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A search for η_c' production in photon–photon fusion at LEP

DELPHI Collaboration

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Abstract

A search for the production of the η_c' meson, the first radial excitation of the ground state of charmonium $\eta_c(2980)$, in the photon–photon fusion reaction at LEP has been performed using the data collected by the DELPHI detector during 1992–1996. No evidence of η_c' production is found in the mass region 3520–3800 MeV/c^2. An upper limit for the ratio of the two-photon widths of the η_c' and η_c is obtained.

1. Introduction

The properties of the charmonium states are well suited for fundamental tests of QCD dynamics [1,2], but they have not yet been well determined. In particular, our understanding of spin-singlet states is extremely poor, being limited to the only well established singlet state in all onium spectroscopy, the $\eta_c(^1S_0)$ ground state of charmonium. The identification of the first radial excitation of the η_c was claimed by the Crystal Ball Collaboration in the inclusive photon spectrum of ψ' decays, with a mass and width [3,4] of $m_{\eta_c'} = 3594 \pm 5$ MeV/c^2 and $\Gamma(\eta_c') < 8$ MeV. Unfortunately, the state has not been observed in any other experiment. The search for η_c' thus poses a worthy challenge to the new ways of studying charmonium spectroscopy, namely $p\bar{p}$ annihilation [2] and photon–photon fusion [5].

Calculations with a variety of $q\bar{q}$ potentials [6], as well as ‘‘model independent’’ calculations based on measured e^+e^- decay widths of J/ψ and ψ' and the well known expression for hyperfine splitting, lead to the prediction that $m_{\eta_c'} = 3615 \pm 10$ MeV/c^2. Lattice gauge calculations cannot yet predict the masses of radially excited states accurately, but the first results are consistent with the above prediction [7]. To first order the two photon widths of η_c and η_c' are proportional to the squares of their respective radial wave functions at the origin [8]. A more elaborate relativistic calculation, which was able to predict $\Gamma_{\gamma\gamma}(\eta_c)$ successfully, predicts that $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) = 0.75 \pm 0.02$ [9] [3].

Precision measurements of the properties of charmonium resonances have been made by Fermilab experiments E760 and E835 via their formation in $p\bar{p}$ annihilation [2]. E760/E835 have successfully identified η_c in the reaction $p\bar{p} \to \eta_c \to \gamma\gamma$ [10,11], but have failed to find any evidence for η_c' in the two photon decay channel. E835 has established a 90% upper confidence limit [11]

$$\frac{Br(p\bar{p} \to \eta_c')\,Br(\eta_c' \to \gamma\gamma)}{Br(p\bar{p} \to \eta_c)\,Br(\eta_c \to \gamma\gamma)} \le 0.16 \tag{1}$$

for an η_c' anywhere in the mass region 3570 to 3670 MeV/c^2 with $\Gamma(\eta_c') \geq 5$ MeV. Thus the η_c' continues to be elusive.

Photon–photon fusion represents another potentially powerful technique for studying positive charge conjugation charmonium resonances R, and several attempts to study these in the reaction

$$e^+e^- \to e^+e^-(\gamma\gamma) \to e^+e^-R \to e^+e^-(\text{hadrons}) \tag{2}$$

have been reported [12]. Measurements at high collider energies at LEP are especially well suited for these

[3] The predicted value of the ratio $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) = 0.75 \pm 0.02$ was calculated for $m_{\eta_c'} = 3590$ MeV/c^2 [9]. The authors estimate that the effect of varying $m_{\eta_c'}$ over the range 3590 ± 50 MeV/c^2 is to change the ratio $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c)$ by $\pm 4\%$.

studies because the two photon flux increases with center-of-mass energy $\sqrt{s}$, and the background decreases. Further, given sufficient statistics, several resonances with common decay channels can be investigated in the same invariant mass spectrum. Thus the η_c and η_c' can be searched for simultaneously.

