New measurement of exclusive decays of the χ_{c0} and χ_{c2} to two-meson final states

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Using a sample of 2.59×10^7 $\psi(2S)$ decays collected by the CLEO-c detector, we present results of a study of χ_{c0} and χ_{c2} decays into two-meson final states. We present the world's most precise measurements of the $\chi_{cJ,(J=0,2)} \to \pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $K^0_S K^0_S$, $\eta\eta$, and $\eta'\eta'$ branching fractions, and a search for χ_c decays into $\eta\eta'$. These results shed light on the mechanism of charmonium decays into pseudoscalar mesons.

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The χ_{cJ} mesons ($J = 0, 1, 2$) form a triplet of $c\bar{c}$ states with one unit of orbital angular momentum. They are not produced directly in e^+e^- annihilations, but the large branching fractions of $\psi(2S) \to \chi_{cJ}\gamma$ make e^+e^- collisions at the $\psi(2S)$ energy a very clean environment for χ_{cJ} investigation.

The χ_{cJ} mesons decay into a wide variety of different multihadron states. Of these, the two-meson states have the benefit of being comparatively straightforward to detect and to model theoretically. However, theoretical models based on the color singlet model make predictions well below the data, even when the parameters of the model are stretched to extremes [1]. Recent theoretical work has focussed on the color octet model [2], whereby contribu-

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tions from the subprocess $c\bar{c}g \to q\bar{q}$ are taken into account. This source has been shown to be a possible mechanism to make up the deficit [3]. However, these theoretical results were made with a very rough model for the color-octet contribution to the wave function of the χ_c. Fits [4] to the existing measurements [5] indicate a reasonable theoretical understanding of the processes involved, but data remain sparse and theoretical uncertainties are still large. The study of the decays to higher mass mesons (η and η'), offers the possibility of investigating the contribution of doubly-OZI suppressed decays (DOZI), which may compete with singly-OZI suppressed decays [4], and may also contribute to the understanding of the structure of the η and η' mesons [6]. The χ_{c1} cannot decay into two pseudoscalar mesons because of spin-parity conservation, so we do not consider it further.

The data were taken by the CLEO-c detector [7] operating at the Cornell Electron Storage Ring (CESR) with e^+e^- collisions at a center of mass energy corresponding to the $\psi(2S)$ mass of 3.686 GeV$/c^2$. The data corresponds to an integrated luminosity of 56.3 pb^{-1} and the total number of $\psi(2S)$ events, determined according to the method described in [8], is calculated as $(2.59 \pm 0.05) \times 10^7$.

Photons were detected using the CsI crystal calorimeter [9], which has an energy resolution of 2.2% at 1 GeV, and 5% at 100 MeV. Photon candidates were required to have a lateral shower shape consistent with that expected for a photon, and to be not matched with any charged track. We combine two photon candidates to make π^0 candidates. Those combinations within 3 standard deviations of the π^0 mass are retained for further analysis and are then kinematically constrained to this mass.

Charged particles were detected in a drift chamber system immersed in 1.0 T solenoidal magnetic field. The solid angle for detecting charged particles was 93% of 4π, and the resolution 0.6% at 1 GeV. To discriminate charged kaons from charged pions, we combined specific ionizations (dE/dx) measured in the drift chamber and log likelihoods obtained from the ring-imaging Čerenkov detector [10] to form a log-likelihood difference $\mathcal{L}(K-\pi) = \mathcal{L}_{\rm RICH}(K) - \mathcal{L}_{\rm RICH}(\pi) + \sigma^2_{dE/dx}(K) - \sigma^2_{dE/dx}(\pi)$, where $\sigma_{dE/dx}(K(\pi))$ refers to the difference between the expected and measured dE/dx for a $K(\pi)$ hypothesis in units of standard deviations, and negative $\mathcal{L}(K-\pi)$ implies the particle is more likely to be kaon than a pion. For all charged kaons we require $\mathcal{L}(K-\pi) < 0$ and $\mathcal{L}(K-p) < 0$, and for charged pions we require $\mathcal{L}(\pi - K) < 0$ and $\mathcal{L}(\pi - p) < 0$. As there is potential contamination from lepton pairs in the $\pi^+\pi^-$ final state, we use the muon chamber and CsI information and require that at least one of the tracks in this mode is inconsistent with being due to either a muon or an electron.

