Measurement of the Mass, Width, and Two-Photon Width of the $\eta_c(1S)$

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Abstract. I present recent measurements of the mass, width, and two-photon width of the $\eta_c(1S)$ obtained with the CLEO detector at the Cornell e^+e^- collider CESR. The $\eta_c(1S)$ has been detected in its decay $\eta_c(1S) \to K^0_S K^- \pi^+$ and its charge conjugate. The results are based upon an integrated luminosity of $13.4\,\mathrm{fb}^{-1}$ at a centre-of-mass energy near the $\Upsilon(4S)$. The $\eta_c(1S)$ mass was measured to be $2980.4 \pm 2.3(\mathrm{stat}) \pm 0.6(\mathrm{syst})\,\mathrm{MeV}/c^2$ and its width $27.0 \pm 5.8(\mathrm{stat}) \pm 1.4(\mathrm{syst})\,\mathrm{MeV}$. The two-photon width of the $\eta_c(1S)$ was measured to be $7.6 \pm 0.8(\mathrm{stat}) \pm 0.4(\mathrm{syst}) \pm 2.3(\mathrm{Br})\,\mathrm{keV}$ with the last uncertainty associated with the branching fraction $\mathcal{B}[\eta_c(1S) \to K\overline{K}\pi]$. The measured mass and two-photon width agree with the world average while the measured width differs from the world average by approximately two standard deviations. The measured width is now agrees with theory for somewhat larger values of α_s.

INTRODUCTION

The measurement of the width and the two-photon width of the $\eta_c(1S)$ are of interest because there are QCD based next-to-leading order (NLO) calculations [1] that relate these to one another and to the partial width of $J/\psi \to e^+e^-$. The world average experimental values are [2] $\Gamma[\eta_c(1S)] = 13.2^{+3.8}_{-3.2}\,\mathrm{MeV}$ and $\Gamma_{\gamma\gamma}[\eta_c(1S) \to \gamma\gamma] = 7.4 \pm 1.4\,\mathrm{keV}$. The experimental value for the two-photon width of the $\eta_c(1S)$ is in good agreement with the NLO theoretical expectation. However, the experimental value for the width of the $\eta_c(1S)$ is barely consistent with the theoretical expectation. Thus a measurement of the width of the $\eta_c(1S)$ is of interest to see if theory and experiment can be reconciled. The precision of the two-photon width is limited by the precision of the branching fraction of the $\eta_c(1S)$ into the hadronic final state under consideration. Unfortunately, these are known only to approximately 30 % as their values all rely upon a 1986 measurement of the inclusive rate [3] of $\eta_c(1S) \to \gamma X$ which has a 28 % error. Thus detecting $\eta_c(1S)$ decay in several decay modes and averaging does not help since the errors in their respective branching fractions are correlated. The NLO calculations have sizable corrections of order α_s making them less precise too. A calculation to order α_s^2 is very desirable.

CLEO has observed the $\eta_c(1S)$ in its decay $\eta_c(1S)\to K_S^0 K^- \pi^+$ (charge conjugate state are implied throughout). After a brief review of theoretical estimates for the width and the two-photon width and a discussion of the CLEO detector, the event selection, and experimentally results on the mass, width, and two-photon width are presented.

THEORETICAL ESTIMATES

The interpretation of the width and the two-photon width of the $\eta_c(1S)$ in terms of QCD based next-to-leading-order (NLO) calculations can be done using the results of Ref. [1]. The ratio of the width to the two-photon width of the $\eta_c(1S)$ is

$$\frac{\Gamma[\eta_c(1S)]}{\Gamma(J/\psi\to\gamma\gamma)} = \frac{9}{8}\left(\frac{\alpha_s}{\alpha}\right)^2 \frac{1+4.8\,\alpha_S/\pi}{1-3.4\,\alpha_s/\pi} \qquad (1)$$

The ratio of the two-photon width of the $\eta_c(1S)$ to the leptonic width of the J/ψ is given in Ref. [1] as

$$\frac{\Gamma(\eta_c(1S)\to\gamma\gamma)}{\Gamma(J/\psi\to e^+e^-)} = \frac{4}{3}\Big(1+1.96\,\frac{\alpha_S}{\pi}\Big)\frac{|\psi(0)|^2_{\eta_c(1S)}}{|\psi(0)|^2_{J/\psi}} \qquad (2)$$

