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

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(Received 23 December 2003; published 5 April 2004)

We report on the observation of the $\eta_c'(2^1S_0)$, the radial excitation of the $\eta_c(1^1S_0)$ ground state of charmonium, in the two-photon fusion reaction $\gamma\gamma \to \eta_c' \to K_S^0 K^\pm \pi^\mp$ in 13.6 fb^{-1} of CLEO II/II.V data and 13.1 fb^{-1} of CLEO III data. We obtain $M(\eta_c') = 3642.9 \pm 3.1(\mathrm{stat}) \pm 1.5(\mathrm{syst})$ MeV and $M(\eta_c) = 2981.8 \pm 1.3(\mathrm{stat}) \pm 1.5(\mathrm{syst})$ MeV. The corresponding values of hyperfine splittings between $^1S_0$ and $^3S_1$ states are $\Delta M_{\mathrm{hf}}(1S) = 115.1 \pm 2.0$ MeV and $\Delta M_{\mathrm{hf}}(2S) = 43.1 \pm 3.4$ MeV. Assuming that the η_c and η_c' have equal branching fractions to $K_S K \pi$, we obtain $\Gamma_{\gamma\gamma}(\eta_c') = 1.3 \pm 0.6$ keV.

DOI: 10.1103/PhysRevLett.92.142001 PACS numbers: 14.40.Gx, 13.20.Gd

Quantum chromodynamics (QCD) is the accepted theory of the strong interaction. Charmonium ($c\bar{c}$) states provide an excellent laboratory for the study of the QCD interactions. Experimental data are generally compared with perturbative predictions with the QCD interaction modeled by a potential. The central part of the popular Cornell potential [1] consists of a one-gluon exchange "Coulombic" part $\propto 1/r$, and a "confinement" part $\propto r$. The spin dependence of this potential, with spin-orbit, spin-spin, and tensor components, is generally assumed to arise only from the vector Coulombic part. The confinement potential is assumed to be scalar with only a minimal spin-orbit contribution due to Thomas precession. There is little experimental evidence to support the assumption of the pure Lorentz scalar nature of the confinement potential. One of the best ways to study the validity of this assumption is to measure the hyperfine splitting of states which sample the confinement region of the $q\bar{q}$ potential. The $2S$ states of charmonium, the ψ' (2^3S_1) and η_c' (2^1S_0), are ideal for this purpose. The mass of the ψ' is known very precisely, $M(\psi') = 3685.96 \pm 0.09$ MeV [2], but the η_c' has not been firmly identified until recently. In this Letter, we report on the observation of the η_c' in independent CLEO II and CLEO III measurements of the two-photon fusion reaction

$$e^+e^- \to e^+e^-(\gamma\gamma), \qquad \gamma\gamma \to \eta_c' \to K_S^0 K^\pm \pi^\mp. \quad (1)$$

In 1982, the Crystal Ball collaboration reported the observation of a small enhancement at $E_\gamma \approx 91$ MeV in the inclusive photon spectrum from the reaction $e^+e^- \to \psi' \to \gamma X$, and interpreted it as due to η_c' with $M(\eta_c') = 3594 \pm 5$ MeV, $\Gamma(\eta_c') < 8$ MeV [2,3]. This observation, which corresponds to a $2S$ hyperfine splitting $\Delta M_{\rm hf}(2S) = M(\psi') - M(\eta_c') = 92 \pm 5$ MeV, was in qualitative accord with the well-established $1S$ hyperfine splitting, $\Delta M_{\rm hf}(1S) = M(J/\psi) - M(\eta_c) = 117 \pm 2$ MeV [2]. However, it was not confirmed, and the listing of the η_c' was dropped by the Particle Data Group [2] from the meson summary list. The Fermilab experiments E760 and E835 [4] failed to identify η_c' in the reaction $\bar{p}p \to \eta_c' \to \gamma\gamma$, for η_c' mass in the range $M(\eta_c') =$ 3575–3660 MeV. Similarly, in e^+e^- collisions at $\sqrt{s} \approx$ 91 GeV DELPHI [5], and later L3 [6], found no evidence for η_c' in the reaction $\gamma\gamma \to$ hadrons, in the mass range 3500–3800 MeV, and concluded that its population in this reaction was less than a third of that of the η_c. A recent preliminary CLEO measurement [7] of the inclusive photon spectrum from $\psi' \to \gamma X$ has also not found any evidence for the excitation of η_c'.

