chi(c0) and chi(c2) decays into eta eta, eta eta ‘, and eta ’eta ’ final states

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Search for $\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0$

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Using 5.63 pb^{-1} of data accumulated at the $\psi(2S)$ resonance with the CLEO III and CLEO-c detectors corresponding to 3.08×10^6 $\psi(2S)$ decays, a search is performed for the decay $\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0$ to test a theoretical prediction based upon the assumption that the $c\bar{c}$ pair in the $\psi(2S)$ does not annihilate directly into three gluons but rather survives before annihilating. No signal is observed, and a combined upper limit from six η_c decay modes is determined to be $\mathcal{B}(\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0) \leq 1.0 \times 10^{-3}$ at 90% C.L. This upper limit is about an order of magnitude below the theoretical expectation.

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In perturbative QCD the charmonium states J/ψ and $\psi(2S)$ are nonrelativistic bound states of a charm and an anticharm quark and it is predicted that the decays of these states are dominated by the annihilation of the charm and anticharm quark into three gluons. The partial width for the decays into an exclusive hadronic state h is then expected to be proportional to the square of the $c\bar{c}$ wave function overlap at zero quark separation, which is well determined from the leptonic width [1].

Since the strong coupling constant, α_s, is not very different at the J/ψ and $\psi(2S)$ masses, it is expected that for any state h the J/ψ and $\psi(2S)$ branching fractions are related by [2]

$$Q_h = \frac{\mathcal{B}(\psi(2S) \to h)}{\mathcal{B}(J/\psi \to h)} \approx \frac{\mathcal{B}(\psi(2S) \to \ell^+\ell^-)}{\mathcal{B}(J/\psi \to \ell^+\ell^-)} = (12.4 \pm 0.4)\%, \tag{1}$$

where $\mathcal{B}$ denotes a branching fraction, and the leptonic branching fractions are taken from the Particle Data Group (PDG) [1]. This relation is sometimes called "the 12% rule". Modest deviations from the rule are expected [3]. Although the rule works well for some specific decay modes, isospin conserving $\psi(2S)$ decays to two-body final states consisting of one vector and one pseudsoscalar meson exhibit strong suppression: $\rho\pi$ is suppressed by a factor of 70 compared to the expectations of the rule (the so-called $\rho\pi$ puzzle) [1,4–6]. Also, vector-tensor channels such as $\rho a_2(1320)$, and $K^*(892)\bar{K}_2^*(1430)$ are significantly suppressed [1,7]. Another issue is the hadronic excess in $\psi(2S)$ decays: the inclusive hadronic decay rate of $\psi(2S)$ is larger than that expected from an extrapolation of the J/ψ hadronic decay branching fraction by 60–70%. A recent review [3] concludes that current theoretical explanations of $\psi(2S)$ decays are unsatisfactory and that more experimental measurements are desirable.

A recent paper [8] suggests that "survival before annihilation" could be an important mechanism in $\psi(2S)$ decays. This model proposes that the $c\bar{c}$ pair in the $\psi(2S)$ does not annihilate directly into three gluons but rather "survives" before annihilating, i.e., the $c\bar{c}$ pair decays by first emitting two or three nonperturbative gluons before annihilating into three or two perturbative gluons. This model, it is claimed, can solve the problem of the apparent hadronic excess in $\psi(2S)$ decays as well as the $\rho\pi$ puzzle. One important prediction of the model is that the $\psi(2S) \to \eta_c\pi^+\pi^-\pi^0$ channel would be a significant decay with a branching fraction of 1% or larger.

We search for the decay $\psi(2S) \to \eta_c\pi^+\pi^-\pi^0$ using the six decay modes of the η_c listed in Table I. The η_c decay modes selected amount to about 10.6% of the total η_c decay rate [1].

The data sample used in this analysis was obtained at the $\psi(2S)$ in e^+e^- collisions produced by the Cornell Electron Storage Ring (CESR) and acquired with the CLEO detector. The CLEO III detector [9] features a solid angle coverage for charged and neutral particles of 93%. The charged particle tracking system, operating in a 1.0 T magnetic field along the beam axis, achieves a momentum resolution of ~0.6% at $p = 1$ GeV/c. The calorimeter attains a photon energy resolution of 2.2% at $E_\gamma = 1$ GeV and 5% at 100 MeV. Two particle identification systems, one based on energy loss (dE/dx) in the drift chamber and the other a ring-imaging Cherenkov (RICH) detector, are used together to separate $K^\pm$ from $\pi^\pm$. The combined dE/dx-RICH particle identification procedure has efficiencies exceeding 90% and misidentification rates below 5% for both $\pi^\pm$ and $K^\pm$ for momenta below 2.5 GeV/c.

