Evidence for Decays of $h_c$ to Multi-Pion Final States

G. S. Adams,1 D. Hu,1 B. Moziak,1 J. Napolitano,1 K. M. Ecklund,2 Q. He,3 J. Insler,3 H. Muramatsu,3 C. S. Park,3 E. H. Thorndike,3 F. Yang,3 M. Artuso,4 S. Blusk,4 S. Khalil,4 R. Mountain,4 K. Randrianarivony,4 S. Stone,4 J. C. Wang,4 L. M. Zhang,4 G. Bonvicini,5 D. Cinabro,5 A. Lincoln,5 M. J. Smith,5 P. Zhou,5 J. Zhu,5 P. Naik,6 J. Rademacker,6 D. M. Asner,7 K. W. Edwards,7 J. Reed,7 A. N. Robichaud,7 G. Tatishvili,7 E. J. White,7 R. A. Briere,8 H. Vogel,8 P. U. E. Onyisi,9 J. L. Rosner,9 J. P. Alexander,10 D. G. Cassel,10 R. Ehrlich,10 L. Fields,10 L. Gibbons,10 S. W. Gray,10 D. L. Hartill,10 B. K. Heltsley,10 J. M. Hunt,10 J. Kandaswamy,10 D. L. Kreinick,10 V. E. Kuznetsov,10 J. Ledoux,10 H. Mahlke-Krüger,10 J. R. Patterson,10 D. Peterson,10 D. Riley,10 A. Ryd,10 A. J. Sadoff,10 X. Shi,10 S. Stroiney,10 W. M. Sun,10 T. Wilksen,10 J. Yelton,11 P. Rubin,12 N. Lowrey,13 S. Mehrabyan,13 M. Selen,13 J. Wiss,13 M. Kornicer,14 R. E. Mitchell,14 M. R. Shepherd,14 C. M. Tarbert,14 D. Besson,15 T. K. Pedlar,16 J. Xavier,16 D. Cronin-Hennessy,17 K. Y. Gao,17 J. Hietala,17 T. Klein,17 R. Poling,17 P. Zweber,17 S. Dobbs,18 Z. Metreveli,18 K. K. Seth,18 B. J. Y. Tan,18 A. Tomaradze,18 S. Brisbane,19 J. Libby,19 L. Martin,19 A. Powell,19 C. Thomas,19 G. Wilkinson,19 H. Mendez,20 J. Y. Ge,21 D. H. Miller,21 I. P. J. Shipsey,21 and B. Xin21

(CLEO Collaboration)

1Rensselaer Polytechnic Institute, Troy, New York 12180, USA
2Rice University, Houston, Texas 77005, USA
3University of Rochester, Rochester, New York 14627, USA
4Syracuse University, Syracuse, New York 13244, USA
5Wayne State University, Detroit, Michigan 48202, USA
6University of Bristol, Bristol BS8 1TL, UK
7Carleton University, Ottawa, Ontario, Canada K1S 5B6
8Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
9University of Chicago, Chicago, Illinois 60637, USA
10Cornell University, Ithaca, New York 14853, USA
11University of Florida, Gainesville, Florida 32611, USA
12George Mason University, Fairfax, Virginia 22030, USA
13University of Illinois, Urbana-Champaign, Illinois 61801, USA
14Indiana University, Bloomington, Indiana 47405, USA
15University of Kansas, Lawrence, Kansas 66045, USA
16Luther College, Decorah, Iowa 52101, USA
17University of Minnesota, Minneapolis, Minnesota 55455, USA
18Northwestern University, Evanston, Illinois 60208, USA
19University of Oxford, Oxford OX1 3RH, UK
20University of Puerto Rico, Mayaguez, Puerto Rico 00681
21Purdue University, West Lafayette, Indiana 47907, USA

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Abstract

Using a sample of $2.59 \times 10^7 \psi(2S)$ decays collected by the CLEO–c detector, we present results of a search for the decay chain $\psi(2S) \rightarrow \pi^0 h_c, h_c \rightarrow n(\pi^+\pi^-)\pi^0, n = 1, 2, 3$. We observe no significant signals for $n = 1$ and $n = 3$ and set upper limits for the corresponding decay rates. First evidence for the decay $h_c \rightarrow \pi^+\pi^-\pi^-\pi^0$ is presented, and a product branching fraction of $B(\psi(2S) \rightarrow h_c) \times B(h_c \rightarrow 2(\pi^+\pi^-)\pi^0) = 1.88^{+0.48+0.47}_{-0.45-0.30} \times 10^{-5}$ is measured. This result implies that $h_c \rightarrow \text{hadrons}$ and $h_c \rightarrow \gamma\eta_c$ have comparable rates, in agreement with expectations.

