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

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Abstract

We report on the observation of the $\eta_c'(2^{1}S_0)$, the radial excitation of $\eta_c(1^{1}S_0)$ ground state of charmonium, in the two-photon fusion reaction $\gamma\gamma \rightarrow \eta_c' \rightarrow K_S^0 K^{\pm}\pi^{\mp}$ in $13.6\ f{b}^{-1}$ of CLEO II/II.V data and $13.1\ f{b}^{-1}$ of CLEO III data. We obtain $M(\eta_c')=3642.9\pm3.1(\text{stat})\pm1.5(\text{syst})\ MeV$, and $M(\eta_c)=2981.8\pm1.3(\text{stat})\pm1.5(\text{syst})\ MeV$. The corresponding values of hyperfine splittings between $1^{1}S_0$ and $3^{3}S_1$ states are $\Delta M_{hf}(1S)=115.1\pm2.0\ MeV$, $\Delta M_{hf}(2S)=43.1\pm3.4\ MeV$. Assuming that the $\eta_c$ and $\eta_c'$ have equal branching fractions to $K_S^0 K\pi$, we obtain $\Gamma_{\gamma\gamma}(\eta_c')=1.3\pm0.6\ keV$. 

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 \(\psi'(2S)\) and \(\eta_c(2S)\), are ideal for this purpose. The mass of the \(\psi'\) is known very precisely, \(M(\psi')=3685.96\pm0.09\) MeV \[^2\], but the \(\eta'_c\) has not been firmly identified until recently. In this Letter we report on the observation of the \(\eta'_c\) in independent CLEO II and CLEO III measurements of the two-photon fusion reaction

\[
e^+e^- \rightarrow e^+e^-(\gamma\gamma), \quad \gamma\gamma \rightarrow \eta'_c \rightarrow K_S^0 K^\pm \pi^\mp. \tag{1}\]

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 \(e^+e^- \rightarrow \psi' \rightarrow \gamma X\), and interpreted it as due to \(\eta'_c\) with \(M(\eta'_c)=3594\pm5\) MeV, \(\Gamma(\eta'_c)<8\) MeV \[^1,2\]. This observation, which corresponds to a 2S hyperfine splitting \(\Delta M_{hf}(2S)=M(\psi')-M(\eta'_c)=92\pm5\) MeV, was in qualitative accord with the well established 1S hyperfine splitting, \(\Delta M_{hf}(1S)=M(J/\psi)-M(\eta_c)=117\pm2\) MeV \[^2\]. However, it was not confirmed, and the listing of the \(\eta'_c\) was dropped by the PDG \[^2\] from the meson summary list. The Fermilab experiments E760/E835 \[^4\] failed to identify \(\eta'_c\) in the reaction \(\bar{p}p \rightarrow \eta'_c \rightarrow \gamma\gamma\), for \(\eta'_c\) mass in the range \(M(\eta'_c)=3575–3660\) MeV. Similarly, in \(e^+e^-\) collisions at \(\sqrt{s} \approx 91\) GeV DELPHI \[^3\], and later L3 \[^6\], found no evidence for \(\eta'_c\) in the reaction \(\gamma\gamma \rightarrow \text{hadrons}\) in the mass range, 3500–3800 MeV, and concluded that its population in this reaction was less than a third of that of the \(\eta_c\). A recent preliminary CLEO measurement \[^7\] of the inclusive photon spectrum from \(\psi' \rightarrow \gamma X\) has also not found any evidence for the excitation of \(\eta'_c\).

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

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

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

\[
\frac{\Delta M_{hf}(2S)}{\Delta M_{hf}(1S)} = \frac{|\Psi(0)/m_c(2S)|^2}{|\Psi(0)/m_c(1S)|^2} = \frac{\Gamma(\psi' \rightarrow e^+e^-)M^2(\psi')}{\Gamma(J/\psi \rightarrow e^+e^-)M^2(J/\psi)}
\]

since \(\Gamma(S_1 \rightarrow e^+e^-)\) is proportional to \(|\Psi(0)|^2/M^2(S_1)\). Substituting experimental values \[^2\] yields, \(\Delta M_{hf}(2S)=68\pm7\) MeV. Buchmiller 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 \(M(S_1)/2\), which leads to \(\Delta M_{hf}(2S)=48\pm5\) MeV.