TABLE I. No evidence is found for $\psi(2S) \to \eta_c\pi^+\pi^-\pi^0$. Number of events in the η_c mass region, detection efficiency, and η_c branching ratio [1].

Decay mode	# Events	Efficiency (%)	$\mathcal{B}(\eta_c)$ (%)
$\eta_c \to K^+K^-\pi^0$	1	3.08	1.2 ± 0.2
$\eta_c \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$	0	2.76	1.3 ± 0.5
$\eta_c \to \eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0$	0	0.80	0.7 ± 0.3
$\eta_c \to K^+K^-\pi^+\pi^-$	7	3.07	1.5 ± 0.6
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$	6	4.06	1.2 ± 0.3
$\eta_c \to K^-\pi^+K^0$	4	1.55	4.7 ± 0.8
All modes combined	18	2.31	10.6 ± 1.2

Half of the $\psi(2S)$ data were taken after a transition to the CLEO-c [10] detector configuration, in which the CLEO silicon small radius tracking detector was replaced with a six-layer all-stereo drift chamber. The two detector configurations also correspond to different accelerator lattices: the former with a single wiggler magnet and a center-of-mass energy spread of 1.5 MeV, the latter (CESR-c [10]) with six wiggler magnets and an energy spread of 2.3 MeV.

The integrated luminosity ($\mathcal{L}$) of the datasets was measured using e^+e^-, $\gamma\gamma$, and $\mu^+\mu^-$ final states [11]. Event counts were normalized with a Monte Carlo (MC) simulation based on the Babayaga [12] event generator combined with GEANT-based [13] detector modeling. The data consist of $\mathcal{L} = 5.63$ pb^{-1} on the peak of the $\psi(2S)$ at $\sqrt{s} = 3.686$ GeV (2.74 pb^{-1} for CLEO III, 2.89 pb^{-1} for CLEO-c).

Standard requirements [14] are used to select charged particles reconstructed in the tracking system and photon candidates in the CsI calorimeter. We require tracks of charged particles to have momenta $p > 100$ MeV/c and to satisfy $|\cos\theta| < 0.90$, where θ is the polar angle with respect to the e^+ direction. Each photon candidate satisfies $E_\gamma > 30$ MeV and is more than 8 cm away from the projections of tracks into the calorimeter. Particle identification from dE/dx and the RICH detector is used for all charged particle candidates. Pions and kaons must be positively and uniquely identified, i.e., pion candidates must not satisfy kaon or proton selection criteria, and kaon candidates obey similar requirements.

The invariant mass of the decay products from the following particles must lie within limits determined from MC studies: $\pi^0(120 \le M_{\gamma\gamma} \le 150$ MeV), $\eta(500 \le M_{\gamma\gamma} \le 580$ MeV), $\eta(530 \le M_{\pi^+\pi^-\pi^0} \le 565$ MeV).

For $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ candidates in events with more than two photons, the combination giving a mass closest to the known π^0 or η mass is chosen, and a kinematically constrained fit to the known parent mass is made. Fake π^0 and η mesons are suppressed by requiring that each electromagnetic shower profile be consistent with that of a photon. For $\eta \to \pi^+\pi^-\pi^0$ the π^0 is selected as described above, and then combined with all possible combinations of two oppositely charged pions choosing the combination that is closest to the η mass. A kinematically constrained fit is not used for this mode.

Events having final state particles consistent with one of the six η_c decay channels and additionally a $\pi^+\pi^-\pi^0$ combination are selected. Energy and momentum conservation requirements are then imposed on the event using the summed vector momentum $\sum \mathbf{p_i}$ and scalar energy E_{vis}. These requirements are based on the experimental resolutions as determined by Monte Carlo for each of the final states. The scaled momentum $|\sum \mathbf{p_i}|/E_{\text{c.m.}}$ is required to be consistent with zero and the scaled energy $E_{\text{vis}}/E_{\text{c.m.}}$ is required to be consistent with unity. The experimental resolutions are less than 1% in scaled energy and 2% in scaled momentum. In order to veto the final states $\psi(2S) \to XJ/\psi$ ($X = \pi^+\pi^-$, $\pi^0\pi^0$, or η) events are rejected in which the mass of any of the following falls within the range $3.05 < m < 3.15$ GeV: the two highest momentum oppositely charged tracks, the recoil mass against the two lowest momentum oppositely charged tracks, or the mass recoiling against the $\pi^0\pi^0$ or η.

The efficiency, ε, for each final state is the weighted average obtained from MC simulations [13] for both detector configurations. No initial state radiation is included in the Monte Carlo, but final state radiation is accounted for. The efficiencies in Table I include the branching fractions of the η [1].

