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Measurement of η_c production in untagged two-photon collisions at LEP

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A study of twelve distinct decay channels of the η_c has been performed with the L3 detector at LEP, for an integrated luminosity of 30 pb^{-1}. Summing all channels, 28 candidate events have been identified, with an estimated background of 11 events. The two-photon radiative width is evaluated to be $\Gamma_{\gamma\gamma}(\eta_c) = 8.0 \pm 2.3 \pm 2.4$ keV.

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1. Introduction

The $J^{PC} = 0^{-+}$ $c\bar{c}$ state, the η_c, may be produced at e^+e^- colliders via the photon–photon collision process $e^+e^- \to e^+e^-\eta_c$, where only the decay products of the η_c are observed in the detector. The outgoing e^+ and e^- are scattered with a large probability at small angles and take the main part of the initial energy. They are not considered in this analysis. The cross section for this process is proportional to the two-photon radiative width of the η_c, $\Gamma_{\gamma\gamma}(\eta_c)$. This quantity may be calculated in non-relativistic potential models of charmonium [1] and so the measurement provides a test of such models. The branching ratio $\Gamma_{\gamma\gamma}(\eta_c)/\Gamma(\eta_c)$ may be calculated in perturbative QCD [2], assuming the dominance of the two-gluon final state in hadronic η_c decays, permitting a measurement, to be made, of the QCD coupling constant α_s. A crude estimate of the value of $\Gamma_{\gamma\gamma}(\eta_c)$, based on a non-relativistic quark model, is provided by the ratio $\Gamma_{\gamma\gamma}(\eta_c)/\Gamma_{e^+e^-}(J) = 4/3$. The measured value $\Gamma_{e^+e^-}(J) = 5.4 \pm 0.3$ keV [3] leads to the estimate $\Gamma_{\gamma\gamma}(\eta_c) \simeq 7.2$ keV.

Previous measurements of $\Gamma_{\gamma\gamma}(\eta_c)$ at e^+e^- colliders have been made by PLUTO [4], TPC/2γ [5], CLEO [6] and ARGUS [7].

Here we report on the first measurement of $\Gamma_{\gamma\gamma}(\eta_c)$ at LEP.

2. The L3 detector

The subdetectors of L3 [8] used in this analysis are: the charged particle tracker TEC (Time Expansion Chamber), the electromagnetic BGO calorimeter, and the small angle luminosity monitor.

The TEC is a cylindrical high resolution drift chamber with a sensitive region between 10 and 45 cm in the radial direction and a polar angle acceptance $13° \leqslant \theta \leqslant 167°$, in a magnetic field of 0.5 T. There are 62 layers of wires with a spatial resolution of $\simeq 50\,\mu$m, giving a p_T resolution $\sigma(p_T)/p_T^2 = 0.02(\mathrm{GeV})^{-1}$. Measurement of $\mathrm{d}E/\mathrm{d}x$ in the TEC with a relative accuracy of about 10% provides the possibility to separate $\pi/K/p$ for momenta below 400 MeV. Fig. 1 shows $\mathrm{d}E/\mathrm{d}x$ versus momentum measured in the TEC for an event sample with enhanced kaon content; π, K and p bands are clearly visible.

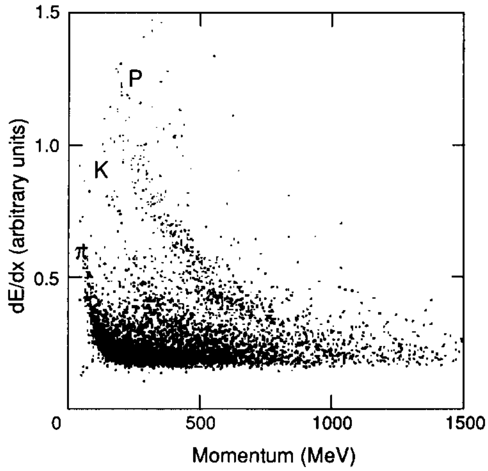

Fig. 1. $\mathrm{d}E/\mathrm{d}x$ versus TEC momentum. Four charged particle events are selected as candidates for untagged photon–photon collisions where the mass of at least one pair of particles corresponds to K_S, K^* or ϕ. The track with the highest $\mathrm{d}E/\mathrm{d}x$ in the event is plotted. The protons come predominantly from beam gas contamination.