Numerous potential model predictions for \(\Delta M_{hf}(1S, 2S)\) exist. Most of them make the assumption that the confinement potential is scalar. The predictions range from
\[ \Delta M_{hf}(2S) = \text{60–100 MeV.} \] A recent calculation with a screened Coulombic potential predicts \[ \Delta M_{hf}(2S) = \text{38 MeV}, \] but it gives splittings for the \[ ^3P_J \] states which are factor of two smaller than experimentally measured. Two recent quenched lattice calculations predict \[ \Delta M_{hf}(2S) = \text{94–106 MeV} \] and \[ \Delta M_{hf}(2S) = \text{25–43 MeV} \], respectively. Most predictions make the caveat that coupled-channel effects, which were not included, may be important for \[ \Delta M_{hf}(2S) \] 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 \( \eta'_c \) came recently from two measurements by the Belle collaboration. In the decay of 45 million \( B \) mesons, \( B \to K(K_S K \pi) \), they observed peaks in the \( K_S K \pi \) invariant mass spectrum corresponding to the \( \eta_c \) and \( \eta'_c \), and reported \( M(\eta'_c) = \text{3654±6±8 MeV} \) \cite{12, 13}. They also reported \( \eta'_c \) observation in double charmonium production, \( e^+ e^- \to J/\psi + \eta'_c \), in 46.2 fb\(^{-1} \) of \( e^+ e^- \) data at \( \sqrt{s} \approx 10 \text{ GeV} \). They reported \( M(\eta'_c) = \text{3622±12(stat) MeV} \). The fact that both masses were significantly larger than that reported by the Crystal Ball collaboration provided great interest in confirming the \( \eta'_c \) observation in independent measurements at CLEO.

At CLEO we had earlier reported \cite{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 \( \Upsilon(4S) \) 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 \( \eta'_c \) mass of \( \sim 3643 \text{ MeV} \). In order to confirm this observation, 13.1 fb\(^{-1} \) of data taken at, and in the vicinity of, the \( \Upsilon(1S \to 4S) \) 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 \cite{14, 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. \cite{15}. \( K_S^0 \) were uniquely reconstructed from the displaced vertex of their \( \pi^+ \pi^- \) decay \cite{17}. \( K/\pi \) separation was done by using the dE/dx and TOF information.

For CLEO III \cite{18}, the charged particle tracking system was replaced with four layers of double-sided silicon detectors, surrounded by a new, 47-layer drift chamber \cite{19}. The CLEO II time-of-flight system was replaced by a ring-imaging Cherenkov detector (RICH) \cite{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 \( \pi \) by the RICH detector. For \( p > 2 \text{ GeV/c} \) (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 \( K/\pi \) discrimination by RICH was not possible, dE/dx measurements from the drift chamber were used. For \( 1 < p < 2 \text{ GeV/c} \), however, \( K/\pi \) separation was difficult using dE/dx, and such events were rejected.

In order to insure 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 \( E_{neut} \) not associated with the charged particles.

The Monte Carlo simulation of the CLEO detector response was based upon GEANT \cite{21}, with events for reaction (1) simulated using the formalism of Budnev et al. \cite{22}. Simulated events were processed in the same manner as the data to determine the \( K_S^0 K^+ \pi^- \) detection efficiency. Efficiencies for trigger, \( K_S^0 \) identification, four–charged track reconstruction, \( \pi/K \) identification, and cuts on \( P_T \) and \( E_{neut} \) were determined. The overall detection efficiencies \( (\epsilon) \) obtained from large statistics Monte Carlo samples are listed in Table I.
The $K^0_SK^±\pi^±$ 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 $\eta_c$ and $\eta_c'$, respectively. There is some evidence for a small enhancement at $\sim 3.1$ GeV, presumably from the population of $J/\psi$ 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%), $\sigma_2=37.2$ MeV (22%). For CLEO III data the corresponding numbers were $\sigma_1=8.7$ MeV (74%), $\sigma_2=26.6$ MeV (26%).

