Experimental Investigation of the Two-Photon Widths of the χ_{c0} and the χ_{c2} Mesons

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Using 12.7 fb^{-1} of data collected with the CLEO detector at CESR, we observed two-photon production of the $c\bar{c}$ states χ_{c0} and χ_{c2} in their decay to $\pi^+\pi^-\pi^+\pi^-$. We measured $\Gamma_{\gamma\gamma}(\chi_c) \times \mathcal{B}(\chi_c \to \pi^+\pi^-\pi^+\pi^-)$ to be $75 \pm 13(\text{stat}) \pm 8(\text{syst})$ eV for the χ_{c0} and $6.4 \pm 1.8(\text{stat}) \pm 0.8(\text{syst})$ eV for the χ_{c2}, implying $\Gamma_{\gamma\gamma}(\chi_{c0}) = 3.76 \pm 0.65(\text{stat}) \pm 0.41(\text{syst}) \pm 1.69(\text{br})$ keV and $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.53 \pm 0.15(\text{stat}) \pm 0.06(\text{syst}) \pm 0.22(\text{br})$ keV. Also, cancellation of dominant experimental and theoretical uncertainties permits a precise comparison of $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$, evaluated to be $7.4 \pm 2.4(\text{stat}) \pm 0.5(\text{syst}) \pm 0.9(\text{br})$, with QCD-based predictions.

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In this Letter, we report a study of two-photon production of the C-even 1^3P charmonium states χ_{c0} and χ_{c2} using the CLEO detector at the Cornell Electron Storage Ring (CESR). The charmonium system is an ideal testing ground for quantum chromodynamics (QCD). Perturbative QCD (PQCD) provides predictions for the two-photon widths $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$. These predictions involve charmed quark mass factors, nonperturbative factors, and wave-function dependence, all of which cancel in the ratio $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$. The experimentally measured quantities are the two products $\Gamma_{\gamma\gamma}(\chi_c) \times \mathcal{B}(\chi_c \to \pi^+\pi^-\pi^+\pi^-)$, $\chi_c \equiv \chi_{c0}$ or χ_{c2}. Systematic uncertainties in the measurements mostly cancel in the ratio of these products. Further, the contribution to the uncertainty on $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$ from the uncertainty on the ratio $\mathcal{B}(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)/\mathcal{B}(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$ is greatly reduced because both branching fractions have been measured in the same experiment [1,2] leading to cancellation of their systematic uncertainties in the ratio. Thus the ratio $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$ affords a more precise comparison of theory and experiment than do the individual $\Gamma_{\gamma\gamma}(\chi_c)$.

The two-photon width of a χ_c meson can be determined by measuring its two-photon cross section. The ratio of this width to the two-gluon width of a χ_c meson can be calculated in PQCD with reduced uncertainties due to cancellation of charmed quark mass factors, nonperturbative factors, and wave function dependence. In next-to-leading order (NLO) PQCD one obtains the following relationships [3]:

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c0})}{\Gamma_{gg}(\chi_{c0})} = \frac{8\alpha^2}{9\alpha_s^2}\frac{(1 + 0.18\alpha_s/\pi)}{(1 + 9.5\alpha_s/\pi)}, \tag{1}$$

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{gg}(\chi_{c2})} = \frac{8\alpha^2}{9\alpha_s^2}\frac{(1 - 5.3\alpha_s/\pi)}{(1 - 2.2\alpha_s/\pi)}. \tag{2}$$

The width of the χ_{c0} meson can be assumed to be dominated by its two-gluon component, so $\Gamma_{gg}(\chi_{c0}) \approx \Gamma_{\text{tot}}(\chi_{c0}) = 14.9^{+2.6}_{-2.3}$ MeV [4]. Using a value of the strong coupling constant $\alpha_s = 0.28$ [3], one obtains the NLO PQCD prediction $\Gamma_{\gamma\gamma}(\chi_{c0}) = 5.0 \pm 0.8$ keV. Because of the uncertainty in the charm mass scale, we also calculate the NLO PQCD prediction at $\alpha_s = 0.35$ and find $\Gamma_{\gamma\gamma}(\chi_{c0}) = 2.9 \pm 0.5$ keV. A measurement reported in a thesis gave $\Gamma_{\gamma\gamma}(\chi_{c0}) = 4.0 \pm 2.8$ keV [5]. The E835 Collaboration reported an upper limit of $\Gamma_{\gamma\gamma}(\chi_{c0}) \leq 3.47$ keV (95% C.L.) [6].

