to be less than 0.04 GeV^2.

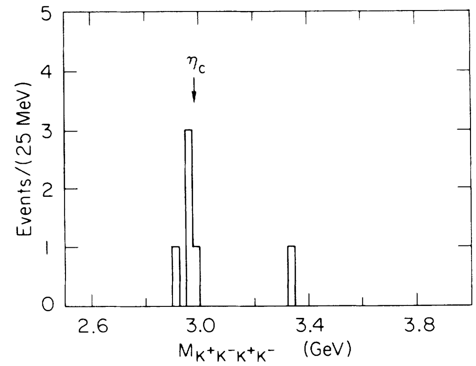

FIG. 1. Effective mass of the $K^+K^-K^+K^-$ events. The bin size (25 MeV) is appproximately equal to the mass resolution.

To determine the acceptance, Monte Carlo events were generated according to the luminosity function for transversely polarized photons.[15] We used a $\gamma\gamma$ cross section based on the matrix element $[(q_1 \cdot q_2)^2 - q_1^2 q_2^2]^{1/2} F(q_1^2, q_2^2)$ for η_c production[16] and $F(q_1^2, q_2^2)$ for χ_0,χ_2 production,[17] where $F^2(0,0) \propto \Gamma_{\gamma\gamma}$. For the q_i^2 dependence of F, $1/[(1-q_1^2/m_{J/\psi}^2)(1-q_2^2/m_{J/\psi}^2)]$ was assumed; this is numerically similar to predictions for the η_c from charmonium sum rules.[3] Generated events were processed through a detector-simulation program (which included resolution effects, energy loss, multiple scattering, nuclear interactions in the detector materials, and a trigger simulation) and then passed through the same cuts as the data. Overall hadronic final-state acceptances ranged from 3% to 7%.

The effective masses of the six $K^+K^-K^+K^-$ events (including two with tags) are shown in Fig. 1. Four of these (including one with a tag) are η_c candidates since their effective masses are within 33 MeV of the nominal[13] η_c mass of 2981 MeV and the mass resolution is $\sigma_M = 22$ MeV. Exclusive η_c production is indicated since all four candidates have $P_\perp^2 < 0.01$ GeV^2. We ascribe the two events at 2903 and 3330 MeV to background, which would imply an average background in the mass range 2981 ± 33 MeV of about 0.1 event. From observed cross sections and a Monte Carlo calculation of misidentification probabilities we determined the contamination from other final states to be less than 0.1 event in the η_c mass range.

The K^+K^- mass spectrum of the six $K^+K^-K^+K^-$ events is shown in Fig. 2. Given a K^+K^- mass resolution of about 10 MeV, one of the η_c events can be classified as $\phi\phi$, two are ϕK^+K^-, and one is $K^+K^-K^+K^-$ with no ϕ content. If the K^+K^- mass spectrum for ϕK^+K^- is taken from a phase-space Monte Carlo calculation, we estimate a probability of

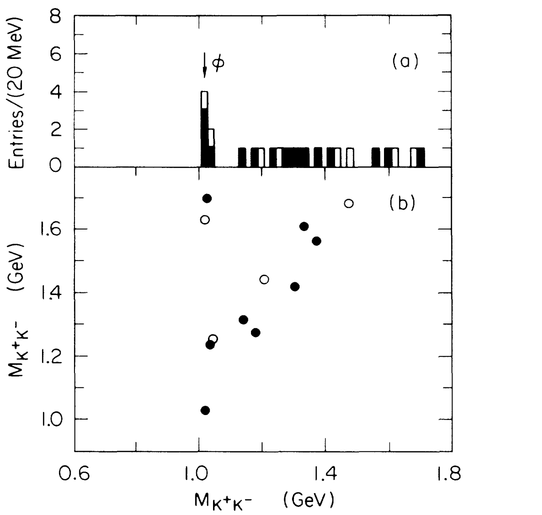

FIG. 2. Effective K^+K^- mass of the six $K^+K^-K^+K^-$ events. The histogram has four and the scatter plot has two entries per event. The filled circles (shaded histogram) denote combinations from the four η_c events while the open circles (unshaded histogram) are from the two background events.

only 3% that three ϕK^+K^- events would include one consistent with $\phi\phi$. This lends credibility to the assignment of one event to the reaction $\eta_c \to \phi\phi$. The two background events are both consistent with a ϕK^+K^- interpretation.

