CLEO CONF95-26

July 13, 1995

MEASUREMENTS OF THE TWO-PHOTON WIDTHS OF THE CHARMONIUM STATES η_c, χ_{c0} AND χ_{c2}.

G. Crawford,[1] J.E. Duboscq,[1] R. Fulton,[1] D. Fujino,[1] K.K. Gan,[1] K. Honscheid,[1] H. Kagan,[1] R. Kass,[1] J. Lee,[1] M. Sung,[1] C. White,[1] A. Wolf,[1] M.M. Zoeller,[1] X. Fu,[2] B. Nemati,[2] W.R. Ross,[2] P. Skubic,[2] M. Wood,[2] M. Bishai,[3] J. Fast,[3] E. Gerndt,[3] J.W. Hinson,[3] T. Miao,[3] D.H. Miller,[3] M. Modesitt,[3] E.I. Shibata,[3] I.P.J. Shipsey,[3] P.N. Wang,[3] L. Gibbons,[4] S.D. Johnson,[4] Y. Kwon,[4] S. Roberts,[4] E.H. Thorndike,[4] T.E. Coan,[5] J. Dominick,[5] V. Fadeyev,[5] I. Korolkov,[5] M. Lambrecht,[5] S. Sanghera,[5] V. Shelkov,[5] T. Skwarnicki,[5] R. Stroynowski,[5] I. Volobouev,[5] G. Wei,[5] M. Artuso,[6] M. Gao,[6] M. Goldberg,[6] D. He,[6] N. Horwitz,[6] S. Kopp,[6] G.C. Moneti,[6] R. Mountain,[6] F. Muheim,[6] Y. Mukhin,[6] S. Playfer,[6] S. Stone,[6] X. Xing,[6] J. Bartelt,[7] S.E. Csorna,[7] V. Jain,[7] S. Marka,[7] D. Gibaut,[8] K. Kinoshita,[8] P. Pomianowski,[8] B. Barish,[9] M. Chadha,[9] S. Chan,[9] D.F. Cowen,[9] G. Eigen,[9] J.S. Miller,[9] C. O'Grady,[9] J. Urheim,[9] A.J. Weinstein,[9] F. Würthwein,[9] D.M. Asner,[10] M. Athanas,[10] D.W. Bliss,[10] W.S. Brower,[10] G. Masek,[10] H.P. Paar,[10] M. Sivertz,[10] J. Gronberg,[11] C.M. Korte,[11] R. Kutschke,[11] S. Menary,[11] R.J. Morrison,[11] S. Nakanishi,[11] H.N. Nelson,[11] T.K. Nelson,[11] C. Qiao,[11] J.D. Richman,[11] D. Roberts,[11] A. Ryd,[11] H. Tajima,[11] M.S. Witherell,[11] R. Balest,[12] K. Cho,[12] W.T. Ford,[12] M. Lohner,[12] H. Park,[12] P. Rankin,[12] J.G. Smith,[12] J.P. Alexander,[13] C. Bebek,[13] B.E. Berger,[13] K. Berkelman,[13] K. Bloom,[13] T.E. Browder,[13*] D.G. Cassel,[13] H.A. Cho,[13] D.M. Coffman,[13] D.S. Crowcroft,[13] M. Dickson,[13] P.S. Drell,[13] D.J. Dumas,[13] R. Ehrlich,[13] R. Elia,[13] P. Gaidarev,[13] R.S. Galik,[13] M. Garcia-Sciveres,[13] B. Gittelman,[13] S.W. Gray,[13] D.L. Hartill,[13] B.K. Heltsley,[13] S. Henderson,[13] C.D. Jones,[13] S.L. Jones,[13] J. Kandaswamy,[13] N. Katayama,[13] P.C. Kim,[13] D.L. Kreinick,[13] T. Lee,[13] Y. Liu,[13] G.S. Ludwig,[13] J. Masui,[13] J. Mevissen,[13] N.B. Mistry,[13] C.R. Ng,[13] E. Nordberg,[13] J.R. Patterson,[13] D. Peterson,[13] D. Riley,[13] A. Soffer,[13] P. Avery,[14] A. Freyberger,[14] K. Lingel,[14] C. Prescott,[14] J. Rodriguez,[14] S. Yang,[14] J. Yelton,[14] G. Brandenburg,[15] D. Cinabro,[15] T. Liu,[15] M. Saulnier,[15] R. Wilson,[15] H. Yamamoto,[15] T. Bergfeld,[16] B.I. Eisenstein,[16] J. Ernst,[16] G.E. Gladding,[16] G.D. Gollin,[16] M. Palmer,[16] M. Selen,[16] J.J. Thaler,[16] K.W. Edwards,[17] K.W. McLean,[17] M. Ogg,[17]