The factor 1.96 is obtained from the ratio of $(1-3.38\alpha_s/\pi)$ and $(1-5.33\,\alpha_s/\pi)$ by the approximation $(1-5.33\,\alpha_s/\pi)^{-1} = (1+5.33\,\alpha/\pi$, good to order $(\alpha_s/\pi)^2$. The NLO calculation neglects terms of order $(\alpha_s/\pi)^2$ so the previous approximation is consistent with that. We prefer not to make that particular approximation and replace (2) by

$$\frac{\Gamma(\eta_c(1S)\to\gamma\gamma)}{\Gamma(J/\psi\to e^+e^-)} = \frac{4}{3}\,\frac{1-3.38\,\alpha_S/\pi}{1-5.33\,\alpha_s/\pi}\,\frac{|\psi(0)|^2_{\eta_c(1S)}}{|\psi(0)|^2_{J/\psi}} \qquad (3)$$

Depending upon the value of α_s used, the ratio in (3) is at least 15% larger than in (2). We show in Fig. 1 the relation between the width and the two-photon width of the $\eta_c(1S)$ as α_s varies from 0.15 to 0.35 in steps of 0.05. We have used the world average value [2] $\Gamma(J/\psi\to e^+e^-) = 5.26\pm0.37\,\mathrm{keV}$ and assumed equal wavefunctions at the origin for the $\eta_c(1S)$ and J/ψ. The datapoint shown with a circle is the world average $\Gamma(\eta_c(1S)) = 13.2^{+3.8}_{-3.2}\,\mathrm{MeV}$ and $\Gamma[\eta_c(1S)\to\gamma\gamma] = 7.5^{+1.6}_{-1.4}$ where the error on the two-photon width does not include the uncertainty from the hadronic branching fraction. It is seen that the world average favors an unreasonably low value $\alpha_s = 0.21$.

The NLO calculations have sizable corrections of order α_s. The term $5.33\,\alpha_s/\pi$ is about 0.5, uncomfortably large. A calculation to order $(\alpha_s/\pi)^2$ is obviously desirable.

DETECTOR, DATASET, AND EVENT SIMULATION

The CLEO II detector [4] is a general purpose detector that provides charged particle tracking, precision electro-magnetic calorimetry, charged particle identification, and muon detection. Charged particle detection over 95% of the solid angle is achieved by tracking devices in two different configurations, situated in a magnetic field of 1.5 T. In the first configuration (CLEO II) tracking is provided by three concentric wire chambers while in the second configuration (CLEO II.V) the innermost wire chamber is replaced by a precision three-layer silicon vertex detector [5]. The momentum resolution is 0.5% at $p = 1\,\mathrm{GeV}$. The drift chambers are surrounded by a time-of-flight (TOF) system. Energy loss (dE/dx) in the outer drift chamber and the TOF system provide pion-kaon separation. A CsI based electro-magnetic calorimeter giving an energy resolution of 4% for 100 MeV electro-magnetic showers provides π^0 detection. A super-conducting coil and muon detectors surround the calorimeter. Redundant triggers provide efficient registration of mutiparticle final states.

The Cornell Electron Storage Ring CESR operates at a center-of-mass energy of approximately 10.6 GeV. The results in this report are based upon on-4S data collected on the $\Upsilon(4S)$ resonance with an integrated luminosity of $9.10\,\mathrm{fb}^{-1}$ and on $4.29\,\mathrm{fb}^{-1}$ off-4S data collected 60 MeV below the $\Upsilon(4S)$ for the study of non-$B\overline{B}$