The electromagnetic calorimeter, placed around the TEC, consists of about 11 000 BGO crystals arranged in two half barrels with polar angle coverage $42° \leqslant \theta \leqslant 138°$ and two endcaps covering $11.6° \leqslant \theta \leqslant 38°$ and $142° \leqslant \theta \leqslant 168.4°$. The energy resolution of the BGO calorimeter is $\simeq 5\%$ at 100 MeV and $\simeq 2.3\%$ at 1 GeV.

The L3 detector is well suited to two-photon physics because of the large acceptance and high resolution of the BGO calorimeter for low energy photons and because of a charged track trigger [9], based on the TEC, which provides a wide angular coverage $25° \leqslant \theta \leqslant 155°$ and a low p_T threshold of approximately 100 MeV. This trigger requires at least one pair of charged tracks back to back, in the plane transverse to the beam, within $\pm 41°$.

3. Event selection

The data were taken at LEP during the years 1991–1992, for an integrated luminosity of $\mathcal{L} = 30$ pb^{-1}. Signals for η_c production are sought in the following decay modes with known branching ratios: $\eta_c \to \eta\pi\pi$ ($\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$), $\eta'\pi\pi$ ($\eta' \to \gamma\gamma, \pi^+\pi^-\gamma$), $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $\phi\phi$, $K_S^0K^\pm\pi^\mp$, $K^+K^-\pi^0$.

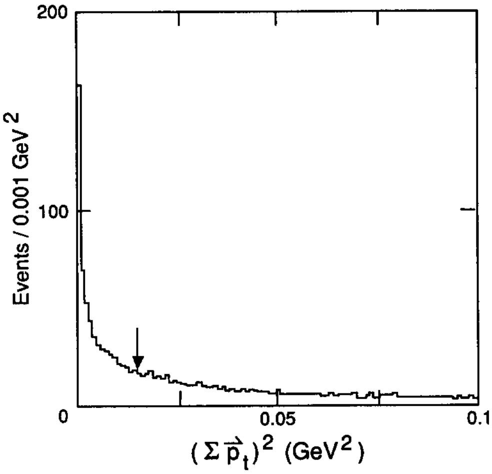

Fig. 2. Distribution of the total transverse momentum squared for events with at least 4 charged particles.

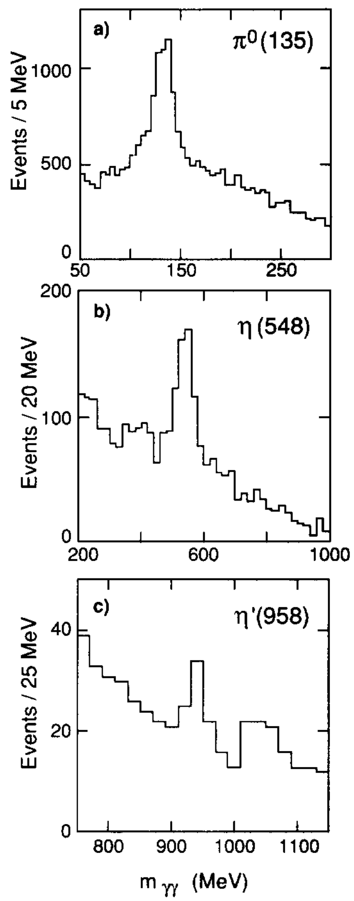

Fig. 3. Two-photon effective mass distribution measured with the BGO electromagnetic calorimeter: (a) around the π^0 mass, (b) around the η mass after π^0 suppression, (c) around the η' mass after η suppression.