After the selection of events consistent with the six exclusive $\psi(2S)$ decay modes, we search for η_c production in these events by examining the invariant mass of combinations of particles consistent with an η_c decay. In all events there are multiple η_c combinations and to be conservative we have taken only one combination per event choosing the one nearest the η_c mass. Figure 1 is the scaled energy distribution for each of the six $\psi(2S)$ exclusive decays after imposing momentum conservation ($|\sum \mathbf{p_i}|/E_{\text{c.m.}} < 0.02$) and for events with an η_c candidate mass greater than 2.7 GeV, which includes the nominal η_c mass region. There is clear evidence of exclusive $\psi(2S)$ production of the final states under study from the accumulation of events near unity. After requiring the scaled energy to be in the range (0.98–1.02), the invariant mass distributions shown in Fig. 2 are analyzed for η_c production. A combined mass distribution for all six modes is shown in Fig. 3. The histograms show the expected signal from Monte Carlo normalized to the branching ratio prediction of $\mathcal{B}(\psi(2S) \to \eta_c\pi^+\pi^-\pi^0 = 1\%$. There is no evidence for η_c production in any of the six individual decay modes or in the combined distribution.

Table I shows the number of events in the η_c mass region (2.91–3.05 GeV), which corresponds to ±3 stan-

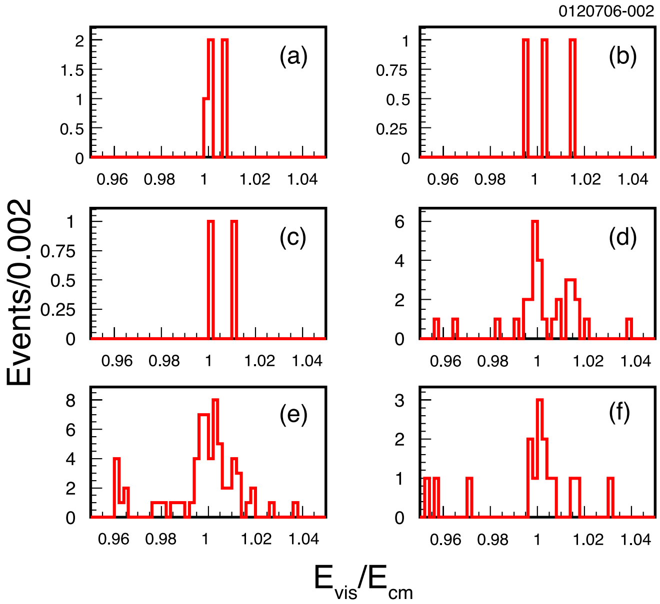

FIG. 1 (color online). The scaled total energy distribution for each $\psi(2S)$ mode for events with the candidate η_c decay having an invariant mass greater than 2.7 GeV. (a) $\eta_c \to K^+K^-\pi^0$. (b) $\eta_c \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$. (c) $\eta_c \to \eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0$. (d) $\eta_c \to K^+K^-\pi^+\pi^-$. (e) $\eta_c \to \pi^+\pi^-\pi^+\pi^-$. (f) $\eta_c \to K^-\pi^+K^0$.

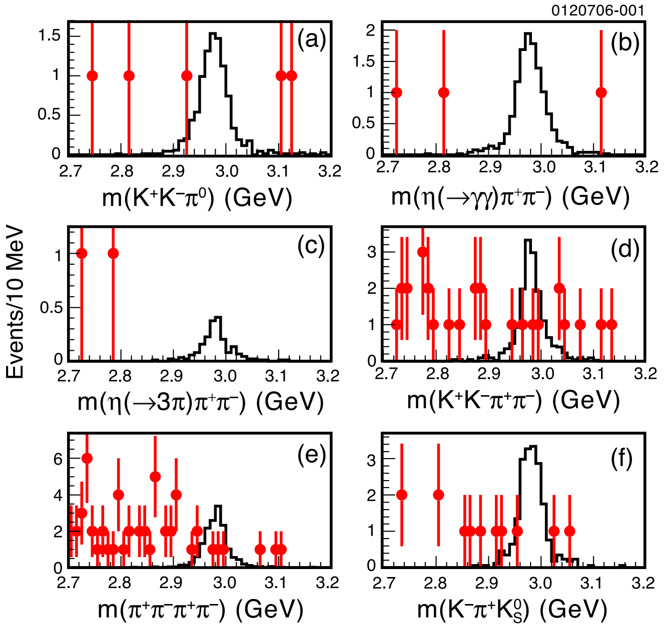

FIG. 2 (color online). The invariant mass distribution for each η_c mode. Histogram: Monte Carlo, normalized to $\mathcal{B}(\psi(2S) \to \eta_c\pi^+\pi^-\pi^0) = 1\%$; filled circles with error bar: data. (a) $\eta_c \to K^+K^-\pi^0$. (b) $\eta_c \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$. (c) $\eta_c \to \eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0$. (d) $\eta_c \to K^+K^-\pi^+\pi^-$. (e) $\eta_c \to \pi^+\pi^-\pi^+\pi^-$. (f) $\eta_c \to K^-\pi^+K^0$.

