Prospects for detecting an $\eta'_c$

in two photon processes

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Abstract

We argue that an experimental search for an $\eta'_c$, the first radial excitation of the $\eta_c(2980)$, may be carried out using the two photon process $e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-\eta'_c$. We estimate the partial width $\Gamma_{\gamma\gamma}(\eta'_c)$ and the branching fraction $B(\eta'_c \rightarrow h)$, where $h$ is an exclusive hadronic channel, and find that for $h = K^0 K^\pm \pi^\mp$ it may be possible to observe this state in two photon collisions at CLEO-II.

The $\eta'_c$ meson is the first radial excitation of the $\eta_c(2980)$, the charmonium ground state with $J^{PC} = 0^{-+}$. The mass and couplings of this state can be used to test potential models and lattice QCD calculations. In this paper we discuss possible experimental signatures and event rates for the $\eta'_c$, and note that it may be observable in future CLEO-II data sets.
The search for the $\eta_c'$, expected near a mass of 3600 MeV, has intrigued workers in the field for over a decade. In an $e^+e^-$ experiment the Crystal Ball collaboration [1] reported evidence for this state near 3590 MeV, with a branching fraction of $0.2% < B(\psi' \to \gamma + \eta_c') < 1.3\%$ at 95\% confidence level. However the Crystal Ball observation has not been confirmed by subsequent experiments over the intervening 13 years.

Since the relative rates for competing electromagnetic decays and transitions to lower charmonium states are expected to be small for the $\eta_c'$, the relation

\[ B(\eta_c' \to h) \approx B(\eta_c \to h), \tag{1} \]

where $h$ is an exclusive final state, can be assumed as a working hypothesis. Since the $\eta_c(2980)$ branching fractions are known for many hadronic channels [3] we can then estimate event rates for $\eta_c'$ decays into the same modes.

Of course there are important uncertainties in these estimates; it is well known that the analogue of Eq.(1) for the $\psi$ and $\psi'$ does not account for the puzzling weakness of certain $\psi' \to h$ modes, notably vector+pseudoscalar final states such as $h = \rho\pi$ and $K^*\bar{K} + h.c.$ [3]. In part these small $\psi'$ branching fractions simply reflect the presence of important $\psi' \to \psi + h$ “hadronic cascade” modes, which have a large branching fraction of 57(4)\%. We expect these cascade modes to be much less important for the $\eta_c'$, due to the larger annihilation width of a $0^{-+}$ state. Of course there remains considerable uncertainty regarding these branching fractions, which merit careful investigation when more data on radial $c\bar{c}$ states becomes available.

For a three-body or four-body hadronic decay mode $h$, such as those considered here for the $\eta_c'$, the corresponding QCD-motivated relation $B(\psi' \to h)/B(\psi \to h) \approx 0.13$, discussed by Brodsky et al. [2] appears to be reasonably well satisfied [3], and the recent BES measurement of $B(\psi' \to K^+K^+\pi^-\pi^-)$ is also consistent with this estimate [4].

As a first possibility for observing the $\eta_c'$ we estimate the number of events expected at BES in the decay chain $\psi' \to \gamma \eta_c' \to \gamma h$, assuming that Eq.(1) is approximately correct. At present there are about $3.4 \times 10^6\psi'$ events in the BES data set, and the two largest
η_c(2980) branching fractions are to $K^*_0 K^\mp \pi^\mp (\approx 1.5 \pm 0.4\%)$ and $\pi^+\pi^- K^+ K^- (\approx 2^{+0.7}_{-0.6})\%$. Taking the lower end of the range reported by Crystal Ball [1], $B(\psi' \to \eta'_c + \gamma) = 0.2\%$, we would expect 102 events from the decay $\psi' \to \gamma \eta'_c \to \gamma h$, $\eta'_c \to K^*_0 K^\mp \pi^\mp$, and 136 events from the corresponding decay with $\eta'_c \to \pi^+\pi^- K^+ K^-$. The average efficiency for detection is approximately 5% with the current BES calorimeter [4] (the photon produced in the radiative transition $\psi' \to \gamma \eta'_c$ is soft, with an energy of < 90 MeV), so unfortunately the total expected number of events is reduced to $5.1 \pm 1.4$ and $6.8^{+2.4}_{-2.0}$ respectively. In a missing-$\gamma$ analysis, in which one does not detect the low-energy $\gamma$, the efficiencies are estimated to be 15 - 25% [3], so the number of events expected would be $15.3 \pm 4.2$ and $20.4^{+7.2}_{-6.0}$ (for 15%) and $25.5 \pm 7.0$ and $34.0^{+12.0}_{-10.0}$ (for 25%). In view of the small event sample anticipated, success of this approach may require a BES upgrade to a detector similar to the Crystal Barrel or a larger integrated luminosity.