We use three decay modes for η detection, $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $\pi^+\pi^-\gamma$, and two modes for η' detection, $\eta\pi^+\pi^-$ and $\gamma\pi^+\pi^-$. In each case we combine the four-momenta of the decay products into an $\eta^{(\prime)}$ candidate, kinematically constrain the candidate to its nominal mass and retain those candidates with a fit $\chi^2 < 9/1$ degree of freedom.

For events with two distinct meson candidates, we combine the candidates into a χ_c candidate. At this stage of the analysis, the invariant mass resolution of the χ_c is approximately 15 MeV$/c^2$. We then search for any unused photon in the event and add that to the χ_c candidate to form a $\psi(2S)$ candidate. This $\psi(2S)$ candidate is then kinematically constrained to the four-momentum of the beam, the energy of which is calculated using the known $\psi(2S)$ mass. The momentum is nonzero due to the finite crossing angle (≈ 3 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 requirement rejects most background combinations. This kinematic fit greatly improves the mass resolution of the χ_c candidate to values ranging from 3.2 to 8.7 MeV$/c^2$ depending on the spin of the χ_c and the decay mode.

To study the efficiency and resolutions, we generated Monte Carlo samples for each χ_c into each final state using a GEANT-based detector simulation [11]. The simulated events have an angular distribution of $(1 + \alpha\cos^2\theta)$, where θ is the radiated photon angle relative to the positron beam direction, and $\alpha = 1$ and $1/13$ for the χ_{c0}, and χ_{c2} respectively, in accordance with expectations for an E1 transition. The decay products of the χ_{c0} are generated with a flat angular distribution. The products of the χ_{c2} are generated according to a double correlation function of the polar angles of the mesons measured in the χ_c rest frame relative to the transition photon direction [12]. The efficiencies are shown in Table I. The efficiencies for η and η' modes include the relevant branching fractions.

The final invariant mass distributions are shown in Fig. 1. These distributions are then fit with two signal shapes comprising Breit-Wigner functions convolved with Gaussian resolutions, together with a constant background term. The masses and widths of the Breit-Wigner functions were fixed according to the Particle Data Group (PDG) averages [5], and the widths of the Gaussian resolution functions were fixed at the values found from Monte Carlo simulation. The yields from these binned likelihood fits are tabulated in Table I.

To convert the yields to branching fractions, we divide by the product of the number of $\psi(2S)$ events in the data sample, the detector efficiency, and the branching fractions for $\psi(2S)$ into χ_{cJ}. For the last factor we use the CLEO measurements of $\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}) = (9.22 \pm 0.11 \pm 0.46)\%$ and $\mathcal{B}(\psi(2S) \to \gamma\chi_{c2}) = (9.33 \pm 0.14 \pm 0.61)\%$ [13]. The results are tabulated in Table II.

We consider systematic uncertainties from many different sources. All modes have a 2% uncertainty from the total number of $\psi(2S)$ decays [8]. The requirement on the

TABLE I. Yields found in the data sample and detection efficiencies obtained from analyses of Monte Carlo generated events.