The present search for η_c' in the DELPHI data was motivated by the experimental results mentioned above and by the potential advantages of photon–photon fusion measurements at LEP. Signals for resonance production in the invariant mass range 3520 to 3800 MeV/c^2 were searched for in the five decay channels in which η_c is known to have large branching ratios for producing charged particles or K_s^0: $\rho^0\rho^0$, $K_s^0 K^+ \pi^- (K_s^0 K^- \pi^+)$, $K^{*0} K^- \pi^+ (\overline{K}^{*0} K^+ \pi^-)$, $K_s^0 K_s^0 \pi^+ \pi^-$ and $K^+K^-K^+K^-$, with $K_s^0 \to \pi^+\pi^-$ and $K^{*0} \to K^+\pi^-$ [4].

The data used for the analysis were collected with the DELPHI detector at LEP in 1992–1996 with integrated luminosities of 130 pb^{-1} at the Z^0 peak, 6 pb^{-1} at 130 and 136 GeV, and 20 pb^{-1} at 161 and 172 GeV.

2. Particle selection

A detailed description of the DELPHI detector can be found in [13]. Most of the DELPHI subdetectors were used in the present analysis.

Charged particles were selected if they fulfilled the following criteria:

- polar angle between 20° and 160°;
- momentum greater than 0.4 GeV/c;
- good quality, assessed as follows:
  - track length greater than 50 cm;
  - impact parameters with respect to the nominal interaction point less than 4 cm (transverse and longitudinal with respect to the beam direction);
  - error in momentum measurement less than 100%.

The K$^\pm$ identification was based on the ionization measured in the Time Projection Chamber and on the measurement of the angle of emission of its Cherenkov light in the Ring Imaging Cherenkov detectors [14]. The K$^\pm$ were selected by imposing the selection criteria in the standard DELPHI algorithm HADSIGN [15].

The K_s^0 mesons were detected by their decay in flight into $\pi^+\pi^-$. Such decays are generally separated from the primary vertex, measured for each event. Candidates for secondary decays were found by considering all pairs of particles with opposite charge and applying the selection criteria described in [15].

Other neutral particles were detected from their shower profiles in the High Density Projection Chamber, the Forward Electromagnetic Calorimeters, the Hadron Calorimeter, and the luminosity monitors, SAT and STIC.

3. Event selection

The final states $\rho^0\rho^0$, $K_s^0 K^+ \pi^-$, $K^{*0} K^- \pi^+$, $K_s^0 K_s^0 \pi^+ \pi^-$ and $K^+K^-K^+K^-$, used for this η_c' search, contain only charged particles and K_s^0 mesons.

The calorimetric information was included in the analysis in order to detect any additional neutral component of the hadronic system and thus provide better rejection of the background. Events containing neutral particles other than K_s^0 mesons, which were not associated with charged particles, were removed from the analysis. For the neutral particle identification the same requirements were used as in [16]:

- energy of the electromagnetic or hadron shower greater than 0.5 GeV;
- additional requirements on shower quality, assessed as follows:
  - showers in the luminosity monitor with deposits in more than one cell;
  - error in the hadron calorimeter shower measurement less than 100%.

Only events with net zero charge were used in the following analysis. The vector sum of the transverse momenta of all particles was required to be less than 1.4 GeV/c. The sum of the energy (electromagnetic and hadronic) of all particles was required to be less than 10 GeV.

The selection criteria described above were applied to all channels studied. Additional selection criteria for each channel were applied as follows.

3.1. Selection of $\gamma\gamma \to \rho^0\rho^0$ events

Candidate events for the production of η_c' decaying into $\rho^0\rho^0 \to \pi^+\pi^-\pi^+\pi^-$ were required to contain just four charged particles, none of which was identified as a charged kaon.

The invariant mass distribution of $\pi^+\pi^-$ pairs for such events is shown in Fig. 1a, where the signal from $\rho^0(770)$ decays is clearly seen. Since the $\rho^0\rho^0$ dynamics largely dominates the $\pi^+\pi^-\pi^+\pi^-$ decay of η_c [17], events were selected only if the invariant mass of both $\pi^+\pi^-$ pairs in $\gamma\gamma \to (\pi^+\pi^-)(\pi^+\pi^-)$ events were in the tightly restricted ρ^0 mass region of $0.70 < M(\pi\pi) < 0.84$ GeV/c^2 for at least one pairing. These cuts are shown in Fig. 1a. The invariant mass distribution of the $\rho^0\rho^0$ pairs in the selected $\gamma\gamma \to \rho^0\rho^0$ events is shown in Fig. 2a.