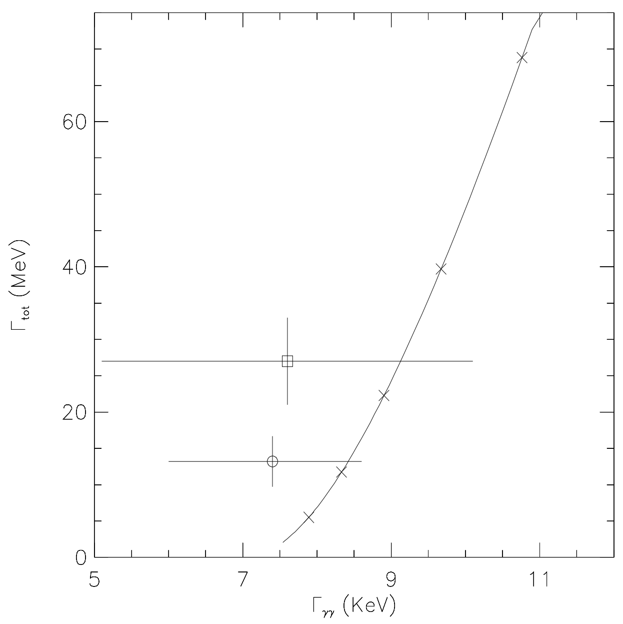

FIGURE 1. Relation of the two-photon width and the width of the $\eta_c(1S)$ when vaying α_s. The crosses correspond to $\alpha_s = 0.15, 0.20, 0.25, 0.30, 0.35$ from smaller to larger widths. The datapoint shown with a circle represents world averages while the square represents CLEO's measurements.

backgrounds. The number of $B\overline{B}$ pairs is $(9.63 \pm 0.19) \times 10^6$.

The event simulation uses uses the BGMS [6] formalism for the event generation. Photon form-factors based upon vector-meson dominance with the J/ψ mass are used. The line shape is parameterized by a relativistic spin zero Breit-Wigner. The Monte Carlo simulation of the CLEO II detector is based upon GEANT. The detector is simulated down to the component level. The trigger simulation and the event reconstruction use this information to determine the detector response. Simulated events are processed in the same manner as the data.

EVENT SELECTION

The $\eta_c(1S)$ is detected through its decay $\eta_c(1S) \to K^0_S K^- \pi^+$ with $K^0_S \to \pi^+\pi^-$. The event selection requires exactly four good quality tracks whose sum of charges is zero. A K^0_S vertex fit is made using pairs of oppositely charged tracks. A vertex is accepted if its corresponding decay path is at least three standard deviations for CLEOII or five for CLEOII.V. The standard deviations are determined on an event-to-event basis and the decay path requirement corresponds to approximately 1.5 mm. We further require that the K^0_S momentum points back to the e^+e^- interaction point and that the $\pi^+\pi^-$ invariant mass is within four standard deviations of the nominal K^0 mass. The mass resolution is also determined on an event-by-event basis and the mass requirement correspond to an approximately 24 MeV/c^2 wide window. If there is more than one K^0_S candidate passing these selection criteria, the event is rejected. Of the remaining two tracks the one with lowest momentum is identified as a pion or a kaon using dE/dx and TOF information which work best at low momentum. The higher momentum particle is identified as a pion or kaon depending upon the assignment of the lower momentum particle. The transverse component of the vector sum of the tracks p_T has to be less than 0.6 GeV and the total energy measured in the calorimeter, not associated with one of the four tracks has to be less then 0.6 GeV. We show in Fig. 2 the p_T distribution of the $K^0_S K^- \pi^+$. The dots with error bars are the sideband subtracted data while the histogram is the result of the simulation. The peak at zero p_T corresponds to signal events. There is good agreement between data and simulation over a wide range of p_T. Because incorrectly evaluated background can cause a disagreement this represents a very stringent check on our understanding of the event selection and its efficiency in the presence of considerable background. The visible energy of the event (the sum of the four track's energies) has to be less then 6 GeV. For the $\eta_c(1S)$ mass measurement only we require that the pion and kaon be in the central region ($|\cos\theta| < 0.71$) and that each has a transverse momentum greater than 225 MeV. This ensures that both tracks traverse the entire tracking volume for optimal momentum resolution and therefore optimal invariant $K^0_S K^- \pi^+$ mass resolution.

To keep the systematics related to the trigger efficiency small, only events satisfying the two-track trigger are used. It's efficiency was measured using the simulation which in turn is checked using data taken with redundant triggers.