A. Bellerive,[18] D.I. Britton,[18] E.R.F. Hyatt,[18] R. Janicek,[18] D.B. MacFarlane,[18]
P.M. Patel,[18] B. Spaan,[18] A.J. Sadoff,[19] R. Ammar,[20] P. Baringer,[20] A. Bean,[20]
D. Besson,[20] D. Coppage,[20] N. Copty,[20] R. Davis,[20] N. Hancock,[20] S. Kotov,[20]
I. Kravchenko,[20] N. Kwak,[20] Y. Kubota,[21] M. Lattery,[21] M. Momayezi,[21]
J.K. Nelson,[21] S. Patton,[21] R. Poling,[21] V. Savinov,[21] S. Schrenk,[21] R. Wang,[21]
M.S. Alam,[22] I.J. Kim,[22] Z. Ling,[22] A.H. Mahmood,[22] J.J. O'Neill,[22] H. Severini,[22]
C.R. Sun,[22] and F. Wappler[22]

(CLEO Collaboration)

[1]*Ohio State University, Columbus, Ohio, 43210*

[2]*University of Oklahoma, Norman, Oklahoma 73019*

[3]*Purdue University, West Lafayette, Indiana 47907*

[4]*University of Rochester, Rochester, New York 14627*

[5]*Southern Methodist University, Dallas, Texas 75275*

[6]*Syracuse University, Syracuse, New York 13244*

[7]*Vanderbilt University, Nashville, Tennessee 37235*

[8]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061*

[9]*California Institute of Technology, Pasadena, California 91125*

[10]*University of California, San Diego, La Jolla, California 92093*

[11]*University of California, Santa Barbara, California 93106*

[12]*University of Colorado, Boulder, Colorado 80309-0390*

[13]*Cornell University, Ithaca, New York 14853*

[14]*University of Florida, Gainesville, Florida 32611*

[15]*Harvard University, Cambridge, Massachusetts 02138*

[16]*University of Illinois, Champaign-Urbana, Illinois, 61801*

[17]*Carleton University, Ottawa, Ontario K1S 5B6 and the Institute of Particle Physics, Canada*

[18]*McGill University, Montréal, Québec H3A 2T8 and the Institute of Particle Physics, Canada*

[19]*Ithaca College, Ithaca, New York 14850*

[20]*University of Kansas, Lawrence, Kansas 66045*

[21]*University of Minnesota, Minneapolis, Minnesota 55455*

[22]*State University of New York at Albany, Albany, New York 12222*

ABSTRACT

Using the CLEO-II detector at the CESR e^+e^- storage ring running at the center-of-mass energy around 10.6 GeV, we have studied exclusive production of charmonium states in two-photon collisions. Employing a dataset comprising 3.0 fb^{-1} we have searched for decays of the η_c, χ_{c0} and χ_{c2} mesons resulting in four charged hadrons. We report on the measurements of the cross sections and two-photon widths of these charmonium states.

---

*Permanent address: University of Hawaii at Manoa

1. Introduction

In this paper we present the results of a study[1] of charmonium states exclusively produced in two-photon collisions. The processes considered here are $e^+e^- \to e^+e^- R_{c\bar{c}}$, where $R_{c\bar{c}}$ is either η_c, χ_{c0} or χ_{c2} mesons. We measure their production rates when neither the scattered electron nor the positron is detected ("untagged" mode). In these processes a meson is coupled to two space-like photons one emitted by the electron, the other by the positron. From the measured production rates we obtain two-photon widths of the mesons. The following decay channels are used in this study: $\eta_c \to K_s^0 K^\pm \pi^\mp$, $\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-$ and $\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-$. We also search for the η_c decaying into four charged pions.

