EVIDENCE FOR EXCLUSIVE η_c PRODUCTION IN $\gamma\gamma$ INTERACTIONS

PLUTO Collaboration

Ch. BERGER, H. GENZEL, W. LACKAS, J. PIELORZ [1], F. RAUPACH, W. WAGNER [2]

I. Physikalisches Institut der RWTH Aachen [3], D-5100 Aachen, Fed. Rep. Germany

A. KLOVNING, E. LILLESTÖL

University of Bergen [4], N-5014 Bergen, Norway

J. BÜRGER, L. CRIEGEE, A. DEUTER, F. FERRAROTTO [5], G. FRANKE, M. GASPERO [5], Ch. GERKE, G. KNIES, B. LEWENDEL, J. MEYER, U. MICHELSEN, K.H. PAPE, B. STELLA [5], U. TIMM, G.G. WINTER, M. ZACHARA [6], W. ZIMMERMANN

Deutsches Elektronen-Synchroton (DESY), D-2000 Hamburg, Fed. Rep. Germany

P.J. BUSSEY, S.L. CARTWRIGHT [7], J.B. DAINTON [8], D. HENDRY, B.T. KING [8], C. RAINE, J.M. SCARR, I.O. SKILLICORN, K.M. SMITH, J.C. THOMSON [9]

University of Glasgow [10], Glasgow G12 8QQ, UK

O. ACHTERBERG, V. BLOBEL, D. BURKART, K. DIEHLMANN, M. FEINDT, H. KAPITZA [11], B. KOPPITZ, M. KRÜGER [12], M. POPPE, H. SPITZER, R. VAN STAA

II. Institut für Experimentalphysik der Universität Hamburg [3], D-2000 Hamburg, Fed. Rep. Germany

C.Y. CHANG, R.G. GLASSER, R.G. KELLOGG, S.J. MAXFIELD [13], R.O. POLVADO [14], B. SECHI-ZORN [1], J.A. SKARD, A. SKUJA, A.J. TYLKA [15], G.E. WELCH, G.T. ZORN

University of Maryland [16], College Park, MD 20742, USA

F. ALMEIDA [17], A. BÄCKER, F. BARREIRO [18], S. BRANDT, K. DERIKUM [19], C. GRUPEN, H.J. MEYER, H, MÜLLER, B. NEUMANN, M. ROST, K. STUPPERICH, G. ZECH

Universität-Gesamthochschule Siegen [3], D-5900 Siegen, Fed. Rep. Germany

G. ALEXANDER, G. BELLA, Y. GNAT, J. GRUNHAUS

Tel-Aviv University [20], Ramat Aviv, Tel-Aviv 699 78 Israel

H. JUNGE, K. KRASKI, C. MAXEINER, H. MAXEINER, H. MEYER and D. SCHMIDT

Universität-Gesamthochschule Wuppertal [3], D-5600 Wuppertal, Fed. Rep. Germany

Received 4 December 1985

We observe for evidence for $\gamma\gamma \to \eta_c$ production in the reaction $e^+e^- \to e^+e^- K^0_S K^\pm \pi^\mp$. The product $\Gamma_{\gamma\gamma}(\eta_c)\cdot B(\eta_c \to K^0_S K^\pm \pi^\mp)$ is measured to be $0.5^{+0.2}_{-0.15} \pm 0.1$ keV.

For footnotes see next page.

0370-2693/86/$ 03.50

The formation of mesons through the interaction of two photons has attracted much attention recently, both experimentally and theoretically. The radiative widths of many light mesons have been determined at e^+e^- storage rings [‡1]. For mesons with intrinsic charm only upper limits on the decay width $\Gamma_{\gamma\gamma}$ have been given [2–4].

In this letter we present evidence for exclusive η_c production by two photons in the process $e^+e^- \to e^+e^-K^0_S K^\pm\pi^\mp$, which is the first direct observation of charm production in two-photon physics. From the observed event rate we calculate a value for the radiative width of the η_c times the branching ratio $B(\eta_c \to K^0_S K^\pm \pi^\mp)$.