The observation of the η_c in the $K^+K^-K^+K^-$ channel at present hardly constrains the value of $\Gamma_{\gamma\gamma}(\eta_c)$, since only the part of the η_c branching fraction to $K^+K^-K^+K^-$ through the $\phi\phi$ intermediate state is known. We have taken a weighted average of the measurements in Ref. 14, including systematic uncertainties, to compute a branching fraction $B(\eta_c \to \phi\phi) = (0.39 \pm 0.14)\%$. On the basis of our single $\eta_c \to \phi\phi$ event, we arrive at a 95%-confidence-level (C.L.) lower limit $\Gamma_{\gamma\gamma}(\eta_c) > 1.7$ keV. The one event represents a value $\Gamma_{\gamma\gamma}(\eta_c) = 39^{+50}_{-28}$ keV.[18]

We found no evidence for charmonium in the mass spectra of $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, and $K^\pm K^0_S\pi^\mp$. We also investigated the $\rho^0\rho^0$ final state (with subsequent decay into $\pi^+\pi^-\pi^+\pi^-$), for which an η_c branching fraction has been reported.[19] Upper limits on $\Gamma_{\gamma\gamma}(R)B(R \to \text{final state})$ from the investigated final states were obtained by a Monte Carlo method as follows. We fitted each spectrum with a smooth continuum to describe the background. The number of events expected from the sum of the background and a signal calculated for a given value of $\Gamma_{\gamma\gamma}B$ in a 125-MeV mass bin centered at a state R was generated according to a Poisson distribution. Errors on acceptance (15%) and luminosity (10%) were included in the procedure by our throwing each time a value for each of these according to a Gaussian distribution, cut off on the low side at 2 standard deviations. The number of Monte Carlo events was then compared with the number of events in the corresponding mass bin in the data and a probability was obtained for the number of Monte Carlo events to exceed the number of data events for the assumed value of $\Gamma_{\gamma\gamma}B$. The procedure was repeated for different values of $\Gamma_{\gamma\gamma}B$ so that a 95%-C.L. upper or lower limit could be found. The values derived from the separate channels are shown in Table I.[20]

TABLE I. Values and 95%-C.L. upper limits on $\Gamma_{\gamma\gamma}(R)B(R \to \text{final state})$ in kiloelectronvolts. (See Ref. 18 for meaning of errors.)

Final State	$\eta_c(2981)$	$\chi_0(3415)$	$\chi_2(3555)$
$\phi\phi$	$0.15^{+0.20}_{-0.11}$	<0.62	<0.14
ϕK^+K^-	$0.36^{+0.25}_{-0.19}$	<0.52	<0.12
$K^+K^-K^+K^-$	<0.29	<0.27	<0.06
$\pi^+\pi^-\pi^+\pi^-$	<0.29	<0.71	<0.11
$\rho^0\rho^0$	<0.20	<0.45	<0.11
$K^\pm K^0_S\pi^\mp$	<0.33	<0.33	<0.15
$K^+K^-\pi^+\pi^-$	<0.30	<0.60	<0.11

