PROCEEDINGS OF SCIENCE

Charmonium at CLEO-c

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The charmonium results presented in this paper are part of a continuing program using the CLEO-c detector to produce high precision results on both open charm decays and charmonium systems [1]. The results include:
Observation of the $h_c(^1P_1)$
Branching fractions for $\mathcal{B}(J/\psi \to e^+e^-)$ and $\mathcal{B}(J/\psi \to \mu^+\mu^-)$
Observation of $\psi(3770) \to \pi\pi J/\psi$ and Measurement of $\Gamma_{ee}[\psi(2S)]$
Branching Fractions for $\psi(2S)$-to-J/ψ Transitions
First Observation of $\psi(3770) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi$
Two Photon Width of χ_{c2}
Hadronic decays of the $\psi(2S)$

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1. Charmonium results from the $\psi(2S)$ and the $\psi(3770)$ [2]

The focus of the current CLEO-c program is on high precision measurements of charm physics, both open charm and charmonium bound states, from data taken at the $\psi(3770)$, $\psi(2S)$ and above $D_s\bar{D}_s$ threshold [1]. In addition the previous detector,CLEO III, accumulated data at the $\psi(2S)$. The results presented in this paper come from 5.85 pb^{-1} taken at the $\psi(2S)$, 20.46 pb^{-1} of continuum taken 50 MeV below the $\psi(2S)$ and 281pb^{-1} at the $\psi(3770)$.This paper summarizes the results and detailed description of each analysis can be found in the references.

1.1 Observation of the $h_c(^1P_1)$ [3]

The $h_c(^1P_1)$ state of charmonium has been observed in the isospin-violating reaction

$$e^+e^- \to \psi(2S) \to \pi^0 h_c \, , \, h_c \to \gamma\eta_c \, , \, \pi^0 \to \gamma\gamma. \qquad (1.1)$$

in which the η_c decays are measured exclusively or inclusively. In the exclusive analysis, η_c are reconstructed in seven channels: $K^0_S K^\pm\pi^\mp$, $K^0_L K^\pm\pi^\mp$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^0$, $\pi^+\pi^-\eta(\to\gamma\gamma)$, and $\pi^+\pi^-\eta(\to\pi^+\pi^-\pi^0)$. The sum of the branching fractions is $(9.7\pm2.7)\%$ [4]. These measurements allow a precise determination of the mass of h_c and the branching fraction product $\mathcal{B}_\psi\mathcal{B}_h$, where $\mathcal{B}_\psi \equiv \mathcal{B}(\psi(2S)\to\pi^0 h_c)$ and $B_h \equiv \mathcal{B}(h_c\to\gamma\eta_c)$. The results are combined to obtain $M(h_c) = 3524.4\pm0.6\pm0.4$ MeV and $\mathcal{B}(\psi(2S)\to\pi^0 h_c)\times\mathcal{B}(h_c\to\gamma\eta_c) = (4.0\pm0.8\pm0.7)\times10^{-4}$. and the hyperfine splitting is:

$$\Delta M_{hf}(\langle M(^3P_J)\rangle - M(^1P_1)) = +1.0\pm0.6\pm0.4\,\mathrm{MeV}.$$

The combined result for $M(h_c)$ is consistent with the spin-weighted average of the χ_{cJ} states.

1.2 Branching fractions for $\mathcal{B}(J/\psi\to e^+e^-)$ and $\mathcal{B}(J/\psi\to\mu^+\mu^-)$ [5]

The measurements of $\mathcal{B}(J/\psi\to e^+e^-)$ and $\mathcal{B}(J/\psi\to\mu^+\mu^-)$ are performed using the decay $\psi(2S)\to\pi^+\pi^- J/\psi$. The experimental procedure is straightforward and consists of determining the ratios of the numbers of exclusive $J/\psi\to\ell^+\ell^-$ decays for $\ell = e$ and μ, $N_{e^+e^-}$ and $N_{\mu^+\mu^-}$, to the number of inclusive $J/\psi\to X$ decays, N_X, where X means all final states. We obtain $\mathcal{B}(J/\psi\to e^+e^-) = (5.945\pm0.067\pm0.042)\%$ and $\mathcal{B}(J/\psi\to\mu^+\mu^-) = (5.960\pm0.065\pm0.050)\%$, leading to an average of $\mathcal{B}(J/\psi\to\ell^+\ell^-) = (5.953\pm0.056\pm0.042)\%$ and a ratio of $\mathcal{B}(J/\psi\to e^+e^-)/\mathcal{B}(J/\psi\to\mu^+\mu^-) = (99.7\pm1.2\pm0.6)\%$, all consistent with, but more precise than, previous measurements.