[1] Deceased.
[2] Present address: University of California at Davis, Davis, CA 95616, USA.
[3] Supported by the BMFT, Fed. Rep. Germany.
[4] Partially supported by the Norwegian Council for Science and the Humanities.
[5] Rome University, partially supported by INFN, Sezione di Roma, I-00135 Rome, Italy.
[6] Institute of Nuclear Physics, PL-30 059 Cracow, Poland.
[7] Present address: Rutherford Appelton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK.
[8] Present address: University of Liverpool, Liverpool, L69 3BX, UK.
[9] Present address: Computer Centre, University of Strathclyde, Glasgow G1 1XQ, UK.
[10] Supported by the UK Science and Engineering Research Council.
[11] Present address: Carleton University, Ottawa, Ontario, Canada K1S 5B6.
[12] Present address: Universität Karlsruhe, D-7500 Karlsruhe, Fed. Rep. Germany.
[13] Present address: University of Massachusetts, Amherst, MA 01003, USA.
[14] Present address: Hughes Aircraft Co., Los Angeles, CA, USA.
[15] Present address: Cosmic Ray Astrophysics Branch, Code 4154.8, US Naval Research Laboratory, Washington, DC 20375, USA.
[16] Partially supported by the Department of Energy, USA.
[17] On leave of absence from Instituto de Fisica, Universidade Federal do Rio de Janeiro, Ilha do Fundão, Rio de Janeiro, RJ, Brazil.
[18] On leave of absence at Universidad Autonoma de Madrid, Canto Blanco, Madrid 34, Spain.
[19] Present address: BESSY, D-1000 Berlin, Germany.
[20] Partially supported by the Israeli Academy of Sciences and Humanities, Basic Research Foundation.
[‡1] For a collection of recent results see ref. [1].

The data were taken with the PLUTO detector at PETRA at an average beam energy of 17.34 GeV and correspond to an integrated luminosity of 45 pb^{-1}. Details of the PLUTO detector have been given elsewhere [5]. For this analysis we use track information from the central track detector and the two forward spectrometers. Electrons and photons are measured by the small angle tagger, the large angle tagger, the barrel and endcap calorimeters. We also take account of the time-of-flight information available for forward spectrometer tracks.

To isolate the hadronic final state $K^0_S K^\pm\pi^\mp$ we look for events with four charged tracks with at least two of them in the central detector. The total charge of the system is required to be zero. Events containing photons are rejected by demanding that no isolated shower with energy larger than 100 MeV is detected. We accept untagged events as well as tagged events. The K^0_S is identified through its decay into $\pi^+\pi^-$. To avoid background we take advantage of the finite mean free path ($c\tau$ = 2.675 cm) of the K^0_S. A secondary vertex (V^0-) searching routine is applied to the data, which searches for oppositely charged pairs of central detector tracks which intersect at a point more than 4 mm radially distant from the interaction point. The latter is determined from Bhabha events on a run-by-run basis. The invariant mass and momentum of the V^0 is calculated from the sum of the two track momenta evaluated at the secondary vertex assuming pion masses. A fit to the V^0-hypothesis taking into account the position of the secondary vertex and the momentum direction of the V^0 is required to have a χ^2 of better than 12 for 4 degrees of freedom. Three different classes of K^0_S decay topologies can be distinguished. V^0's with no track being compatible (<3 standard deviations) with originating from the interaction point are labelled class 0. If one track or both tracks are compatible with coming from the interaction point the V^0 is assigned to class 1 or class 2 respectively. For class 0 vertices the K^0_S signal is clearly separated from the low mass background from converted photons. To reduce background from V^0's simulated by multiple scattering in the beam pipe and random crossing points of tracks originating at the interaction point we require the following conditions for class 1 and 2: the secondary vertex has to be 20–100 mm from the beam line, the opening angle to be between 30° and 130°, and the shower energy linked with any of the de-

