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Physics Letters B 584 (2004) 16–21
PHYSICS LETTERS B
www.elsevier.com/locate/physletb

Measurement of the two photon decay of the $\chi_{c_0}(1\,^3\mathrm{P}_0)$ state of charmonium

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Received 2 December 2003; received in revised form 8 January 2004; accepted 14 January 2004

Editor: L. Rolandi

Abstract

We report on the decay to two photons of the $\chi_{c_0}(1\,^3\mathrm{P}_0)$ charmonium resonance formed in $\bar{p}p$ interactions at Fermilab experiment E835. We have measured the product of branching ratios $BR(\chi_{c_0} \to \bar{p}p) \times BR(\chi_{c_0} \to \gamma\gamma) = (6.52 \pm 1.18(\mathrm{stat})^{+0.48}_{-0.72}(\mathrm{sys})) \times 10^{-8}$. Using values from the 2002 PDG, this measurement leads to the partial width $\Gamma(\chi_{c_0} \to \gamma\gamma) = 2.9 \pm 0.9$ keV.

One of the first applications of perturbative QCD was the calculation of the decay rates of heavy quarkonia to two photons. Observations of these processes remain useful tests of heavy-quark interaction models.

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0370-2693/$ – see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.physletb.2004.01.024

We report results of a measurement of two-photon decays of χ_{c_0} mesons produced in $\bar{p}p$ annihilations at the Fermilab Antiproton Source.

Fermilab experiment E835 was designed to study charmonium resonances formed in $\bar{p}p$ annihilations using the finely-tunable antiproton beam in the Antiproton Source. A particular advantage of studying quarkonia in $\bar{p}p$ annihilations is that all quantum states can be formed. This allows mass and width determinations of charmonium resonances from excitation curves generated by changing the $\bar{p}$ beam energy, without having to make precise measurements of the momenta of the outgoing particles.

In E835, a jet of molecular-hydrogen gas intercepted the antiproton beam. The beam was tuned to the desired energy, and specific resonance decay modes were identified from the decay products. The momentum spread of the beam was typically $\sigma_p/p \sim 10^{-4}$, giving a rms center-of-mass energy spread of ~ 350 keV. The absolute rms center-of-mass energy uncertainty was ~ 200 keV.

We report a measurement of the decay of the $\chi_{c_0}(1\,{}^3\mathrm{P}_0)$ charmonium resonance to two photons, based on a 32 pb^{-1} data sample collected in the year 2000 at 17 different beam energy settings. We previously determined and reported the mass and width of the $\chi_{c_0}(1\,{}^3\mathrm{P}_0)$ using $J/\psi\gamma$ events [1]. In that article we tabulated the data-taking, consisting of ~ 20 pb^{-1} taken across the χ_{c_0} resonance, and ~ 12 pb^{-1} taken away from the resonance to measure backgrounds.

The $\bar{p}p$ inelastic cross section at charmonium energies is several orders of magnitude larger than the charmonium-formation cross section. In order to suppress the hadronic background, the E835 detector was optimized to select electromagnetic final states. As the detector is described in detail elsewhere [2], we limit our description to the components used in this analysis. The outermost detector (CCAL) consisted of 1280 lead-glass counters arranged in 20 rings of 64 blocks. These surrounded the interaction region, covering the full azimuth (ϕ) for polar angles (θ) between 10° to 70°. Both pulse-height and timing information were recorded. The CCAL efficiently detected photons with energies above 20 MeV. The average energy resolution of the detector for electrons and photons was $\sigma_E = 6\%/\sqrt{E} + 1.4\%$. The average angular resolution was $\sigma_\theta = 6$ mrad and $\sigma_\phi = 11$ mrad. For the two-photon analysis discussed here, we used a two-branch trigger system to select neutral events having either two large back-to-back energy deposits, or at least 80% of the total available energy deposited in the CCAL. Two (of three) concentric cylindrical scintillating hodoscopes within the CCAL and occupying the same angular region, called H1 and H2′, and a scintillating hodoscope in the forward direction were used to veto on charged particles for neutral triggers. The absolute luminosity was obtained by measuring the $\bar{p}p$ forward elastic scattering through the detection of recoil protons at $\sim 90°$ in the lab frame, using solid state detectors.

