Two-photon widths of the chi(cJ) states of charmonium

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Using a data sample of 24.5×10^6 $\psi(2S)$ the reactions $\psi(2S) \to \gamma\chi_{cJ}$, $\chi_{cJ} \to \gamma\gamma$ have been studied for the first time to determine the two-photon widths of the χ_{cJ} states of charmonium in their decay into two photons. The measured quantities are $\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}) \times \mathcal{B}(\chi_{c0} \to \gamma\gamma) = (2.17 \pm 0.32 \pm 0.10) \times 10^{-5}$ and $\mathcal{B}(\psi(2S) \to \gamma\chi_{c2}) \times \mathcal{B}(\chi_{c2} \to \gamma\gamma) = (2.68 \pm 0.28 \pm 0.15) \times 10^{-5}$. Using values for $\mathcal{B}(\psi(2S) \to \gamma\chi_{c0,c2})$ and $\Gamma(\chi_{c0,c2})$ from the literature the two-photon widths are derived to be $\Gamma_{\gamma\gamma}(\chi_{c0}) = (2.36 \pm 0.35 \pm 0.22)$ keV, $\Gamma_{\gamma\gamma}(\chi_{c2}) = (0.66 \pm 0.07 \pm 0.06)$ keV, and $\mathcal{R} \equiv \Gamma_{\gamma\gamma}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c0}) = 0.278 \pm 0.050 \pm 0.036$. The importance of the measurement of $\mathcal{R}$ is emphasized. For the forbidden transition, $\chi_{c1} \to \gamma\gamma$, an upper limit of $\Gamma_{\gamma\gamma}(\chi_{c1}) < 0.03$ keV is established.

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Charmonium spectroscopy has provided some of the most detailed information about the quark-antiquark interaction in quantum chromodynamics (QCD). The most practical and convenient realization of QCD for the spectroscopy of charmonium and bottomonium is in terms of perturbative QCD (pQCD), modeled after quantum electrodynamics (QED). Two-photon decays of charmonium states $\chi_{cJ}(^3P_J)$ offer the closest parallel between QED and QCD, being completely analogous to the decays of the corresponding triplet states of positronium. Of course, the masses of the quarks and the wave functions of the χ_c states differ from those of positronium, but even these cancel out in the ratio of the two-photon decays, so that for both positronium and charmonium $\mathcal{R}^{(0)}_{\rm th} \equiv \Gamma(^3P_2 \to \gamma\gamma)/\Gamma(^3P_0 \to \gamma\gamma) = 4/15 \simeq 0.27$ [1]. The departure from this simple lowest order prediction can arise due to strong radiative corrections and relativistic effects, and the measurement of $\mathcal{R}$ provides a unique insight into these effects. The two-photon decay of the spin one χ_{c1} state is forbidden by the Landau-Yang theorem [2]. There are numerous theoretical potential model predictions of $\Gamma_{\gamma\gamma}(\chi_{c0,c2})$ available in the literature, with some employing relativistic and/or radiative corrections. As shown in Table I, the predictions vary over a wide range. This underscores the importance of measuring these quantities with the highest possible precision.

Most of the existing measurements of $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ are based on *formation* of χ_{cJ} in two-photon fusion. The only existing measurements based on the *decay* of χ_{cJ} into two photons are from the Fermilab E760/E835 experiments [12–14] with χ_{cJ} formation in $p\bar{p}$ annihilation. We report here results for $\Gamma_{\gamma\gamma}(\chi_{cJ})$ measured in the *decay* of χ_{cJ} into two photons. For these measurements we use the reactions

$$\psi(2S) \to \gamma_1\chi_{cJ}, \qquad \chi_{cJ} \to \gamma_2\gamma_3, \tag{1}$$

which have not been studied before. Since $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ are obtained from the same measurement, we also obtain $\mathcal{R}$ with a good control of systematic errors. Few such simultaneous measurements have been reported.

A data sample of 24.5×10^6 $\psi(2S)$ obtained in 48 pb^{-1} e^+e^- annihilations at the CESR electron-positron collider was used. The reaction products were detected and identified using the CLEO-c detector.