2. The Detector

A brief description of the major components of the CLEO-II detector[2] and its trigger system[3] can be found in these proceedings.[4] Additional features of the detector relevant to this analysis are: Charged particle identification provided by measurements of ionization losses in the drift chamber (dE/dx) and time-of-flight measurements from scintillation counters; Electron identification making use of the dE/dx and E/p ratio, where E is the energy of the cluster produced by the electron candidate in the calorimeter and p is the magnitude of the charged track momentum measured using the drift chambers; Muon identification uses the depth of particle penetration into the hadron filter. This analysis utilizes data recorded with triggers which are designed to be efficient for events containing multiple charged tracks.

3. The Event Selection

In order to select event candidates we require that the following selection criteria be satisfied.

- There are exactly four charged tracks with zero net charge.
- The root-mean-squared residual of the hits associated with each track is less than 0.4 mm.
- The total detected energy is less than 6.0 GeV.
- The total amount of energy collected in extra cluster(s)[4] not associated with any of the charge tracks is less than 500 MeV for the $K_s^0 K^\pm \pi^\mp$ mode and less than 650 MeV for the four charged pions mode.
- There are no particles identified as electrons, positrons or muons.

Additional criteria specific to the considered decay channel are discussed in the next two sections.

4. The $\eta_c \to K_s^0 K^\pm \pi^\mp$ Decay Channel

The decay $K_s^0 \to \pi^+\pi^-$ is identified taking advantage of the large K_s^0 decay length ($c\tau = 2.675$ cm). We look for pairs of oppositely charged tracks intersecting at a transverse distance (*i.e.* projected distance in the plane perpendicular to the beam axis) greater than 1 mm from the primary interaction point. The momentum of each pair is calculated using the track momenta evaluated at the secondary vertex. The energy is calculated assuming that tracks are produced by pions. The invariant mass of each pair is then calculated. The resulting mass spectrum in Fig.1a shows clear evidence of K_s^0 decays.[a] A pair is accepted as a K_s^0 candidate if its invariant mass falls within 12.0 MeV/c^2 of the peak position. We reject events if the two remaining tracks are consistent with a K_s^0 decay: *i.e.* if their invariant mass falls within 12.0 MeV/c^2 of the peak position of the previously discussed distribution. To supress beam-gas background events and to select events of reasonable quality we require that the two tracks recoiling against the K_s^0 come from the nominal interaction region: their closest approach to the primary interaction point is less than 50 mm in the longitudinal direction and less than 5 mm in the transverse plane. These tracks are assigned the K and π masses and the $K_s^0 K^\pm \pi^\mp$ mass value is calculated for each of the two possible mass assignments. The upper tail probability of the χ^2

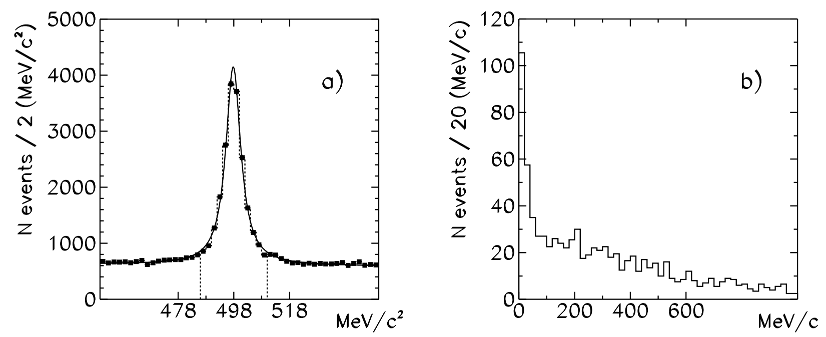

Fig. 1. a) The invariant mass spectrum for the K_s^0 candidates in four-prong events. The curve shows the result of the fit described in the text. b) The transverse momentum ($p_\perp$) distribution for the $K_s^0 K^\pm \pi^\mp$ candidates with the invariant mass from 2.7 GeV/c^2 to 3.3 GeV/c^2.