3.2. Selection of $\gamma\gamma \to K_s^0 K^\pm \pi^\mp$ events

The selection of $\gamma\gamma \to K_s^0 K^\pm \pi^\mp$ events required exactly two charged particles, only one of which was a charged kaon, and one reconstructed K_s^0 meson. The invariant mass distribution of the $K_s^0 K^\pm \pi^\mp$ in the selected events is shown in Fig. 2b.

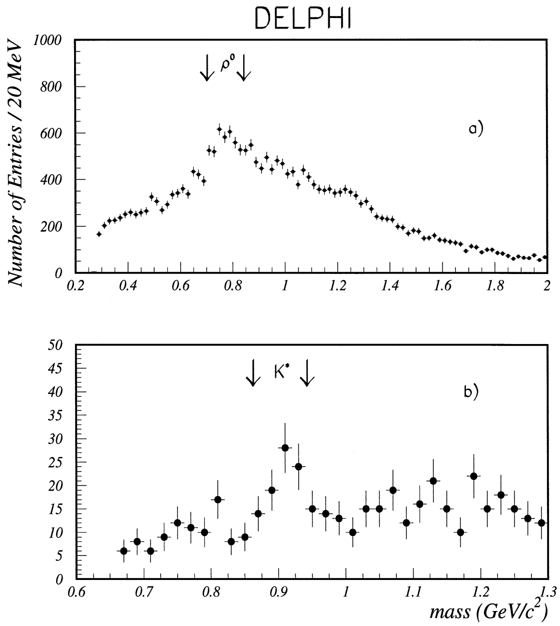

Fig. 1. Invariant mass distributions (a) for $\pi^+\pi^-$ pairs in $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ events, (b) for $K^+\pi^-$ and $K^-\pi^+$ pairs in $\gamma\gamma \to K^+K^-\pi^+\pi^-$ events.

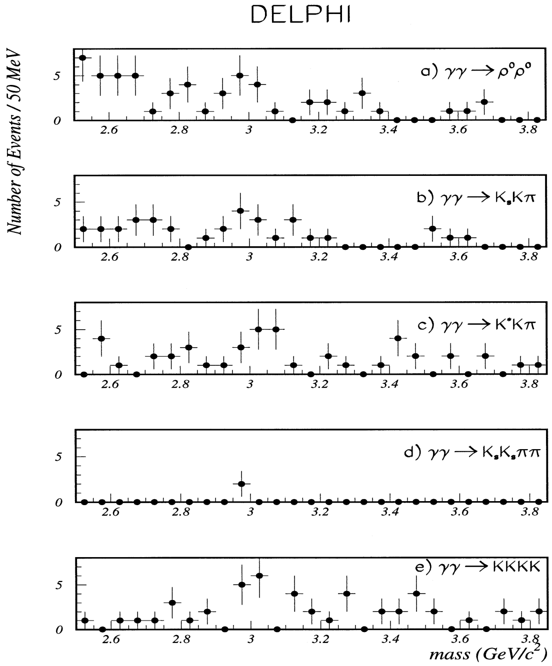

Fig. 2. Invariant mass distributions of final state particles for the channels (a) $\gamma\gamma \to \rho^0\rho^0$, (b) $\gamma\gamma \to K_s^0 K^{\pm}\pi^{\mp}$, (c) $\gamma\gamma \to K^{*0}K^-\pi^+$ and $\gamma\gamma \to \bar{K}^{*0}K^+\pi^-$, (d) $\gamma\gamma \to K_s^0 K_s^0 \pi^+\pi^-$, (e) $\gamma\gamma \to K^+K^-K^+K^-$.