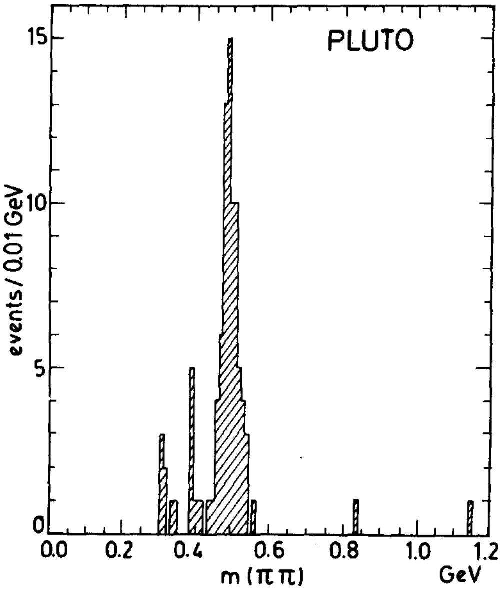

Fig. 1. Invariant $\pi^+\pi^-$-mass distribution calculated from secondary vertex tracks for four prong events with no photon.

cay particles to be less than 1 GeV.

The combined $\pi\pi$ mass spectrum of the selected 88 V^0's is shown in fig. 1. There is a clear K_S^0 peak consisting of 69 events with a background of 5 ± 1 events estimated from neighbouring mass bins. A fit results in a central mass value of 0.490 ± 0.003 GeV and a resolution σ of 0.020 ± 0.003 GeV, which is consistent with the values obtained in the Monte Carlo simulation of the detector. For the following kinematical analysis we use the V^0's with measured $\pi\pi$ mass between 0.45 and 0.54 GeV as K_S^0 candidates and assign the nominal mass of 497.7 MeV to them.

To select exclusive $\gamma\gamma$ events we only use events which have a missing transverse momentum $p_{T,\mathrm{miss.}}$ of less than 0.25 GeV for no tag events, and 0.35 GeV including the scattered electron for the few tagged events. Monte Carlo studies show that – with slight dependence on the invariant mass W and the production form factor – about 90% of exclusive $K_S^0K^\pm\pi^\mp$ events lie within these cuts. Since we have a clear strangeness signature from the K_S^0 we do not have to restrict the momenta of the additional two particles to allow their identification. Fig. 2a shows therefore the $K_S^0K^\pm\pi^\mp$ mass spectrum of all events with two entries each, for the $K_S^0K^+\pi^-$ and the $K_S^0K^-\pi^+$ hypothesis.