The theoretical situation was equally uncertain. The perturbative prediction for the hyperfine splitting of the S states of charmonia is, in the lowest order,

$$\Delta M_{\rm hf}(S) = [32\pi\alpha_s/(9m_c^2)]|\Psi(0)|^2. \quad (2)$$

Thus, assuming that the strong coupling constant $\alpha_s(2S) = \alpha_s(1S)$,

$$\frac{\Delta M_{\rm hf}(2S)}{\Delta M_{\rm hf}(1S)} = \frac{|\Psi(0)/m_c|^2_{2S}}{|\Psi(0)/m_c|^2_{1S}} = \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)}\frac{M^2(\psi')}{M^2(J/\psi)},$$

since $\Gamma(^3S_1 \to e^+e^-)$ is proportional to $|\Psi(0)|^2/M^2(^3S_1)$. Substituting experimental values [2] yields, $\Delta M_{\rm hf}(2S) = 68 \pm 7$ MeV. Buchmüller and Tye [8] have pointed out that, in order to take approximate account of binding energy, m_c in Eq. (2) can be replaced by $M(^3S_1)/2$, which leads to $\Delta M_{\rm hf}(2S) = 48 \pm 5$ MeV.

Numerous potential model predictions for $\Delta M_{\rm hf}(1S, 2S)$ exist. Most of them make the assumption that the confinement potential is scalar. The predictions range from $\Delta M_{\rm hf}(2S) =$ 60–100 MeV. A recent calculation with a screened Coulombic potential [9] predicts $\Delta M_{\rm hf}(2S) = 38$ MeV, but it gives splittings for the ^3P_J states which are factor of 2 smaller than experimentally measured. Two recent quenched lattice calculations predict $\Delta M_{\rm hf}(2S) =$ 94–106 MeV [10], and $\Delta M_{\rm hf}(2S) =$ 25–43 MeV [11], respectively. Most predictions make the caveat that coupled-channel effects, which were not included, may be important for $\Delta M_{\rm hf}(2S)$ because of the proximity of the $2S$ states to the $D\bar{D}$ threshold at 3.73 GeV.

The first reports of a successful identification of η_c' came recently from two measurements by the Belle collaboration. In the decay of 45×10^6 B mesons, $B \to K(K_S K\pi)$, they observed peaks in the $K_S K\pi$ invariant mass spectrum corresponding to the η_c and η_c', and reported $M(\eta_c') = 3654 \pm 6 \pm 8$ MeV [12,13]. They also reported [14] η_c' observation in double charmonium production, $e^+e^- \to J/\psi + \eta_c'$, in 46.2 fb^{-1} of e^+e^- data at $\sqrt{s} \approx 10$ GeV. They reported $M(\eta_c') = 3622 \pm 12$(stat) MeV. The fact that both masses were significantly larger than that reported by the Crystal Ball collaboration provided for great interest in confirming the η_c' observation in independent measurements at CLEO.

At CLEO, we had earlier reported [15] the identification and study of $\eta_c(^1S_0)$ in the two-photon fusion reaction of Eq. (1) in 13.6 fb^{-1} of CLEO II data at the Υ (4S) and vicinity. We have reanalyzed CLEO II data with the resonance search extended for $M(K_S K\pi)$ up to 4.1 GeV. A positive signal was observed for an η_c' mass of $\sim$3643 MeV. In order to confirm this observation, 13.1 fb^{-1} of data taken at, and in the vicinity of, the Υ ($1S \to 4S$) resonances with the improved CLEO III detector were analyzed. Results which were consistent with those from the CLEO II data were obtained.

Charged particle tracking and dE/dx measurements in the CLEO II [16,17] detectors were done by various concentric devices (straw tube chamber, drift chamber, and silicon vertex detector) operating in a 1.5 T superconducting solenoid. They have been described in detail in Ref. [15]. K_S^0 were uniquely reconstructed from the displaced vertex of their $\pi^+\pi^-$ decay [15]. K/π

separation was done by using the dE/dx and time-of-flight information.