The two-gluon component of the χ_{c2} width can be extracted from its width $\Gamma_{\text{tot}}(\chi_{c2}) = 2.00 \pm 0.18$ MeV [4] by subtracting the radiative width $\Gamma(\chi_{c2} \to \gamma J/\psi)$ and the color-octet width in which the χ_{c2} decays via three gluons to light hadrons. This latter contribution has been shown in Ref. [7] to be equal to the hadronic width of the χ_{c1} meson. In the case of the χ_{c2} meson, the color octet contribution to the full width is significant; for the χ_{c0} meson, it is negligible. Hence, one obtains the NLO PQCD prediction $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.47 \pm 0.04$ keV using a value of $\alpha_s = 0.28$. This prediction becomes $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.25 \pm 0.02$ keV for $\alpha_s = 0.35$. The Particle Data Group (PDG) value of $\Gamma_{\gamma\gamma}(\chi_{c2})$ is 0.47 ± 0.17 keV [4], where the uncertainty includes a scale factor of 1.9 to account for the poor consistency among the various measurements [8]. The recent measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.270 \pm 0.049(\text{stat}) \pm 0.033(\text{syst})$ keV [6] by the E835 Collaboration was not included in this average.

The comparison of experimental results with the theoretical predictions is hampered by the lack of precision in the measured χ_c hadronic branching fractions, which are needed to extract $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$. Exploiting the fact that the χ_{c0} and the χ_{c2} mesons were both detected in their decay into $\pi^+\pi^-\pi^+\pi^-$, we calculate the ratio of their two-photon widths where the dominant branching fraction uncertainties cancel. In addition, some of the dominant systematic uncertainties in the $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ measurements cancel in the ratio because the χ_{c0} and the χ_{c2} mesons were detected in the same experiment. The NLO PQCD prediction for the ratio of the two-photon widths is [3]

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c0})}{\Gamma_{\gamma\gamma}(\chi_{c2})} = \frac{15}{4}\frac{(1 + 0.18\alpha_s/\pi)}{(1 - 5.3\alpha_s/\pi)}, \tag{3}$$

Here, too, charmed quark mass factors have canceled, and we have assumed $|\Psi'_{\chi_{c0}}(0)|^2 = |\Psi'_{\chi_{c2}}(0)|^2$ in the nonrelativistic limit, where $\Psi'_{\chi_c}(0)$ denotes the derivative of the χ_c wave function at the origin. Relativistic corrections due to explicit modification of the meson decay amplitudes decrease the above ratio, whereas corrections arising from the modification of the χ_c wave functions increase the above ratio [9]. In NLO PQCD, predictions for this ratio range from 7 to 9 when α_s varies from 0.28 to 0.35. Experimentally, this ratio is found to be 8.7 ± 6.9, using the single available $\Gamma_{\gamma\gamma}(\chi_{c0})$ measurement [5] and the PDG value of $\Gamma_{\gamma\gamma}(\chi_{c2})$ [4]. Thus a precise measurement of the individual two-photon widths of the χ_{c0} and the χ_{c2} mesons and, more importantly, their ratio are of interest for a comparison with theory.

At CESR, C-even charmonium states are produced via the fusion of two spacelike photons, radiated by the 5.3 GeV e^+ and e^- beams. The data used in this study correspond to an integrated luminosity of 12.7 fb^{-1} and were collected with two configurations (CLEO II [10] and CLEO II.V [11]) of the CLEO detector. Approximately one-third of the data was taken with the CLEO II configuration. The detector components most useful for this study were the concentric tracking devices for charged particles, operating in a 1.5 T solenoidal magnetic field. For CLEO II, this tracking system consisted of a 6-layer straw tube chamber, a 10-layer precision drift chamber, and a 51-layer main drift chamber. The main drift chamber also provided measurements of the specific ionization loss, dE/dx, used for particle identification. For CLEO II.V, the straw tube chamber was replaced by a 3-layer, double-sided silicon vertex detector, and the gas in the main drift chamber was changed from a 50:50 mixture of argon-ethane to a 60:40 mixture of helium-propane. These changes gave rise to a significant improvement in the momentum and dE/dx resolutions for charged particles. Photons were detected using the high-resolution electromagnetic calorimeter consisting of 7800 CsI crystals. The Monte Carlo simulation of the CLEO detector response was based upon GEANT [12]. Simulated events were processed in the same manner as the data to determine the $\chi_c \to \pi^+\pi^-\pi^+\pi^-$ detection efficiencies and the $\pi^+\pi^-\pi^+\pi^-$ mass resolutions at the two χ_c meson masses.