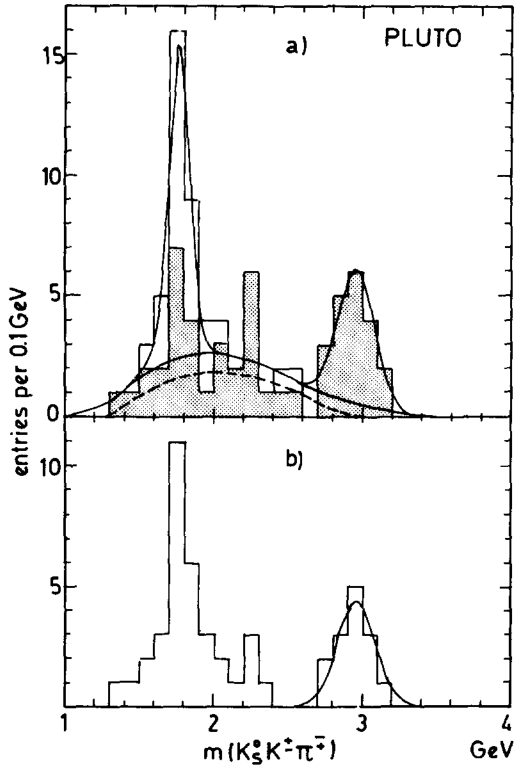

Fig. 2. Invariant $K_S^0K^\pm\pi^\mp$-mass distribution, two entries per event. (a) Full data sample. The background contribution from non exclusive final states and faked K_S^0 is indicated by the dashed line. The solid line is a fit of a polynomial background and two gaussians for the f′ and the η_c, where position and width of the peaks have been fixed to the Monte Carlo expectation. The shaded histogram corresponds to events which are not compatible with the final state $K_S^0K_S^0$. (b) Data sample restricted to unambiguously separated secondary vertices (class 0 and 1, see text). The solid line is the expected mass distribution for exclusive η_c events, normalised to the observed number of candidates.

The histogram is dominated by two peaks, one at 1.8 GeV and one around 3 GeV.

The background contribution due to events with missing particles in this sample is estimated from the $p_{T,\mathrm{miss.}}$ distribution to be about 4 events. The sidebands and hence the background below the K_S^0 peak contribute only to low $K_S^0K^\pm\pi^\mp$ masses with no entries above 2.8 GeV. The combined mass spectrum of the two background sources is indicated as dashed line in fig. 2a.

The peak at 1.8 GeV is explained by events of the type $\gamma\gamma \to f' \to K^0_S K^0_S$ where one of the kaons decays so rapidly that only one secondary vertex is reconstructed. The mass shift is due to the wrong mass assignment. The position and width of the peak agree with the Monte Carlo expectation of the process. The normalisation is consistent with the TASSO measurement of $\Gamma_{\gamma\gamma}(f')$ [6]. The peak disappears if we demand the $\pi^+\pi^-$ mass of the tracks assigned as $K^\pm\pi^\mp$ to be more than 135 MeV away from the K^0_S value (shaded area in fig. 2a). A detailed analysis of these events will be presented in a future publication.

There remains a cluster of 20 entries around 3 GeV which originate from 10 events with both mass combinations in that peak. We interpret these events as evidence for exclusive η_c production. None of them is consistent with a $K^0_S K^0_S$ decay. The mass distribution of these events is in good agreement with the expectation from a Monte Carlo simulation of exclusive η_c production which is described in detail below. The solid line in fig. 2a is the result of a fit of a polynomial shape of background and two gaussians for the f′ and η_c to the mass spectrum. The fitted polynomial background curve is slightly higher than the dashed background line discussed above, and leaves room for a few (7 ± 5) events of non-resonant $K^0_S K^\pm\pi^\mp$ production. The position and width of the η_c peak are fixed by the Monte Carlo expectation and only the normalisation is a free parameter in the fit.

The background below the K^0_S peak can be further reduced by rejecting events where all four tracks are consistent with originating from the interaction point, i.e. by using only events with class 0 or 1 secondary vertices. The $K^0_S K^\pm\pi^\mp$ mass distribution of these selected events is shown in fig. 2b. Here the η_c candidate peak consisting of 7 events is clearly separated from the f′ and possible $K^0_S K^\pm\pi^\mp$ continuum and background events at low masses. The reduction of the signal by this cut is consistent with the 31% loss expected from a Monte Carlo simulation described below.

Other exclusive $\gamma\gamma$-processes which can simulate a $K^0_S K^\pm\pi^\mp$ final state are $\Lambda\bar{\Lambda}$, $\Lambda\bar{p}K^+$ and $\bar{\Lambda}pK^-$ production. In these cases the invariant mass of the secondary vertex must be compatible with 1.115 GeV, assuming one particle is a (anti-) proton and the other a pion. Two of the η_c candidates have a V^0 which is compatible both with a K^0_S and a Λ interpretation, in agreement with the Monte Carlo estimate of 22%. For one of these events the Λ assignment is ruled out because it has a forward track which from baryon number conservation must be an antiproton of the V^0 is a Λ. The time-of-flight measurement of this track is incompatible with the antiproton hypothesis by more than 5σ.

