Observation of $\eta'_{c}$ Production in $\gamma\gamma$ Fusion at CLEO

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30 Jun 2003
Abstract

We report on the observation of the $\eta'_c(2^1S_0)$, the radial excitation of $\eta_c(1^1S_0)$ ground state of charmonium, in the two-photon fusion reaction $\gamma\gamma \rightarrow \eta'_c \rightarrow K^0_S K^\pm \pi^\mp$ in 13.4 fb$^{-1}$ of CLEO II/II.V data and 9.2 fb$^{-1}$ of CLEO III data. The data have been analyzed to extract the $\eta'_c$ resonance parameters.

*Submitted to the International Europhysics Conference on High Energy Physics, July 2003, Aachen
I. INTRODUCTION

Knowledge of the hyperfine (spin singlet–triplet) splitting is important for the understanding of the spin–spin interaction in quarkonia. The existing experimental knowledge is limited to the 117±2 MeV splitting between $J/\psi(1^3S_1)$ and $\eta_c(1^1S_0)$[3]. It is important to find out the magnitude of the corresponding splitting between the radial excitations $\psi'(2^3S_1)$ and $\eta'_c(2^1S_0)$, which samples more confinement-dominated part of the $c\bar{c}$ potential whose spin dependence is open to speculation. The proximity of $\psi'$ and $\eta'_c$ to the $D\bar{D}$ breakup threshold also brings in channel–coupling effects. Several searches for $\eta'_c$ have been reported in the literature[2]–[6].

The Crystal Ball Collaboration at SLAC reported the identification of $\eta'_c$ in the radiative decay of $\psi'$. Structure due to a purported $\gamma$ of energy 91±5 MeV was interpreted as the signal for $M(\eta'_c) = 3594\pm 5$ MeV, and a 95% confidence level upper limit on its total width was set as 8 MeV. The E760 experiment at Fermilab made an unsuccessful search for $\eta'_c$ in the reaction $\bar{p}p \to \eta'_c \to \gamma\gamma$ in the mass range 3591–3621 MeV with $\sim6$ pb$^{-1}$ of invested luminosity[3]. They set a 90% confidence upper limit for $B(\eta'_c \to \bar{p}p) \times \Gamma_{\gamma\gamma}(\eta'_c)$ of $\approx 0.7$ eV for assumed total widths between 5 and 10 MeV. The search was repeated by the successor experiment E835 with the measurement with $\sim30$ pb$^{-1}$ of luminosity. No evidence for $\eta'_c$ was found in the mass region 3575–3600 MeV, and a 90% confidence upper limit for $B(\eta'_c \to \bar{p}p) \times \Gamma_{\gamma\gamma}(\eta'_c)$ of $\approx 0.7$ eV was again set for assumed total widths $\leq 15$ MeV[4]. It is worth noting that the corresponding value for $\eta_c$ is $B(\eta_c \to \bar{p}p) \times \Gamma_{\gamma\gamma}(\eta_c) \approx 9$ eV, i.e., about an order of magnitude larger.

The next search for $\eta'_c$ was done by DELPHI in the $\gamma\gamma$ fusion reaction $e^+e^- \to e^+e^- (\gamma\gamma) \to e^+e^- (\eta'_c)$, $\eta'_c \to \rho\rho$, $K_S^0K\pi$, $K^{*0}K\pi$, $K^0\bar{K}_S^0\pi\pi$ and $K^+K^-K^+K^-$. No signal was observed in the mass range of 3500–3800 MeV, and a 90% confidence upper limit $\Gamma_{\gamma\gamma}(\eta'_c)/\Gamma_{\gamma\gamma}(\eta_c) \leq 0.34$ was set[5] assuming equal decay branching ratios for $\eta_c$ and $\eta'_c$. In a similar search L3 established a 95% confidence limit of $\Gamma_{\gamma\gamma}(\eta'_c)/\Gamma_{\gamma\gamma}(\eta_c) \leq 0.29$[6].