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Although the field of charmonium spectroscopy is now thirty-five years old, data on the $c\bar{c}$ singlet state, the $h_c(1P_J)$, remains sparse. Two experiments have identified the $h_c$ and accurately measured its mass. The CLEO [1, 2] measurements were made using the decay chain $\psi(2S) \rightarrow \pi h_c, \pi \rightarrow \gamma\gamma, h_c \rightarrow \gamma\eta_c$, and identifying the $h_c$ either by fully reconstructing the event using many different hadronic decay channels of the $\eta_c$, or by reconstructing the $\pi$ and $\gamma$ in the decay chain and inferring the existence of the $\eta_c$. The E835 experiment [3] made scans of antiproton energy and observed the reaction $\bar{p}p \rightarrow h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow \gamma\gamma$. The experiment also searched for the evidence of the suppressed decay $h_c \rightarrow \pi^0 J/\psi$ but none was found. The $h_c$ is also expected to decay directly to multi-hadron final states; however, such decays have yet to be observed. The $h_c$ width into such states is expected to be, by coincidence, comparable to that of the radiative decays; Godfrey and Rosner [4] predict branching fractions of 38% for $\gamma\eta_c$ decays and 57% $\gamma\gamma\gamma$ decays, with the remainder being $\gamma\gamma\eta_c$. The $h_c$, unlike the $\chi_{cJ}$ mesons, has negative G-parity, and thus its multi-pion decays are likely to involve an odd number of pions. Here we report the results of a search for the decays of the $h_c$ into $n(\pi^+\pi^-)\pi^0$, with $n = 1, 2, 3$.

The data presented here were taken by the CLEO-c detector [3] 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. The data correspond to an integrated luminosity of 56.3 pb$^{-1}$ and the total number of $\psi(2S)$ events, determined according to the method described in [6], is calculated as $(2.59 \pm 0.05) \times 10^7$. Like the previous CLEO analyses, we search for the $h_c$ mesons produced by the isospin-violating decay $\psi(2S) \rightarrow \pi^0 h_c$.

Charged particles are detected in a cylindrical wire chamber system immersed in a 1.0 T axial magnetic field induced by a superconducting solenoid. The solid angle for detecting charged particles is 93% of $4\pi$, and the resolution 0.6% at 1 GeV. To identify the pions, we measure the specific ionization, $dE/dx$, in the drift chamber and require that it be within 4 standard deviations of that expected for a pion. Photons are detected using the CsI crystal calorimeter also inside the magnet coil, which has an energy resolution of 2.2% at 1 GeV and 5% at 100 MeV. Photon candidates are required to have a lateral shower shape consistent with that expected for a photon and not to align with the projection of any charged particle into the calorimeter. We combine photon pairs to make $\pi^0$ candidates, and kinematically constrain them to the known $\pi^0$ mass; combinations with a $\chi^2$ of less than 10 for the one degree of freedom are retained for further analysis.

For each decay mode, we combine the requisite number of charged pion candidates with one $\pi^0$ candidate to form an $h_c$ candidate. These particles are kinematically constrained with the beamspot to form a primary event vertex. We then add a second $\pi^0$ candidate in the event, ensuring that no photon is used in both candidates, to make 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 non-zero only due to the crossing angle ($\approx 3$ mrad per beam) in CESR. To make our final selection, we require the $\psi(2S)$ candidate to have a $\chi^2$ of less than 25 for the four degrees of freedom for this fit; this requirement rejects most background combinations.

