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Observation of η_c' Production in $\gamma\gamma$ Fusion at CLEO *

J. Ernst,[1] H. Severini,[2] P. Skubic,[2] S.A. Dytman,[3] J.A. Mueller,[3] S. Nam,[3] V. Savinov,[3] G. S. Huang,[4] J. Lee,[4] D. H. Miller,[4] V. Pavlunin,[4] B. Sanghi,[4] E. I. Shibata,[4] I. P. J. Shipsey,[4] D. Cronin-Hennessy,[5] C. S. Park,[5] W. Park,[5] J. B. Thayer,[5] E. H. Thorndike,[5] T. E. Coan,[6] Y. S. Gao,[6] F. Liu,[6] R. Stroynowski,[6] M. Artuso,[7] C. Boulahouache,[7] S. Blusk,[7] E. Dambasuren,[7] O. Dorjkhaidav,[7] R. Mountain,[7] H. Muramatsu,[7] R. Nandakumar,[7] T. Skwarnicki,[7] S. Stone,[7] J.C. Wang,[7] A. H. Mahmood,[8] S. E. Csorna,[9] I. Danko,[9] G. Bonvicini,[10] D. Cinabro,[10] M. Dubrovin,[10] A. Bornheim,[11] E. Lipeles,[11] S. P. Pappas,[11] A. Shapiro,[11] W. M. Sun,[11] A. J. Weinstein,[11] R. A. Briere,[12] G. P. Chen,[12] T. Ferguson,[12] G. Tatishvili,[12] H. Vogel,[12] M. E. Watkins,[12] N. E. Adam,[13] J. P. Alexander,[13] K. Berkelman,[13] V. Boisvert,[13] D. G. Cassel,[13] J. E. Duboscq,[13] K. M. Ecklund,[13] R. Ehrlich,[13] R. S. Galik,[13] L. Gibbons,[13] B. Gittelman,[13] S. W. Gray,[13] D. L. Hartill,[13] B. K. Heltsley,[13] L. Hsu,[13] C. D. Jones,[13] J. Kandaswamy,[13] D. L. Kreinick,[13] A. Magerkurth,[13] H. Mahlke-Krüger,[13] T. O. Meyer,[13] N. B. Mistry,[13] J. R. Patterson,[13] T. K. Pedlar,[13] D. Peterson,[13] J. Pivarski,[13] S. J. Richichi,[13] D. Riley,[13] A. J. Sadoff,[13] H. Schwarthoff,[13] M. R. Shepherd,[13] J. G. Thayer,[13] D. Urner,[13] T. Wilksen,[13] A. Warburton,[13] M. Weinberger,[13] S. B. Athar,[14] P. Avery,[14] L. Breva-Newell,[14] V. Potlia,[14] H. Stoeck,[14] J. Yelton,[14] B. I. Eisenstein,[15] G. D. Gollin,[15] I. Karliner,[15] N. Lowrey,[15] C. Plager,[15] C. Sedlack,[15] M. Selen,[15] J. J. Thaler,[15] J. Williams,[15] K. W. Edwards,[16] D. Besson,[17] V. V. Frolov,[18] K. Y. Gao,[18] D. T. Gong,[18] Y. Kubota,[18] S. Z. Li,[18] R. Poling,[18] A. W. Scott,[18] A. Smith,[18] C. J. Stepaniak,[18] J. Urheim,[18] Z. Metreveli,[19] K.K. Seth,[19] A. Tomaradze,[19] and P. Zweber[19]

(CLEO Collaboration)

[1]*State University of New York at Albany, Albany, New York 12222*
[2]*University of Oklahoma, Norman, Oklahoma 73019*
[3]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[4]*Purdue University, West Lafayette, Indiana 47907*
[5]*University of Rochester, Rochester, New York 14627*
[6]*Southern Methodist University, Dallas, Texas 75275*
[7]*Syracuse University, Syracuse, New York 13244*
[8]*University of Texas - Pan American, Edinburg, Texas 78539*
[9]*Vanderbilt University, Nashville, Tennessee 37235*
[10]*Wayne State University, Detroit, Michigan 48202*
[11]*California Institute of Technology, Pasadena, California 91125*
[12]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[13]*Cornell University, Ithaca, New York 14853*
[14]*University of Florida, Gainesville, Florida 32611*
[15]*University of Illinois, Urbana-Champaign, Illinois 61801*
[16]*Carleton University, Ottawa, Ontario, Canada K1S 5B6*
and the Institute of Particle Physics, Canada
[17]*University of Kansas, Lawrence, Kansas 66045*
[18]*University of Minnesota, Minneapolis, Minnesota 55455*
[19]*Northwestern University, Evanston, Illinois 60208*

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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 $\gamma\gamma \to \eta_c' \to K_S^0 K^{\pm}\pi^{\mp}$ 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 η_c' resonance parameters.