The CLEO-c detector [15], which has a cylindrical geometry, consists of a CsI electromagnetic calorimeter, an inner vertex drift chamber, a central drift chamber, and a ring-imaging Cherenkov (RICH) detector, inside a superconducting solenoid magnet providing a 1.0 T magnetic field. For the present measurements the most important component of the detector is the CsI calorimeter which has an acceptance of 93% of 4π and photon energy resolutions of 2.2% at $E_\gamma = 1$ GeV, and 5% at 100 MeV.

The event selection for the final state required three photon showers, each with $E_\gamma > 70$ MeV and angle θ with respect to the e^+ beam direction with $|\cos\theta| < 0.75$, and no charged particles. An energy-momentum conservation constrained 4C-fit was performed and events with $\chi^2/\text{d.o.f.} < 6$ were accepted as determined by $S/\sqrt{B}$ optimization. To prevent overlap of the lowest energy photon γ_1 with the high energy photons $\gamma_{2,3}$ events were rejected if $\cos\theta' > 0.98$, where θ' is the laboratory angle between γ_1 and either γ_2 or γ_3 (γ_2 is the more energetic photon of the two).

Data were analyzed in two equivalent ways, by constructing the energy spectrum of $E(\gamma_1)$ and the invariant mass spectrum of $M(\gamma_2\gamma_3)$. Consistent results were obtained. Figure 1 shows the $E(\gamma_1)$ spectrum. The enhancements due to the excitation of χ_{c0} and χ_{c2} over substantial backgrounds are clearly observed.

In order to analyze these spectra we need to determine the shapes of the background and the resonance peaks. For determining peak shapes and efficiencies fifty thousand signal Monte Carlo (MC) events were generated for χ_{c0} and χ_{c2} each, with masses and widths as given by PDG 08 [16]. The radiative transition $\psi(2S) \to \gamma_1\chi_{c0}$ is, of course, pure E1, and there is strong experimental evidence that the

TABLE I. Potential model predictions for two-photon widths of χ_{c2} and χ_{c0} and the ratio $\mathcal{R}$. In references marked with asterisks ($*$) relativistic corrections were incorporated in different approximations. References marked with daggers (+) include first-order radiative corrections. The last row is from a recent lattice calculation.

Reference	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV)	$\Gamma_{\gamma\gamma}(\chi_{c0})$ (eV)	$\mathcal{R}$
Barbieri [1]	930	3500	0.27
Godfrey [3]*	459	1290	0.36
Barnes [4]*	560	1560	0.36
Bodwin [5]	820 ± 230	6700 ± 2800	$0.12^{+0.15}_{-0.06}$
Gupta [6]*†	570	6380	0.09
Münz [7]*	440 ± 140	1390 ± 160	$0.32^{+0.16}_{-0.12}$
Huang [8]†	490 ± 150	3720 ± 1100	$0.13^{+0.11}_{-0.06}$
Ebert [9]*†	500	2900	0.17
Schuler [10]	280	2500	0.11
Dudek [11]		2410 ± 1040	

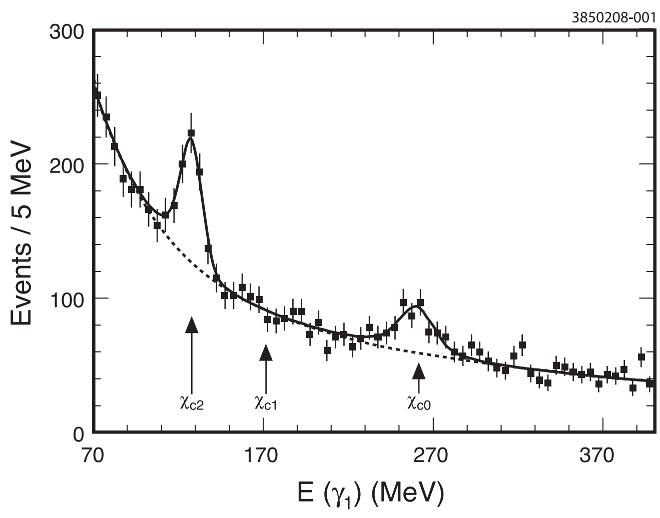

FIG. 1. Fitted spectrum for $E(\gamma_1)$. The expected positions of $E(\gamma_1)$ from χ_{c0}, χ_{c1}, χ_{c2} are marked with arrows. The dashed line represents the fitted background.