1.3 Observation of $\psi(3770)\to\pi\pi J/\psi$ [6]

Using the decays $\psi(3770)\to XJ/\psi$, $X = \pi^+\pi^-$ (13σ significance) and $\pi^0\pi^0$ (3.8σ) the following branching fractions are obtained: $\mathcal{B}(\psi(3770)\to\pi^+\pi^- J/\psi) = (214\pm25\pm22)\times10^{-5}$ and $\mathcal{B}(\psi(3770)\to\pi^0\pi^0 J/\psi) = (97\pm35\pm20)\times10^{-5}$. The radiative return process $e^+e^-\to\gamma\psi(2S)$ populates the same event sample and is used to measure $\Gamma_{ee}[\psi(2S)] = (2125\pm26\pm82)$ eV.

1.4 Branching Fractions for $\psi(2S)$-to-J/ψ Transitions [9]

New measurements have been made of the inclusive and exclusive branching fractions for $\psi(2S)$. which are either the most precise measurements to date or the first direct measurements. These results are shown in Table 1.

Table 1: For each mode: The detection efficiency, ϵ, in percent; the numbers of events found in the $\psi(2S)$ and continuum samples, $N_{\psi(2S)}$ and $N_{\rm cont}$; the number of $\psi(2S)$ related background events, $N_{\rm bgd}$; the branching fraction in percent and its ratio to $\mathcal{B}_{XJ/\psi}$ and $\mathcal{B}_{\pi^+\pi^- J/\psi}$, also in percent.

Channel	ϵ	$N_{\psi(2S)}$	$N_{\rm cont}$	$N_{\rm bgd}$	$\mathcal{B}$	$\mathcal{B}/\mathcal{B}_{XJ/\psi}$	$\mathcal{B}/\mathcal{B}_{\pi^+\pi^- J/\psi}$
$\pi^+\pi^- J/\psi$	49.3	60344	221	113	$33.54 \pm 0.14 \pm 1.10$	$56.37 \pm 0.27 \pm 0.46$	
$\pi^0\pi^0 J/\psi$	22.2	13399	67	115	$16.52 \pm 0.14 \pm 0.58$	$27.76 \pm 0.25 \pm 0.43$	$49.24 \pm 0.47 \pm 0.86$
$\eta J/\psi$	22.6	2793	17	116	$3.25 \pm 0.06 \pm 0.11$	$5.46 \pm 0.10 \pm 0.07$	$9.68 \pm 0.19 \pm 0.13$
$\eta(\to \gamma\gamma) J/\psi$	16.9	2065	14	103	$3.21 \pm 0.07 \pm 0.11$	$5.39 \pm 0.12 \pm 0.06$	$9.56 \pm 0.21 \pm 0.14$
$\eta(\to \pi^+\pi^-\pi^0) J/\psi$	5.8	728	3	13	$3.39 \pm 0.13 \pm 0.13$	$5.70 \pm 0.21 \pm 0.13$	$10.10 \pm 0.38 \pm 0.22$
$\pi^0 J/\psi$	13.9	88	3	20	$0.13 \pm 0.01 \pm 0.01$	$0.22 \pm 0.02 \pm 0.01$	$0.39 \pm 0.04 \pm 0.01$
$\gamma\chi_{c0} \to \gamma\gamma J/\psi$	23.4	172	20	17	$0.18 \pm 0.01 \pm 0.02$	$0.31 \pm 0.02 \pm 0.03$	$0.55 \pm 0.04 \pm 0.06$
$\gamma\chi_{c1} \to \gamma\gamma J/\psi$	30.6	3688	46	21	$3.44 \pm 0.06 \pm 0.13$	$5.77 \pm 0.10 \pm 0.12$	$10.24 \pm 0.17 \pm 0.23$
$\gamma\chi_{c2} \to \gamma\gamma J/\psi$	28.6	1915	56	62	$1.85 \pm 0.04 \pm 0.07$	$3.11 \pm 0.07 \pm 0.07$	$5.52 \pm 0.13 \pm 0.13$
XJ/ψ	65.3	151138	37916	123	$59.50 \pm 0.15 \pm 1.90$		