3.3. Selection of $\gamma\gamma \to K^{*0}K^-\pi^+$ and $\gamma\gamma \to \bar{K}^{*0}K^+\pi^-$ events

Events containing two oppositely charged kaons and two oppositely charged pions were selected to study the channels $\gamma\gamma \to K^{*0}K^-\pi^+$ and $\gamma\gamma \to \bar{K}^{*0}K^+\pi^-$, where the $K^{*0}(890)$ and $\bar{K}^{*0}(890)$ mesons decay into $K^+\pi^-$ and $K^-\pi^+$, respectively. The invariant mass distribution of the two possible $K\pi$ pairs $(K^+\pi^-$ and $K^-\pi^+)$ in the events is shown in Fig. 1b. Events were used only if at least one $K\pi$ pair had an invariant mass in the K^{*0} mass region of $0.86 < M(K\pi) < 0.94$ GeV/c^2, as indicated in Fig. 1b. The invariant mass distribution of selected final state $K^{*0}K^-\pi^+$ and $\bar{K}^{*0}K^+\pi^-$ particles is shown in Fig. 2c.

3.4. Selection of $\gamma\gamma \to K_s^0 K_s^0 \pi^+\pi^-$ events

The decay channel $K_s^0 K_s^0 \pi^+\pi^-$ was studied using the events with two K_s^0 mesons and two oppositely charged particles, neither of which was identified as a charged kaon. The invariant mass distribution of final state particles in selected $\gamma\gamma \to K_s^0 K_s^0 \pi^+\pi^-$ events is presented in Fig. 2d.

3.5. Selection of $\gamma\gamma \to K^+K^-K^+K^-$ events

The decay channel with four charged kaons $K^+K^-K^+K^-$ in the final state was studied using events with four charged particles of which at least three were identified as charged kaons. The invariant mass distribution of selected final state $K^+K^-K^+K^-$ particles is shown in Fig. 2e.

4. Results

As seen in Fig. 2, the invariant mass distributions of final state particles have similar behaviour for all channels; there is an excess of events in the $\eta_c(2980)$ mass region, while no evidence of the $\eta_c'(3594)$ is seen. This is made especially clear in Fig. 3, where the sum of the invariant mass distributions of all five decay channels is shown. There is a clear η_c signal above the background and no visible peak near the $\eta_c'(3594)$. In order to quantify these conclusions, the following analysis was performed.

The observed counts $N(m)$ at invariant mass m can be written as the sum of the background counts $N_B(m)$ and the contributions $N_{\eta_c}(m)$ and $N_{\eta_c'}(m)$ of the η_c and η_c' resonances

$$N(m) = N_B(m) + N_{\eta_c}(m) + N_{\eta_c'}(m)\,. \tag{3}$$

The background counts in Fig. 3 appear to vary linearly with mass, as is indeed expected approximately from the well known two photon flux function $L(s,m)$ [4], where s is the square of the e^+e^- center-of-mass energy. Therefore, $N_B(m)$ was replaced by $a + bm$. The resonance contribution can be written as

$$N_R(m) = \mathscr{L}\, L(s,m)\, \sigma_{BW}\big(m, m_R, \Gamma_R, \Gamma_{\gamma\gamma}(R)\big)\, Br(R \to F)\, \epsilon_F(m)\,. \tag{4}$$

Here $\mathscr{L}$ is the e^+e^- luminosity; $L(s,m)$ is the two photon flux function; σ_{BW}, which is proportional to $(2J_R + 1)\Gamma_{\gamma\gamma}(R)$, is the Breit-Wigner cross section for the formation of resonance R with mass m_R, total width Γ_R, and two photon width $\Gamma_{\gamma\gamma}(R)$; $Br(R \to F)$ is the branching fraction for the decay of the resonance into the final state F; and $\epsilon_F(m)$ is the efficiency for detecting this final state.