Recently, the BELLE Collaboration has reported an $\eta'_c$ signal with $>6\sigma$ significance in the decay of $B \to K\eta'_c$, with $\eta'_c \to K_S^0K^\mp\mp$, from which they determined $M(\eta'_c) = 3654\pm 6(\text{stat})\pm 8(\text{syst})$ MeV[7], and $\Gamma_{\text{tot}}(\eta'_c) = 15^{+24}_{-15}(\text{stat})$ MeV. The BELLE Collaboration also presented evidence at the 3.4$\sigma$ level for an $\eta'_c$ signal in the reaction $e^+e^- \to (J/\psi)\eta'_c$, with $M(\eta'_c) = 3622\pm 12(\text{stat})$ MeV[8].

Theoretical predictions for the mass and width of the $\eta'_c$ meson have been so far based on potential model calculations and an analogy between the radial excitation pairs $(J/\psi)/\psi'$ and $\eta_c/\eta'_c$. The predictions for masses range from $M(\eta'_c) = 3594$ MeV to $M(\eta'_c) = 3629$ MeV, and the predictions for the ratio of the two-photon partial widths, $\Gamma_{\gamma\gamma}(\eta'_c)/\Gamma_{\gamma\gamma}(\eta_c)$, range from 0.38 to 0.77. Thus, the current best experimental results for both the mass and two–photon partial width of the $\eta'_c$ are at variance with theoretical predictions. This makes for great interest in determining these parameters with precision.

At CLEO we have searched for the $\eta'_c$ meson in the final state $K_S^0K^\pm\mp$ via $\gamma\gamma$ fusion in $e^+e^-$ data at the $\Upsilon(4S)$ resonance and its vicinity, using 13.4 fb$^{-1}$ of CLEO II/II.V data. Having observed strong evidence for the $\eta'_c$, we searched for its corroboration in 9.2 fb$^{-1}$ of CLEO III data. The observation of $\eta_c$ in the same reaction and decay channel was reported by CLEO earlier[9].

Preliminary results of the present study were presented earlier[10]. The BaBar Collaboration has also recently presented their preliminary results of the study of $\eta_c$ and $\eta'_c$ production in the same reaction[11].
The layout of the paper is the following. Section II describes our data samples and event selection criteria. Section III discusses our analysis procedures, while Section IV presents our estimates of systematic uncertainties. A summary of the results is given in Section V.

II. DATA SAMPLE AND EVENT SELECTIONS

The CLEO II/II.V data sample consists of 13.4 fb$^{-1}$ of $e^+e^-$ luminosity. Approximately one-third of the data were taken with the CLEO II configuration of the detector, and two-thirds with the CLEO II.V configuration. The total luminosity of CLEO III data used in the current analysis is 9.2 fb$^{-1}$, $\sim 70\%$ of the CLEO II/II.V luminosity. However, this newer data have the advantage of the superior hadron identification, as described below.

The detector components most useful for this study were the concentric tracking devices for measurements of charged particles, operating in a 1.5 T superconducting solenoid. For CLEO II[12], this tracking system consisted of a 6–layer straw tube chamber, a 10–layer precision drift chamber, and a 51–layer main drift chamber. The main drift chamber also provided measurements of the specific ionization loss, dE/dx, used for particle identification. For CLEO II.V, the innermost chamber was removed and replaced with a three–layer silicon vertex detector[13]; in addition the gas in the main drift chamber was changed from a 50–50 mixture of argon–ethane to 60–40 helium–propane.

For CLEO III[14], the entire charged particle tracking system was replaced. The new tracking system consists of four layers of double-sided silicon strip detector, surrounded by a new, 47-layer drift chamber with a smaller outer diameter[15]. Careful design optimization led to the momentum resolution of this tracking system comparable to that of CLEOII/II.V. The CLEOII time-of-flight system was eliminated and in the space created by it and the smaller drift chamber a ring imaging Cerenkov detector (RICH)[16] was installed.

The RICH distinguishes charged kaons from pions over 80% of the solid angle, which is smaller than hadron identification with dE/dx. For charged tracks with momenta below 2 GeV/c (the momentum range of most of our kaon candidates) the RICH identifies kaons with efficiency greater than 81% while having less than 2% probability that a pion is misidentified as a kaon.