In the two-photon process $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\chi_c \to e^+e^-\pi^+\pi^-\pi^+\pi^-$, the photon propagators dictate that the photons are almost real ("on shell"). Therefore the incident leptons are scattered at very small angles to the beam and remain undetected. Such "untagged" events typically have low transverse momentum ($p_T \equiv |\sum_i \vec{p}_{T_i}|$, $i = 1$–4) and low visible energy.

The events were required to have exactly four charged particles with zero total charge. The background from processes other than two-photon production was suppressed by requiring that the χ_c candidate reconstructed from these four charged particles has $p_T < 0.4$ GeV$/c$ and that the visible energy in the event be less than 6.0 GeV. A χ^2 probability was constructed using the dE/dx information from the four tracks, and required to be greater than 10%. Also, because the final state had no expected energy deposits in the calorimeter from neutral particles, the total calorimeter energy in the event not matched to charged particles was required to be less than 0.6 GeV. We required that at least two tracks traversed all tracking layers to assure a well-modeled trigger simulation.

The invariant mass distribution of the selected four-pion events is shown in Fig. 1. Enhancements near the known χ_{c0} and χ_{c2} masses are seen upon a smooth background. The background was fitted with a power law function: $A \cdot W_{\gamma\gamma}^n$, with $W_{\gamma\gamma}$ the $4\pi^\pm$ invariant mass and A and n parameters to be fit. The χ_{c0} signal was fitted with a spin-0 relativistic Breit-Wigner function with a width [4] of 14.9 MeV (the natural line shape) convolved with a double Gaussian function (the detector resolution). The χ_{c2} signal was fitted using only a double Gaussian resolution function as its width [4] of 2.0 MeV is negligible compared to our mass resolution. The parameters of the detector resolution functions were determined from Monte Carlo samples, generated with zero width. The invariant mass resolution was approximately 9 MeV for both resonances. We performed a simultaneous, binned, maximum-likelihood fit to the invariant mass distribution using these three functions.

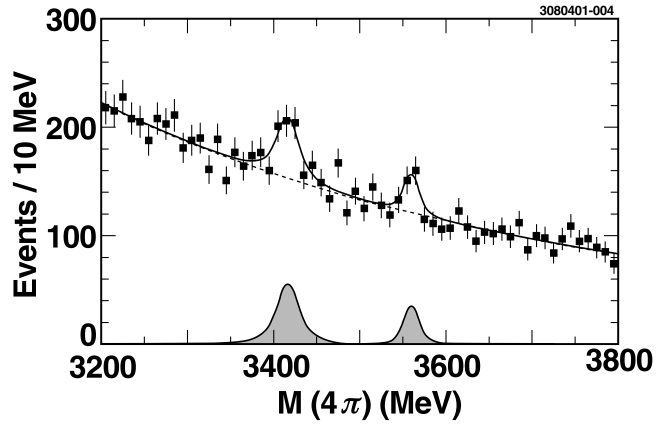

FIG. 1. The $\pi^+\pi^-\pi^+\pi^-$ invariant mass (data point with errors). The solid line is the fit with a χ^2/d.o.f. $= 44/54$. The shaded area corresponds to the signal shape. The dashed line corresponds to the background shape.

From the fit, we obtained 234 ± 40 candidate χ_{c0} events and 89 ± 25 candidate χ_{c2} events, with masses of 3416.5 ± 3.0 MeV and 3559.9 ± 2.9 MeV, respectively. Our measured masses are consistent with the PDG values, 3415.0 ± 0.8 MeV and 3556.18 ± 0.13 MeV [4], respectively.