For CLEO III [18], the charged particle tracking system was replaced with four layers of double-sided silicon detectors, surrounded by a new, 47-layer drift chamber [19]. The CLEO II time-of-flight system was replaced by a ring-imaging Cherenkov detector (RICH) [20] which distinguishes $K^{\pm}$ from $\pi^{\pm}$ over 80% of solid angle. The two charged tracks not from the K_S^0 decay were tested as being either kaons or pions. All events were used in which the charged particle candidate is identified as a K or π by the RICH detector. For $p > 2$ GeV$/c$ (as for most of our $K^{\pm}$ candidates) the RICH identifies kaons with efficiency greater than 81% while having less than 2% probability of a pion faking a kaon. When K/π discrimination by RICH was not possible, dE/dx measurements from the drift chamber were used. For $1 < p < 2$ GeV$/c$, however, K/π separation was difficult using dE/dx, and such events were rejected.

In order to ensure production via two-photon fusion and only four-charged particles in the event, additional cuts were made in total transverse momentum P_T of the $K_S K\pi$ system, and in neutral energy $E_{\rm neut}$ not associated with the charged particles.

The Monte Carlo simulation of the CLEO detector response was based upon GEANT [21], with events for reaction (1) simulated using the formalism of Budnev *et al.* [22]. Simulated events were processed in the same manner as the data to determine the $K_S^0 K^{\pm}\pi^{\mp}$ detection efficiency. Efficiencies for trigger, K_S^0 identification, four-charged track reconstruction, π/K identification, and cuts on P_T and $E_{\rm neut}$ were determined. The overall detection efficiencies (ϵ) obtained from large statistics Monte Carlo samples are listed in Table I.

The $K_S^0 K^{\pm}\pi^{\mp}$ invariant mass plots using the event selections for CLEO II and CLEO III are shown in Fig. 1. Clear enhancements at masses $\sim$2982 and $\sim$3643 MeV are visible in both, which we label as η_c and η_c', respectively. There is a some evidence for a small enhancement at $\sim$3.1 GeV, presumably from the population of J/ψ via initial state radiation, but it is found that its inclusion has no effect on our best fit parameters.

In order to extract numerical results from these data, we have made maximum likelihood fits to these spectra using a polynomial background and two resonances with Breit-Wigner parametrization, convoluted with double Gaussians representing the experimental resolution functions as obtained from Monte Carlo simulations. For CLEO II data, the widths (relative magnitudes) of the Gaussians were $\sigma_1 = 10.0$ MeV (78%) and $\sigma_2 = 37.2$ MeV (22%). For CLEO III data, the corresponding numbers were $\sigma_1 = 8.7$ MeV (74%) and $\sigma_2 = 26.6$ MeV (26%).

As described in our previous publication [15], most of the observed background under our signal events is expected to arise from non-$\gamma\gamma \to K_S^0 K^{\pm}\pi^{\mp}$ sources such as events with at least one missing π^0 or γ, as well as events of the type $e^+e^- \to$ hadrons, $e^+e^- \to \tau^+\tau^-$, and $\gamma\gamma \to \tau^+\tau^-$. We have therefore not taken into account possible interference between resonance and continuum in fitting our data. The results presented in Table I are based on our final event selections, $P_T < 0.6$ GeV, $E_{\rm neut} < 0.2$ GeV (CLEO II), or $E_{\rm neut} < 0.4$ GeV (CLEO III), second-order polynomial backgrounds, and separate fits in the mass regions 2.5–3.5 GeV (η_c), and 3.3–4.1 GeV (η_c'). The "significance levels" of the enhancements listed in Table I were obtained as $\sigma \equiv \sqrt{-2\ln(L_0/L_{\rm max})}$, where $L_{\rm max}$ is the maximum likelihood value from the fits described above, and L_0 is the likelihood value from the fits with either no η_c or no η_c' resonance. Combining the independent significance levels of the CLEO II and CLEO III measurements in quadrature gives the significance level for our observation of η_c' as 6.5σ.