distribution[5] ($P_{\rm utp}$) is calculated for each mass assignment using TOF and dE/dx

---

[a]The position of the peak in the mass distribution is obtained by fitting this distribution with a Breit-Wigner function for the signal and a constant for the background.

information. In the ideal case, the correct choice of particle combinations produces a uniform $P_{\rm utp}$ distribution while incorrect particle combinations tend to congregate near zero. To suppress unwanted background events which do not contain charged kaons $P_{\rm utp}$ is required to be greater than 0.05. Most candidates fail this condition while the remaining events are dominated by a single acceptable mass assignment. Events are given a net weight of one. For events with two acceptable combinations, each possibility is given a weight proportional to its value of $P_{\rm utp}$.

In the two-photon untagged events substantial energy and momentum are carried away by the electron and positron scattered at small angles. However, since the transverse momenta of scattered electrons are small, that of the hadronic system should also be small. Hence, the distribution of the transverse momentum of the hadronic system ($p_\perp$) peaks at zero as shown in Fig.1b. Events with a transverse momentum ($p_\perp$) of the hadronic system less than 200 MeV/c are accepted into the final invariant mass plot for the $K^0_s K^\pm \pi^\mp$ candidates which is shown in Fig.2a. To obtain the number of events in the signal peak we fit this distribution with a signal shape function[a] obtained by running a GEANT-based detector simulation program. A smooth background contribution is approximated by a power function of the form $N(W) = N_0 W^x$, where N_0 is a normalization parameter, x is a power parameter and W is the invariant mass. The number of observed events is shown in Table I.

5. The $\pi^+\pi^-\pi^+\pi^-$ Decay Channel

To identify the decay mode into four charged pions we require that all charged tracks originate from the interaction region. To satisfy this requirement each track must have a separation from the beam crossing in the longitudinal direction of less than 50 mm and in the transverse plane of less than 5 mm. The upper tail probability of the χ^2 distribution is determined from TOF and dE/dx measurements assuming all four tracks to be pions. Candidates with $P_{\rm utp}$ greater than 0.1 are accepted into the $\pi^+\pi^-\pi^+\pi^-$ invariant mass plot. In addition, we require that $p_\perp$ of the hadronic system be less than 200 MeV/c. Signals for both the χ_{c0} and χ_{c2} are seen in Fig.2c. The numbers of signal events are obtained in the same way as in the previous section. The background contribution is approximated by an exponential function.

We do not observe η_c in the decay mode into four charged pions. The distribution of the invariant mass around the region where one expects η_c is shown in Fig.2b. The

---

[a]The signal shape function is a combination of two Gaussians with different widths and the same peak position. It reflects the variation of the detector resolution over the angular and energy ranges of the decay products.

vertical arrow shows where an η_c signal is expected.

6. Results

We obtain the detection efficiency by running a detector simulation program which includes trigger simulation. The trigger is efficient for 70% of all events and for 94% of events which would satisfy analyses selection criteria. These efficiencies agree within 5% with trigger efficiencies measured in data using redundancies between different triggers.