All these decay channels contain two or four charged tracks. Candidate events are therefore selected with the following requirements [10]:

- Two or four good tracks in the TEC. A good track requires more than 19 hits out of a maximum of 62, thus limiting the angular acceptance to $27° \leqslant \theta \leqslant 153°$. For tracks originating from the interaction point we require a distance of closest approach (DCA) in the transverse plane of less than 3 mm.
- The total charge of the event must be zero.
- At least one track must correspond to a BGO cluster within 175 mrad in ϕ. When a charged particle is detected by the BGO the θ angle is defined by the cluster position ($\sigma_\theta \simeq 11$ mrad); otherwise the value is provided by the TEC ($\sigma_\theta \simeq 20$ mrad). The momentum and ϕ angle are always measured by the TEC.
- Photons are identified as a BGO cluster with an energy greater than 50 MeV and a minimum separation from the nearest track of 300 mrad in θ and 200 mrad in ϕ.
- Events with electrons, which are identified by a BGO energy deposition compatible with the TEC momentum, are removed from the present analysis.
- Beam–gas events are removed by identifying protons with the dE/dx measured by the TEC (fig. 1).
- Exclusive events are selected by requiring a total transverse momentum squared of all particles ($|\sum p_T|^2$) smaller than 0.015 GeV^2 (fig. 2).

For momenta below 400 MeV a statistical separation between charged pions and kaons is possible using the momentum and dE/dx information from TEC, combined with the BGO energy deposition.

The π^0, η and η' are identified by their 2γ decays (fig. 3). A band of ± 30 MeV around the known mass value is used to identify π^0; the mass band is ± 60 MeV for η and η'. The η, η' are also recognised in the decay channels $\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$ (fig. 4) respectively, in bands of ± 60 MeV around the known mass values. The K_S^0 is identified by requiring at least one track with the DCA greater than 5 mm and the corresponding $\pi^+\pi^-$ effective mass within ± 60 MeV of the K_S^0 mass (fig. 5a). Candidates for $K^*(892)$ are defined by an effective mass band of ± 60 MeV around the nom-

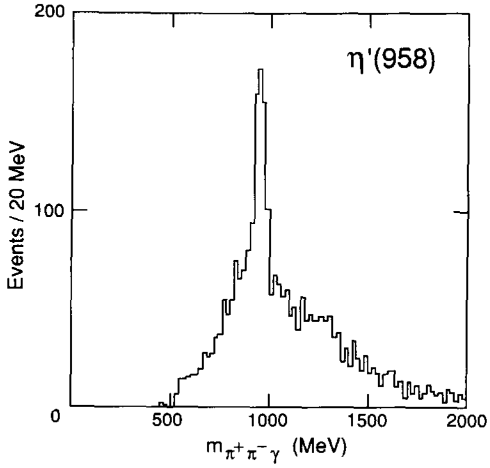

Fig. 4. $\pi^+\pi^-\gamma$ effective mass.

inal mass value, allowing all possible $K^\pm\pi^\mp$ mass assignments (fig. 5b). The ϕ is defined by a ± 60 MeV wide band in K^+K^- effective mass around the nominal mass value, assuming the K mass hypothesis for each pair of the tracks in turn.

4. η_c Reconstruction

For each channel of interest 10000 Monte Carlo events were generated [11]. The two-photon Monte Carlo follows the formalism of [12] in generating the η_c pseudoscalar. The η_c decays were generated according to phase space. The detector acceptance $\mathcal{A}$ is determined by a full detector simulation, including the same analysis cuts as for real data.

Details of the 12 different final states which were studied are presented in table 1. For each decay channel, entries are included for the measured branching ratio [3], the calculated detector acceptance, the number of observed events in the mass interval 2900–3100 MeV and the number of background events, estimated from an exponential fit of the mass distribution or from the $|\sum p_T|^2$ distribution of each channel, excluding the signal region.

A total of 28 η_c candidates are found (fig. 6). A gaussian fit to the peak with an exponential background gives as parameters $M = (3003 \pm 15)$ MeV, $\sigma = (45 \pm 12)$ MeV compatible with the mass value given by the Particle Data Group (2979 ± 2) MeV [3].