The positions and energies of photons are reconstructed using signals from the individual elements of the CCAL. For this analysis, the energy in a cluster of 9 blocks is required to be greater than 20 MeV. The method for forming the clusters is described in [2]. In order to reduce accidental background, each γ candidate is required to be within 10 ns of the nominal event time derived from the trigger, and events are rejected if there are more than two clusters within the timing window. Low energy clusters (< 70 MeV) often do not have timing information. If there are clusters without timing information in the event, we require that the invariant mass for each of these and each gamma candidate is farther than 35 MeV from the π^0 mass. A four-constraint kinematic fit is then performed, which is required to yield a nominal confidence level $> 10\%$.

The primary background in the $\gamma\gamma$ channel comes from $\pi^0\gamma$ and $\pi^0\pi^0$ events where, respectively, one or two of the photons are not detected. A π^0 can mimic a single photon in two different ways. In a highly asymmetrical decay, the detected photon carries most of the π^0 energy and the low energy photon is either below the detection threshold or outside of the detector acceptance. In a symmetrical decay, the showers from the two photons may coalesce and be misidentified as a single photon.

The background from $\pi^0\gamma$ and $\pi^0\pi^0$ events is calculated for each energy point. The $\pi^0\gamma$ and $\pi^0\pi^0$ cross sections are obtained from our data. A Monte Carlo simulation of the detector is used to determine the probability that a $\pi^0\pi^0$ or $\pi^0\gamma$ event mimics a $\gamma\gamma$ event. The probability that a π^0 mimics a single photon is $\sim 1.5\%$ near 90° in the center-of-mass frame and is greater for forward π^0. The background rate is computed from the $\pi^0\pi^0$ and $\pi^0\gamma$ cross sections

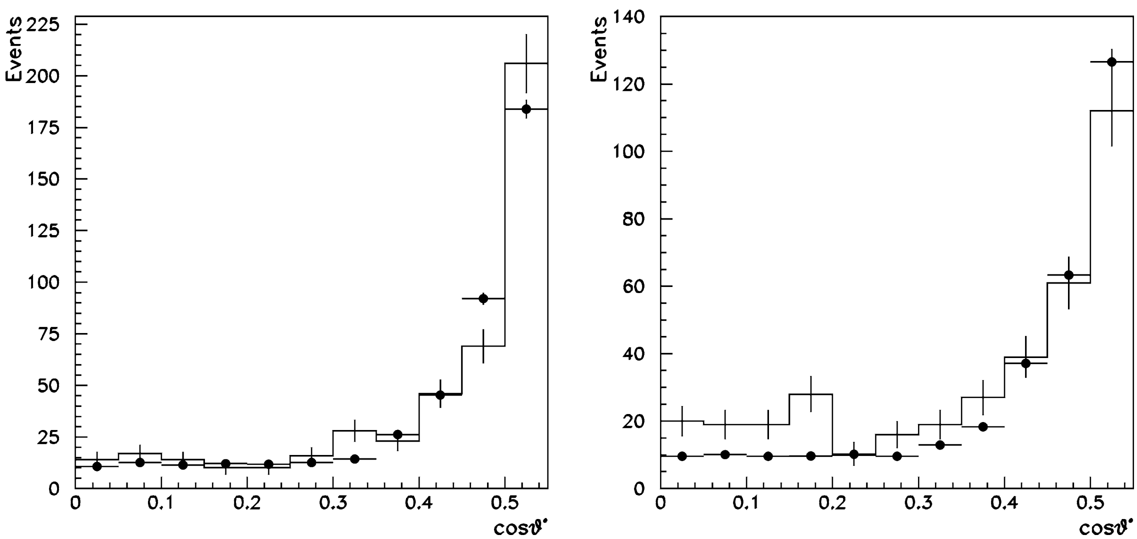

Fig. 1. The angular distribution of the selected $\gamma\gamma$ events (histogram) and the background calculated from the measured $\pi^0\pi^0$ and $\pi^0\gamma$ cross sections (solid dots). The left plot contains events from background energies, the right from on-resonance energies.