Comparison of the measured two-photon cross section with that estimated from Monte Carlo simulation, based upon the formalism of Budnev *et al.* [13], for a given two-photon width allows extraction of $\Gamma_{\gamma\gamma}$. The cross section in data was calculated by dividing the fitted event yield by the detection efficiency, the integrated luminosity, and the branching fraction $\mathcal{B}(\chi_c \to \pi^+\pi^-\pi^+\pi^-)$. The detection efficiencies were 19.6% and 21.7% for the χ_{c0} and the χ_{c2}, respectively. Because of the large uncertainties in the branching fractions, we preferred to express our primary results as the products of these and the two-photon widths: $\Gamma_{\gamma\gamma}(\chi_{c0}) \times \mathcal{B}(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-) = 75 \pm 13(\text{stat}) \pm 8(\text{syst})$ eV and $\Gamma_{\gamma\gamma}(\chi_{c2}) \times \mathcal{B}(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-) = 6.4 \pm 1.8(\text{stat}) \pm 0.8(\text{syst})$ eV. From these primary results we obtained the ratio $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2}) = 7.4 \pm 2.4(\text{stat}) \pm 0.5(\text{syst}) \pm 0.9(\text{br})$, where the last uncertainty corresponds to branching fraction uncertainties that do not cancel in the ratio. Using the known branching fractions, $\mathcal{B}(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-) = (2.0 \pm 0.9)\%$ and $\mathcal{B}(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-) = (1.2 \pm 0.5)\%$ [4], we obtained the two-photon widths as $\Gamma_{\gamma\gamma}(\chi_{c0}) = 3.76 \pm 0.65(\text{stat}) \pm 0.41(\text{syst}) \pm 1.69(\text{br})$ keV and $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.53 \pm 0.15(\text{stat}) \pm 0.06(\text{syst}) \pm 0.22(\text{br})$ keV, where the last uncertainties correspond to the systematic uncertainties arising from the hadronic branching fraction.

Sources of systematic uncertainty are summarized in Table I, with those that were correlated marked by (*).

TABLE I. Systematic uncertainties in the two $\Gamma_{\gamma\gamma}(\chi_c) \times \mathcal{B}(\chi_c \to \pi^+\pi^-\pi^+\pi^-)$ measurements. The total systematic uncertainties were obtained by adding the individual contributions in quadrature. Most systematic uncertainties are pairwise correlated and are marked with an asterisk.

Source of uncertainty	χ_{c0} (%)	χ_{c2} (%)
Event p_T*	7	7
Particle identification*	4	6
Unmatched neutral energy*	4	4
Helicity	0	4
Mass calibration*	1	3
Width of resonance	4	0
ρ^0 Substructure*	2	2
Trigger*	2	2
Tracking*	2	2
Detector resolution parameter*	2	2
Luminosity*	1	1
Total	11	12

These were added in quadrature to obtain the total systematic uncertainty. The systematic uncertainty of the ratio of the two-photon widths takes into account correlations among the uncertainties.

The systematic uncertainties were dominated by those of the simulation of the signal p_T distribution, the particle identification procedure and the simulation of the unmatched neutral energy. These uncertainties were estimated by varying the selection criteria within reasonable limits and studying the corresponding variation in $\Gamma_{\gamma\gamma}$. For the uncertainty arising from the simulation of p_T, we also included the effects due to uncertainty in the pole mass in the form factor [13]. We varied the pole mass from ρ-meson mass to infinite mass.

In our cross-section estimate from Monte Carlo we had assumed that the χ_{c2} meson was produced only in the helicity 2 state. The helicity 0 state has zero two-photon width in the nonrelativistic approximation, while in relativistic models it is predicted to be up to 4% of the helicity 2 state [9]. We allowed the mass of each resonance to vary between our measurement and the PDG value to estimate the systematic uncertainty from uncertainty in the mass calibration. We similarly varied the width of the χ_{c0} within its known uncertainty.