RESULTS

We show in Fig. 3 the $K_S^0 K^- \pi^+$ invariant mass distribution, separately for CLEOII and CLEOII.V. Clear peaks are seen just below 3.0 GeV. The solid line is the result of a simultaneous fit to the CLEOII and CLEOII.V mass plots. A spin 0 relativistic Breit-Wigner convolved with two Gaussian's is used to fit the signal. Its parameters are taken from the Monte Carlo simulation. The background is fit with a form $A[m(K_S^0 K^- \pi^+)]^{-n}$ where A and n are constants and are determined by the fit. There are 300 ± 32 events in the mass peaks. To measure the mass of the $\eta_c(1S)$, tighter cuts are used as discussed in the Section on event selection and there are now 195 ± 24 events in the mass peaks. With these tighter cuts the resolution of the $K_S^0 K^- \pi^+$ invariant mass is approximately $8\,\mathrm{MeV}/c^2$. There are now 195 ± 24 events in the mass peaks. The fitted mass $M[\eta_c(1S)] = 2980.4 \pm 2.3(\mathrm{stat}) \pm 0.6(\mathrm{syst})\,\mathrm{MeV}/c^2$. The mass scale is calibrated using the measured masses of the K_S^0, ϕ, D^0, and J/ψ. The 0.6 MeV systematic error is estimated from these calibrations. The world average value [2] is $2979.8 \pm 1.8\,\mathrm{MeV}/c^2$, there is excellent agreement.

A fit to the invariant mass distribution of Fig. 3 in the manner discussed above gives a width $\Gamma[\eta_c(1S)] = 27.0 \pm 5.8(\mathrm{stat}) \pm 1.4(\mathrm{syst})\,\mathrm{MeV}$. The fit has a $\chi^2 = 226$

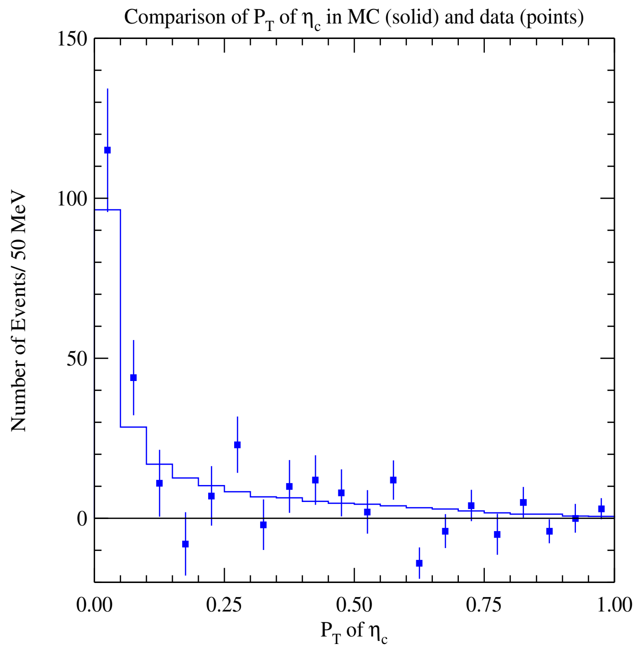

FIGURE 2. Transverse momentum distribution p_T of $K_S^0 K^- \pi^+$. The dots with error bars are the sideband subtracted data while the histogram is the simulation.

for 243 degrees of freedom. To determine the systematic error the mass resolution needs to be calibrated. This is done using the D^+ in its decay $D^+ \to K^0_S K^- \pi^+$ for a comparison of the mass resolution in data and simulation. The agreement is better than 0.1 MeV leading to a negligible contribution to the systematic error. Particle identification errors in pion-kaon separation (misidentification contributes to tails in the invariant mass distribution) and imperfect understanding of detector resolution are the main contributers to the 1.4 MeV systematic error. The CLEO measurement may be compared with the world average [2] value $\Gamma[\eta_c(1S)] = 13.2^{+3.8}_{-3.2}$ MeV. CLEO's measurement. The world average differs by approximately two standard deviations.