radiative transition $\psi(2S) \to \gamma_1 \chi_{c2}$ is also almost pure E1 [17,18]. Further, $\gamma_2\gamma_3$ in the decay $\chi_{c2} \to \gamma_2\gamma_3$ are expected to be produced with pure helicity two amplitudes [4]. With these assumptions the angular distributions are predicted to be [19]

$$\chi_{c0}\colon\ dN/d\cos\Theta_1 \propto 1 + \cos^2\Theta_1, \tag{2}$$

$$\begin{aligned}\chi_{c2}\colon\ & d^3N/(d\cos\Theta_1 d\cos\Theta_2 d\phi_2)\\ &\propto 9\sin^2\Theta_1\sin^2 2\Theta_2 + (1+\cos^2\Theta_1)[(3\cos^2\Theta_2 - 1)^2\\ &\quad + 9\sin^4\Theta_2] + 3\sin 2\Theta_1 \sin 2\Theta_2[3\cos^2\Theta_2 - 1\\ &\quad - 3\sin^2\Theta_2]\cos\phi_2 + 6\sin^2\Theta_1\sin^2\Theta_2\\ &\quad \times (3\cos^2\Theta_2 - 1)\cos 2\phi_2,\end{aligned} \tag{3}$$

$$\chi_{c2}\colon\ dN/d\cos\Theta_1 \propto 1 + (1/13)\cos^2\Theta_1. \tag{4}$$

Here Θ_1 is the angle between γ_1 and the e^+ beam direction in the $\psi(2S)$ frame, and Θ_2 and ϕ_2 are the polar and azimuthal angles of the γ_2 in the rest frame of χ_{c2} with respect to the direction of γ_1. The angle ϕ_2 is defined with respect to the e^+ beam direction. These angular distributions were assumed in the MC simulations.

The energy resolutions determined by the MC simulations were $\sigma(E_{\gamma_1}) = (8.2 \pm 0.1)$ MeV for χ_{c0} and $\sigma(E_{\gamma_1}) = (6.3 \pm 0.1)$ MeV for χ_{c2}. The overall efficiencies determined from these MC samples were $\epsilon(\chi_{c0}) = (39.1 \pm 0.5)\%$ and $\epsilon(\chi_{c2}) = (50.7 \pm 0.7)\%$. The difference between $\epsilon(\chi_{c0})$ and $\epsilon(\chi_{c2})$ arises primarily from the $\cos\Theta_1$ distributions [Eqs. (2) and (4)].

Because the background in our spectrum was large, it was important to determine its shape accurately. For this purpose the distributions of $E(\gamma_1)$ were examined in the 21 pb^{-1} of off-$\psi(2S)$ data taken at $\sqrt{s} = 3671$ MeV, as well as the 280 pb^{-1} of large statistics $\psi(3770)$ data taken at $\sqrt{s} = 3772$ MeV. As shown in Fig. 2, it was found that

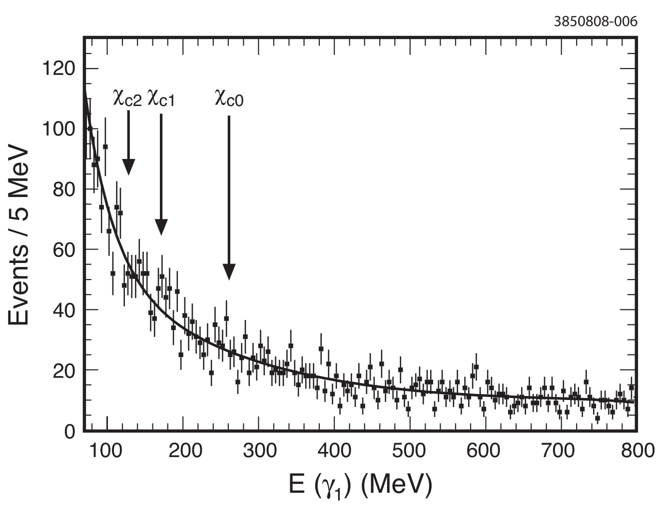

FIG. 2. Background spectrum for $E(\gamma_1)$. The points are from the off-$\psi(2S)$ data. The curve is from fit to the $\psi(3770)$ data.