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 test whether the observed η_c' peaks are due primarily to two-photon events, we have examined the production of η_c' in several subregions of transverse momentum. We find that both the CLEO II and CLEO III P_T distributions are statistically consistent [23] with the expectations from our two-photon Monte Carlo simulations [21,22], and we conclude that in both data sets the η_c' peak is mainly due to two-photon fusion.

TABLE I. Summary of the results for η_c and η_c' for both CLEO II and CLEO III data sets. The errors shown are statistical only.

	CLEO II		CLEO III	
	η_c	η_c'	η_c	η_c'
ϵ (%)	10.0	13.8	8.9	11.9
N, events	282 ± 30	28^{+13}_{-10}	310 ± 29	33^{+14}_{-11}
M (MeV)	2984.2 ± 2.0	3642.4 ± 4.4	2980.0 ± 1.7	3643.4 ± 4.3
Γ (MeV)	24.7 ± 5.1	3.9 ± 18.0	24.8 ± 4.5	8.4 ± 17.1
Significance (σ)	15.1	4.4	17.0	4.8
$R(\eta_c'/\eta_c)$	0.17 ± 0.07		0.19 ± 0.08	

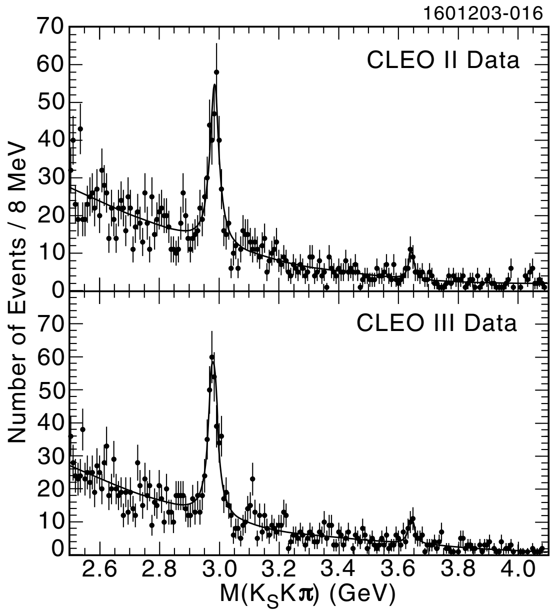

FIG. 1. Invariant mass distributions for $K_S^0 K^\pm \pi^\mp$ events from (top) the CLEO II data and (bottom) the CLEO III data. The curves in the figures are results of fits described in the text.

It is of interest to compare the two-photon partial width of η_c' to that of η_c. The quantity that can be directly obtained from the data is

$$R(\eta_c'/\eta_c) \equiv \frac{\Gamma_{\gamma\gamma}(\eta_c') \times \mathcal{B}(\eta_c' \to K_S K\pi)}{\Gamma_{\gamma\gamma}(\eta_c) \times \mathcal{B}(\eta_c \to K_S K\pi)}.$$

In terms of the measured quantities

$$R(\eta_c'/\eta_c) = \frac{N(\eta_c')}{N(\eta_c)} \times \frac{\Phi(m_{\eta_c})}{\Phi(m_{\eta_c'})} \times \frac{\epsilon(\eta_c)}{\epsilon(\eta_c')}.$$

$\Phi(m_{\eta_c})/\Phi(m_{\eta_c'}) = 2.40 \pm 0.05$ is the ratio of the two-photon fluxes at the η_c and η_c' masses [22]. This leads to results for $R(\eta_c'/\eta_c)$ given in Table I.

We have attempted to determine the uncertainty in our mass measurements due to the calibration of our mass scale by comparing the masses we measure from our data for $K_S^0(\to \pi^+\pi^-)$, $D^0(\to K_S^0\pi^\pm\pi^\mp)$, and $D^\pm(\to K^\pm\pi^\pm\pi^\mp)$ with their known values [2]. We estimate this uncertainty to be ≤ 1 MeV in the η_c and η_c' mass regions for both CLEO II and CLEO III data. Systematic uncertainties may also arise due to the fitting procedures for the invariant mass spectra. We find that the different choices of the background parametrization (polynomials, power law, or exponential) and peak shape parametrization lead to variations in mass of $\leq$0.5 MeV. It is also found that Monte Carlo events have a reconstructed invariant $K_S^0 K^\pm \pi^\mp$ mass that differs from the input mass at levels $\leq$1 MeV.