By passing Monte Carlo generated events through the full DELPHI detector simulation [15], it was determined that the experimental mass resolution functions for all the decay channels studied here are

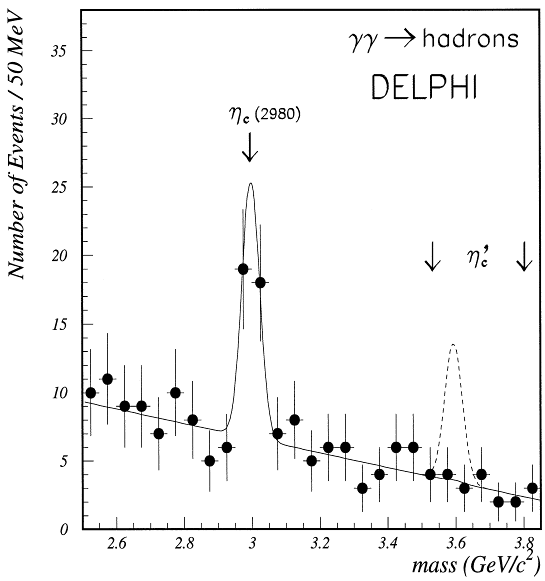

Fig. 3. The sum of the invariant mass distributions of final state particles of the five $\gamma\gamma \to$ hadrons channels shown in Fig. 2. The full curve shows the result of the fit with the sum of two Gaussian functions for the η_c and η_c' signals and a linear term for the background contribution (see text). The dashed curve shows the expected signal of η_c' production for $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) = 0.75$.

approximately Gaussian with nearly the same width, $\sigma = 26$ MeV and FWHM $\simeq 60$ MeV. This width is much larger than the natural width of the η_c or η_c'. This allows Eq. (4) to be rewritten as:

$$N_R(m) = \alpha_R\, G_R(m,m_R)\,, \tag{5}$$

where $G_R(m,m_R)$ is the Gaussian shape function for resonance R and

$$\alpha_R = k\,\mathscr{L}\,L(s,m_R)\,\epsilon_F(m_R)\,Br(R\to F)\,(2J_R+1)\,\Gamma_{\gamma\gamma}(R)\,, \tag{6}$$

where k is a constant.

Thus Eq. (3) reduces to

$$N(m) = a + bm + \alpha_{\eta_c}\left[G_{\eta_c}(m,m_{\eta_c}) + \frac{\alpha_{\eta_c'}}{\alpha_{\eta_c}}G_{\eta_c'}(m,m_{\eta_c'})\right], \tag{7}$$

where

$$\alpha \equiv \frac{\alpha_{\eta_c'}}{\alpha_{\eta_c}} = \left[\frac{L(\eta_c')}{L(\eta_c)}\right]\left[\frac{\epsilon(\eta_c')}{\epsilon(\eta_c)}\right]\left[\frac{Br(\eta_c'\to\text{hadrons})}{Br(\eta_c\to\text{hadrons})}\right]\left[\frac{\Gamma_{\gamma\gamma}(\eta_c')}{\Gamma_{\gamma\gamma}(\eta_c)}\right]. \tag{8}$$

The invariant mass spectrum $N(m)$ can therefore be fitted with six free parameters: a, b, α_{η_c}, m_{η_c}, α and $m_{\eta_c'}$.

In practice, the value of $m_{\eta_c'}$ was fixed at a series of values covering the range 3520 to 3800 MeV$/c^2$ in 20 MeV$/c^2$ steps, and the best fit values of the remaining five parameters were obtained in each case. The ratio $L(\eta_c')/L(\eta_c)$ was calculated analytically [4] and found to vary from 0.57 to 0.44. The ratio $\epsilon(\eta_c')/\epsilon(\eta_c)$ for the sum of all decay channels studied was determined from Monte Carlo simulations and found to vary from 1.33 to 1.50. It has been predicted [18,9] that the ratio of the corresponding hadronic decay widths of η_c and η_c', $\Gamma(\eta_c'\to h_i)/\Gamma(\eta_c\to h_i)$, is a constant [4] and that the total widths of both η_c and η_c' are nearly 100% hadronic, leading to $Br(\eta_c'\to\text{hadrons})/Br(\eta_c\to\text{hadrons}) \simeq 1$. Assuming this to be true for the decay channels used here [5] gives $m_{\eta_c} = 2999 \pm 8$ MeV$/c^2$, a total number of counts in the η_c peak of 25.1 ± 6.4, and