In addition, the trigger for CLEOIII was improved in its flexibility, efficiency, and redundancy. Given that it relies on fewer types of devices with better design than in CLEOII, the trigger is also easier to reliably simulate.

The Monte Carlo simulation of CLEO detector response was based upon GEANT. Simulated events were processed in the same manner as the data to determine the $K^0_S K^\pm \pi^\mp$ detection efficiency. Efficiencies obtained in this fashion are listed for major selection criteria for both CLEO II/II.V and CLEO III in Table I. The overall detection efficiency for $\eta_c$ is 13.8% (CLEO II) and 11.6% (CLEO III).

The data sample used contained four charged particles, with at least one $K^0_S$ candidate. The $K^0_S$ vertex was reconstructed from its decay to $\pi^+\pi^-$ and was required to be displaced from the $e^+e^-$ interaction point. The mass of $K^0_S$ candidate was also required to be within 0.490 < $M(\pi\pi)$ < 0.505 GeV/c$^2$ (0.488 to 0.508 GeV/c$^2$ for CLEO III). Furthermore, the $K^0_S$ momentum vector was required to point back to the interaction point. The efficiency of these criteria, as determined from our simulations, was 77% for $\eta_c$ and 79% for $\eta_c'$. As shown in Table I, the CLEOIII efficiencies were somewhat smaller than those of CLEO II/II.V.

The two charged particles other than those from $K^0_S$ decay were examined for the hypotheses of being either kaons or pions. In CLEO II/II.V, this was done by using the dE/dx
TABLE I: Efficiencies for detecting the $\eta_c$ and $\eta_c'$ signals in %. Efficiencies for asterisked cuts were obtained for events which have passed all other cuts.

|                  | CLEO II/II.V | CLEO III |
|------------------|--------------|----------|
|                  | $\eta_c$ | $\eta_c'$ | $\eta_c$ | $\eta_c'$ |
| 4 reconstructed tracks | 35  | 40  | 34  | 37  |
| $K_S$ identification | 77  | 79  | 61  | 64  |
| $K/\pi$ particle ID * | 90  | 93  | 75  | 78  |
| $P_T < 0.6$ GeV/c * | 93  | 95  | 84  | 84  |
| Small $E_{neut}$ * | 84  | 83  | 82  | 80  |
| Trigger * | 69  | 73  | 99  | 99  |
| Overall | 10.0 | 13.8 | 9.8 | 11.6 |

and TOF information (when available), and by applying appropriate probability criteria. The efficiency of this particle identification, again determined from our simulations, was 90% for the $\eta_c$ and 93% for the $\eta_c'$. For CLEO III, all events were used in which the charged kaon candidate is identified as a $K$ by the RICH detector. When the $K$ candidate was not identifiable by the RICH (mostly when it is outside the RICH fiducial volume), it was identified by dE/dx measurements from the drift chamber. When its momentum lay between 1 and 2 GeV/c, however, it was difficult to distinguish $K$ from a charged pion using dE/dx and we did not use those $K$ candidates. Other criteria used included using specific trigger requirements, requiring a small transverse momentum of the $K_S^0K^\pm\pi^\mp$ system ($P_T<0.6$ GeV/c), and requiring the sum of neutral energy not associated with the charged particles be minimal, ($E_{neut}<0.2$ GeV for CLEOII/II.V; <0.3 GeV for CLEO III).

III. ANALYSIS

The $K_S^0K^\pm\pi^\mp$ invariant mass plot using our final event selection for CLEO II/II.V is shown in Fig. 1a. Enhancements at masses $\sim$2985 and $\sim$3643 MeV are visible. Henceforth we call these $\eta_c$ and $\eta_c'$ enhancements, respectively.