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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 $\eta_c(1^1S_0)$[1]. 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 ψ' and η_c' to the $D\bar{D}$ breakup threshold also brings in channel–coupling effects. Several searches for η_c' have been reported in the literature[2]–[6].

The Crystal Ball Collaboration at SLAC reported the identification of η_c' in the radiative decay of ψ'[2]. Structure due to a purported γ 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 η_c' in the reaction $\bar{p}p \rightarrow \eta_c' \rightarrow \gamma\gamma$ in the mass region 3591–3621 MeV with ~6 pb^{-1} of invested luminosity[3]. They set a 90% confidence upper limit for $B(\eta_c' \rightarrow \bar{p}p) \times \Gamma_{\gamma\gamma}(\eta_c')$ of ≈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 ~30 pb^{-1} of luminosity. No evidence for η_c' was found in the mass region 3575–3600 MeV, and a 90% confidence upper limit for $B(\eta_c' \rightarrow \bar{p}p) \times \Gamma_{\gamma\gamma}(\eta_c')$ of ≈0.7 eV was again set for assumed total widths ≤15 MeV[4]. It is worth noting that the corresponding value for η_c is $B(\eta_c \rightarrow \bar{p}p) \times \Gamma_{\gamma\gamma}(\eta_c)$ ≈9 eV, *i.e.*, about an order of magnitude larger.

The next search for η_c' was done by DELPHI in the $\gamma\gamma$ fusion reaction $e^+e^- \rightarrow e^+e^-(\gamma\gamma) \rightarrow e^+e^-(\eta_c')$, $\eta_c' \rightarrow \rho^0\rho^0, K_S^0K\pi, K^{*0}K\pi, K_S^0K_S^0\pi\pi$ 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 η_c and η_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 η_c' signal with >6σ significance in the decay of $B \rightarrow K\eta_c'$, with $\eta_c' \rightarrow K_S^0K^{\pm}\pi^{\mp}$, from which they determined $M(\eta_c') = 3654 \pm 6(stat) \pm 8(syst)$ MeV[7], and $\Gamma_{tot}(\eta_c')= 15\ ^{+24}_{-15}$(stat) MeV. The BELLE Collaboration also presented evidence at the 3.4σ level for an η_c' signal in the reaction $e^+e^- \rightarrow (J/\psi)\eta_c'$, with $M(\eta_c') = 3622 \pm 12(stat)$ MeV[8].

Theoretical predictions for the mass and width of the η_c' meson have been so far based on potential model calculations and an analogy between the radial excitation pairs $(J/\psi)/\psi'$ and η_c/η_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 η_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 η_c' meson in the final state $K_S^0K^{\pm}\pi^{\mp}$ via $\gamma\gamma$ fusion in e^+e^- data at the Υ(4S) resonance and its vicinity, using 13.4 fb^{-1} of CLEO II/II.V data. Having observed strong evidence for the η_c', we searched for its corroboration in 9.2 fb^{-1} of CLEO III data. The observation of η_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 η_c and η_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 $K_S^0K^\pm\pi^\mp$ 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 η_c' is 13.8%(CLEO II) and 11.6%(CLEO III).

The data sample used contained four charged particles, with at least one K_S^0 candidate. The K_S^0 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_S^0 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_S^0 momentum vector was required to point back to the interaction point. The efficiency of these criteria, as determined from our simulations, was 77% for η_c and 79% for η_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_S^0 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 η_c and η_c' signals in %. Efficiencies for asterisked cuts were obtained for events which have passed all other cuts.

