

Two-Photon Widths of the χ_{cJ} States of Charmonium

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Abstract

Using a data sample of 24.5 million $\psi(2S)$ the reactions $\psi(2S) \rightarrow \gamma\chi_{cJ}$, $\chi_{cJ} \rightarrow \gamma\gamma$ 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 $\mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0}) \times \mathcal{B}(\chi_{c0} \rightarrow \gamma\gamma) = (2.22 \pm 0.32 \pm 0.10) \times 10^{-5}$, and $\mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c2}) \times \mathcal{B}(\chi_{c2} \rightarrow \gamma\gamma) = (2.70 \pm 0.28 \pm 0.15) \times 10^{-5}$. Using values for $\mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0,c2})$ and $\Gamma(\chi_{c0,c2})$ from the literature the two-photon widths are derived to be $\Gamma_{\gamma\gamma}(\chi_{c0}) = (2.53 \pm 0.37 \pm 0.26)$ keV, $\Gamma_{\gamma\gamma}(\chi_{c2}) = (0.60 \pm 0.06 \pm 0.06)$ keV, and $\mathcal{R} \equiv \Gamma_{\gamma\gamma}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c0}) = 0.237 \pm 0.043 \pm 0.034$. The importance of the measurement of \mathcal{R} is emphasized. For the forbidden transition, $\chi_{c1} \rightarrow \gamma\gamma$, an upper limit of $\Gamma_{\gamma\gamma}(\chi_{c1}) < 0.03$ keV is established.

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 onium spectroscopy 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 $\mathcal{R} \equiv \Gamma(^3P_2 \rightarrow \gamma\gamma)/\Gamma(^3P_0 \rightarrow \gamma\gamma)=4/15 \simeq 0.27$ [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. 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 precision.

TABLE I: Potential model predictions for two-photon widths of χ_{c2} and χ_{c0} and the ratio \mathcal{R} derived from them.

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

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

$$\psi(2S) \rightarrow \gamma_1 \chi_{cJ}, \quad \chi_{cJ} \rightarrow \gamma_2 \gamma_3, \quad (1)$$

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 in the literature.

A data sample of 24.5 million $\psi(2S)$ obtained in $48 \text{ pb}^{-1} e^+e^-$ 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 e^+ beam direction with $|\cos\theta| < 0.75$, and no charged particles. An energy-momentum conservation constrained 4C-fit was performed and events with $\chi^2/d.o.f. < 6$ were accepted. 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 .

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. Fig. 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 07 [16]. The radiative transition $\psi(2S) \rightarrow \gamma_1\chi_{c0}$ is, of course, pure E1, and there is strong experimental evidence that the radiative transition $\psi(2S) \rightarrow \gamma_1\chi_{c2}$ is also almost pure E1 [17, 18]. Further, $\gamma_2\gamma_3$ in the decay $\chi_{c2} \rightarrow \gamma_2\gamma_3$ are expected to be produced with pure helicity two amplitudes [5]. With these assumptions the angular distributions are predicted to be [19]

$$\chi_{c0} : dN/d \cos \Theta_1 = 1 + \cos^2 \Theta_1, \quad (2)$$

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

$$\chi_{c2} : dN/d \cos \Theta_1 = 1 - (1/13) \cos^2 \Theta_1. \quad (4)$$

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 $\gamma_2\gamma_3$ axis in the rest frame of $\chi_{c0,c2}$. 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 is large, it is 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 is found that the off- $\psi(2S)$ data are 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]. 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.

