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χ_{c0} and χ_{c2} Decays into $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ Final States

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Abstract

Using a sample of 3×10^6 $\psi(2S)$ decays collected by the CLEO III and CLEO–c detector configurations, we present results of a study of χ_{c0} and χ_{c2} decays into $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ final states. We find $B(\chi_{c0} \to \eta\eta) = (0.31 \pm 0.05 \pm 0.04 \pm 0.02)\%$, $B(\chi_{c0} \to \eta\eta') < 0.05\%$ at the 90% confidence level, and $B(\chi_{c0} \to \eta'\eta') = (0.17 \pm 0.04 \pm 0.02 \pm 0.01)\%$. We also present upper limits for the decays of χ_{c2} into these final states. These results give information on the decay mechanism of χ_c states into pseudoscalars.

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In the standard quark model, the χ_{cJ} ($J = 0, 1, 2$), mesons are $c\bar{c}$ states in an $L = 1$ configuration. As they cannot be produced directly in e^+e^- collisions, they are less well studied than the ψ states. However, $\psi(2S) \to \gamma\chi_{cJ}$ decays yield many χ_{cJ} mesons, and $e^+e^- \to \psi(2S)$ is a very clean environment for χ_{cJ} investigation. In this paper, we concentrate on the two-body decays of the χ_{c0} and χ_{c2} into $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ final states[1]. Knowledge from these decay rates leads to information on the quark and gluon nature of both the χ_c parents and their pseudo-scalar daughters, and a greater understanding of the decay mechanisms of the χ_c mesons [1].

The data presented here were taken by the CLEO detector operating at the Cornell Electron Storage Ring with a center of mass energy corresponding to the $\psi(2S)$ mass of 3.686 GeV/c^2. The data were taken with two different detector configurations. An integrated luminosity of 2.74 pb^{-1} was collected using the CLEO III detector configuration [2], and 2.89 pb^{-1} using the CLEO-c detector configuration [3]. The total number of $\psi(2S)$ events is calculated as 3.08×10^6, determined according to the method described in [4]. The vital detector component for this analysis, the CsI crystal calorimeter [5], is common to the two configurations and has an energy resolution of 2.2% at 1 GeV, and 4.0% at 100 MeV.

We detect our η candidates in the decay modes $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $\pi^+\pi^-\gamma$, and our η' candidates in the modes $\gamma\pi^+\pi^-$ and $\eta\pi^+\pi^-$, where the η is reconstructed using the η decay modes previously listed. We look for all combinations of distinct η and η' candidates, with the exception of the case where both η candidates in the event decayed to $\gamma\gamma$. This last case was excluded because its detection depends on the operation of an all-neutral trigger whose efficiency varied over the running period because of hardware changes. All our final states thus contain at least two charged particles, and the trigger efficiency for these events is close to 100% after all other requirements.

We define photon candidates as clusters in the CsI having a shower shape consistent with being due to a photon. We form $\eta \to \gamma\gamma$ candidates, from pairs of photon candidates, using the event vertex found from the charged tracks as the position of origin of the photons. We kinematically constrain the two-photon combination to the known η mass, and those with a $\chi^2 < 10$ (for one degree of freedom) for this fit are retained for further analysis. The same procedure is used for π^0 candidates. We then proceed to make $\eta \to \pi^+\pi^-\pi^0$ candidates by constraining the $\pi^+\pi^-\pi^0$ combinations to the nominal η mass and again requiring a χ^2 of less than 10 for one degree of freedom. Similarly η' candidates are built, either from the $\eta\pi^+\pi^-$ combinations, or from combining $\pi^+\pi^-$ and γ candidates (with E_γ >50 MeV), mass constraining the resultant 4-momentum to the η' mass and requiring them to have a $\chi^2 < 10$ for the one degree of freedom of this constraint. The mass resolution of the reconstructed $\eta \to \gamma\gamma$ combinations is around 12 MeV/c^2 before the mass constraint, and the analogous numbers for $\eta \to \pi^+\pi^-\pi^0$, $\eta' \to \gamma\pi^+\pi^-$, and $\eta' \to \eta\pi^+\pi^-$ are 3 MeV/c^2, 7 MeV/c^2, and 2.5 MeV/c^2 respectively.

If we have two distinct $\eta^{(\prime)}$ candidates, we combine them into a χ_c candidate. At this stage of the analysis, the signal to noise ratio is poor, and the invariant mass resolution of the χ_c is around 15 MeV/c^2. We then search for any unused photon in the event, and add that to the χ_c candidate to make a $\psi(2S)$ candidate. This $\psi(2S)$ is then kinematically constrained to the 4-momentum of the beam, the energy of which is taken as the known $\psi(2S)$ mass, and the momentum is non-zero only by a tiny amount due to the finite crossing

[1] We do not consider χ_{c1} decays into these final states, as they are forbidden by simple spin-parity conservation.

angle ($\approx$ 2 mrad per beam) in CESR. To make our final selection, we require the $\psi(2S)$ candidate to have a χ^2 of less than 25 for the 4 degrees of freedom for this fit; this cut rejects many background combinations. This kinematic fit greatly improves the mass resolution of the χ_c candidate.