and their respective probabilities to mimic a $\gamma\gamma$ event. This method is described in greater detail in Ref. [3]. The statistical uncertainty of the background cross section is 6–10% for these data. We estimate the systematic uncertainty as 5%, due mainly to a small difference in the coalesced-π^0 reconstruction efficiency in the Monte Carlo compared to data.

The $\gamma\gamma$ efficiency is

$$\epsilon_{\gamma\gamma} = \epsilon_{\mathrm{trig}}\epsilon_{\mathrm{anal}}(1 - P_{\mathrm{conv}})^2, \tag{1}$$

where ϵ_{trig} is the neutral hardware trigger efficiency and P_{conv} is the probability that a photon converts in the innermost elements of the detector and triggers the charged veto. The two branches of the neutral hardware trigger each had very high efficiency (~ 0.99) [2]. For monitoring purposes, 1% of the events in each branch were passed to a separate data set, reducing ϵ_{trig} to ~ 0.98 [3]. P_{conv} is determined from a study of $\pi^0\pi^0$ events [4]. The mean value of P_{conv} for $\chi_{c_0} \to \gamma\gamma$ is 0.0116 ± 0.0004.

The geometrical and cut efficiencies are included in ϵ_{anal}, which is calculated using the detector simulation, and includes the effects of dead calorimeter channels as well as stack-by-stack variations in the calibration. The effect of overlapping events due to extraneous interactions close-in-time to the signal event is included in ϵ_{anal}, by overlaying the data from randomly-timed triggers onto each simulated event. Efficiencies are calculated for each energy point in order to take into account the different run conditions. The $\gamma\gamma$ efficiency was typically 0.7 for topologies within the central calorimeter acceptance. The method of using the detector simulation to calculate $\gamma\gamma$ efficiencies was checked previously [5] using $J/\psi \to e^+e^-$ events.

The angular distribution of the background from $\pi^0\pi^0$ and $\pi^0\gamma$ events is forward-peaked, as shown in Fig. 1, in contrast to the isotropic decay of the χ_{c_0}. To maximize the signal-to-background ratio, we limit the acceptance to the central region. While $\cos\theta^* < 0.4$ was shown to be the optimal cut for estimating the $\gamma\gamma$ branching ratio in our previous work [5], which neglected interference, we find that, because of the apparent presence of an interfering $\bar{p}p \to \gamma\gamma$ continuum process, a more suitable angular cut is $\cos\theta^* < 0.2$ as discussed below.

To determine the χ_{c_0} branching ratio to two photons, we fit the measured cross section to a Breit–Wigner resonance plus a term to account for the interfering continuum process. The background from $\pi^0\pi^0$ and $\pi^0\gamma$ (σ_{bkgd}), for each energy point, is fixed to its calculated value. The statistical error for the background cross section is added in quadrature to that of the measured cross section.