In order to extract numerical results from these data we have made maximum likelihood fit to this spectrum using a second order polynomial background and two Breit–Wigners, with their parameters kept free. This fit is overlaid in the Figure. As presented in Table III the fit gives $36^{+15}_{-11}$ events at a mass of $M(\eta_c') = (3642.7\pm4.1(stat.))$ MeV. A fit using a Breit-Wiegner convolved with a double Gaussian representing the resolution function extracted from Monte Carlo for each of the signals is in good agreement with the fit using Breit-Wigners only. Note that we assumed that the potential interference between the $\eta_c(\eta_c')$ signal and the continuum two-photon production of $K_SK\pi$ is negligible when we equate the peaks of the distribution with the masses of the $\eta_c(\eta_c')$. The same assumption was made for the rate measurements.

The “significance levels” of the enhancements in this Table were obtained as $\sigma \equiv \sqrt{-2\ln(L_0/L_{max})}$, where $L_{max}$ is the maximum likelihood returned by the fit described above, and $L_0$ is the likelihood returned by the fit with either no $\eta_c$ or no $\eta_c'$ resonance. The search for $\eta_c'$ resonance was made in the mass region 3580–3700 MeV. Since the mass and
FIG. 1: $K_{s}^{0}K^{\pm}\pi^{\mp}$ invariant mass in the reaction $\gamma\gamma \rightarrow K_{s}^{0}K^{\pm}\pi^{\mp}$ from the (a) the CLEO II/II.V data and (b) the CLEO III data. The curves in the figures are fit results using a second order polynomial for the background. For CLEO II/II.V two Breit–Wigners are used for the $\eta_c$ and $\eta'_c$ enhancements; for CLEO III the fit shown uses Breit–Wigners convolved with Gaussians.

width are not \textit{a priori} known, a more appropriate way of estimating the signal significance is to determine the probability that the counts for the background alone could statistically fluctuate to the level of the counts of signal plus background. It is found that the significance levels determined in this manner is smaller than those listed in Table II by about $0.5\sigma$.

Fig. 1(b) shows the preliminary $K_{s}^{0}K^{\pm}\pi^{\mp}$ invariant mass distribution from CLEO III after all criteria were applied. It shows clear enhancements at the $\eta_c$ mass as well as at the mass at which the CLEO II/II.V data indicated the $\eta'_c$. This is strong confirmation that the $\eta'_c$ signal we observed in the CLEO II/II.V data is real and not due to statistical fluctuation or some other artifact.

We fit the mass spectrum with second order polynomial representing the background under the $\eta'_c$ candidate peak and a Breit–Wigner function convolved with a double Gaussian representing the instrumental resolution of 5.7 MeV (96%) and 40 MeV (4%) as determined from our Monte Carlo simulation. We have also used power–law background and exponential background shapes and averaging over all three background shapes, we obtain preliminary
TABLE II: The results of the analysis. The yields of events and the masses are from the fits to the data. The significance of the enhancements are based on changes of likelihood as described in the text. The CLEO III results are preliminary.

|               | CLEO II/II.V | CLEO III (preliminary) |
|---------------|--------------|------------------------|
| Yield (events)| 287 ± 28    | 203 ± 22               |
| Mass (MeV)    | 2984.7 ± 2.1| 2982 ± 2              |
| significance  | 15.9σ       | 14.2σ                 |

The significance of the enhancements are based on changes of likelihood as described in the text. The CLEO III results are preliminary.

results of (29±8) events in the peak at a mass of (3642.5±3.6(stat)) MeV. These fit results are also shown in Table II. This measurement of the η′_c mass is completely consistent with that obtained from the CLEO II/II.V data. The statistical significance of the η′_c signal is determined to be 5.7σ, using the likelihood method described above. Note that in this case, this significance is the appropriate quantity since we search for the η′_c at a particular mass, namely that determined in the CLEO II/II.V analysis.

Photon–photon fusion is expected to populate positive charge conjugation resonances mainly when the photons are almost real, i.e., when the transverse momenta of both of them, and therefore of the sum of final state particles is small. In order to examine whether the observed η′_c peaks are due primarily to two–photon events, we examined the production of η′_c in two subregions of transverse momentum: 0 < P_T < 0.2 GeV/c and 0.2 < P_T < 0.6 GeV/c. Table III shows the results of this study. The CLEO II/II.V and CLEO III results are statistically consistent with the expectations from our two–photon Monte–Carlo simulations.