the off-$\psi(2S)$ data were in excellent agreement with the high statistics $\psi(3770)$ data, in which transitions to either χ_{c0} or χ_{c2} resonances were expected to yield ≤ 2 events [20]. By generating $e^+e^- \to 3\gamma$ MC events using the Babayaga QED event generator [21] it was confirmed that both the shape and magnitude of background observed at $\sqrt{s} = 3671$ MeV and $\sqrt{s} = 3772$ MeV are consistent with being due to this QED process. The $E(\gamma_1)$ distribution for the $\psi(3770)$ data was fitted with a polynomial and used as the shape of the background in the $\psi(2S)$ data shown in Fig. 1.

It was determined that the contribution to the background due to radiative decays through η, η', and 3 γ decays of $\psi(2S)$ are nonpeaking and spread over the full range of $E(\gamma_1)$. The size of the $\psi(2S) \to 3\gamma$ background was estimated by using the recently measured $J/\psi \to 3\gamma$ branching fraction [22]. All of these radiative decays do not change the shape of the background and their total is less than 2% of the background. Using literature values of $\mathcal{B}(\chi_{c0,c2} \to \pi^0\pi^0)$ [16], it is estimated by MC simulations that the $\pi^0\pi^0$ decays contribute 4.5 ± 0.8 counts in the χ_{c0} peak and 1.9 ± 0.3 counts in the χ_{c2} peak.

A maximum likelihood fit was done to the binned $E(\gamma_1)$ spectrum shown in Fig. 1. In the fit the background shape was fixed but its normalization was kept free. The peak shapes of the χ_{c0} and χ_{c2} resonances used in the fit were obtained by convolving Breit-Wigner resonance functions with the intrinsic widths of χ_{c0} and χ_{c2} [16] with the Crystal Ball line shapes [23] fitted to the MC determination of the instrumental resolution. The photon energies corresponding to the masses of χ_{c0} and χ_{c2}, and the areas of the peaks were the free parameters of the fit. The fit with $\chi^2/\text{d.o.f.} = 41/61$ is shown in Fig. 1. It was found that after subtraction of the $\pi^0\pi^0$ contributions the peak counts were $N(\chi_{c0}) = 207 \pm 31$ and $N(\chi_{c2}) = 333 \pm 35$. The product branching fractions were determined as $N(\chi_{cJ})/[\epsilon(\chi_{cJ}) \times N(\psi(2S))]$ with the results

$$\begin{aligned}&\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}) \times \mathcal{B}(\chi_{c0} \to \gamma\gamma)\\ &\qquad = (2.17 \pm 0.32(\text{stat})) \times 10^{-5},\\ &\mathcal{B}(\psi(2S) \to \gamma\chi_{c2}) \times \mathcal{B}(\chi_{c2} \to \gamma\gamma)\\ &\qquad = (2.68 \pm 0.28(\text{stat})) \times 10^{-5}.\end{aligned} \tag{5}$$

Various possible sources of systematic errors in our results were investigated. The number of $\psi(2S)$ produced was determined using the background-subtracted and efficiency-corrected yield of hadronic events following the procedure described in detail in [24]. The background was estimated using the off-$\psi(2S)$ data. The efficiency was estimated by a MC simulation of generic $\psi(2S)$ decays. The systematic uncertainty was determined by varying the hadronic event selection and online trigger criteria by large amounts in both data and MC. It was found that while the MC determined efficiency changes from 65% to 91% the efficiency-corrected yield changes by no more than 2%,

TABLE II. Estimates of systematic uncertainties. Asterisks denote the systematic sources common to both χ_{c0} and χ_{c2}. The resonance fitting error for χ_{c2} is larger than that for χ_{c0} because χ_{c2} sits on a rapidly rising background.