$$\frac{\Gamma_{\gamma\gamma}(\eta_c')}{\Gamma_{\gamma\gamma}(\eta_c)} = (0.00 \text{ to } 0.06) \pm (0.14 \text{ to } 0.17) \tag{9}$$

for values of $m_{\eta_c'}$ running from 3520 to 3800 MeV$/c^2$. The fit for $m_{\eta_c'} = 3600$ MeV$/c^2$ is shown in Fig. 3 by the solid curve.

If the data for the different decay channels are analyzed separately, the combined result for the ratio of two photon widths of the η_c' and η_c is found to be consistent with Eq. (9). The error in Eq. (9) is only statistical. Systematic errors in the ratio due to variation of the event selection criteria, estimation of efficiency, and the

[4] An analagous prediction about the constancy of the ratio $\Gamma(\psi'\to h_i)/\Gamma(\psi\to h_i)$ has been found to hold for many channels. But there are some striking exceptions, for which there is no generally accepted explanation. The most striking one being the $\rho\pi$ final state, this long-standing problem is often called the ''$\rho\pi$ puzzle''. For a new explanation of the $\rho\pi$ puzzle, as well as references to earlier work, see [19].

[5] Failure of this assumption would presumably indicate that an interesting counterpart of the '$\rho\pi$ puzzle' (see previous footnote) occurs also in the $\eta_c - \eta_c'$ system.

simplifying assumptions made in the analysis are estimated to be ≤ 0.05. Expressed in terms of an upper limit the above result corresponds to

$$\frac{\Gamma_{\gamma\gamma}(\eta_c')}{\Gamma_{\gamma\gamma}(\eta_c)} \leq 0.34, \quad (90\%\,\mathrm{CL}). \tag{10}$$

5. Discussion

The result of the E835 experiment in Eq. (1) can be written as

$$\frac{\Gamma_{\gamma\gamma}(\eta_c')}{\Gamma_{\gamma\gamma}(\eta_c)} \left[\frac{\Gamma_{p\bar{p}}(\eta_c')}{\Gamma_{p\bar{p}}(\eta_c)} \frac{\Gamma^2(\eta_c)}{\Gamma^2(\eta_c')} \right] \leq 0.16, \quad (90\%\,\mathrm{CL}). \tag{11}$$

The smallness of this ratio can be due either to the ratio of the hadronic widths in the square bracket or to the ratio of the $\gamma\gamma$ widths. The results in Eqs. (9) and (10) indicate that it is the two photon width of the η_c' which is much smaller than the two photon width of the η_c. As mentioned in the introduction, the prediction of a relativistic calculation is that $\Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) = 0.75 \pm 0.02$. This would correspond to the η_c' signal illustrated by the dashed curve in Fig. 3. The 90% confidence limit in Eq. (10) is more than a factor two smaller, and it poses an interesting and challenging problem for theory.

6. Summary

The first attempt to search for η_c' production in two photon reactions has been made using the data collected by the DELPHI detector at LEP during 1992-1996. No evidence of η_c' production in $\gamma\gamma$ reactions within the mass region 3520–3800 MeV/c^2 has been found. Assuming that, as predicted [18,9], the η_c and η_c' have the same decay branching ratios, at least for the five channels studied here, the upper limit for the ratio of two-photon widths of η_c' and η_c is found to be

$$\frac{\Gamma_{\gamma\gamma}(\eta_c')}{\Gamma_{\gamma\gamma}(\eta_c)} \leq 0.34, \quad (90\%\,\mathrm{CL}). \tag{12}$$

This limit is essentially determined by event statistics. The high energy running of LEP now in progress is expected to yield a total integrated e^+e^- luminosity of about $500\,\mathrm{pb}^{-1}$, with an additional factor of about 1.5 increase in the two photon flux. Thus a factor five increase in the number of events may be hoped for. This should lead to more definitive results for the identification of the η_c' and the determination of its two photon width.

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