To study the efficiency and resolutions, we generated Monte Carlo samples for each χ_c state into each final state, using a GEANT-based detector simulation[6]. The simulated events have a distribution of $(1+\lambda\cos^2\theta)$, where θ is the radiated photon angle relative to the positron beam direction, and $\lambda = 1$ for the χ_{c0} and $\lambda = 1/13$ for the χ_{c2}, in accordance with expectations for an E1 transition. The mass resolution and efficiencies are shown in Table I. The resolutions varied a little with the detector configuration and decay chain, but are approximated by single Gaussian functions. The efficiencies shown include all the relevant branching fractions of the η and η'.

TABLE I: Efficiencies (in %) and resolutions (in MeV/c^2) obtained from analysis of Monte Carlo generated events.

Mode	χ_{c0}		χ_{c2}	
	Efficiency %	Resolution MeV/c^2	Efficiency %	Resolution MeV/c^2
$\eta\eta$	5.46	7.6	5.60	6.3
$\eta\eta'$	5.47	7.0	5.47	5.8
$\eta'\eta'$	4.69	5.4	4.67	4.9

The final mass plots are shown in Fig. 1. Clear peaks are found for the decays $\chi_{c0} \to \eta\eta$ and $\chi_{c0} \to \eta'\eta'$, but the other four decays under consideration show no significant signals. These plots are each fit with two signal shapes comprising Breit-Wigner functions convolved with Gaussian resolutions, together with a flat background term. The masses and widths of the Breit-Wigner functions were fixed at their standard values [7], and the widths of the Gaussian resolution functions fixed at the values shown in Table I. We find signals of 47.8 ± 7.7 events for $\chi_{c0} \to \eta\eta$, and 22.7 ± 5.3 events for $\chi_{c0} \to \eta'\eta'$. To find the limits on the number of events for each of the other decay modes, we plot the probability function for a series of different signal yields, and place the limit so that 90% of the physically allowed region is below its value. The signal yields and limits are summarized in Table II. Our detected signal events in χ_{c0} decays have a θ angle distribution consistent with the value of $\lambda = 1$ as defined above. They also make a uniform band of events in the $M^2(\gamma\eta_1)$ versus $M^2(\gamma\eta_2)$ Dalitz plot, as expected for the decay of a spin-0 particle.

To convert the yields to branching fractions, we divide by the number of $\psi(2S)$ events in the data sample multiplied by the detector efficiency and by the branching fractions for $\psi(2S)$ into χ_{cJ}, for which we use the CLEO measurements of $B(\psi(2S) \to \gamma\chi_{c0}) = 9.22 \pm 0.11 \pm 0.46\%$, and $B(\psi(2S) \to \gamma\chi_{c2}) = 9.33 \pm 0.14 \pm 0.61\%$ [4].

The systematic uncertainties in the branching fractions are summarized in Table III. The systematic uncertainties due to fitting the peaks were evaluated by floating, in turn, the mass, instrinsic width, and Gaussian resolution width. The maximum change in yield for our highest-statistics signal ($\chi_{c0} \to \eta\eta$) from this process gives us our measure of this systematic uncertainty, 5%. The requirement on the χ^2 of the constraint to the beam 4-momentum has been checked by changing the cut and noting the change in the yield. This has been done for the modes under investigation here, and also in other modes such as $\eta\pi^+\pi^-$ that have higher statistics. Based on this study we place a systematic uncertainty of

3.5% on the efficiency of this requirement. The uncertainties due to track reconstruction are small and well understood. The biggest systematic uncertainty is that due to the photon reconstruction, which is set at 2% per photon. This was derived from a series of studies of photon reconstruction in well understood decays such as $\psi(2S) \to J/\psi\pi^0\pi^0$. For the two signals $\chi_{c0} \to \eta\eta$ and $\chi_{c2} \to \eta\eta'$ we add the systematic uncertainties in quadrature, except for the one due to the $\psi(2S) \to \gamma\chi_c$ branching fractions which we keep separate, when calculating the final branching fractions. For evaluating the limits in the cases where there is no significant signal, we take the probability density function, and divide each entry by the efficiency smeared by the total systematic uncertainty, and find the branching fraction that includes 90% of the total area. A rough check on our ability to find the efficiency of the entire decay chain is possible by measuring the number of events consistent with the decay chain $\psi(2S) \to \eta J/\psi, J\psi \to \gamma\eta'$. This has the same final state particles as $\psi(2S) \to \gamma\chi_c, \chi_c \to \eta\eta'$. Using the Review of Particle Properties[7] values of the branching fractions, we expect to see 19.2 ± 2.4 events in this mode, and we observe 20.8 ± 4.7, which is consistent with this expectation.