TABLE III: The transverse momentum dependence of production.

| P_T   | 0–0.2 GeV/c | 0.2–0.6 GeV/c |
|-------|-------------|--------------|
| 2 γ   | Expectations| 74%          | 26%          |
| CLEO II/II.V | (55 ± 18)% | (45 ± 18)%   |
| CLEO III   | (62 ± 19)% | (38 ± 19)%   |

Also of interest is the two-photon partial width of the η′_c as compared to that of the η_c. The ratio of the number of events of η′_c and η_c is:

\[
\frac{N(\eta'_c)}{N(\eta_c)} = \frac{\Gamma_{\gamma\gamma}(\eta'_c) \times B(\eta'_c \rightarrow K_SK\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \rightarrow K_SK\pi)} \times \frac{\epsilon(\eta'_c)}{\epsilon(\eta_c)} .
\]  

Here, for the CLEO II/II.V analysis:

\[\frac{N(\eta'_c)}{N(\eta_c)} = 0.125^{+0.054}_{-0.041}\] is the ratio of η′_c and η_c events from Table II.

\[\Phi(m_{\eta'_c})/\Phi(m_{\eta_c}) = 0.42\] is the ratio of the two–photon fluxes at the η′_c and η_c masses, as calculated using the known two–photon flux function. This ratio has a systematic uncertainty of ±2%.

\[\epsilon(\eta'_c)/\epsilon(\eta_c) = 1.38\] is the ratio of efficiencies as calculated from Monte Carlo simulation, and is shown in Table II.
Using these values in the equation above, we obtain

\[
R(\eta_c'/\eta_c) \equiv \frac{\Gamma_{\gamma\gamma}(\eta_c') \times B(\eta_c' \to K\bar{K}\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K\bar{K}\pi)} = 0.22^{+0.09}_{-0.07}(\text{stat}). \tag{2}
\]

Performing this same calculation for the CLEO III data, we obtain \(R(\eta_c'/\eta_c) = 0.29 \pm 0.09(\text{stat})\), which is preliminary but consistent with the CLEO II/II.V result.

IV. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the CLEO III results are still being investigated; therefore we only discuss those for the CLEO II/II.V analysis below.

A. Mass of the \(\eta_c'\) meson

We estimate systematic uncertainties on our mass determinations with the following considerations.

- It is difficult to estimate the contributions to systematic biases which arise from different choices of event selection when statistical uncertainties dominate. However, the statistical errors in the \(\eta_c\) peak are much smaller than those of the \(\eta_c'\) peak, and we consider the extreme variation in \(\eta_c\) mass in the different event selections we have attempted as providing an upper limit of 1 MeV as the systematic uncertainty due to event selections.

- We have made a Monte Carlo study of how the masses of \(\eta_c\) and \(\eta_c'\) shift between the input values and those obtained after the detector simulation. For an input mass and width of \(M = 2980\) MeV, \(\Gamma_{\text{tot}} = 27\) MeV, the shift, \(\Delta M(\eta_c)\), is \(0.9 \pm 0.6\) MeV. With an input mass and width of \(M = 3640\) MeV, \(\Gamma_{\text{tot}} = 15\) MeV, the shift, \(\Delta M(\eta_c')\), is \(0.7 \pm 0.3\) MeV. We conclude that the systematic error due to this source is \(\pm 1.0\) MeV.

- We have also tested how the masses of the particles that can be reconstructed compare with their known masses. We find that the reconstructed mass \(M(K_{S0}^0) = 497.69 \pm 0.06\) MeV. The PDG\(^1\) value is \(M(K_{S0}^0) = 497.67 \pm 0.03\) MeV. This small deviation, \(\Delta M(K_{S0}^0) = 0.02 \pm 0.07\) MeV, is consistent with the conclusions reached for the mass of the \(J/\psi\) meson, namely \(\Delta M(J/\psi) = 0.4 \pm 0.4\) MeV, which was measured separately. We therefore conclude that the absolute calibration of our mass scale has an uncertainty of \(\leq 1.0\) MeV.