Although the transition $\psi' \to \gamma \eta'_c$ required to detect the $\eta'_c$ in this approach has not been observed since the Crystal Ball experiment [1], we note that the branching fraction of 0.2% we used for our estimates is quite conservative; in comparison, Godfrey and Isgur [6] quote a $\langle \psi' | \mu | \eta'_c \rangle$ transition magnetic moment that corresponds to $B(\psi' \to \gamma \eta'_c(3590)) = 0.8\%$. Of course this branching fraction could be somewhat smaller; it scales as $E_\gamma^3$ and roughly as $1/m_c^2$, so a somewhat higher $\eta'_c$ mass and a larger $m_c$ value than is normally assumed could conceivably reduce the branching fraction to 0.2%.

E835 proposes to search for the $\eta'_c$ at FERMILAB in the process $p\bar{p} \to \eta'_c \to \gamma\gamma$, which requires rejection of a large hadronic background. The preceding experiment, E760, searched for evidence of an $\eta'_c$ in the mass range 3584-3624 MeV without success. For the $\eta_c$, E760 reported $B(\eta_c \to \gamma\gamma) = (2.80^{+0.67}_{-0.58} \pm 1.0) \times 10^{-4}$ [3]; this is close to a perturbative QCD estimate of $B(\eta_c \to \gamma\gamma) = 3.0 \times 10^{-4}$ [3], but the signal is seen at a mass of $2988^{+3.3}_{-3.1}$ MeV, somewhat higher than the PDG value of $2978 \pm 1.9$ MeV. It is especially interesting that E760 finds a rather large width for the $\eta_c$, $\Gamma_{\eta_c} = 23.9^{+13.6}_{-7.1}$ MeV, compared to the PDG value of $10.3^{+3.8}_{-3.4}$ MeV. This number is required to convert the E760 $\eta_c \to \gamma\gamma$ branching fraction
to the theoretically more accessible $\gamma\gamma$ partial width, so until $\Gamma_{\eta_c}$ is accurately measured a definitive comparison with theory will not be possible.

Of course the absence of an $\eta'_c(3600)$ signal at E760 may be due to a weak $\eta'_c - p\bar{p}$ coupling relative to $\eta_c - p\bar{p}$, as has been observed in the $\psi' - p\bar{p}$ and $\psi - p\bar{p}$ couplings; the PDG branching fraction $B(\psi' \rightarrow p\bar{p})$ is an order of magnitude smaller than $B(\psi \rightarrow p\bar{p})$. Although Brodsky and Lepage \[9\] anticipated a weak coupling of the $\eta'_c$ to $p\bar{p}$ in perturbative QCD, their results should apply to the ground state $\eta_c$ as well; the expected weak $\eta_c - p\bar{p}$ coupling is not supported by experiment. Clearly the relative annihilation amplitudes of ground-state and radial quarkonia to exclusive hadronic final states is a vitally important question for these experiments, and it is unfortunately not well understood at present.

From Eq.(1), we expect the $\eta'_c$ branching fraction ratio $B(\eta'_c \rightarrow \gamma\gamma) / B(\eta'_c \rightarrow h)$ to be comparable to the $\eta_c(2980)$ ratio. Thus in the absence of a magnetic spectrometer to detect exclusive hadronic modes $h$, $p\bar{p}$ experiments such as E835 will have to contend with a correspondingly weak signal in the search for the $\eta'_c$.