The final fit to the $E(\gamma_1)$ spectrum obtained with fixed χ_{c0} and χ_{c2} masses and intrinsic widths [16] is shown in Fig. 1. The $\chi^2/d.o.f. = 41/61$ for the fit. It was found that

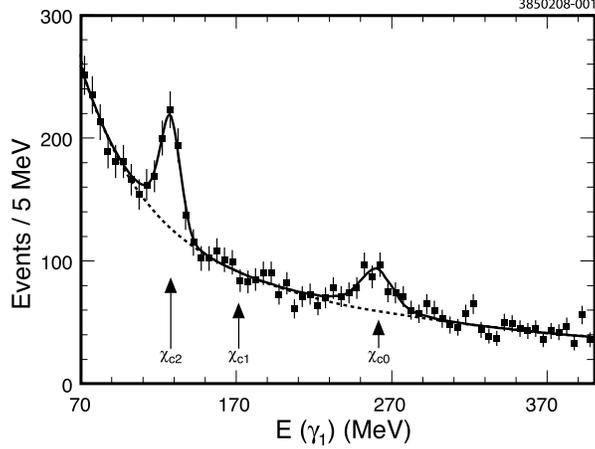


FIG. 1: Fitted spectrum for $E(\gamma_1)$. The expected positions of $E(\gamma_1)$ from χ_{c0} , χ_{c1} , χ_{c2} are marked with arrows.

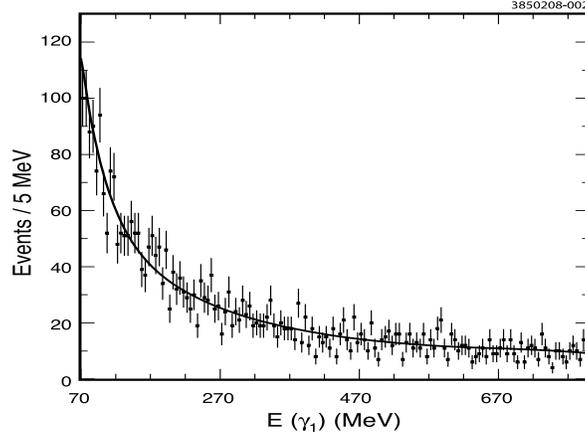


FIG. 2: Background spectrum for $E(\gamma_1)$. The points are from the off- $\psi(2S)$ data. The curve is from fit to the $\psi(3770)$ data.

$N(\chi_{c0})=212\pm 31$ and $N(\chi_{c2})=335\pm 35$. The product branching ratios were determined as $N(\chi_{cJ})/[\epsilon(\chi_{cJ}) \times N(\psi(2S))]$ with the results

$$\begin{aligned}
 & \mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0}) \times \mathcal{B}(\chi_{c0} \rightarrow \gamma\gamma) \\
 & = (2.22 \pm 0.32(\text{stat})) \times 10^{-5}, \\
 & \mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c2}) \times \mathcal{B}(\chi_{c2} \rightarrow \gamma\gamma) \\
 & = (2.70 \pm 0.28(\text{stat})) \times 10^{-5}.
 \end{aligned} \tag{5}$$

Various possible sources of systematic errors in our results were investigated. The number of $\psi(2S)$ produced is determined using the background-subtracted and efficiency-corrected yield of hadronic events following the procedure described in detail in [21]. The background is estimated using the off- $\psi(2S)$ data. The efficiency is estimated by a MC simulation of generic $\psi(2S)$ decays. The systematic uncertainty is determined by varying the hadronic event selection and online trigger criteria by large amounts in both data and MC. It is

found that while the MC determined efficiency changes from 65% to 91% the efficiency-corrected yield changes by no more than 2%, which we include as a systematic error. The neutral trigger efficiency is uncertain by 0.2%. The uncertainty in our MC determination of absolute efficiency for three-photon detection was estimated as $3 \times 0.4\% = 1.2\%$ [22]. The systematic error due to the simulation of the event selection criteria ($\chi^2/d.o.f.$ distribution for 4C fit, acceptance variation, and shower overlap cut) was determined by varying the cuts. 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 [21] convoluted 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 [5] 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 [23] for the two photon decay of the 2^{++} light quark state $a_2(1320)$. 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} .

TABLE II: Estimates of systematic uncertainties. Asterisks denote the systematic sources common to both χ_{c0} and χ_{c2} .