- It is possible that the choice of background shape effects the mass determination. From the fits made with polynomial, power–law, and exponential backgrounds we find that \(M(\eta_c)\) varies by \(\leq 0.7\) MeV, and \(M(\eta_c')\) varies by \(\leq 0.1\) MeV. We therefore estimate that this source contributes \(\leq 1.0\) MeV to the systematic uncertainty in masses of \(\eta_c\) and \(\eta_c'\).

Adding the above contributions in quadrature we determine the systematic uncertainty in the mass of \(\eta_c'\) to be \(\leq 2\) MeV. We note, however, that \(\eta_c\) mass obtained in the present study (Table II) differs from our earlier published result\(^2\) by \(\sim 4\) MeV. Provided this difference, we assign the systematic uncertainty in our measurement as \(\pm 4\) MeV, at present. Studies are being made to understand the mass difference, and we expect that systematic uncertainties at the level of \(\pm 2\) MeV will be achieved in the final results.
B. \( R(\eta'_c/\eta_c) \)

This value of \( R \) cited earlier was obtained using second order polynomial function for the background. The major source of systematic uncertainty in the ratio \( R \) is found to be the choice of background shape. The values in case of power–law and exponential backgrounds is essentially the same, \( R = 0.13^{+0.05}_{-0.04}(\text{stat}) \) and \( R = 0.14^{+0.06}_{-0.05}(\text{stat}) \). As our final result for \( R \) we quote the average of the extreme values and assign the difference as systematic error. The systematic error due to efficiency ratio was \( \sim 2\% \), which is negligible.

Thus,

\[
R(\eta'_c/\eta_c) \equiv \frac{\Gamma_{\gamma\gamma}(\eta'_c) \times B(\eta'_c \to K_SK\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K_SK\pi)} = 0.17^{+0.07}_{-0.06}(\text{stat}) \pm 0.04(\text{syst}). \quad (3)
\]

V. SUMMARY

We have analyzed 13.4 fb\(^{-1}\) of \( e^+e^- \) data of CLEO II/II.V and 9.2 fb\(^{-1}\) data of CLEO III at \( \Upsilon(4S) \) and its vicinity for resonances in the reaction \( e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\eta'_c \to e^+e^- (K^0_SK^+\pi^-) \).

In the \( K^0_SK^+\pi^- \) invariant mass plot resulting from the CLEO II/II.V data, we see an excess of events at mass of \( \sim 3643 \) MeV with the significance level of over 4\( \sigma \) in addition to \( \eta_c \). We attribute this excess to the excitation of the \( \eta'_c \) resonance. Observation of an excess at the same mass in the CLEO III data confirms the discovery of \( \eta'_c \) in the CLEO II/II.V data.

Our results for the \( \eta'_c \) meson are as follows.

The value of its mass has been found to be:

\[
M(\eta'_c)_{\text{CLEO II}} = (3642.7 \pm 4.1(\text{stat}) \pm 4.0(\text{syst})) \text{ MeV}, \quad (4)
\]

\[
M(\eta'_c)_{\text{CLEO III}} = (3642.5 \pm 3.6(\text{stat})) \text{ MeV(preliminary)}, \quad (5)
\]

thus,

\[
\Delta M \equiv M(\psi') - M(\eta'_c) = (43 \pm 4(\text{stat}) \pm 4(\text{syst})) \text{ MeV}. \quad (6)
\]

We also determine the ratio

\[
R(\eta'_c/\eta_c)_{\text{CLEO II}} \equiv \frac{\Gamma_{\gamma\gamma}(\eta'_c) \times B(\eta'_c \to K_SK\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K_SK\pi)} = 0.17^{+0.07}_{-0.06}(\text{stat}) \pm 0.04(\text{syst}). \quad (7)
\]

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 Research Corporation, and the Texas Advanced Research Program.

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