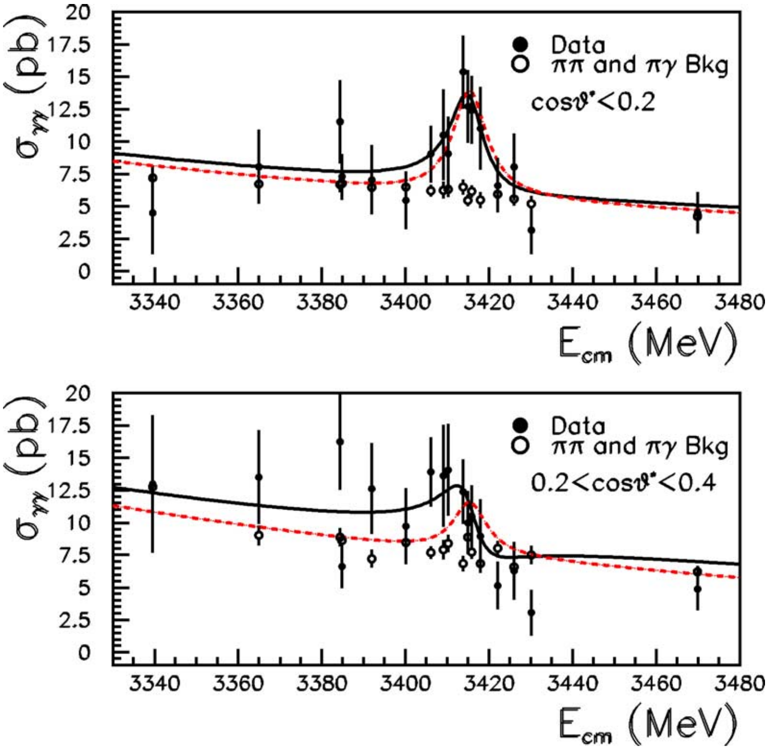

Fig. 2. The $\gamma\gamma$ data (solid) and calculated background (open) for angular ranges $0 < \cos\theta^* < 0.2$ (top) and $0.2 < \cos\theta^* < 0.4$ (bottom). The best fit results without (dashed line) and with (solid line) interference are also included. The error bars are statistical.

We fit to

$$\sigma_{\text{fit}} = \sigma_{\text{bkgd}} + \int_{\cos\theta^*_{\min}}^{\cos\theta^*_{\max}} \left| Ae^{i\delta} - \frac{B}{x+i} \right|^2 d\cos\theta^*, \qquad (2)$$

where

$$x \equiv \frac{2(M_{\chi_{c_0}} - \sqrt{s}\,)}{\Gamma_{\chi_{c_0}}}. \qquad (3)$$

The mass and width are fixed to the values measured by E835 in the $\chi_{c_0} \to J/\psi\gamma$ channel, 3415.4 ± 0.4 MeV and 9.8 ± 1.0 MeV, respectively [1]. The quantity B is given by

$$B^2 = \frac{\pi}{k^2} BR(\chi_{c_0} \to \bar{p}p) BR(\chi_{c_0} \to \gamma\gamma), \qquad (4)$$

$$k^2 = \frac{M^2_{\chi_{c_0}} - 4m_p^2}{4}. \qquad (5)$$

The data are fit both with and without the interfering continuum term, in two different angular intervals, $\cos\theta^* < 0.2$ and $0.2 < \cos\theta^* < 0.4$. The data and fits are shown in Fig. 2. For the interval $0 < \cos\theta^* < 0.2$, the Breit–Wigner component of the signal decreases by 8.3% and the χ^2/NDF decreases from $8.3/15$ to $6.9/13$ when the continuum and interference terms are included. For $0.2 < \cos\theta^* < 0.4$, χ^2/NDF decreases from $32/15$ to $18/13$ with continuum and interference. The data are compatible with no significant interference for the interval $\cos\theta^* < 0.2$ but potentially significant interference for the interval $0.2 < \cos\theta^* < 0.4$. We therefore restrict the fit region to $\cos\theta^* < 0.2$ and omit the continuum and interference terms. Our result is

$$BR(\chi_{c_0} \to \bar{p}p) \times BR(\chi_{c_0} \to \gamma\gamma) = \left(6.52 \pm 1.18(\text{stat})^{+0.48}_{-0.72}(\text{sys})\right) \times 10^{-8}. \qquad (6)$$

The systematic errors are summarized in Table 1. Those from uncertainties in the χ_{c_0} mass and width are obtained by fixing these parameters to $\pm 1\sigma$ of their nominal values and refitting. The systematic error due to the background uncertainty is found by

Table 1
Systematic errors in the $\bar{p}p \to \chi_{c0} \to \gamma\gamma$ branching ratio product and in the ratio $\Gamma(\chi_{c0} \to \gamma\gamma)/\Gamma(\chi_{c0} \to \psi\gamma)$