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	-	1.3%
Sum in quadrature	4.5%	5.7%

Our final results for the measured quantities, $\mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0,c2}) \times \mathcal{B}(\chi_{c0,c2} \rightarrow \gamma\gamma)$ are presented in Table III. We use the PDG 07 average results,

$$\begin{aligned}
\mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0}) &= (9.2 \pm 0.4) \times 10^{-2}, \\
\Gamma(\chi_{c0}) &= (10.5 \pm 0.9) \text{ MeV}, \\
\mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c2}) &= (8.8 \pm 0.5) \times 10^{-2}, \\
\Gamma(\chi_{c2}) &= (1.95 \pm 0.13) \text{ MeV},
\end{aligned} \tag{6}$$

to derive $\mathcal{B}(\chi_{c0,c2} \rightarrow \gamma\gamma)$, $\Gamma_{\gamma\gamma}(\chi_{c0,c2})$, 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 the 90% confidence limit $\mathcal{B}(\chi_{c1} \rightarrow \gamma\gamma) < 3.5 \times 10^{-5}$, which is nearly two orders of magnitude lower than the present limit quoted in PDG 07 [16]. It corresponds to the 90% confidence limit $\Gamma_{\gamma\gamma}(\chi_{c1}) < 0.03 \text{ keV}$.

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

TABLE III: Results of the present measurements. 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} . $\mathcal{B}_1 \equiv \mathcal{B}(\psi(2S) \rightarrow \gamma\chi_{c0,c2})$, $\mathcal{B}_2 \equiv \mathcal{B}(\chi_{c0,c2} \rightarrow \gamma\gamma)$, $\Gamma_{\gamma\gamma} \equiv \Gamma_{\gamma\gamma}(\chi_{c0,c2} \rightarrow \gamma\gamma)$.

Quantity	χ_{c0}	χ_{c2}
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^5$	$2.22 \pm 0.32 \pm 0.10$	$2.70 \pm 0.28 \pm 0.15$
$\mathcal{B}_2 \times 10^4$	$2.41 \pm 0.35 \pm 0.11 \pm 0.10$	$3.06 \pm 0.32 \pm 0.17 \pm 0.17$
$\Gamma_{\gamma\gamma}$ (keV)	$2.53 \pm 0.37 \pm 0.11 \pm 0.24$	$0.60 \pm 0.06 \pm 0.03 \pm 0.05$
\mathcal{R}	$0.237 \pm 0.043(\text{stat}) \pm 0.015(\text{syst}) \pm 0.031(\text{PDG})$	

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 $\Gamma_{\gamma\gamma}(\chi_{cJ})$ from the directly measured quantities.

From Table IV we notice that although the individual results for $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$ show large variations, their average agrees with our results.

We note in Table IV that there are few simultaneous measurements of $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$, and even in those few cases \mathcal{R} is seldom calculated. To put our result for \mathcal{R} in perspective, we have calculated \mathcal{R} for all simultaneous measurements in Table IV. A weighted average of these is $\mathcal{R}=0.20 \pm 0.03$ which is in good agreement with our result, $\mathcal{R}=0.24 \pm 0.06$.

The theoretical pQCD prediction for \mathcal{R} is [32]

$$\begin{aligned} \mathcal{R}_{th} &= (4/15) [1 - 1.76\alpha_s], \quad \text{since} \\ \Gamma_{\gamma\gamma}(\chi_{c2}) &= 4(|\Psi'(0)|^2 \alpha_{em}^2 / m_c^4) \times [1 - 1.70\alpha_s], \\ \Gamma_{\gamma\gamma}(\chi_{c0}) &= 15(|\Psi'(0)|^2 \alpha_{em}^2 / m_c^4) \times [1 + 0.06\alpha_s]. \end{aligned}$$

where the quantities in the square brackets are the first order radiative correction factors.