1.5 First Observation of $\psi(3770) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi$ [10]

The non-$D\bar{D}$ decay $\psi(3770) \to \gamma\chi_{c1}$ is observed. The two-photon cascades to J/ψ and $J/\psi \to \ell^+\ell^-$ are analyzed and the results are: $\sigma(e^+e^- \to \psi(3770)) \times \mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (20.4 \pm 3.7 \pm 2.4)$ pb and branching fraction $\mathcal{B}(\psi(3770) \to \gamma\chi_{c1}) = (3.2 \pm 0.6 \pm 0.4) \times 10^{-3}$. The 90% C.L. upper limits for the transition to χ_{c2} (χ_{c0}) : $\sigma \times \mathcal{B} < 10.8$ pb (< 295 pb) and $\mathcal{B} < 1.7 \times 10^{-3}$ ($< 46 \times 10^{-3}$).

1.6 Two Photon Width of χ_{c2} [11]

A new measurement has been made of the two-photon width of χ_{c2} using reaction

$$e^+e^- \to e^+e^-(\gamma\gamma)\ ,\ \gamma\gamma \to \chi_{c2} \to \gamma J/\psi \to \gamma l^+l^-. \tag{1.2}$$

The results are $\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to \gamma J/\psi)\mathcal{B}(J/\psi \to e^+e^- + \mu^+\mu^-) = 13.2 \pm 1.4(\mathrm{stat}) \pm 1.1(\mathrm{syst})$ eV, and $\Gamma_{\gamma\gamma}(\chi_{c2}) = 559 \pm 57(\mathrm{stat}) \pm 48(\mathrm{syst}) \pm 36(\mathrm{br})$ eV. This result is in excellent agreement with the result of two-photon fusion measurement by Belle [7] and also the $\bar{p}p \to \chi_{c2} \to \gamma\gamma$ measurement [8], when they are both reevaluated using the recent CLEO result for the radiative decay $\chi_{c2} \to \gamma J/\psi$.

1.7 Hadronic decays of the $\psi(2S)$ [12]

The states J/ψ and $\psi(2S)$ are non-relativistic bound states of a charm and an anti-charm quark. In perturbative QCD the decays of these states are expected to be dominated by the annihilation of the constituent $c\bar{c}$ into three gluons or a virtual photon. The partial width for the decays into an exclusive hadronic state h is 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 [4]. 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 ratios are related by:

$$Q_h = \frac{\mathcal{B}(\psi(2S) \to h)}{\mathcal{B}(J/\psi \to h)} \approx \frac{\mathcal{B}(\psi(2S) \to \ell^+\ell^-)}{\mathcal{B}(J/\psi \to \ell^+\ell^-)} = (12.7 \pm 0.5)\%, \tag{1.3}$$

where $\mathcal{B}$ denotes a branching fraction, and the leptonic branching fractions are taken from the Particle Data Group (PDG) [4]. This relation is sometimes called "the 12% rule". The results for a wide variety of mesonic and baronic decays with and without strange particles are shown in tables 2 and 3.

Table 2: For each final state h the following quantities are given: the decay mode, the number of events attributable to $\psi(2S)$ decay, N_S, the average efficiency, ϵ; the absolute branching fraction with statistical (68% C.L.) and systematic errors; previous branching fraction measurements from the PDG [4], and the Q_h value. For $\eta 3\pi$, the two decays modes $\eta 3\pi(\eta \to \gamma\gamma)$ and $\eta 3\pi(\eta \to 3\pi)$ are combined on line $\eta 3\pi$.