We consider the above contributions as being independent of each other and, by combining them in quadrature, we obtain a conservative estimate of possible systematic bias in the η_c and η_c' masses to be 1.5 MeV for both CLEO II and CLEO III.

Using high statistics samples of D mesons and the larger η_c samples, we have checked that variations in particle identification and event selection criteria do not give rise to changes in our results in a statistically significant way.

The dominant source of systematic uncertainty in the determination of total widths, two-photon widths, and the ratio R is found to be the choice of the background shape.

The present analysis of the CLEO II data (Table I), including the systematic errors, yields $M(\eta_c) = 2984.2 \pm 2.0 \pm 1.5$ MeV. In our earlier publication for the same data, we reported [15] $M(\eta_c) = 2980.4 \pm 2.3 \pm 0.6$ MeV. A careful examination of the event selection used there has revealed that an algorithm used for charged track identification led to the inclusion of some ($\sim$13%) false and poorly measured events. Rejection of these events is the main reason for the larger mass obtained here. The present determination supersedes the earlier reported mass value. The present analysis of CLEO II data also yields $\Gamma(\eta_c) = 24.7 \pm 5.1 \pm 3.5$ MeV and $\Gamma_{\gamma\gamma}(\eta_c) = 7.2 \pm 0.8 \pm 0.7 \pm 2.2(\mathrm{br})$ keV [the last error is due to the uncertainty in the branching ratio $\mathcal{B}(\eta_c \to K_S^0 K^\pm \pi^\mp)$], which are in agreement with our previously reported values. The two-photon width from CLEO III data is $\Gamma_{\gamma\gamma}(\eta_c) = 7.5 \pm 0.5 \pm 0.5 \pm 2.3(\mathrm{br})$ keV. The average of the two results is $\Gamma_{\gamma\gamma}(\eta_c) = 7.4 \pm 0.4 \pm 0.5 \pm 2.3(\mathrm{br})$ keV.

In summary, in independent analyses of CLEO II and CLEO III data sets for the reaction $e^+e^- \to e^+e^-(\gamma\gamma) \to e^+e^-(\eta_c') \to e^+e^-(K_S^0 K^\pm \pi^\mp)$, we see clear evidence for the excitation of the η_c (1^1S_0), and another resonance which we assign to η_c' (2^1S_0). We combine the separate results of CLEO II and CLEO III presented in Table I to obtain the following as our final results

$$M(\eta_c) = 2981.8 \pm 1.3 \pm 1.5 \text{ MeV}, \quad \Gamma(\eta_c) = 24.8 \pm 3.4 \pm 3.5 \text{ MeV}, \quad R(\eta_c'/\eta_c) = 0.18 \pm 0.05 \pm 0.02,$$

$$M(\eta_c') = 3642.9 \pm 3.1 \pm 1.5 \text{ MeV}, \quad \Gamma(\eta_c') = 6.3 \pm 12.4 \pm 4.0 \text{ MeV}, \quad \text{or} \quad \leq 31 \text{ MeV (90\% C.L.)},$$

Using the known masses of the J/ψ and ψ' [2], and combining statistical and systematic errors in quadrature, these correspond to $\Delta M_{\mathrm{hf}}(1S) = 115.1 \pm 2.0$ MeV and $\Delta M_{\mathrm{hf}}(2S) = 43.1 \pm 3.4$ MeV.

Assuming that the branching fractions for η_c and η_c' decays to $K_S K\pi$ are equal [24], and using the average value of $\Gamma_{\gamma\gamma}(\eta_c)$ as obtained above, our result for R leads to the first estimation of $\Gamma_{\gamma\gamma}(\eta_c') = 1.3 \pm 0.6$ keV.

As mentioned earlier, all new measurements contradict the earlier Crystal Ball identification of η_c' with a mass of 3594 ± 5 MeV, and therefore $\Delta M_{\mathrm{hf}}(2S) = 92 \pm 5$ MeV. The present results reduce this hyperfine splitting by nearly a factor of 2. We hope that this will lead to a reexamination of the $c\bar{c}$ hyperfine interaction in the confinement region, as well as coupled-channel effects for $^3S_1$ and $^1S_0$ states.

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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