TABLE II: Signal yields and branching fraction results for each decay mode. The uncertainties are statistical, systematic due to this measurement, and systematic due to the $\psi(2S) \to \chi_{cJ}$, respectively. The limits on the branching fractions include all systematic uncertainties.

Mode	χ_{c0}		χ_{c2}	
	Yield	B.F. (%)	Yield	B.F. (%)
$\eta\eta$	47.8 ± 7.7	$0.31 \pm 0.05 \pm 0.04 \pm 0.02$	< 7.2	< 0.047
$\eta\eta'$	< 7.5	< 0.050	< 3.4	< 0.023
$\eta'\eta'$	22.7 ± 5.3	$0.17 \pm 0.04 \pm 0.02 \pm 0.01$	< 4.0	< 0.031

TABLE III: Systematic uncertainties expressed in percent.

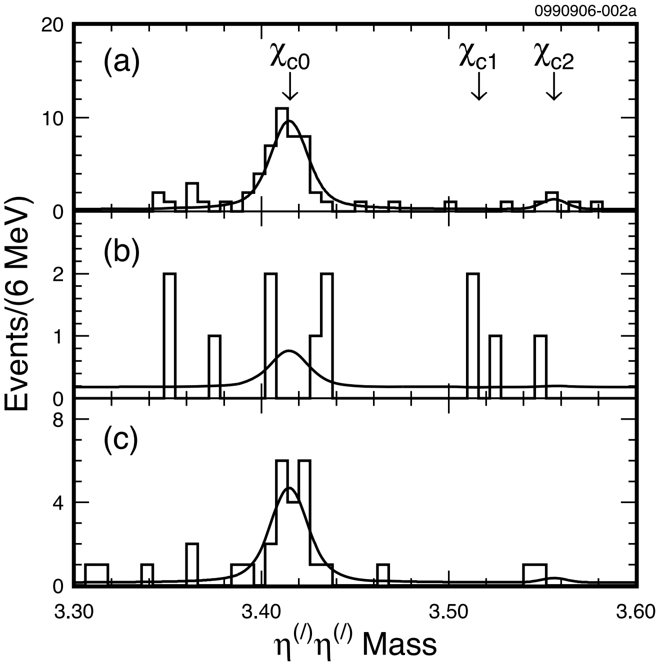
Mode	$N_{\psi(2S)}$	Trig.	Fit	Tracks	γ	MC stats	Cuts	Total
$\eta\eta$	3	1	5	1.4	10	3	3.5	12
$\eta\eta'$	3	1	5	2.1	8	3	3.5	11
$\eta'\eta'$	3	1	5	2.8	6	3	3.5	10

Our results can be interpreted in the model of Qiang Zhao [1], who predicts these decay rates as a function of the QCD parameter, r, which is the ratio of doubly- to singly-OZI-suppressed decay diagrams. The measurements are consistent with small values of r, which indicates that it is the singly suppressed OZI diagram that dominates these decays. We also present a limit on the branching fraction for χ_{c2} decays to $\eta\eta$ that is tighter than that of BES [8], and the first limits for χ_{c2} decays into $\eta\eta'$ and $\eta'\eta'$. The limit for $\chi_{c2} \to \eta\eta$ is slightly below the theoretically predicted branching fraction for $r = 0$, but all three limits are consistent with r being small and negative. More definitive conclusions require a larger sample of χ_{c2} decays.

In summary, we find a branching fraction for $\chi_{c0} \to \eta\eta$ of $(0.31 \pm 0.05 \pm 0.04 \pm 0.02)$%. This is larger than, but consistent with, two lower-statistics measurements of BES [8] and E-835 [9]. We make the first measurement of $\chi_{c0} \to \eta'\eta'$ of $(0.17 \pm 0.04 \pm 0.02 \pm 0.01)$%. We find no signal for $\chi_{c0} \to \eta\eta'$ and are able to set an upper limit on this branching fraction of < 0.05% at the 90% confidence level. We also set limits of the branching fraction for χ_{c2}

decaying to $\eta\eta$, $\eta\eta'$, and $\eta'\eta'$ of 0.047%, 0.023% and 0.031% respectively. Our results imply that singly OZI-suppressed diagrams dominate in these decays.

FIG. 1: Invariant mass distributions for (a) $\eta\eta$, (b) $\eta\eta'$, and (c) $\eta'\eta'$. The fits are described in the text.



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