Source of systematic uncertainty	χ_{c0}	χ_{c2}
Number of $\psi(2S)^*$	2.0%	2.0%
Neutral trigger efficiency *	0.2%	0.2%
Photon detection efficiency *	1.2%	1.2%
Event selection simulation	2.0%	2.0%
Resonance fitting	3.3%	4.6%
Helicity 2 angular distribution	$\cdots$	1.3%
$\pi^0\pi^0$ contribution	0.4%	0.1%
Sum in quadrature	4.5%	5.7%

which we include as a systematic error. The neutral trigger efficiency was uncertain by 0.2%. The uncertainty in our MC determination of absolute efficiency for three-photon detection was estimated as $3 \times 0.4\% = 1.2\%$ [25]. The systematic error due to the simulation of the event selection criteria (χ^2/d.o.f. distribution for 4C fit, acceptance variation, and shower overlap rejection) was determined by varying them. Similarly, systematic uncertainties due to our choice of the background and signal shapes were estimated by using a free-parameter polynomial background shape and a free-parameter Crystal Ball line shape [23] convolved with appropriate Breit-Wigner resonance shapes for the peaks. The extreme changes in the resonance yields obtained with these changes were taken as measures of systematic errors. We have assumed pure helicity two decay of χ_{c2}. In a relativistic calculation Barnes [4] predicts the helicity zero component to be only 0.5%. To be very conservative, we have determined the change in our result for χ_{c2} by including a helicity zero component of 8%, which is the experimental upper limit established by CELLO [26] for the two-photon decay of the 2^{++} light quark state $a_2(1320)$. The systematic errors in the estimation of the $\pi^0\pi^0$ contributions are estimated to be 0.4% and 0.1% for χ_{c0} and χ_{c2}, respectively. All individual systematic errors are listed in Table II. The sums of the systematic errors, added in quadrature are $\pm 4.5\%$ for χ_{c0} and $\pm 5.7\%$ for χ_{c2}.

Our final results for the measured quantities, $\mathcal{B}(\psi(2S) \to \gamma\chi_{c0,c2}) \times \mathcal{B}(\chi_{c0,c2} \to \gamma\gamma)$ are presented in Table III. We use the PDG 08 average results,

$$\begin{aligned} \mathcal{B}(\psi(2S) \to \gamma\chi_{c0}) &= (9.4 \pm 0.4) \times 10^{-2}, \\ \Gamma(\chi_{c0}) &= (10.2 \pm 0.7)\ \mathrm{MeV}, \\ \mathcal{B}(\psi(2S) \to \gamma\chi_{c2}) &= (8.3 \pm 0.4) \times 10^{-2}, \\ \Gamma(\chi_{c2}) &= (2.03 \pm 0.12)\ \mathrm{MeV}, \end{aligned} \tag{6}$$

to derive $\mathcal{B}(\chi_{c0,c2} \to \gamma\gamma)$, $\Gamma_{\gamma\gamma}(\chi_{c0,c2})$, and $\mathcal{R}$. These are also listed in Table III.

By requiring an additional resonance in the spectrum of Fig. 1 corresponding to $\chi_{c1}(^3P_1)$, whose two-photon decay is forbidden by the Landau-Yang theorem [2], we obtain an upper limit at 90% confidence level of $\mathcal{B}(\chi_{c1} \to \gamma\gamma) < 3.5 \times 10^{-5}$, which is nearly 2 orders of magnitude lower than the present limit quoted in PDG 08 [16]. It corresponds to an upper limit at 90% confidence level of $\Gamma_{\gamma\gamma}(\chi_{c1}) < 0.03$ keV.