We now assume that the observed signal is due to η_c production. In order to determine the radiative width $\Gamma_{\gamma\gamma}(\eta_c)$ we have generated Monte Carlo events of the process $e^+e^- \to e^+e^-\eta_c \to e^+e^-K^0_S K^\pm\pi^\mp$. Since the η_c has spin–parity 0^-, its production can be treated in analogy to π^0, η and η' production. The differential cross section $d\sigma_{e^+e^-\to e^+e^-\eta_c}$ factorises into a luminosity function and the two-photon cross section $\sigma_{\gamma\gamma\to\eta_c}(Q_1^2, Q_2^2)$, where Q_i^2 denote the negative of the invariant masses-squared of the virtual photons. The photon luminosity is generated according to the exact photon flux formula of Budnev et al. [7]. The two-photon cross section $\sigma_{\gamma\gamma\to\eta_c}(Q_1^2, Q_2^2)$ is linked through a single transition form factor $F(Q_1^2, Q_2^2)$ to the radiative width $\Gamma_{\gamma\gamma}(\eta_c)$, since longitudinal photons cannot couple to a pseudoscalar resonance. A more detailed discussion can be found in ref. [8].

The form factors of the η' and f^0 have been measured to be consistent with a ρ^0-propagator [8] ‡2, but it could well be that the η_c form factor behaves as the much flatter J/ψ-propagator. For this reason we have studied both possibilities in our Monte Carlo simulation. The decay of the η_c into $K^0_S K^\pm\pi^\mp$ is generated according to three-particle phase space.

The generated events are passed through a detailed detector simulation program which in particular also simulates the decay of the K^0_S after a finite path length in the detector as well as energy loss and multiple scattering in detector material. Event reconstruction proceeds as for real data, using simulated wire hits and deposited energies in the shower counters. Making the same selections as used for the data and also using two possible entries per event we find a gaussian peak in the $K^0_S K^\pm\pi^\mp$ mass spectrum at a mass of 2.98 GeV and a width of 0.1 GeV. The reconstructed mass values for the $K^0_S K^+\pi^-$ and the $K^0_S K^-\pi^+$ hypotheses turn out to lie both in the peak, owing to the high track momenta involved. The gaussian fit to the Monte Carlo spectrum, normalised to the number of observed η_c candidates is shown in figs. 2a and 2b along with the data. Good agreement is observed.

‡2 Preliminary PEP4/9 results on η' and f^0 can be found in ref. [9].

The resulting efficiency to detect the process $e^+e^- \to e^+e^-\eta_c \to e^+e^-K^0_S K^\pm\pi^\mp$ with our procedure is 5.0% (±0.1% from Monte Carlo statistics) in case of an assumed J/ψ form factor, and 6.3% for a ρ^0 form factor. This makes the determination of the total cross section $\sigma_{e^+e^-\to e^+e^-\eta_c}$ model dependent, since one has to integrate up to high Q^2, and one obtains different results for the different form factors. Fortunately the determination of the radiative width is much less model dependent. $\Gamma_{\gamma\gamma}(\eta_c)$ is a measure of the differential cross section at $Q_1^2 = Q_2^2 = 0$, so that for 90% of the observed events only a very small extrapolation is necessary. The results obtained using the different form factors agree to better than 4%.

An experimental decision between the two form factors is not possible within the limited statistics available. In one of the ten η_c candidates we observe a SAT tag, where we expect 5% tagged events for the ρ-form factor and 18% for the J/ψ-form factor assumption.