Using the known branching fractions of the χ_{c0} and χ_{c2} [1] into $\rho^0\pi^+\pi^-$ and estimating the difference in detection efficiencies using Monte Carlo we assigned the systematic uncertainty due to the presence of resonant ρ^0 substructure in the χ_c decay.

The uncertainty in the efficiency of the trigger requirements satisfied by our selected events was found using other, redundant trigger conditions. For the tracking efficiency the uncertainty was estimated by comparisons of 1-prong vs 3-prong τ-pair events in data and simulation. Systematic uncertainty associated with the parametrization of the detector resolution functions was estimated by comparing the Monte Carlo signal shape of the D meson, which has zero intrinsic width, with that of data. The background shape was a free parameter in the fit and hence uncertainty due to small variations in this shape is included as part of the statistical uncertainty.

We investigated the possible effects of interference between the $4\pi^\pm$ decay of the χ_c states and nonresonant production of $4\pi^\pm$ in two-photon interactions. From Monte Carlo simulation we found that a fifth of the selected events were from annihilation τ-pair production. Another one-third were estimated to be not of two-photon origin based on the candidate p_T distribution. Interference can distort the signal shape derived from the signal Monte Carlo. We observed no such distortion demonstrated by the good fit χ^2 in the two regions of the resonances: 12.4 for 12 degrees of freedom.

The systematic uncertainty of 0.5 in the ratio $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$ takes the correlations marked by an asterisk in Table I into account. The systematic uncertainty of 0.9 from the ratio of branching fractions was calculated taking into account correlations as ascertained from Refs. [1] and [2]. The ratio of the branching fractions has significantly lower relative uncertainty than the branching fractions themselves due to partial cancellation of correlated systematic uncertainties. Though the individual measurements of $\mathcal{B}(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)$ and $\mathcal{B}(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$ have poor consistency, the ratios of these two branching fractions are consistent. The branching fractions $\mathcal{B}[\psi(2S) \to \gamma\chi_c]$ were from Ref. [14], taking into account correlations between them.

Our result $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2}) = 7.4 \pm 2.4(\text{stat}) \pm 0.5(\text{syst}) \pm 0.9(\text{br})$ represents a significant improvement upon the current value of 8.7 ± 6.9 and is compared with the NLO PQCD prediction [Eq. (3)] in Fig. 2. There is good agreement for reasonable values of α_s; however, one wishes for increased theoretical and experimental precision. Our $\Gamma_{\gamma\gamma}(\chi_{c0})$ measurement of $3.76 \pm 0.65(\text{stat}) \pm 0.41(\text{syst}) \pm 1.69(\text{br})$ keV is a significant improvement in experimental precision over the single available measurement of 4.0 ± 2.8 keV [5], but limited by poor knowledge of the branching fraction. The NLO

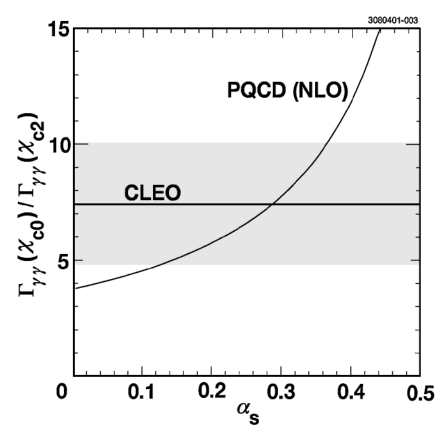

FIG. 2. Comparison of the measurement of the ratio $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$ (shaded region corresponds to $\pm1\sigma$) with its prediction from NLO PQCD as a function of α_s.

PQCD prediction of 3–5 keV is consistent with our measurement. Our $\Gamma_{\gamma\gamma}(\chi_{c2})$ measurement of 0.53 ± 0.15(stat) ± 0.06(syst) ± 0.22(br) keV is consistent with the PDG value of 0.47 ± 0.17 keV [4]. The PDG average of $\Gamma_{\gamma\gamma}(\chi_{c2})$ neglects correlated systematic uncertainties between experiments. The NLO PQCD prediction of 0.25–0.47 keV is consistent with our measurement and the PDG value. Our measurements show that PQCD based calculations are able to predict the ratios of decay rates, where nonperturbative effects cancel; however, the uncertainties in both theory and experiment limit the precision of such comparisons.

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