Charmonium at CLEO-c

David H Miller
Purdue University, West Lafayette, USA
E-mail: miller@physics.purdue.edu

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 $B(J/\psi \rightarrow e^+e^-)$ and $B(J/\psi \rightarrow \mu^+\mu^-)$
Observation of $\psi(3770) \rightarrow \pi\pi J/\psi$ and Measurement of $\Gamma_{ee}[\psi(2S)]$
Branching Fractions for $\psi(2S)$-to-$J/\psi$ Transitions
First Observation of $\psi(3770) \rightarrow \gamma \chi_{c1} \rightarrow \gamma \gamma J/\psi$
Two Photon Width of $\chi_{c2}$
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 $5.85 \text{ pb}^{-1}$ taken at the $\psi(2S)$, $20.46 \text{ pb}^{-1}$ of continuum taken 50 MeV below the $\psi(2S)$ and $281 \text{ pb}^{-1}$ 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

$$e^+e^- \rightarrow \psi(2S) \rightarrow \pi^0 h_c, \quad h_c \rightarrow \gamma \eta_c, \quad \pi^0 \rightarrow \gamma \gamma.$$  \hspace{1cm} (1.1)

in which the $\eta_c$ decays are measured exclusively or inclusively. In the exclusive analysis, $\eta_c$ are reconstructed in seven channels: $K^0_S K^+\pi^-$, $K^0_L K^+\pi^-$, $K^+K^-\pi^+$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^-$, $\pi^+\pi^-\eta(\rightarrow \gamma \gamma)$, and $\pi^+\pi^-\eta(\rightarrow \pi^+\pi^-\pi^0)$. The sum of the branching fractions is $(9.7 \pm 2.7)\%$ [4]. These measurements allow a precise determination of the mass of $h_c$ and the branching fraction product $B_\psi B_h$, where $B_\psi \equiv B(\psi(2S) \rightarrow \pi^0 h_c)$ and $B_h \equiv B(h_c \rightarrow \gamma \eta_c)$. The results are combined to obtain $M(h_c) = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}$ and $B(\psi(2S) \rightarrow \pi^0 h_c) \times B(h_c \rightarrow \gamma \eta_c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}$. and the hyperfine splitting is:

$$\Delta m_{h_c}(M(3P_3) - M(1P_1)) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}.$$  

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

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

The measurements of $B(J/\psi \rightarrow e^+e^-)$ and $B(J/\psi \rightarrow \mu^+\mu^-)$ are performed using the decay $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$. The experimental procedure is straightforward and consists of determining the ratios of the numbers of exclusive $J/\psi \rightarrow \ell^+\ell^-$ decays for $\ell = e$ and $\mu$, $N_{e^+e^-}$ and $N_{\mu^+\mu^-}$, to the number of inclusive $J/\psi \rightarrow X$ decays, $N_X$, where $X$ means all final states. We obtain $B(J/\psi \rightarrow e^+e^-) = (5.945 \pm 0.067 \pm 0.042)\%$ and $B(J/\psi \rightarrow \mu^+\mu^-) = (5.960 \pm 0.065 \pm 0.050)\%$, leading to an average of $B(J/\psi \rightarrow \ell^+\ell^-) = (5.953 \pm 0.056 \pm 0.042)\%$ and a ratio of $B(J/\psi \rightarrow e^+e^-)/B(J/\psi \rightarrow \mu^+\mu^-) = (99.7 \pm 1.2 \pm 0.6)\%$, all consistent with, but more precise than, previous measurements.

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

Using the decays $\psi(3770) \rightarrow X J/\psi$, $X = \pi^+\pi^-$ (13σ significance) and $\pi^0\pi^0$ (3.8σ) the following branching fractions are obtained: $B(\psi(3770) \rightarrow \pi^+\pi^- J/\psi) = (214 \pm 25 \pm 22) \times 10^{-5}$ and $B(\psi(3770) \rightarrow \pi^0\pi^0 J/\psi) = (97 \pm 35 \pm 20) \times 10^{-5}$. The radiative return process $e^+e^- \rightarrow \gamma \psi(2S)$ populates the same event sample and is used to measure $\Gamma_{ee}[\psi(2S)] = (2125 \pm 26 \pm 82) \text{ eV}$.

1.4 Branching Fractions for $\psi(2S)$-to-$J/\psi$ 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.
The C.L. upper limits for the transition to $\pi^+\pi^- J/\psi$. The results are surement [8], when they are both reevaluated using the recent CLEO result for the radiative decay of the constituent quark. In perturbative QCD the decays of these states are expected to be dominated by the annihilation of the constituent $e\bar{e}$ 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 $e\bar{e}$ wave function overlap at zero quark separation, which is well determined from the leptonic width [4]. Since the strong coupling constant, $\alpha_s$, is not very different at the $J/\psi$ and $\psi(2S)$ masses, it is expected that for any state $h$ the $J/\psi$ and $\psi(2S)$ branching ratios are related by:

$$Q_h = \frac{B(\psi(2S) \rightarrow h)}{B(J/\psi \rightarrow h)} \approx \frac{B(\psi(2S) \rightarrow \ell^+\ell^-)}{B(J/\psi \rightarrow \ell^+\ell^-)} = (12.7 \pm 0.5)\%,$$  \hspace{1cm} (1.3)
where $B$ 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, $\varepsilon$; 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 decay modes $\eta 3\pi (\eta \to \gamma \gamma)$ and $\eta 3\pi (\eta \to 3\pi)$ are combined on line $\eta 3\pi$.

| mode                  | $h$      | $N_s$     | $\varepsilon$ | $B(\psi(2S) \to h)$ (units of $10^{-4}$) | $B$ (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     | 0.4697        | 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 |
| $\eta \pi^+\pi^-$     |          | 72        | 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        | 0.0199        | 8.1±1.4±1.6                              | -                             | -         |
| $\eta 3\pi$           |          | 749.0     | 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 |
| $\phi K^+K^-$          |          | 223.8     | 0.3361        | 2.2±0.2±0.4                              | -                             | -         |
| $K^+K^-\pi^+\pi^-\pi^0$ |         | 47.6      | 0.1744        | 0.9±0.2±0.1                              | 1.50±0.28                     | 11.07±3.30|
| $\eta K^+K^-$         |          | 711.6     | 0.1818        | 12.7±0.5±1.0                             | -                             | 10.59±2.81|
| $\omega K^+K^-$       |          | 47.8      | 0.1288        | $<1.3$                                   | -                             | -         |
| $2(K^+K^-)$            |          | 59.2      | 0.3118        | 0.6±0.1±0.1                              | -                             | 6.71±2.74 |
| $\phi K^+K^-$         |          | 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 |
| $p\bar{p}$            |          | 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     | $S_{\psi(2S)}$ | $B_{\psi(2S)}$ | $Q(\%)$ | $f_S \cdot B_c$ | $B_{c f}$ |
|-----------|----------------|----------------|---------|-----------------|---------|
| $\psi\overline{\psi}$ | 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 |
| $\Xi^{-}\overline{\Xi}^+$ | 0.6% | 0.72$^{+1.48}_{-0.62}$ ± 0.10 | - |
| ($<3.2 @90 CL$) | | | | |
| $\Omega^{-}\overline{\Omega}$ | 1.9% | 0.70$^{+0.55}_{-0.33}$ ± 0.10 | - |
| ($<1.6 @90 CL$) | | | | |

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