The kinematic fit produces an $h_c$ mass resolution which is much improved over a direct measurement of $M(n(\pi^+\pi^-)\pi^0)$ and slightly improved compared to a measurement of the missing mass using the measured parameters of the transition $\pi^0$ alone. To study the efficiency and resolutions, we generated Monte Carlo samples for each $h_c$ decay using a GEANT-based detector simulation [8]. The decay products of the $h_c$ were generated according to phase space. For each of the three multi-pion decays sought, the MC studies
show that the $h_c$ mass distribution is well-represented by a double Gaussian signal shape over a slowly varying background. For the $n = 2$ case, for example, the shape parameters are $\sigma_{\text{narrow}} = 1.19$ MeV, $\sigma_{\text{wide}} = 3.18$ MeV, and $N_{\text{narrow}}/N_{\text{total}} = 0.643$. The efficiencies are shown in Table I.

TABLE I: For each $h_c$ decay mode, the efficiency, the raw event yield with statistical uncertainties obtained from the fit to the data, and the product branching fraction $B_1 \times B_2$, where $B_1 = B(\psi(2S) \rightarrow \pi^0 h_c)$, and $B_2 = B(h_c \rightarrow n(\pi^+\pi^-)\pi^0)$, including systematic uncertainties. Upper limits are quoted at 90% confidence level, and include the effects of systematic errors as described in the text.

| Mode | Efficiency (%) | Yield | $B_1 \times B_2 \times 10^5$ |
|------|----------------|-------|-----------------------------|
| $\pi^+\pi^-\pi^0$ | 27.0 | $1.6^{+6.7}_{-5.9}$ | <0.19 |
| $2(\pi^+\pi^-)\pi^0$ | 18.8 | $92^{+23}_{-22}$ | $(1.88^{+0.48+0.47}_{-0.45-0.36})$ |
| $3(\pi^+\pi^-)\pi^0$ | 11.5 | $35 \pm 26$ | $(1.2 \pm 0.9 \pm 0.3)$ ($<2.5$) |

The final invariant mass distributions are shown in Figs. 1(a), 2(a) and 1(c). In the case of $h_c \rightarrow \pi^+\pi^-\pi^0$ the events are dominated by $\psi(2S) \rightarrow \pi^0\pi^0 J/\psi$, with the subsequent decay of the $J/\psi$ into two charged particles. The $J/\psi$ has a very large branching into $\mu^+\mu^-$ and these events will, in general, pass all selection criteria and enter the plot (Fig. 1(a)). The most efficacious way of eliminating these events is to reject those events with $3.0 < M_{\pi^+\pi^-} < 3.2$ GeV/c$^2$. Figure 1(b) shows the plot after this cut has been made. Neither Figs. 1(a) or 1(b) show any excess in the $h_c$ region. These histograms are fit to a background function (second order polynomial for Fig. 1(a) and an ARGUS style background function,9 for Fig. 1(b)), and signal function of fixed mass and width; the $h_c$ mass is taken from [2] to find 90% confidence level upper limits of < 94 and < 14 events respectively.

Fig. 2(a) shows the invariant mass distribution for $h_c \rightarrow 2(\pi^+\pi^-)\pi^0$. It shows a distinct excess in the region of the $h_c$. The distribution is fit to an ARGUS style background function, plus a floating mass signal with a fixed shape from the Monte Carlo studies. The measured peak mass is 3525.6 ± 0.5 MeV, which may be compared with the Particle Data Group [7] number of 3525.93 ± 0.27 MeV and the more recent CLEO [2] measurement of 3525.28 ± 0.22 MeV. The yield is $92^{+23}_{-22}$ events, and has a significance of 4.4$\sigma$. We also analyzed a large sample of Monte Carlo events generated using the known decays of the $\psi(2S)$ and designed to mimic the real data sample. Those events where an $h_c$ meson was generated are explicitly excluded. Figure 2(b) shows the $2(\pi^+\pi^-)\pi^0$ mass plot from the remaining events and, as expected, it shows no sign of an excess in the $h_c$ region. This mass distribution falls slightly faster than the equivalent one in data, demonstrating the lack of complete knowledge of $\psi(2S)$ decays, but it can be well fit by an ARGUS type background function.

Fig. 1(c) shows the mass distribution for $h_c \rightarrow 3(\pi^+\pi^-)\pi^0$. It shows a small, but not statistically significant, excess in the signal region. The fit shown uses the same fixed mass of the $h_c$ and the measured yield is $35 \pm 26$ events, corresponding to a 90% confidence level upper limit of 70.