Mode	χ_{c0} Yield	Efficiency (%)	χ_{c2} Yield	Efficiency (%)
$\pi^+\pi^-$	8934 ± 111	58.7 ± 2.4	2543 ± 56	66.2 ± 2.7
$\pi^0\pi^0$	2807 ± 62	40.0 ± 4.4	793 ± 33	48.5 ± 5.3
K^+K^-	8156 ± 100	53.8 ± 2.5	1645 ± 42	60.2 ± 2.8
$K_S^0K_S^0$	2109 ± 49	25.3 ± 1.1	373 ± 20	29.3 ± 1.3
$\eta\eta$	930 ± 35	12.3 ± 1.1	156 ± 14	12.6 ± 1.1
$\eta\eta'$	35 ± 13	9.2 ± 0.8	3.3 ± 8.0	10.5 ± 0.9
$\eta'\eta'$	413 ± 24	8.2 ± 0.6	12 ± 7	8.8 ± 0.5

χ^2 of the constraint to the beam four-momentum has been checked by changing the cut value in the range 12–50 and noting the change in the yield in these, and other similar decay modes. Based on this study we place a systematic uncertainty of 2.5% on the efficiency of this requirement. The uncertainties due to track reconstruction are 0.3% per charged track (0.67% for kaons). The limited Monte Carlo statistics introduces an uncertainty that is in all cases less than 1.5%. The systematic uncertainty due to the photon detection and shower-shape criteria is set at 2% per photon both for the transition photon and for the decay products of η and π^0 decays. In the cases including η decays, this contribution is incorporated taking into account the fraction of those decays that proceed through each η decay mode. The final signal plots are all well fit using the functions described above. By studying the variation of the yields of the high statistics modes resulting from floating the signal parameters, we assign a 2% uncertainty in each mode due to the uncertainties in the fitting procedure. In addition we allow an extra 2% uncertainty in the yield of the χ_{c0} to account for the possibility of a coherent component of the background that might interfere with the signal. This was evaluated by introducing such a component into the fits and noting the changes in yields. We have checked that the yields from the various decay modes of the $\eta^{(\prime)}$ mesons are consistent with their branching fractions and efficiencies. When calculating the final branching fractions, we add the above systematic uncertainties in quadrature. The uncertainty due to the $\psi(2S) \to \gamma\chi_c$ branching fractions is kept separate and quoted as a second systematic uncertainty.

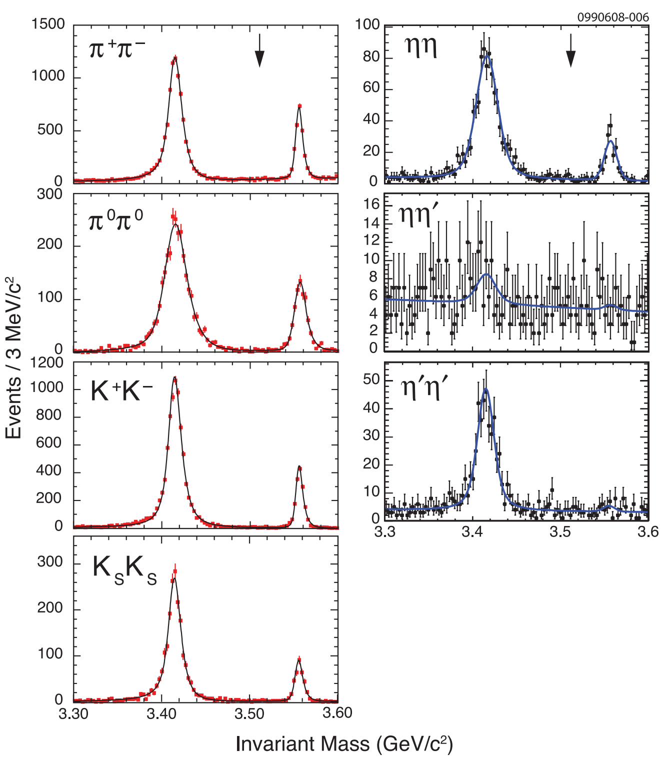

FIG. 1 (color online). Invariant mass distributions for $\pi^+\pi^-$, $\pi^0\pi^0$, K^+K^-, $K_S^0K_S^0$, $\eta\eta$, $\eta\eta'$, $\eta'\eta'$. The fits are described in the text. The downward arrows are at the value of the invariant mass of the χ_{c1}.