	CLEO II/II.V		CLEO III	
	η_c	η_c'	η_c	η_c'
4 reconstructed tracks	35	40	34	37
K_S identification	77	79	61	64
K/π 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 η_c and 93% for the η_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 $K_S^0 K^\pm \pi^\mp$ 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 $K_S^0 K^\pm \pi^\mp$ invariant mass plot using our final event selection for CLEO II/II.V is shown in Fig. 1a. Enhancements at masses ∼2985 and ∼3643 MeV are visible. Henceforth we call these η_c and η_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 II, the fit gives 36^{+15}_{-11} events at a mass of $M(\eta_c') = (3642.7 \pm 4.1(stat.))$ 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 $K_S K\pi$ is negligible when we equate the peaks of the distribution with the masses of the $\eta_c^{(\prime)}$. The same assumption was made for the rate measurements.

The "significance levels" of the enhancements in this Table were obtained as $\sigma \equiv \sqrt{-2ln(L_0/L_{max})}$, 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 η_c or no η_c' resonance. The search for η_c' resonance was made in the mass region 3580–3700 MeV. Since the mass and

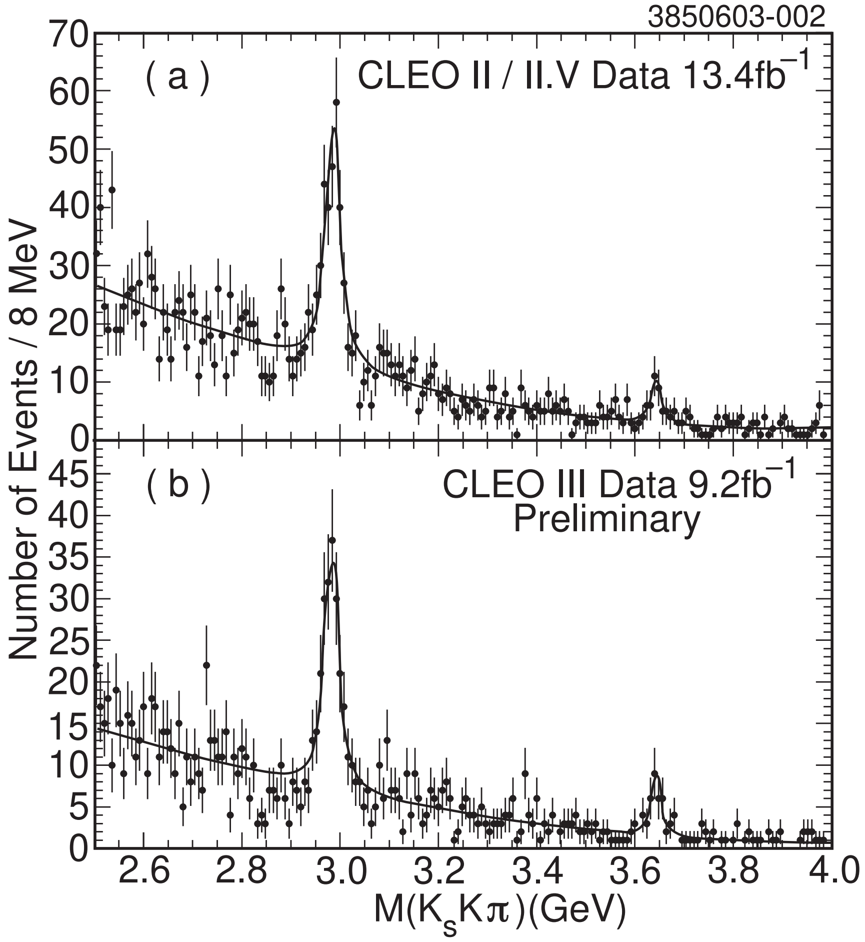

FIG. 1: $K_S^0 K^{\pm}\pi^{\mp}$ invariant mass in the reaction $\gamma\gamma \to K_S^0 K^{\pm}\pi^{\mp}$ from the (a) the CLEO II/II.V data and (b) the CLEO III data. The curves in the figures are fit results using a second order polynomial for the background. For CLEO II/II.V two Breit–Wigners are used for the η_c and η_c' enhancements; for CLEO III the fit shown uses Breit–Wigners convolved with Gaussians.

width are not *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 0.5σ.