We consider systematic uncertainties from many different sources, and these are listed for the $2(\pi^+\pi^-)\pi^0$ mode in Table II. We assign uncertainties of 0.3% and 2%, respectively, on the detection efficiency for each track and for each photon. The largest systematic uncertainty in the $2(\pi^+\pi^-)\pi^0$ mode is due to uncertainties in the fitting procedure. The fit is performed in small mass bins to minimize fluctuations due to choice of binning, and has a $\chi^2$ per degree freedom of 242/235. Using a background function of a second order
Chebyshev polynomial gives higher yields but a less satisfactory fit. Fits are also performed over wider and narrower mass ranges and using higher order polynomial background shapes. The systematic uncertainty is calculated from observing the range of yields from different, reasonable, fitting procedures. The $h_c$ is known to be relatively narrow and our Monte Carlo simulation assumed an intrinsic width of 0.9 MeV. We assign a systematic uncertainty based upon the variation of yield if this number was in the range 0-1.5 MeV. To evaluate the systematic uncertainty due to our knowledge of the resolution, we allowed for variations of up to 10\% in the width of the resolution function. To account for possible substructure in the $5\pi$ decay products a series of Monte Carlo samples were generated where the $\pi$ mesons are the product of intermediate $\rho$ mesons, and we look at the spread of different efficiencies calculated.

To convert the yields to product branching fractions, we divide by the product of the number of $\psi(2S)$ events in the data sample and the efficiency from Table I. 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.

| Source | Uncertainty (\%) |
|--------|------------------|
| Efficiency of tracks and photons | 10\% |
| Background function and fitting range | $\pm 25\%$ |
| $\chi^2$ cut efficiency | 4\% |
| Signal natural width | 5\% |
| Signal resolution | 8\% |
| Possible substructure | 6\% |
| Possible decays to $J/\psi$ | $+0\%$ $-3\%$ |
| $N(\psi(2S))$ | 2\% |
| Total | $+29\%$ $-16\%$ |

The product branching fraction, $B(\psi(2S) \to h_c) \times B(h_c \to 2(\pi^+\pi^-)\pi^0)$ is calculated to be $(1.88^{+0.48}_{-0.45}^{+0.47}) \times 10^{-5}$. We note that this is $\approx 5\%$ of $B(\psi(2S) \to h_c) \times B(h_c \to \gamma\eta_c)$ \cite{2}. Given the large number of different hadronic final states that are available for $h_c$ decays, we can conclude that these hadronic states have a width the same order of magnitude as the radiative decays into the $\eta_c$.

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FIG. 1: Invariant mass plots for (a) $\pi^+\pi^-\pi^0$ (b) $\pi^+\pi^-\pi^0$ with a $J/\psi$ veto (c) $3(\pi^+\pi^-)\pi^0$. Fig 1(a) is fit using a second order Chebychev polynomial shape background. Figs. 1(b), and 1(c) are fit using an ARGUS type background function.
FIG. 2: Invariant mass plots for $2(\pi^+\pi^-)\pi^0$ for (a) data, and (b) non-$h_c$ Monte Carlo events. In each case the background function is an ARGUS type function.
[1] J.L. Rosner et al. (CLEO Collaboration), Phys. Rev. Lett. 95, 102003 (2005); P. Rubin et al. (CLEO Collaboration), Phys. Rev. D 72, 092004 (2005).
[2] S. Dobbs et al. (CLEO Collaboration), Phys. Rev. Lett. 101, 182003 (2008).
[3] M. Andreotti et al. (E-835 Collaboration), Phys. Rev. D 72, 032001 (2005).
[4] S. Godfrey and J. Rosner, Phys Rev. D 66, 014012 (2002).
[5] Y. Kubota et al. (CLEO Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 320, 66 (1992).
    R.A. Briere et al. (CESR-c and CLEO-c Taskforces, CLEO-c Collaboration), Cornell University, LEPP Report No. CLNS 01/1742 (2001) (unpublished), G. Viehhauser et al., Nucl. Instrum. Meth. A 462, 146 (2001).
[6] H. Mendez et al. (CLEO Collaboration), Phys. Rev. D 78, 011102 (2008).
[7] C. Amsler et al. (Particle Data Group), Phys. Lett. B 667, 1 (2008).
[8] R. Brun et al. (Geant) 3.21, CERN Program Library Long Writeup W5013 (1993) (unpublished).
[9] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990).