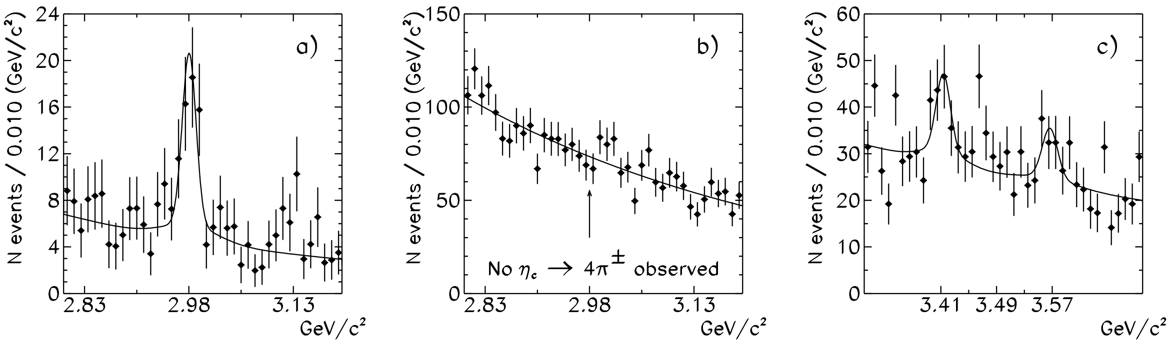

Fig. 2. The mass distributions for the candidates: a) $K_s^0 K^{\pm}\pi^{\mp}$, b) $\pi^+\pi^-\pi^+\pi^-$ for η_c mass range and c) $\pi^+\pi^-\pi^+\pi^-$ for χ_c mass range. The curves show the results of the fits described in the text.

For simulation of the two-photon processes we use Monte Carlo generators based on the formalism of Budnev.[6] The intrinsic properties of the charmonium resonances are described by a double pole form factor model.[7] The pole mass has been varied from zero to the J/ψ mass. We estimate that the uncertainty in the pole mass and form factor model are sources of a relative systematic error of 10%. Other sources of systematic errors include uncertainties in the detection efficiency due to the event selection criteria, trigger and detector simulation and tracking. Overall detection efficiencies are 12%, 20% and 21% for the $\eta_c \rightarrow K_s^0 K^{\pm}\pi^{\mp}$, $\chi_{c0} \rightarrow 4\pi^{\pm}$ and $\chi_{c2} \rightarrow 4\pi^{\pm}$ decay channels, respectively.

The results of this study are summarized in Table I. The first two errors quoted are statistical and systematic. The third error in the two-photon widths arises from the uncertainties in the corresponding branching fractions. Our measurement of the $\Gamma_{\gamma\gamma}(\eta_c) = 4.3$ KeV using the $\eta_c \rightarrow K_s^0 K^{\pm}\pi^{\mp}$ decay mode is consistent with previous measurements which are in the 5-28 KeV range, though most recent and more precise measurements fall below 10 KeV. The upper limit on $\Gamma_{\gamma\gamma}(\eta_c)$ derived from the decay $\eta_c \rightarrow \pi^+\pi^-\pi^+\pi^-$ is $\Gamma_{\gamma\gamma}(\eta_c) < 2.4$ KeV at the 90% confidence level. Our measurements

Table I. Summary of η_c, χ_{c0} and χ_{c2} measurements.

Channel	Number observed	Branching Fractions(%)[8]	$Br \cdot \Gamma_{\gamma\gamma}$ (0.01 × KeV)	$\Gamma_{\gamma\gamma}$ (KeV)
$\eta_c \to K_s^0 K^{\pm}\pi^{\mp}$	54.1 ± 12.6	1.5 ± 0.4	$6.5 \pm 1.5 \pm 1.1$	$4.3 \pm 1.0 \pm 0.7 \pm 1.4$
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$		1.2 ± 0.4	< 2.7 (90% CL)	< 2.4 (90% CL)
$\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-$	47.2 ± 15.5	3.7 ± 0.7	$6.4 \pm 2.1 \pm 1.5$	$1.7 \pm 0.6 \pm 0.4 \pm 0.3$
$\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-$	41.9 ± 13.8	2.2 ± 0.5	$1.5 \pm 0.5 \pm 0.3$	$0.7 \pm 0.2 \pm 0.1 \pm 0.2$

of $\Gamma_{\gamma\gamma}$ for χ_{c0} and χ_{c2} mesons are consistent with results of previous experiments.[8]

7. Discussion and Summary

The nonrelativistic quark model predicts that the two-photon width of the bound $q\bar{q}$ state with angular momentum l is proportional to the square of the l-th derivative of the $q\bar{q}$ pair wavefunction at the origin (*i.e.* at contact). To calculate the two-photon width one needs to know this wave function, or in terms of the Fourier transform, the momentum distribution of the $q\bar{q}$ pair inside the meson. This momentum distribution can be obtained from the nonrelativistic potential model. However, due to this non-perturbative calculation the overall normalization of the width is not very reliable. This uncertainty can be partially removed when one considers the ratio of two partial widths of the same meson or similar mesons. The ratio of the widths may be calculated more accurately using a relativistic approach.