As described in our previous publication [15], most of the observed background under our signal events is expected to arise from non $\gamma\gamma \rightarrow K^0_SK^±\pi^±$ sources such as events with at least one missing $\pi^0$ or $\gamma$, as well as events of the type $e^+e^- \rightarrow$ hadrons, $e^+e^- \rightarrow \tau^+\tau^-$, and $\gamma\gamma \rightarrow \tau^+\tau^-$. 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, $E_{neut}<0.2$ GeV (CLEO II), or $E_{neut}<0.4$ GeV (CLEO III), second-order polynomial backgrounds, and separate fits in the mass regions $2.5-3.5$ GeV($\eta_c$), and $3.3-4.1$ GeV($\eta'_c$). The “significance levels” of the enhancements listed in Table I were obtained as $\sigma \equiv \sqrt{-2\ln(L_0/L_{max})}$, where $L_{max}$ is the maximum likelihood value from the fits described above, and $L_0$ is the likelihood value from the fits with either no $\eta_c$ or no $\eta'_c$ resonance. Combining the independent significance levels of the CLEO II and CLEO III measurements in quadrature gives the significance level for our observation of $\eta'_c$ as $6.5\sigma$.

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...
TABLE I: Summary of the results for $\eta_c$ and $\eta'_c$ for both CLEO II and CLEO III data sets. The errors shown are statistical only.

|          | CLEO II | CLEO III |
|----------|---------|----------|
| $\epsilon$ (%) | 10.0    | 8.9      |
| $N$, events   | 282$\pm$30 | 310 $\pm$29 |
| $M$(MeV)     | 2984.2$\pm$2.0 | 2980.0$\pm$1.7 |
| $\Gamma$(MeV) | 24.7$\pm$5.1  | 24.8$\pm$4.5  |
| signif.$(\sigma)$ | 15.1    | 17.0     |
| $R(\eta'_c/\eta_c)$ | 0.17$\pm$0.07 | 0.19$\pm$0.08 |

them, and therefore of the sum of final state particles is small. In order to test whether the observed $\eta'_c$ peaks are due primarily to two-photon events, we have examined the production of $\eta'_c$ in several subregions of transverse momentum. We find that both the CLEO II and CLEO III $P_T$ distributions are statistically consistent \cite{23} with the expectations from our two-photon Monte Carlo simulations \cite{21, 22}, and we conclude that in both data sets the $\eta'_c$ peak is mainly due to two-photon fusion.

It is of interest to compare the two-photon partial width of $\eta'_c$ to that of $\eta_c$. The quantity that can be directly obtained from the data is

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

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 $\eta_c$ and $\eta'_c$ masses \cite{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 $K^0_S(\to \pi^+\pi^-)$, $D^0(\to K^0_S\pi^+\pi^-)$, and $D^\pm(\to K^\pm\pi^+\pi^-)$ with their known values \cite{2}. We estimate this uncertainty to be $\leq 1$ MeV in the $\eta_c$ and $\eta'_c$ 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 $K^0_S K^{\pm}\pi^{\mp}$ 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 $\eta_c$ and $\eta'_c$ masses to be 1.5 MeV for both CLEO II and CLEO III.

Using high statistics samples of $D$ mesons and the larger $\eta_c$ 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 $M(\eta_c) = 2980.4 \pm 2.3 \pm 0.6$ 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 $\Gamma_{\gamma\gamma}(\eta_c) = 7.2 \pm 0.8 \pm 0.7 \pm 2.2$ (br) keV (the last error is due to the uncertainty in the branching ratio $B(\eta_c \rightarrow K^0_S K^{\pm}\pi^\mp)$), which are in agreement with our previously reported values. The two-photon width from CLEO III data is $\Gamma_{\gamma\gamma}(\eta_c) = 7.5 \pm 0.5 \pm 0.5 \pm 2.3$ (br) keV. The average of the two results is $\Gamma_{\gamma\gamma}(\eta_c) = 7.4 \pm 0.4 \pm 0.5 \pm 2.3$ (br) keV.

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

\[
M(\eta_c) = 2981.8 \pm 1.3 \pm 1.5 \text{ MeV,} \\
\Gamma(\eta_c) = 24.8 \pm 3.4 \pm 3.5 \text{ MeV,} \\
M(\eta_c') = 3642.9 \pm 3.1 \pm 1.5 \text{ MeV,} \\
\Gamma(\eta_c') = 6.3 \pm 12.4 \pm 4.0 \text{ MeV, or } \leq 31 \text{ MeV (90\% CL),} \\
R(\eta_c'/\eta_c) = 0.18 \pm 0.05 \pm 0.02. 
\]

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

Assuming that the branching fractions for $\eta_c$ and $\eta_c'$ decays to $K_S^0 K\pi$ are equal, 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 $\eta_c'$ with a mass of $3594 \pm 5$ MeV, and therefore $\Delta M_{hf}(2S) = 92 \pm 5$ MeV. The present results reduce this hyperfine splitting by nearly a factor two. 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.

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