Our final results are compared to those of previous measurements in Table IV. As mentioned earlier, most of the results for $\Gamma_{\gamma\gamma}(\chi_{cJ})$ in Table IV are from measurements of the *formation* of χ_{cJ} in two-photon fusion. The results listed in Table IV for $\Gamma_{\gamma\gamma}(\chi_{cJ})$ have been updated by using the current PDG [16] values for the branching fractions and widths required for evaluating $\Gamma_{\gamma\gamma}(\chi_{cJ})$ directly from the measured quantities.

From Table IV we notice that our results for $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ have smaller fractional errors than most of the earlier individual measurements, but are in reasonable agreement with the PDG 08 global averages, $\Gamma_{\gamma\gamma}(\chi_{c0}) = (2.40 \pm 0.29)$ keV, $\Gamma_{\gamma\gamma}(\chi_{c2}) = (0.49 \pm 0.05)$ keV. We also note that although there are several simultaneous measurements of $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$, only an earlier CLEO measurement [30] reports the ratio $\mathcal{R}$. To put our result for $\mathcal{R}$ in perspective, we note that the PDG 08 global fits lead to $\mathcal{R}_{\mathrm{PDG}} = 0.21 \pm 0.03$ which is in good agreement with our result, $\mathcal{R} = 0.28 \pm 0.06$.

If the first-order radiative corrections, shown in the square brackets below, are used

TABLE III. Results of the present measurements. The first error is statistical, second is systematic, and third is due to the PDG parameters used. The common systematic errors have been removed in calculating $\mathcal{R}$. $\mathcal{B}_1 \equiv \mathcal{B}(\psi(2S) \to \gamma\chi_{c0,c2})$, $\mathcal{B}_2 \equiv \mathcal{B}(\chi_{c0,c2} \to \gamma\gamma)$, $\Gamma_{\gamma\gamma} \equiv \Gamma_{\gamma\gamma}(\chi_{c0,c2} \to \gamma\gamma)$.

Quantity	χ_{c0}	χ_{c2}
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^5$	$2.17 \pm 0.32 \pm 0.10$	$2.68 \pm 0.28 \pm 0.15$
$\mathcal{B}_2 \times 10^4$	$2.31 \pm 0.34 \pm 0.10 \pm 0.10$	$3.23 \pm 0.34 \pm 0.18 \pm 0.16$
$\Gamma_{\gamma\gamma}$ (keV)	$2.36 \pm 0.35 \pm 0.11 \pm 0.19$	$0.66 \pm 0.07 \pm 0.04 \pm 0.05$
$\mathcal{R}$	$0.278 \pm 0.050 \pm 0.018 \pm 0.031$	

TABLE IV. Compilation of experimental results for two-photon partial widths of χ_{c0} and χ_{c2}.

Experiment [Ref.]	Measured	$\Gamma_{\gamma\gamma}(\chi_{c0})$ keV[a]	$\Gamma_{\gamma\gamma}(\chi_{c2})$ keV[a]	$\mathcal{R}$
E760(1993) [12]	$\mathcal{B}(\bar{p}p \to \chi_{c2}) \times \mathcal{B}_{\gamma\gamma}$		$0.49 \pm 0.12 \pm 0.07$	
E835(2000) [13]	$\mathcal{B}(\bar{p}p \to \chi_{cJ}) \times \mathcal{B}_{\gamma\gamma}$	$1.90 \pm 0.97 \pm 0.21$	$0.40 \pm 0.07 \pm 0.03$	
E835(2004) [14]	$\mathcal{B}(\bar{p}p \to \chi_{c0}) \times \mathcal{B}_{\gamma\gamma}$	$3.09 \pm 0.56 \pm 0.45$		
OPAL(1998) [27]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$		$1.19 \pm 0.32 \pm 0.26$	
L3(1999) [28]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$		$0.69 \pm 0.27 \pm 0.11$	
CLEO(1994) [29]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$		$0.74 \pm 0.21 \pm 0.18$	
CLEO(2001) [30]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 4\pi)$	$3.36 \pm 0.58 \pm 0.47$	$0.56 \pm 0.16 \pm 0.09$	$0.17 \pm 0.06 \pm 0.03$
CLEO(2006) [31]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$		$0.55 \pm 0.06 \pm 0.05$	
Belle(2002) [32]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$		$0.56 \pm 0.05 \pm 0.05$	
Belle(2007) [33]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to K_S^0 K_S^0)$	$2.48 \pm 0.23 \pm 0.35$	$0.48 \pm 0.08 \pm 0.08$	
Belle(2007) [34][b]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 4\pi)$	$2.00 \pm 0.16 \pm 0.28$	$0.44 \pm 0.04 \pm 0.07$	
	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 2\pi 2K)$	$2.17 \pm 0.21 \pm 0.33$	$0.47 \pm 0.05 \pm 0.08$	
	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 4K)$	$2.81 \pm 0.46 \pm 0.49$	$0.60 \pm 0.11 \pm 0.11$	
PDG 08 global fit results		2.40 ± 0.29	0.49 ± 0.05	0.21 ± 0.03
This measurement	$\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ}) \times \mathcal{B}_{\gamma\gamma}$	$2.36 \pm 0.35 \pm 0.22$	$0.66 \pm 0.07 \pm 0.06$	$0.28 \pm 0.05 \pm 0.04$