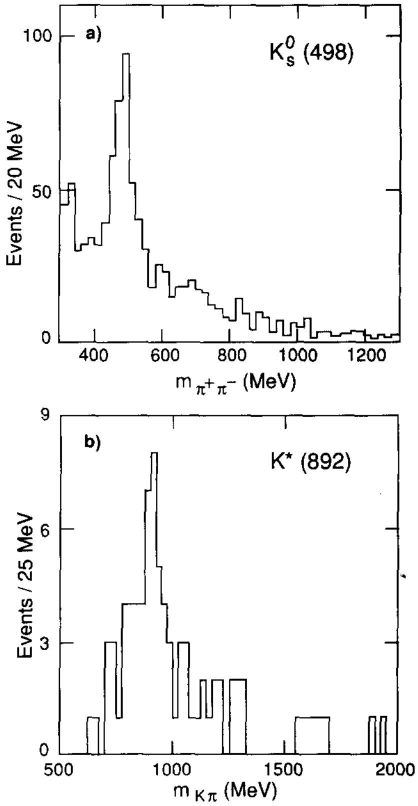

Fig. 5. Distribution of the effective mass of two charged tracks when four tracks are seen in the event. (a) At least one track with DCA greater than 5 mm, (b) with DCA smaller than 3 mm and at least one of the four tracks recognised as a kaon, identified by the dE/dx information from TEC and by the BGO energy deposition. The effective mass of the four tracks is selected to be greater than 2.6 GeV.

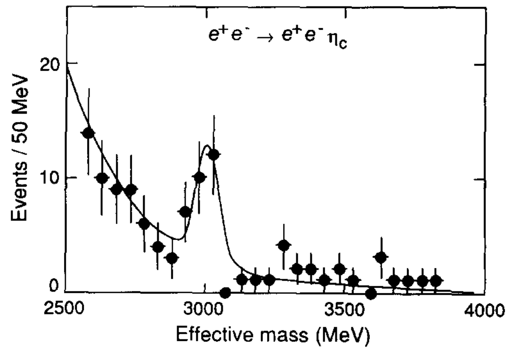

Fig. 6. Effective mass distribution summed over the 12 channels in table 1. The background is fitted by an exponential function. The η_c peak is fitted by a gaussian curve.

Table 1
The η_c decay modes explored in this analysis with their measured branching ratio, the detector acceptance, the number of observed events in the mass interval 2900–3100 MeV and their estimated background.

Channel	BR (%) [3]	Acceptance (%)	N_{obs}	N_{back}
$\eta\pi^+\pi^-(\eta\to\gamma\gamma)$	1.27±0.47	2.4 ±0.1	1	0.0
$\eta\pi^+\pi^-\ (\eta\to\pi^+\pi^-\pi^0)$	0.77±0.28	0.53±0.07	2	0.8±0.6
$\eta'\pi^+\pi^-(\eta'\to\rho^0\gamma)$	0.82±0.34	5.2 ±0.2	2	0.5±0.3
$\eta'\pi^+\pi^-(\eta'\to\pi^+\pi^-\eta)$	0.47±0.19	1.3 ±0.2	0	0.5±0.6
$\eta'\pi^+\pi^-(\eta'\to\gamma\gamma)$	0.06±0.02	3.0 ±0.2	1	0.0
$\pi^+\pi^-\pi^+\pi^-$	1.2 ±0.4	3.7 ±0.1	8	1.7±0.3
$K^+K^-\pi^+\pi^-$	2.0 ±0.7	3.6 ±0.2	4	3.2±0.4
$K^{*0}K^\pm\pi^\mp(K^{*0}\to K^\mp\pi^\pm)$	1.33±0.46	6.6 ±0.2	5	2.9±0.3
$K^{*0}K^{*0}(K^{*0}\to K^\pm\pi^\mp)$	0.19±0.06	5.8 ±0.3	1	0.5±0.2
$\phi\phi(\phi\to K^-K^+)$	0.17±0.07	5.6 ±0.2	0	0.0
$K^0_SK^\pm\pi^\mp(K^0_S\to\pi^-\pi^+)$	1.51±0.41	6.9 ±0.3	3	0.5±0.2
$K^+K^-\pi^0$	1.10±0.30	3.8 ±0.2	1	0.2±0.1

The estimated average mass resolution of 60 MeV is consistent with the fitted value, and much larger than the total width of the η_c of (10 ± 4) MeV [3].