The number of signal events in the mass peaks in the invariant mass plot can be related to the product of $\Gamma[\eta_c(1S) \to \gamma\gamma] \mathcal{B}[\eta_c(1S) \to K^0_S K^- \pi^+]$. The branching fraction $\mathcal{B}[\eta_c(1S) \to K^0_S K^- \pi^+] = \frac{1}{3}\mathcal{B}[\eta_c(1S) \to K\overline{K}\pi] = \frac{1}{3}(5.5 \pm 1.7) \times 10^{-2}$. This 30 % error is large and dominates the determination of the two-photon width of the $\eta_c(1S)$. Using the acceptance from the simulation and the integrated luminosity we find $\Gamma[\eta_c(1S) \to \gamma\gamma] = 7.6 \pm 0.8(\mathrm{stat}) \pm 0.4(\mathrm{syst}) \pm 2.3(\mathrm{Br})$ keV. The systematic error is dominated by uncertainties in the trigger efficiency (0.2 keV), tracking efficiency (0.2 keV), and the possible presence of $K^*(892)K$ substructure in the final state (0.2 keV). The last error due to uncertainty in the branching fraction. The CLEO measurement (without the error from the uncertainty in the $\eta_c(1S) \to K\overline{K}\pi$ branching fraction) may be compared with the world average [2]

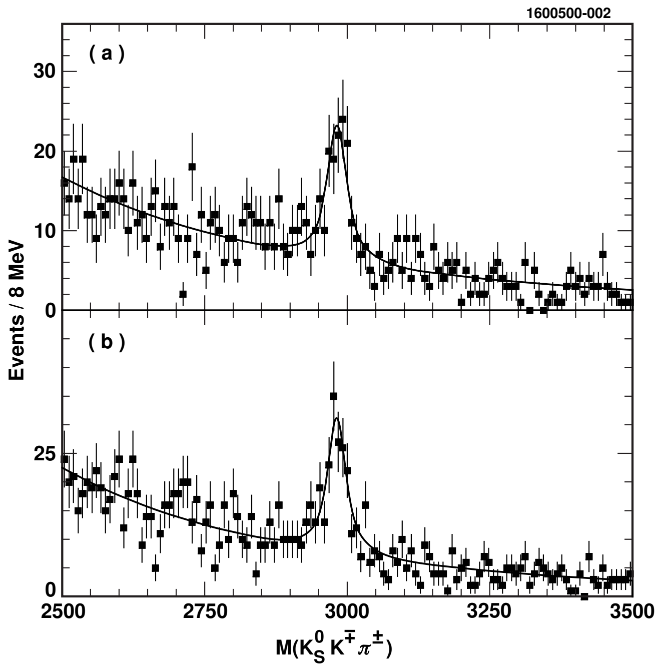

FIGURE 3. Invariant mass of $K^0_S K^- \pi^+$ for (a) CLEOII and (b) for CLEOII.V. The data are the dots with error bars, the fit is a simultaneous fit to CLEOII and CLEOII.V data, see text.

value $\Gamma[\eta_c(1S)\to\gamma\gamma] = 7.5^{+1.6}_{-1.4}$. There is excellent agreement between the two in part due to the fact that the same central values for the branching fractions are used.

INTERPRETATION

We show in Fig. 1 the CLEO measurements of the width and the two-photon width of the $\eta_c(1S)$. Also shown are their world averages. The curve is discussed in the Section on Theoretical Estimates. It is seen that the CLEO measurements are consistent with the NLO calculations, as are the world averages, but with a larger but still low value of $\alpha_s = 0.26 \pm 0.02$.

The largest α_s/π correction in (1) and (3) is the term with $5.33\alpha_s/\pi$ and or approximately 0.5. It is clearly desirable that a calculation to order are of order $(\alpha_s/\pi)^2$ be done to improve the accuracy of the calculation. Perhaps this is the reason for the still unreasonably low value of α_s.

On the experimental side, the hadronic branching fractions of the $\eta_c(1S)$ need to be determined with much better precision. They are all dependent upon a (1986) measurement of the branching fraction of the inclusive decay $\eta_c(1S)\to\gamma X$ [3] which has a 28 % error. Even worse, the uncertainties in the various hadronic decay modes are correlated because of their common dependence upon the inclusive decay rate so averaging measurements of the two-photon widths from different hadronic decay modes will not help. A new measurement of the branching fraction of the inclusive decay $\eta_c(1S)\to\gamma X$ is desirable.

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