Further Monte Carlo studies prove that the peak at the η_c mass is not simulated by acceptance effects or selection criteria. We have generated events of the type $e^+e^- \to e^+e^-K^0_S K^\pm\pi^\mp$ for invariant $\gamma\gamma$ masses W from threshold to 6 GeV and calculated the acceptance of our experimental procedure as a function of W using a constant $\gamma\gamma$ cross section. Fig. 3 presents the expected

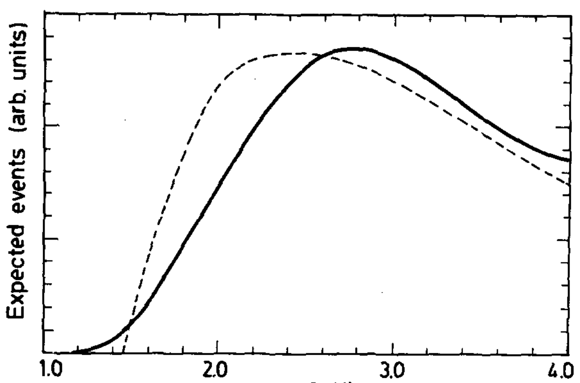

Fig. 3. Expected event rate for the process $e^+e^- \to e^+e^-K^0_S K^\pm\pi^\mp$ as a function of the $\gamma\gamma$ invariant mass W for a constant cross section $\sigma_{\gamma\gamma}(W)$ (arbitrary normalisation). The solid curve indicates the expectation for a three-particle phase space decay of the $\gamma\gamma$ system, whereas the dashed line represents a decay through the $K^*(1430)$ resonance (see text).

event rate as a function of W (full curve). It is smoothly varying around 3 GeV, so that the interpretation of the η_c candidate peak as an artifact due to falling luminosity function and rising acceptance is ruled out.

We have made further Monte Carlo calculations of the processes $\gamma\gamma \to$ hadrons, using VDM and QPM (udsc) mechanisms with LUND fragmentation, and also of $e^+e^- \to \tau\tau$ and $\gamma\gamma \to \tau\tau$. After applying the described selection criteria no τ event and about 4 hadronic events are expected in our data sample. The mass distribution of these does not extend beyond 2.6 GeV, since events with higher W are expected to decay preferentially into higher multiplicity final states.

In 1984 the Mark III Collaboration reported preliminary indications that the decay $\eta_c \to K\bar{K}\pi$ may partly proceed via $K^*(1430)$ [10]. However in their final analysis [11] no conclusive statement about the decay dynamics is made because of limited statistics and the presence of background events. Since our efficiency could be changed considerably by a resonance in the final state, we have also made a Monte Carlo simulation of the decay chain $\eta_c \to K^*\bar{K} \to K\pi\bar{K}$. This considered K^* excitation in the $K^0_S\pi^\pm$ and $K^\pm\pi^\mp$ channels and also the interference term, using the matrix element for the process $J^P = 0^- \to 0^-2^+, 2^+ \to 0^-0^-$. The acceptance at the η_c mass turns out to be 8% lower than for a phase space decay (see dashed line in fig. 3).

In the absence of charged kaon identification our sample of ten events does not allow us to distinguish between phase space decay and decay through an intermediate K^* experimentally. However we have two candidates for the decay chain $\eta_c \to K^*(1430)\bar{K}$, $K^*(1430) \to K^*(892)\pi$, $K^*(892) \to K\pi$ in the reaction $\gamma\gamma \to K^0_S K^\pm\pi^\mp\pi^0$. This is consistent with the hypothesis of the existence of a $K^*(1430)$ in the η_c decay.

The result of our analysis of the reaction $e^+e^- \to e^+e^-K^0_S K^\pm\pi^\mp$ is

$$\Gamma_{\gamma\gamma}(\eta_c) \cdot B(\eta_c \to K^0_S K^\pm\pi^\mp)$$

$$= 0.5\,^{+0.2}_{-0.15}\,(\text{stat.}) \pm 0.1\,(\text{syst.})\ \text{keV}\,.$$

The systematic error has been estimated from uncertainties in luminosity measurement (3%), trigger efficiency (10%), background subtraction (10%), modelling of the η_c production form factor (4%) and the decay dynamics (8%) as well as the effect of changing the particular cuts (10%), all added in quadrature.