Error source	$BR(\chi_{c0} \to \gamma\gamma)$ (%)	$\frac{\Gamma(\chi_{c0}\to\gamma\gamma)}{\Gamma(\chi_{c0}\to\psi\gamma)}$ (%)
χ_{c0} mass	± 0.6	–
χ_{c0} width	± 3.2	–
Background correction	± 6.0	± 6.0
Interference	-8.3	-8.3
Luminosity	± 2.5	–
Efficiency	< 1	< 1
$BR(\psi \to e^+e^-)$	–	± 1.7
Total	$^{+7.3}_{-11.0}$	$^{+6.2}_{-10.4}$

varying the background level in both directions by its 5% systematic uncertainty and refitting. In each case we take the error as the change in the product of branching ratios. The systematic error resulting from neglecting resonance-continuum interference is taken as the -8.3% decrease obtained when interference is included. There is a $\pm 2.5\%$ systematic error in the absolute luminosity measurement [2]. We estimate the systematic error in ϵ_{anal} by using the detector simulation. By varying the values of the confidence-level, timing, and π^0-invariant-mass cuts, this error is determined to be $< 1\%$.

Although our primary result is the product of branching ratios, we report the $\gamma\gamma$ partial width in order to compare with previous measurements and theoretical predictions. Using $BR(\chi_{c0} \to \bar{p}p) = (2.2 \pm 0.5) \times 10^{-4}$ from the 2002 PDG [6] and $\Gamma_{\chi_{c0}} = 9.8 \pm 1.0$ MeV measured by E835 [1] we obtain

$$\Gamma_{\gamma\gamma} = 2.90 \pm 0.52(\text{stat})^{+0.19}_{-0.31}(\text{sys}) \pm 0.66\big(BR(\chi_{c0} \to \bar{p}p)\big) \pm 0.30(\Gamma_{\chi_{c0}})\ \text{keV}. \tag{7}$$

Fig. 3 summarizes the previous partial-width determinations (Table 2) and the theoretical predictions (Table 3).

Using these data and those reported in [1], we determine the ratio $\Gamma(\chi_{c0} \to \gamma\gamma)/\Gamma(\chi_{c0} \to \psi\gamma)$. This ratio will be useful together with a future high-statistics measurement by BaBar and/or Belle of $\Gamma(\chi_{c0} \to \gamma\gamma)\Gamma(\chi_{c0} \to \psi\gamma)$ for the separate determination of $\Gamma(\chi_{c0} \to \gamma\gamma)$ and $\Gamma(\chi_{c0} \to \psi\gamma)$. Because of common factors in the numerator and denominator, uncertainties in the luminosity measurement and χ_{c0} mass, width and branching fraction to $\bar{p}p$ do not contribute to the systematic error for the partial-width ratio, and contributions from acceptance and efficiency uncertainties are reduced. We use only the nine data points in the center-of-mass energy range $3406 \leqslant \sqrt{s} \leqslant 3426$ MeV, representing 18.84 pb^{-1}, and find

$$\frac{\Gamma(\chi_{c0} \to \gamma\gamma)}{\Gamma(\chi_{c0} \to \psi\gamma)} = 0.022 \pm 0.004(\text{stat})^{+0.001}_{-0.002}(\text{sys}). \tag{8}$$

The systematic errors are given in Table 1.

Within the framework of perturbative QCD, factors containing the charmonium wave function cancel in the ratio of the $\gamma\gamma$ and gluon–gluon partial widths, leaving only terms containing the electromagnetic and strong coupling constants. This ratio is given, with (large) lowest order gluonic radiative corrections, by [7]

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}} = \frac{8\alpha^2}{9\alpha_s^2} \frac{[1 + \frac{0.2}{\pi}\alpha_s]}{[1 + \frac{9.5}{\pi}\alpha_s]}. \tag{9}$$

The partial width of χ_{c0} to two gluons is 99% of the total width; the balance is due to radiative decays. By taking $\alpha_s = 0.32$ [6] and the E835 χ_{c0} width of 9.8 ± 1.0 MeV, the PQCD prediction for the $\gamma\gamma$ partial