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 η_c mass as well as at the mass at which the CLEO II/II.V data indicated the η_c'. This is strong confirmation that the η_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 η_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*)	
	η_c	η_c'	η_c	η_c'
Yield (events)	287 ± 28	$36\ ^{+15}_{-11}$	$203{\pm}22$	$29{\pm}8$
Mass (MeV)	2984.7 ± 2.1	3642.7 ± 4.1	$2982{\pm}2$	$3642.5{\pm}3.6$
significance	15.9σ	5.0σ	14.2σ	5.7σ

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	$(55 \pm 18)\%$	$(45 \pm 18)\%$
CLEO III	$(62 \pm 19)\%$	$(38 \pm 19)\%$

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:

$$\frac{N(\eta_c')}{N(\eta_c)} = \frac{\Gamma_{\gamma\gamma}(\eta_c') \times B(\eta_c' \to K_S K\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K_S K\pi)} \times \frac{\Phi(m_{\eta_c'})}{\Phi(m_{\eta_c})} \times \frac{\epsilon(\eta_c')}{\epsilon(\eta_c)} \quad . \tag{1}$$

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

$N(\eta_c')/N(\eta_c) = 0.125^{+0.054}_{-0.041}$ 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[1]. 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 I.

Using these values in the equation above, we obtain

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

Performing this same calculation for the CLEO III data, we obtain $R(\eta_c'/\eta_c) = 0.29 \pm 0.09(stat)$, 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 η_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 η_c peak are much smaller than those of the η_c' peak, and we consider the extreme variation in η_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 η_c and η_c' shift between the input values and those obtained after the detector simulation. For an input mass and width of M=2980 MeV, Γ_{tot}=27 MeV, the shift, $\Delta M(\eta_c)$, is 0.9±0.6 MeV. With an input mass and width of M=3640 MeV, Γ_{tot}=15 MeV, the shift, $\Delta M(\eta_c')$, is 0.7±0.3 MeV. We conclude that the systematic error due to this source is ±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 $M(K_S^0)$=497.69±0.06 MeV. The PDG[1] value is $M(K_S^0)$=497.67±0.03 MeV. This small deviation, $\Delta M(K_S^0)$=0.02±0.07 MeV, is consistent with the conclusions reached for the mass of the J/ψ meson, namely $\Delta M(J/\psi)$=0.4±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 η_c and η_c'.

Adding the above contributions in quadrature we determine the systematic uncertainty in the mass of η_c' to be $\leq$2 MeV. We note, however, that η_c mass obtained in the present study (Table II) differs from our earlier published result[9] by $\sim$4 MeV. Provided this difference, we assign the systematic uncertainty in our measurement as ±4 MeV, at present. Studies are being made to understand the mass difference, and we expect that systematic uncertainties at the level of ±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, $R = 0.13^{+0.05}_{-0.04}(stat)$ and $R = 0.14^{+0.06}_{-0.05}(stat)$. 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,

$$R(\eta_c'/\eta_c) \equiv \frac{\Gamma_{\gamma\gamma}(\eta_c') \times B(\eta_c' \to K_S K \pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K_S K \pi)} = 0.17^{+0.07}_{-0.06}(stat) \ \pm 0.04(syst)\,. \tag{3}$$

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 Υ(4S) and its vicinity for resonances in the reaction $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\eta_c' \to e^+e^-(K_S^0 K^\pm \pi^\mp)$.

In the $K_S^0 K^\pm \pi^\mp$ 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 4σ in addition to η_c. We attribute this excess to the excitation of the η_c' resonance. Observation of an excess at the same mass in the CLEO III data confirms the discovery of η_c' in the CLEO II/II.V data.

Our results for the η_c' meson are as follows.

The value of its mass has been found to be:

$$M(\eta_c')_{\rm CLEOII} = (3642.7 \pm 4.1(stat) \pm 4.0(syst))\ \text{MeV}\,, \tag{4}$$

$$M(\eta_c')_{\rm CLEOIII} = (3642.5 \pm 3.6(stat))\ \text{MeV(preliminary)}\,, \tag{5}$$

thus,

$$\Delta M \equiv M(\psi') - M(\eta_c') = (43 \pm 4(stat) \pm 4(syst))\ \text{MeV}\,. \tag{6}$$

We also determine the ratio

$$R(\eta_c'/\eta_c)_{\rm CLEOII} \equiv \frac{\Gamma_{\gamma\gamma}(\eta_c') \times B(\eta_c' \to K_S K \pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times B(\eta_c \to K_S K \pi)} = 0.17^{+0.07}_{-0.06}(stat) \pm 0.04(syst)\,. \tag{7}$$

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