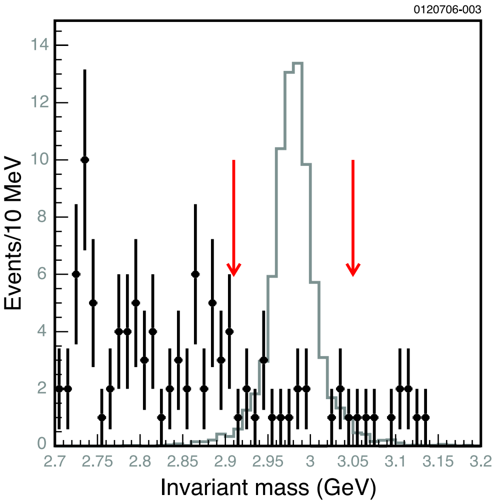

FIG. 3 (color online). The invariant mass distribution for all six η_c modes combined. Histogram: Monte Carlo, normalized to $\mathcal{B}(\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0) = 1\%$; filled circles with error bar: data.

dard deviations of the expected η_c mass resolution, the efficiency and the η_c branching ratio for each of the decay channels. No evidence is found for $\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0$.

The following sources of systematic uncertainties have been considered. The number of $\psi(2S)$ decays (3.0%), trigger efficiency (1.0%), and the uncertainty associated with the resolution defining a signal region in the scaled energy and resonant mass (2.0%) contribute identical systematic uncertainties to each channel. Other sources vary by channel, for example, Monte Carlo statistics (2.7%–7.4%). The systematic uncertainty associated with the charged track finding is 0.7% per track. This uncertainty adds coherently for each charged track in the event. The particle identification uncertainty is 0.3% per charged pion, and 1.3% per charged kaon. This uncertainty adds coherently for each charged track in the event since PID is used for every track. The systematic uncertainty associated with π^0 and $\eta \to \gamma\gamma$ finding is 4.4%.

We determine a $\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0$ branching fraction upper limit at 90% C.L. combining all η_c decay modes using

$$\mathcal{B} = \frac{N_S}{(\sum \varepsilon_i \cdot \mathcal{B}(\eta_c \to h_i)) \cdot N_{\psi(2S)}}, \qquad (2)$$

where N_S is the upper limit on the number of signal events, ε_i and $\mathcal{B}(\eta_c \to h_i)$ are the efficiency and the branching fraction for η_c decay mode i; and $N_{\psi(2S)}$ is the total number of $\psi(2S)$ decays. The number of $\psi(2S)$ decays $N_{\psi(2S)}$ was determined to be 3.08×10^6 by the method described in [15]. The combined efficiency, which includes the branching fractions for η_c decays, is defined as

$$\varepsilon = \frac{\sum \varepsilon_i \cdot \mathcal{B}(\eta_c \to h_i)}{\sum \mathcal{B}(\eta_c \to h_i)}, \qquad (3)$$

and is also shown in Table I. To determine the upper limit on the number of signal events, N_S, the data distribution in Fig. 3 is fit using a polynomial and a Gaussian with fixed signal shape obtained from MC. By fixing the signal amplitude and maximizing the fit likelihood with respect to the parameters for background, we obtain the fit likelihood as a function of the signal amplitude and determine the upper limit on the number of signal events to be <6.7 at 90% C.L. After combining the systematic uncertainties and the uncertainties in the η_c branching ratios in quadrature and increasing the upper limit on the number of observed events by 1 standard deviation of the combined uncertainty, the branching fraction upper limit is computed to be 1.0×10^{-3}. [Alternative methods of computing a 90% C.L. upper limit using the number of events in the signal and sideband regions of the invariant mass give slightly lower limits [1,16].]

In summary we have searched for the decay $\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0$ using six decay modes of the η_c. We have determined a combined upper limit at 90% confidence level for the branching fraction of the decay $\psi(2S) \to \eta_c \pi^+ \pi^- \pi^0$ to be 1.0×10^{-3}. This upper limit is about an order of magnitude below the theoretical prediction of the survival before annihilation model meaning that the survival of the $c\bar{c}$ pair to form an η_c is highly suppressed.

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