Our result is consistent with the upper limit for the product $\Gamma_{\gamma\gamma}(\eta_c) \cdot B(\eta_c \to K\bar{K}\pi) < 4.4$ keV (at 95% CL) published by the TASSO Collaboration [3], which corresponds to the measured product $\Gamma_{\gamma\gamma}(\eta_c) \cdot B(\eta_c \to K_S^0 K^\pm \pi^\mp) < 1.47$ keV (at 95% CL) [12].

The computation of the radiative width $\Gamma_{\gamma\gamma}(\eta_c)$ is affected by large uncertainties in the η_c branching fractions. The currently accepted value [13] for $B(\eta_c \to K_S^0 K^\pm \pi^\mp) = (3.5^{+2.8}_{-2.5}) \times 10^{-2}$ results from the 1980 Mark II [14] measurement of $B(\psi' \to \gamma\eta_c) \cdot B(\eta_c \to K_S^0 K^\pm \pi^\mp)$ which is based on 8 events, and the 1980 Crystal Ball measurement [15] of $B(\psi' \to \gamma\eta_c)$. Recently the Mark III Collaboration reported the much smaller value $(1.5 \pm 0.6) \times 10^{-2}$ on the $\eta_c \to K_S^0 K^\pm \pi^\mp$ branching ratio [11]. This value relies on an unpublished [16] branching ratio $B(J/\psi \to \gamma\eta_c) = (1.27 \pm 0.36) \times 10^{-2}$ which is obtained in a simultaneous fit to inclusive photon spectra from radiative J/ψ and ψ' decays measured with the Crystal Ball detector. Using the PDG value leads to $\Gamma_{\gamma\gamma}(\eta_c) = 14 \pm 12$ keV where our statistical and systematic errors as well as the error on the branching ratio have been added in quadrature. Taking the Mark III value for $B(\eta_c \to K_S^0 K^\pm \pi^\mp)$ results in $\Gamma_{\gamma\gamma}(\eta_c) = 33 \pm 20$ keV.

These numbers can be compared with the upper limit on $\Gamma_{\gamma\gamma}(\eta_c)$ from the $p\bar{p} \to \eta_c \to \gamma\gamma$ measurement at ISR [4], which is a measure of the product $B(\eta_c \to p\bar{p}) \cdot B(\eta_c \to \gamma\gamma)$. Using the (unpublished) [16] total width $\Gamma_{tot}(\eta_c) = 11.5^{+4.5}_{-4.0}$ MeV as measured by Crystal Ball and the recent Mark III value [11] for $B(\eta_c \to p\bar{p})$ an upper limit of $\Gamma_{\gamma\gamma}(\eta_c) < 7$ keV (95% CL) is derived. Within the large uncertainties of all values involved this is consistent with our result.

Theoretical predictions of the η_c two-photon width range between 1 and 12 keV [‡3]. The experimental errors are too large to exclude particular models. A better knowledge of the branching ratio $B(\eta_c \to K\bar{K}\pi)$ and the decay mechanism is needed.

In summary we observe clear evidence for $\gamma\gamma \to \eta_c$ production in the reaction $e^+e^- \to e^+e^- K_S^0 K^\pm \pi^\mp$. This measurement provides the first direct evidence for charm production in two-photon physics. The product $\Gamma_{\gamma\gamma}(\eta_c) \cdot B(\eta_c \to K_S^0 K^\pm \pi^\mp)$ is measured to be $0.5^{+0.2}_{-0.15} \pm 0.1$ keV.

[‡3] See the list of references in ref. [17]. For 4.24 keV, see ref. [18]; for 1 keV, see ref. [19]; for 5 keV, see ref. [20]; for 6 keV, see ref. [21].

We wish to thank the members of the DESY directorate for the hospitality extended to the university groups. We are indebted to the PETRA machine group for having provided us with such outstanding beam conditions in 1981/82 and the DESY computer center for their excellent performance. We gratefully acknowl edge the efforts of all the engineers and technicians who have participated in the construction of the apparatus.

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