For the η_c meson a nonrelativistic model[9] with next-to-leading order quantum chromodynamics corrections predicts: $\Gamma_{\gamma\gamma}(\eta_c)/\Gamma_{\mu^+\mu^-}(J/\psi) = (4/3)(1 + 1.96\alpha_s/\pi)$. Using the measured width $\Gamma(J/\psi \to \mu^+\mu^-) \approx 5.3$ KeV[8] with a choice of the $\alpha_s \approx 0.28$, this yields $\Gamma(\eta_c \to \gamma\gamma) \approx 8.2$ KeV. This calculation assumes that the η_c and J/ψ wavefunctions are identical at the origin, ignoring hyperfine mass splitting and coupled-channel effects. Indeed, the hyperfine effects would be likely to enhance the wavefunction of the η_c relative to that of the J/ψ.[9] Some evidence that the wavefunctions are not identical comes from the suppression of the $J/\psi \to \gamma\eta_c$ magnetic transition. On the other hand a description which incorporates relativistic effects[10] with a wavefunction obtained from a potential model predicts $\Gamma_{\gamma\gamma}(\eta_c) \approx 4.8$ KeV.[a] This calculation agrees with our measurement of the $\Gamma_{\gamma\gamma}(\eta_c) = 4.3 \pm 1.0 \pm 0.7 \pm 1.4$ KeV obtained in the $K_s^0 K^\pm \pi^\mp$ mode.

For the χ_{c0} and χ_{c2} states a naive nonrelativistic quark model predicts $\Gamma_{\gamma\gamma}(\chi_{c0}) : \Gamma_{\gamma\gamma}(\chi_{c2}) = 15/4 : 1$. The next-to-leading order quantum chromodynamics corrections[9] change this ratio by a factor of $(1 + 0.2\alpha_s/\pi)/(1 - 16\alpha_s/(3\pi))$. By evaluating this expression at $\alpha_s \approx 0.28$ we obtain $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2}) \approx 7.3$. The relativistic calculation[11] predicts this number to be around 2.8. Only the latter value is consistent with our measurement of $2.4 \pm 1.1 \pm 0.7$.

8. Acknowledgements

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Heisenberg Foundation, the Alexander von Humboldt Stiftung, the Natural Sciences and Engineering Research Council of Canada, and the A.P. Sloan Foundation.

1. Details of this analysis can be found in R.Fulton, Two-Photon Production of Charmonium States, Ph.D. thesis, The Ohio State University, 1995.
2. Y.Kubota *et al.*, CLEO Coll., *Nucl. Inst. and Meth.* **A320** (1992) 66.
3. C.Bebek *et al.*, CLEO Coll., *Nucl. Inst. and Meth.* **A302** (1992) 261.
4. V.Savinov, *et al.*, these proceedings.
5. M.Abramowitz and I.A.Stegun (eds.), Handbook of mathematical functions (National Bureau of Standards, Washington; D.C., 1964) The upper tail probility of the χ^2 distribution ($P_{\rm utp}$) is the area of the χ^2 distribution with N degrees of freedom above measured χ^2 value. Number of degrees of freedom is the number of measurements.
6. V.M. Budnev *et al.*, *Phys. Rep.* **C15** (1975) 181.
7. See, for example, M. Poppe, *Int. J. Mod. Phys.* **A1** (1986) 545.
8. Review of Particle Properties, *Phys. Rev.* **D50** (1994) 1.
9. W.Kwong *et al.*, *Phys. Rev.* **D37** (1988) 3210.
10. E.S. Ackleh and T.Barnes, *Phys. Rev.* **D45** (1992) 232.

[a]This is evaluated assuming the mass of the c quark (m_c) to be 1.4 GeV. A somewhat larger m_c = 1.6 GeV leads to the $\Gamma_{\gamma\gamma}(\eta_c) = 3.4$ KeV. The choice of the c quark mass becomes even more important for P-wave $q\bar{q}$ states because of the higher power of the c quark mass involved.

11. T.Barnes, Proc. IXth International Workshop on Photon-Photon Collisions, UC San Diego, CA, USA, March 1992, page 263, World Scientific.