mode h	N_S	ε	$\mathcal{B}(\psi(2S) \to h)$ (units of 10^{-4})	$\mathcal{B}$ (PDG) (units of 10^{-4})	Q_h (%)
$2(\pi^+\pi^-)$	308.0	0.4507	2.2±0.2±0.2	4.50±1.00	5.55±1.53
$\rho\pi^+\pi^-$	285.5	0.4679	2.0±0.2±0.4	4.20±1.50	-
$2(\pi^+\pi^-)\pi^0$	1702.6	0.2115	26.1±0.7±3.0	30.00±8.00	7.76±1.10
$\eta\pi^+\pi^-$	7.2	0.0416	< 1.6	-	-
$\omega\pi^+\pi^-$	391.0	0.1553	8.2±0.5±0.7	4.80±0.90	11.35±1.94
$\eta 3\pi(\eta \to \gamma\gamma)$	201.7	0.0639	10.3±0.8±1.4	-	-
$\eta 3\pi(\eta \to 3\pi)$	50.0	0.0199	8.1±1.4±1.6	-	-
$\eta 3\pi$			9.5±0.7±1.5	-	-
$\eta' 3\pi$	12.8	0.0092	4.5±1.6±1.3	-	-
$K^+K^-\pi^+\pi^-$	817.2	0.3742	7.1±0.3±0.4	16.00±4.00	9.85±3.23
ρK^+K^-	223.8	0.3361	2.2±0.2±0.4	-	-
$\phi\pi^+\pi^-$	47.6	0.1744	0.9±0.2±0.1	1.50±0.28	11.07±3.30
$K^+K^-\pi^+\pi^-\pi^0$	711.6	0.1818	12.7±0.5±1.0	-	10.59±2.81
ηK^+K^-	4.3	0.0354	< 1.3	-	-
ωK^+K^-	76.8	0.1288	1.9±0.3±0.3	1.50±0.40	10.19±2.96
$2(K^+K^-)$	59.2	0.3118	0.6±0.1±0.1	-	6.71±2.74
ϕK^+K^-	36.8	0.1511	0.8±0.2±0.1	0.60±0.22	5.14±1.53
$2(K^+K^-)\pi^0$	44.7	0.1339	1.1±0.2±0.2	-	-
$p\bar{p}\pi^+\pi^-$	904.5	0.4943	5.9±0.2±0.4	8.00±2.00	9.90±1.16
$\rho p\bar{p}$	61.1	0.4119	0.5±0.1±0.2	-	-
$p\bar{p}\pi^+\pi^-\pi^0$	434.9	0.1921	7.3±0.4±0.6	-	18.70±5.80
$\eta p\bar{p}$	9.8	0.0399	0.8±0.3±0.3	-	3.80±2.09
$\omega p\bar{p}$	21.2	0.1129	0.6±0.2±0.2	0.80±0.32	4.69±2.22
$p\bar{p}K^+K^-$	30.1	0.3671	0.3±0.1±0.0	-	-
$\phi p\bar{p}$	4.3	0.1732	< 0.24	< 0.26	-
$\Lambda\bar{\Lambda}\pi^+\pi^-$	73.4	0.0844	2.8±0.4±0.5	-	-
$\Lambda\bar{p}K^+$	74.0	0.2472	1.0±0.1±0.1	-	10.92±2.93
$\Lambda\bar{p}K^+\pi^+\pi^-$	45.8	0.0847	1.8±0.3±0.3	-	-

Table 3: Branching ratios of $\psi(2S)$ decaying to baryon-antibaryon pairs. The last column shows the background subtracted continuum cross-section..

Modes	$S_{\psi(2S)}$	$B_{\psi(2S)}$	$f_S \cdot B_c$	B_{xf}
ϵ	$\mathcal{B}(10^{-4})$	Q(%)	$\sigma_{cont}(pb)$	
$p\overline{p}$	66.6%	2.87±0.12±0.15	13.6±1.1	1.5±0.37±0.13
$\Lambda\overline{\Lambda}$	20.1%	3.28±0.23±0.25	25.2±3.5	<2.0 @90 CL
$\Sigma^+\overline{\Sigma^+}$	4.1%	2.57±0.44±0.68	-	-
$\Sigma^0\overline{\Sigma^0}$	7.2%	2.63±0.35±0.21	20.7±4.2	-
$\Xi^-\overline{\Xi^-}$	8.6%	2.38±0.30±0.21	13.2±2.2	<3.5 @90 CL
$\Xi^0\overline{\Xi^0}$	2.4%	2.75±0.64±0.61		<14 @90 CL
$\Xi^{*0}\overline{\Xi^{*0}}$	0.6%	$0.72^{+1.48}_{-0.62} \pm 0.10$ (<3.2 @90 CL)	-	-
$\Omega^-\overline{\Omega^-}$	1.9%	$0.70^{+0.55}_{-0.33} \pm 0.10$ (<1.6 @90 CL)	-	-

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