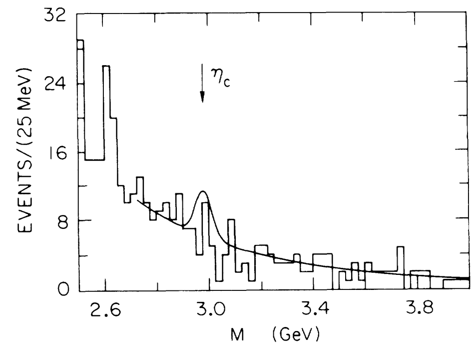

FIG. 3. Effective mass of the $\phi\phi \to K^+K^-K^+K^-$, $K^\pm K^0_S\pi^\mp$ ($K^0_S \to \pi^+\pi^-$), $K^+K^-\pi^+\pi^-$, and $\pi^+\pi^-\pi^+\pi^-$ events combined. The curve is the sum of the Monte Carlo-generated continuum and the expected signal for $\Gamma_{\gamma\gamma}(\eta_c) = 15.5$ keV.

The sum of the mass spectra for the final states $\phi\phi$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, and $K^\pm K^0_S\pi^\mp$ is shown in Fig. 3. To extract a best value and upper limit for $\Gamma_{\gamma\gamma}(\eta_c)$, a likelihood technique was used to treat simultaneously these four final states. In this case the Monte Carlo procedure also took into account the uncertainties in the branching fractions (typically 30%). Care was taken to treat separately those uncertainties which are correlated between channels, including that in $B(J/\psi \to \gamma\eta_c)$,[13] which is a common ingredient in all values of η_c decay branching fractions. For $K^\pm K^0_S\pi^\mp$, isospin conservation and the $K^0_S \to \pi^+\pi^-$ decay reduce the $K\bar{K}\pi$ branching fraction by a factor of 0.23, while the $\phi \to K^+K^-$ decay reduces the $\phi\phi$ branching fraction by a factor of 0.25. We find a 95%-C.L. upper limit $\Gamma_{\gamma\gamma}(\eta_c) < 15.5$ keV and a central value $\Gamma_{\gamma\gamma}(\eta_c) = 6.4^{+5.0}_{-3.4}$

keV.[18,21] This is lower than the PLUTO Collaboration's measured value of 28 ± 15 keV,[9,22] while it is in agreement with the value of $4.3^{+3.4}_{-3.7} \pm 2.4$ keV (Ref. 10) from $p\bar{p}$ annihilation.

From the combined spectra of $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$, and the known branching fractions,[13] we find the 95%-C.L. upper limits $\Gamma_{\gamma\gamma}(\chi_0) < 17.0$ keV and $\Gamma_{\gamma\gamma}(\chi_2) < 4.2$ keV. The upper limit on $\Gamma_{\gamma\gamma}(\chi_0)$ is compatible with the value of 4.0 ± 2.8 keV quoted in Ref. 11. The upper limit on $\Gamma_{\gamma\gamma}(\chi_2)$ is consistent with the values of 2.8 ± 2.0 and $2.9^{+1.3}_{-1.0} \pm 1.7$ keV quoted in Refs. 10 and 11, respectively. Our findings on the three charmonium states are in accord with the predictions of potential models[1,2] and the dispersion-relation approach.[3,4]

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[20] The event selection procedure was insensitive to the possible presence of low-energy photons. No evidence for such photons was found in the $\phi\phi$ event. Low-energy calorimeter signals in the ϕK^+K^- events are compatible with the effects from secondary interactions by charged particles in the calorimeters. However, because a calorimeter signal in the $K^+K^-K^+K^-$ event cannot easily be explained in this manner, we quote only an upper limit on $\Gamma_{\gamma\gamma}(\eta_c)$ for this channel.

[21] The combined analysis implies a 95%-C.L. lower limit of ≈ 1.5 keV.

[22] From Table I, our 95%-C.L. upper limit on $\Gamma_{\gamma\gamma}(\eta_c)B(\eta_c \rightarrow K^\pm K_S^0\pi^\mp)$ is 0.33 keV, compared to the PLUTO Collaboration's measurement of $0.5^{+0.2}_{-0.15} \pm 0.1$ keV.