Having discussed searches for the $\eta'_c$ in $\psi' \rightarrow \gamma\eta'_c$ and $p\bar{p} \rightarrow \eta'_c$, we now consider a third possibility, the reaction

$$e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-\eta'_c.$$ 

It is interesting to consider whether this process is likely to lead to an observable signal with present and future data sets. (One of us previously suggested that the $\chi_{cJ} (J= 0, 2)$ states expected near 3.95 GeV, the radial excitations of the $\chi_{cJ}$ states, could be observed in this manner [10].)

CLEO-II and LEP experiments such as L3 are well equipped to study exclusive hadronic modes $h$. Indeed, these experiments have confirmed the existence of the ground state $\eta_c(2980)$ in this manner \[11\]-\[13\]. To estimate the number of $\eta'_c$ events in these $\gamma\gamma$ experiments we again assume the validity Eq.(1); in addition we require a theoretical estimate of the $\Gamma_{\gamma\gamma}(\eta'_c)$ partial width.

The partial width $\Gamma_{\gamma\gamma}(\eta'_c(3590))$ has been calculated by Ackleh and Barnes \[14\] using
nonrelativistic quark potential model wavefunctions attached to relativistic Feynman decay amplitudes; this gives \( \Gamma_{\gamma\gamma}(\eta_c'(3590)) = 3.7 \) keV. For comparison, this approach applied to the \( \eta_c \) gave the prediction

\[
\Gamma_{\gamma\gamma}^{\text{th}}(\eta_c) = 4.8 \text{ keV},
\]

which is consistent with recent E760, CLEO-II and L3 measurements;

\[
\Gamma_{\gamma\gamma}^{\text{exp}}(\eta_c) = \begin{cases} 
6.7^{+2.4}_{-1.7} \pm 2.3 \text{ keV} & \text{E760 [8]} \\
4.3 \pm 1.0 \pm 0.7 \pm 1.4 \text{ keV} & \text{CLEO [12]} \\
8.0 \pm 2.3 \pm 2.4 \text{ keV} & \text{L3 [13]}
\end{cases}
\]

(The E760 reference gives a more complete summary of previous experimental results, in their Table V.)

An important conclusion of Ackleh and Barnes is that \( \Gamma_{\gamma\gamma} \) widths of quarkonia are not strongly suppressed with radial excitation for light or heavy quarks. This suggests that a radially excited \( \eta_c'(\approx 3600) \) may be observable in \( \gamma\gamma \) collisions, provided that the exclusive hadronic channel studied does not have an unusually weak coupling to the \( \eta_c' \).

The level of uncertainty in the \( \eta_c' \gamma\gamma \) width in the model of Ackleh and Barnes can be estimated by considering a likely range of \( M(\eta_c') \) values, and allowing plausible variations in the three model parameters. The effect of varying \( M(\eta_c') \) over the range \( 3590 \pm 50 \) MeV is to change \( \Gamma_{\gamma\gamma}(\eta_c') \) by \( \pm 0.15 \) keV, a \( \pm 4\% \) change. Variations in the three parameters \( \alpha_s \), \( b \) (GeV/fm), and \( m_c \) have also been considered. The effect of varying the first two is quite small; the width is most sensitive to the charm quark mass \( m_c \), which was taken to be 1.4 GeV in Ref. [14] and our Eq.(2). As we increase \( m_c \) from 1.3 to 1.8 GeV, \( \Gamma_{\gamma\gamma}(\eta_c') \) decreases monotonically by about a factor of two. Fortunately, \( \Gamma_{\gamma\gamma}(\eta_c') \) and \( \Gamma_{\gamma\gamma}(\eta_c) \) show similar \( m_c \) dependences, so the ratio \( \Gamma_{\gamma\gamma}(\eta_c')/\Gamma_{\gamma\gamma}(\eta_c) \) only changes from 0.73 to 0.77. Comparison with the experimental \( \eta_c \) values then supports our use of \( \Gamma_{\gamma\gamma}(\eta_c') = 3.7 \) keV as a reasonable first estimate in determining numbers of events. It should be noted however that no radial excitations have yet been identified in \( \gamma\gamma \) collisions, so this width calculation is a theoretical estimate in a regime in which the theory has not been tested.
In two-photon physics, the number of events is related to the production cross section in $e^+e^-$ by \[ N_{\text{obs}} = \epsilon L B(R_{cc} \rightarrow F_s) \sigma_{\text{exp}}(e^+e^- \rightarrow e^+e^-R_{cc}) , \tag{4} \]