[a]The first error is statistical. The second error is a systematic error combined in quadrature with the error in the branching fractions and widths used. The results from the literature have been reevaluated by using the branching fractions and total widths from the PDG 08 global fit.
[b]The Belle publication [34] does not report $\Gamma_{\gamma\gamma}(\chi_{c0}, \chi_{c2})$, but only the product branching fractions $\Gamma_{\gamma\gamma}(\chi_{c0}, \chi_{c2}) \times \mathcal{B}(\chi_{c0,c2} \to$ hadrons). We have calculated $\Gamma_{\gamma\gamma}(\chi_{c0}, \chi_{c2})$ by using the PDG 08 [16] values of branching fractions for the individual decays.

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 4(|\Psi'(0)|^2 \alpha_{em}^2/m_c^4) \times [1 - 1.70\alpha_s],$$
$$\Gamma_{\gamma\gamma}(\chi_{c0}) = 15(|\Psi'(0)|^2 \alpha_{em}^2/m_c^4) \times [1 + 0.06\alpha_s],$$

the theoretical prediction is [35]

$$\mathcal{R}_{\rm th}^{(1)} = (4/15)[1 - 1.76\alpha_s].$$

The radiative correction factor for $\Gamma_{\gamma\gamma}(\chi_{c2})$ (for $\alpha_s = 0.32 \pm 0.02$ [16]) is approximately a factor of 2, which strongly suggests possible problems with the radiative corrections. Unfortunately, a measurement of $\Gamma_{\gamma\gamma}(\chi_{c2})$ alone cannot provide further insight into the problem because the charm quark mass m_c and derivative of the wave function at origin $\Psi'(0)$ are not known. However, since both unknowns cancel in the ratio $\mathcal{R}$, a measurement of $\mathcal{R}$ can do so, as noted, for example, by Voloshin [36]. For $\alpha_s = 0.32 \pm 0.02$, the predicted value, which only depends on radiative corrections, is $\mathcal{R}_{\rm th}^{(1)} = 0.116 \pm 0.010$. Our experimental result, $\mathcal{R} = 0.28 \pm 0.06$, together with the $\mathcal{R}_{\rm PDG} = 0.21 \pm 0.03$ leads to the average $\langle\mathcal{R}\rangle = 0.22 \pm 0.03$. This result provides experimental confirmation of the inadequacy of the present first-order radiative corrections, which have been often used to make theoretical predictions of $\Gamma_{\gamma\gamma}(\chi_{cJ})$ and experimental derivations of α_s.

The above experimental results for $\mathcal{R}$, and similar results for several other ratios which can be constructed for χ_{c0} and χ_{c2} decay widths (e.g., hadronic decays), emphasize the need for calculations of radiative corrections to higher orders. Alternatively, as noted by Buchmüller [37], a different choice of the renormalization scheme and renormalization scale should be considered in order to arrive at a more convergent way of specifying the radiative corrections.

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