The radiative correction factor for $\Gamma_{\gamma\gamma}(\chi_{c2})$ (for $\alpha_s \simeq 0.32$ [16]) is nearly a factor of two, 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 [33]. For $\alpha_s=0.32$, the predicted value, which only depends on radiative corrections, is $\mathcal{R}_{th}=0.12$. Our experimental result, $\mathcal{R}_{exp}=0.24 \pm 0.06$, together with the other determinations of \mathcal{R} in Table IV leads to the average $\langle \mathcal{R}_{exp} \rangle = 0.20 \pm 0.02$. 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} emphasize the need for calculations of radiative corrections to higher orders. Alternatively, as noted by Buchmüller [34], 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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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*	$\Gamma_{\gamma\gamma}(\chi_{c2})$ keV*	\mathcal{R}
E760(1993) [12]	$\mathcal{B}(\bar{p}p \rightarrow \chi_{c2}) \times \mathcal{B}_{\gamma\gamma}$	-	$0.47 \pm 0.12 \pm 0.07$	-
E835(2000) [13]	$\mathcal{B}(\bar{p}p \rightarrow \chi_{cJ}) \times \mathcal{B}_{\gamma\gamma}$	$2.01 \pm 1.03 \pm 0.24$	$0.39 \pm 0.07 \pm 0.03$	$0.20 \pm 0.11 \pm 0.03$
E835(2004) [14]	$\mathcal{B}(\bar{p}p \rightarrow \chi_{c0}) \times \mathcal{B}_{\gamma\gamma}$	$3.3 \pm 0.6 \pm 0.5$	-	-
OPAL(1998) [24]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \rightarrow \gamma J/\psi)$	-	$1.19 \pm 0.32 \pm 0.26$	-
L3(1999) [25]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \rightarrow \gamma J/\psi)$	-	$0.69 \pm 0.27 \pm 0.11$	-
CLEO(1994) [26]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \rightarrow \gamma J/\psi)$	-	$0.74 \pm 0.21 \pm 0.18$	-
CLEO(2001) [27]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \rightarrow \gamma J/\psi)$	$3.09 \pm 0.54 \pm 0.44$	$0.51 \pm 0.14 \pm 0.09$	$0.17 \pm 0.06 \pm 0.04$
CLEO(2006) [28]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \rightarrow \gamma J/\psi)$	-	$0.55 \pm 0.06 \pm 0.05$	-
Belle(2002) [29]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \rightarrow \gamma J/\psi)$	-	$0.56 \pm 0.05 \pm 0.05$	-
Belle(2007) [30]	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \rightarrow K_S^0 K_S^0)$	$2.53 \pm 0.23 \pm 0.40$	$0.46 \pm 0.08 \pm 0.09$	$0.18 \pm 0.03 \pm 0.04$
Belle(2007) [31]**	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \rightarrow 4\pi)$	$1.84 \pm 0.15 \pm 0.27$	$0.40 \pm 0.04 \pm 0.07$	$0.22 \pm 0.03 \pm 0.05$
	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \rightarrow 2\pi 2K)$	$2.07 \pm 0.20 \pm 0.40$	$0.44 \pm 0.04 \pm 0.16$	$0.21 \pm 0.03 \pm 0.09$
	$\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \rightarrow 4K)$	$2.88 \pm 0.47 \pm 0.53$	$0.62 \pm 0.12 \pm 0.12$	$0.21 \pm 0.05 \pm 0.06$
This measurement	$\mathcal{B}(\psi(2S) \rightarrow \gamma \chi_{cJ}) \times \mathcal{B}_{\gamma\gamma}$	$2.53 \pm 0.37 \pm 0.26$	$0.60 \pm 0.06 \pm 0.06$	$0.24 \pm 0.04 \pm 0.03$
Averages (weighted by total errors)		$2.31 \pm 0.10 \pm 0.12$	$0.51 \pm 0.02 \pm 0.02$	$0.20 \pm 0.01 \pm 0.02$

* The first error is statistical. The second error is 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 current PDG values for branching fractions and total widths. For these results the errors in \mathcal{R} have been evaluated without taking into account possible correlations in the systematic errors in $\Gamma_{\gamma\gamma}(\chi_{c0})$ and $\Gamma_{\gamma\gamma}(\chi_{c2})$.

** The Belle publication gives only the product branching fractions $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c0,c2} \rightarrow \text{hadrons})$. We have calculated $\Gamma_{\gamma\gamma}$ and \mathcal{R} by using the PDG 07 [16] values of branching fractions for the individual decays.

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