where $\epsilon$ is the efficiency for detecting the final state $F_s$, $B(R_{cc} \rightarrow F_s)$ is the branching fraction for $R_{cc}$ into $F_s$, $L$ is the luminosity, and $N_{\text{obs}}$ is the number of $R_{cc} \rightarrow F_s$ events observed. Here we specialize to $R_{cc} = \eta_c(2980), R'_{cc} = \eta'_c(3590), F_s$ an exclusive final state $h$, and the luminosities are $L$ and $L'$ respectively. The ratio of the number of events $N'_{\text{obs}}$ expected for an $\eta'_c(3590)$ to the $\eta_c(2980)$ number is then

\[ \frac{N'_{\text{obs}}}{N_{\text{obs}}} = \frac{\epsilon' L'}{\epsilon L} \frac{B(\eta'_c \rightarrow F_s)}{B(\eta_c \rightarrow F_s)} \frac{\Gamma_{\gamma\gamma}(\eta'_c)}{\Gamma_{\gamma\gamma}(\eta_c)} , \tag{5} \]

where we have taken the ratio of $\gamma\gamma$ production cross sections for an $\eta'_c$ and the $\eta_c(2980)$ to be the ratio of their respective $\gamma\gamma$ widths, up to photon flux factors. \[16\].

For the photon flux factors we have $L'/L = 1/2.02$ \[16\]. Since we assume Eq.(1) it follows that $\epsilon' = \epsilon$, i.e. the detection efficiencies are equal because the final states are identical. (We assume that the difference in invariant mass of the two states has no significant effect on the efficiency.) From the theoretical estimate above we have $\Gamma_{\gamma\gamma}(\eta'_c)/\Gamma_{\gamma\gamma}(\eta_c) \approx 1/1.3$. Using the yield $N_{\text{obs}} = 54.1 \pm 12.6$ events for $h = K^o_sK^{\pm}\pi^\mp$ reported by CLEO-II for the $\eta_c$, (c.f. Savinov and Fulton in ref. \[12\]), we obtain $N'_{\text{obs}} \approx 20.6 \pm 4.8$ for the $\eta'_c$. Note the large number of exclusive events expected at CLEO-II, in contrast with LEP experiment L3, for which the corresponding $N_{\text{obs}}$ for $\eta_c \rightarrow K^o_sK^{\pm}\pi^\mp$ is 3 events \[13\]. The difference is primarily due to the smaller integrated luminosity available at the LEP experiments.

It would be useful for CLEO-II to extend their search to include $\eta'_c \rightarrow \pi^+\pi^-K^+K^-$, which is also expected to have a large branching ratio ($\sim 2\%$ according to Eq.(1)). Of course the CLEO-II detector (now at the CESR $e^+e^-$ storage ring, and running at a center-of-mass energy near the $\Upsilon(4S)$, $\approx 10.6$ GeV), is continually accumulating data, so prospects for finding the $\eta'_c$ will improve with time. The value of $N'_{\text{obs}}$ estimated above assumes a dataset with an integrated luminosity of 3.0 fb$^{-1}$, and should be scaled with the size of the dataset. It
is anticipated for example that the CLEO dataset will have an integrated luminosity of about 10.0 fb$^{-1}$ by 1998 \cite{17}, so our expected number of $\eta'_c$ events would then be $N'_{\text{obs}} = 68.7 \pm 16.0$.

In summary, we have considered some possible experimental signatures for $\eta'_c$ production, and suggest that $e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-\eta'_c$, $\eta'_c \rightarrow K^0_sK^{\pm}\pi^{\mp}$ may be feasible at CLEO-II. Searches for the $\eta'_c$ in this process can be conducted at CLEO-II, LEP, and future B factories.

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