Table 2
Previous determinations of the partial width $\chi_{c0} \to \gamma\gamma$. The partial widths from CBALL(85) and E835(99) are obtained using branching ratios from the 2002 PDG [6]

	Method	$\Gamma_{\chi_{c0}\to\gamma\gamma}$ (keV)
CBALL(85) ([8])	$\psi' \to \chi_{c0}\gamma,\ \chi_{c0} \to \gamma\gamma$	4.0 ± 2.8
CLEO(95) ([9])	$\gamma\gamma \to \chi_{c0} \to \pi^+\pi^-\pi^+\pi^-$	2.6 ± 1.1
E835(99) ([5])	$\frac{\chi_{c0}\to\gamma\gamma}{\chi_{c0}\to J/\psi\gamma}$	1.5 ± 0.8
CLEO(01) ([10])	$\gamma\gamma \to \chi_{c0} \to \pi^+\pi^-\pi^+\pi^-$	3.76 ± 1.85
E835(03)	$\bar{p}p \to \chi_{c0} \to \gamma\gamma$	2.9 ± 0.9

Table 3
Theoretical predictions for the partial width $\chi_{c0} \to \gamma\gamma$

	$\Gamma_{\chi_{c0}\to\gamma\gamma}$ (keV)
Novikov et al. [11]	2.7–5.4
Barnes [12]	1.56
Bodwin et al. [13]	6.7 ± 2.8
Huang et al. [14]	3.7 ± 1.1
Munz [15]	1.39 ± 0.16
Gupta et al. [16]	6.38
	8.13 (alternate theory)
Fajfer et al. [17]	4.6
Ebert et al. [18]	2.9

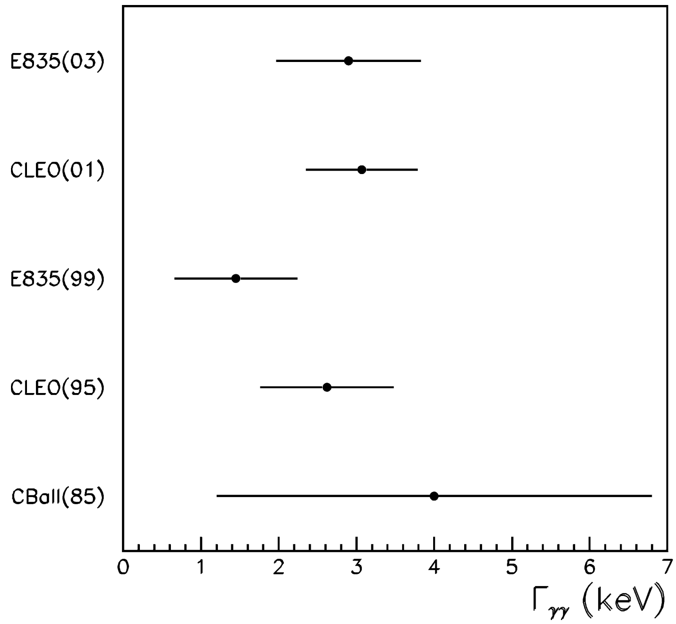

Fig. 3. Summary of $\chi_{c_0} \to \gamma\gamma$ measurements. The partial widths from Crystal Ball and E835 are obtained using branching ratios from the 2002 PDG [6]. In the 2002 PDG, individual branching ratios are extracted by fitting all ψ' and χ measurements simultaneously [19]. Thus, the values for partial widths from previous experiments are not independent.

width is

$$\Gamma_{\gamma\gamma,\mathrm{PQCD}} = 2.35 \pm 0.24\ \mathrm{keV}, \tag{10}$$

in agreement with our observation.

Acknowledgements

We are grateful for the technical support provided by Fermilab, in particular the Beams Division's Antiproton Source Department, and by the staffs of our institutions. This research is supported by the US Department of Energy and the Italian Istituto Nazionale di Fisica Nucleare.

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