5. Determination of $\Gamma_{\gamma\gamma}(\eta_c)$

Assuming the dominance of virtual photon–photon collisions in the production of the η_c, the observed total cross section is given by the relation

$$\sigma_{tot}(e^+e^-\to\eta_c e^+e^-) = \int d^5\mathcal{L}_{\gamma\gamma}(\alpha_i)\sigma(\gamma^*\gamma^*\to\eta_c)\,, \qquad (1)$$

where $d^5\mathcal{L}_{\gamma\gamma}$ is the differential luminosity function [12], a pure QED factor giving the flux of virtual transverse photons. It is a function of the variables α_i $(i=1,...,5)$ describing the energies and angles of the scattered electrons and positrons.

If the virtual photons are almost real,

$$\sigma(\gamma^*\gamma^*\to\eta_c) = 8\pi\left(\frac{m}{W}\right)^2\frac{\Gamma_{\gamma\gamma}(\eta_c)\Gamma(\eta_c)}{(W^2-m^2)^2+m^2\Gamma^2(\eta_c)}\,, \qquad (2)$$

where W is the photon–photon center of mass energy and m the η_c mass

Eqs. (1) and (2) lead to a linear relation between the observed cross section for η_c production and $\Gamma_{\gamma\gamma}(\eta_c)$:

$$\sigma_{tot}(e^+e^-\to e^+e^-\eta_c) = \mathcal{K}\Gamma_{\gamma\gamma}(\eta_c)\,.$$

We calculated the factor $\mathcal{K}$ by Monte Carlo integration [11].

For each channel the measured value of $\Gamma_{\gamma\gamma}(\eta_c)$ is then given by the relation

$$\Gamma_{\gamma\gamma}(\eta_c) = \frac{N_{obs}-N_{back}}{\mathcal{K}\mathcal{A}\epsilon\,\mathrm{BR}\,\mathcal{L}}\,,$$

where N_{obs} is the number of observed events, N_{back} is the number of background events, $\mathcal{A}$ is the detector acceptance, ϵ is the detector efficiency, BR is the η_c branching ratio, and $\mathcal{L}$ is the integrated luminosity.

The factor ϵ includes the average efficiency of the TEC trigger (0.95 ± 0.01), the reconstruction efficiency for a track (0.97 ± 0.02) and the matching efficiency between the TEC track and the BGO cluster which is 0.97 for two tracks events and 0.998 for four tracks events [10].

The value of $\Gamma_{\gamma\gamma}(\eta_c)$ best describing the number of observed events in the different channels is given by maximising the likelihood function,

$$L(\Gamma_{\gamma\gamma}(\eta_c)) = \prod_{i=1}^{12} P(N^i_{obs}|N^i_{exp})\,,$$

where N_{exp} is the number of events expected to be seen in the detector and $P(n|m)$ is the Poisson distribution function.

The result thus obtained is

$$\Gamma_{\gamma\gamma}(\eta_c) = 8.0\pm 2.3\pm 2.4\ \mathrm{keV}\,,$$

where the first error is statistical and the second one is systematic. The systematic error is obtained by varying the background and the expected number of events according to gaussian distributions with variances given by their estimated errors. This error is dominated by the large uncertainty in the branching ratio: BR($J \to \gamma\eta_c$) = $(1.27 \pm 0.36)\%$, since the branching ratios of all the η_c decay channels we have studied are determined in the reaction $J \to \gamma\eta_c$ relative to the total η_c width observed in the inclusive γ spectrum [3]. The correlated errors on the branching ratios of the different channels were taken into account in estimating the systematic error. Variation of the cuts in the region of their nominal values was found to give a negligible contribution (≈ 0.15 keV) to the systematic error.

The present result is in agreement with the estimation from the $J \to e^+e^-$ width and is consistent with previous measurements.

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