For evaluating the limits in the cases where there is no significant signal, we take the probability density function and convolve this with Gaussian systematic uncertainties. We then find the branching fraction that includes 90% of the total area.

Our results are summarized in Table II, and compared with the PDG fits [5] to results from BES [14] and CLEO [15]. These fits explicitly assume that $B(\chi_c \to \pi^+\pi^-) = 2B(\chi_c \to \pi^0\pi^0)$. Our results do not include that constraint, but the data are consistent with this isospin symmetry. Our results are also consistent with the expected result that $B(\chi_c \to K^+K^-) = 2B(\chi_c \to K_S^0K_S^0)$, whereas previous results had indicated that this might not be so in the $J = 2$ case. The largest deviation from previous results ($\approx 3\sigma$) is in the case of $\chi_{c0} \to \pi^+\pi^-$. In the case of the χ_{c2}, our limit for the branching fraction into $\eta\eta'$ is below the fit value obtained from previous data by Q. Zhao [4], suggesting that the DOZI decays of the χ_{c2} may contribute less than indicated by that phenomenological analysis. We note that there is an overlap of datasets in the results presented here and those of our previous analysis of $\eta^{(\prime)}\eta^{(\prime)}$ decays, and so our new results should replace rather than augment our previous measurements.

In summary, we measure branching fractions for χ_{c0} and χ_{c2} decays into $\pi^0\pi^0$, $\pi^+\pi^-$, K^+K^-, $K_S^0K_S^0$, $\eta\eta$, and $\eta'\eta'$. The decay $\chi_{c2} \to \eta\eta$ is observed for the first time

TABLE II. Branching fraction results (in units of 10^{-3}) for each decay mode. The uncertainties are statistical, systematic due to this measurement, and systematic due to the $\psi(2S) \to \chi_{cJ}\gamma$ rate, respectively. The limits on the branching fractions include all systematic uncertainties, and central values for those measurements are included in parentheses.

Mode		χ_{c0}	χ_{c2}
$\pi^+\pi^-$	This work	$6.37 \pm 0.08 \pm 0.31 \pm 0.32$	$1.59 \pm 0.04 \pm 0.07 \pm 0.10$
	PDG [5]	4.87 ± 0.40	1.42 ± 0.16
$\pi^0\pi^0$	This work	$2.94 \pm 0.07 \pm 0.32 \pm 0.15$	$0.68 \pm 0.03 \pm 0.07 \pm 0.04$
	PDG	$2.43 \pm .20$	0.71 ± 0.08
K^+K^-	This work	$6.47 \pm 0.08 \pm 0.35 \pm 0.32$	$1.13 \pm 0.03 \pm 0.06 \pm 0.07$
	PDG	5.5 ± 0.6	0.78 ± 0.14
$K_S^0K_S^0$	This Work	$3.49 \pm 0.08 \pm 0.18 \pm 0.17$	$0.53 \pm 0.03 \pm 0.03 \pm 0.03$
	PDG	2.77 ± 0.34	0.68 ± 0.11
$\eta\eta$	This work	$3.18 \pm 0.13 \pm 0.31 \pm 0.16$	$0.51 \pm 0.05 \pm 0.05 \pm 0.03$
	PDG	2.4 ± 0.4	<0.5
$\eta\eta'$	This work	<0.25	<0.06
		$(0.16 \pm 0.06 \pm 0.01 \pm 0.01)$	$(0.013 \pm 0.031 \pm 0.001 \pm 0.001)$
	PDG	<0.5	<0.26
$\eta'\eta'$	This work	$2.12 \pm 0.13 \pm 0.18 \pm 0.11$	<0.10
			$(0.056 \pm 0.032 \pm 0.005 \pm 0.003)$
	PDG	1.7 ± 0.4	<0.4

and in all other cases these measurements are more precise than any previously made. These results may be used to test the role of the color octet mechanism model of χ_{cJ} decays. The improved limits on decays into $\eta\eta'$ are further proof of the small contributions made by DOZI decays in this system.

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