Charmonium Review

Frederick A. Harris

aDept. of Physics and Astronomy,
The University of Hawaii,
Honolulu, HI 96822, USA

During the last few years there has been a renaissance in charm and charmonium spectroscopy with higher precision measurements at the $\psi$ and $\psi(3770)$ coming from BESII and CLEOc and many new discoveries coming from B-factories. In this paper, I will review the status of $\psi(3770)$ and below.

1. Introduction

An admonishment says “May you live in exciting times”. It turns out that for charm and charmonium spectroscopy, we are. Only 10 $CC$ resonances were discovered from 1974 to 1977; none were discovered from 1978 to 2002. However from 2002 to 2005, seven new $CC$ resonances were discovered by Belle, BaBar, CLEOc, CDF, and D0. I will review the $\psi(3770)$ and below, where there has been much progress from BES, CLEOc, B-factories, etc. Brian Petersen will cover the new resonances were discovered from 1978 to 2002. However from 1974 to 1977; none were discovered from 1978 to 2002. However from 2002 to 2005, seven new $CC$ resonances were discovered by Belle, BaBar, CLEOc, CDF, and D0. I will review the $\psi(3770)$ and below, where there has been much progress from BES, CLEOc, B-factories, etc. Brian Petersen will cover the new states: X, Y, Z, etc.

2. Old but new states

2.1. $\eta_c'$

Prior to 2002, there was an unconfirmed candidate for the $\eta_c$ by the Crystal Ball experiment [1] at a mass of $3594 \pm 5$ MeV/$c^2$. In 2002, Belle observed clear peaks in the $X$ mass distribution in $B \rightarrow KX, X \rightarrow K_SK\pi$ at the $\eta_c$, the $J/\psi$, and at a mass of $3654 \pm 10$ MeV/$c^2$ [2]. CLEO [3] and BaBar [4] quickly confirmed the higher mass value in $\gamma \gamma \rightarrow K_SK\pi$ with mass measurements of $3642$ MeV/$c^2$ and $3633$ MeV/$c^2$, respectively. Belle also found a peak in $e^+e^- \rightarrow J/\psi X$ at $M_X = 3630$ MeV/$c^2$ [5].

Combining the results, excluding Crystal Ball, yields a mass of $M_{avg} = 3637 \pm 4$ MeV/$c^2$, and hyperfine splittings of $\Delta M(1S) = M_{J/\psi} - M_{\eta_c} = 117 \pm 1$ MeV/$c^2$ and $\Delta M(2S) = M_{\psi(2S)} - M_{\eta_c} = 49 \pm 4$ MeV/$c^2$. The higher mass is more consistent with lattice calculations (LQCD) and potential models [6].

2.2. $h_c$

The $h_c$ or $^1P_1CC$ state has $J^{PC} = 1^{+-}$. This state is important to learn more about the hyperfine (spin-spin) interaction of P wave states. It is expected to have a mass near the center of gravity of the $3P_1$ states $m_{h_c} = m_{c,offg.} = 3525.31 \pm 0.07$ MeV/$c^2$, to be narrow ($\Gamma < 1$ MeV/$c^2$), and to decay to $\eta_c\gamma$.

In 1992, E760 using 16 pb$^{-1}$ of $p\bar{p}$ data observed a structure near 3526 MeV/$c^2$ in $p\bar{p} \rightarrow J/\psi\pi^0$ [7]. The successor experiment E835 using 113 pb$^{-1}$ of data was unable to confirm this peak! However E835 also searched for $p\bar{p} \rightarrow h_c \rightarrow \gamma\eta_c, \eta_c \rightarrow \gamma\gamma$ and found a signal at $M = 3525.8 \pm 0.2 \pm 0.2$ MeV/$c^2$ for $\Gamma = 0.5$ to 1 MeV/$c^2$ [8].

CLEOc quickly substantiated this with evidence for $h_c$ production from $e^+e^- \rightarrow \psi(2S) \rightarrow \pi^0h_c \rightarrow 3\gamma\eta_c$ at CESR [9] with a sample of $3 \times 10^6 \psi(2S)$ events. Using an inclusive analysis where they measured the mass recoiling from the $\pi^0$, they obtained $M(h_c) = 3524.9 \pm 0.7 \pm 0.4$ MeV/$c^2$. From an exclusive analysis, where they measured $h_c$ decays to $K.SK\pi, KL\pi\pi, K\pi\pi\pi$, and $\pi\pi\eta$, they obtained $M(h_c) = 3523.6 \pm 0.9 \pm 0.5$ MeV/$c^2$. The consistency between the two measurements was good giving an overall $M(h_c) = 3524.4 \pm 0.6 \pm 0.4$ MeV/$c^2$. 

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and a product branching fraction \( B(\psi(2S) \rightarrow \pi^0 h_C) B(h_C \rightarrow \gamma \eta_C) = (4.0 \pm 0.6 \pm 0.4) \times 10^{-4} \), in agreement with a pQCD prediction of \( B = (1.9 - 5.8) \times 10^{-4} \) [10]. The mass splitting \( \Delta M_{hf} = < M(3P_J) > - M(\ell P_1) = 1.0 \pm 0.6 \pm 0.4 \text{MeV}/c^2 \) agrees with expectations \((\approx 0)\), but the sign and difference are not yet well enough determined to provide a real test.

Now the charmonium family below the \( \psi(3770) \) is complete, and the mass values can be used in potential models to predict masses of higher states.

### 3. \( \psi(2S) \) radiative and hadronic transitions

#### 3.1. \( \psi(2S) \) radiative transitions

CLEOc with its CsI calorimeter \( (\Delta E/E = 5.0\% \text{ at } 100 \text{ MeV}) \) allows a good measurement of the inclusive \( \gamma \) spectrum. Using \( 3 \times 10^6 \psi(2S) \) events, they measured \( \psi(2S) \rightarrow \gamma \chi_{cJ} \) \( (E1 \text{ transition}) \) and \( \psi(2S) \rightarrow \gamma \eta \) \( (M1 \text{ transition}) \) [11]. Results are shown in Table 1. Note the big change from PDG04 [12] for \( \psi(2S) \rightarrow \gamma \chi_{c2} \); this will affect \( \chi_{c2} \) branching fractions! The combined transistions, \( \psi(2S) \rightarrow \gamma \chi_{cJ}, \psi(2S) \rightarrow \gamma \chi_{cJ} \rightarrow \gamma J/\psi, J/\psi \rightarrow \mu^+ \mu^-, e^+ e^- \) have also been measured by BESII [13] and CLEOc [14], and the product branching fractions are shown in Table 2. Branching fractions for \( \chi_{cJ} \rightarrow \gamma J/\psi \) are given in Table 3. BESII is calculated using the CLEOc branching fractions for \( \psi(2S) \rightarrow \gamma \chi_{cJ} \) from Table 1 and the BESII results in Table 2.

| Decay | PDG04 (%) | CLEOc [%] |
|-------|-----------|-----------|
| \( \psi(2S) \rightarrow \gamma \chi_{c0} \) | 8.6 ± 0.7 | 9.22 ± 0.47 |
| \( \psi(2S) \rightarrow \gamma \chi_{c1} \) | 8.4 ± 0.8 | 9.07 ± 0.55 |
| \( \psi(2S) \rightarrow \gamma \chi_{c2} \) | 6.4 ± 0.6 | 9.33 ± 0.63 |
| \( \psi(2S) \rightarrow \gamma \eta_c \) | 0.28 ± 0.08 | 0.32 ± 0.07 |

#### 3.2. \( \psi(2S) \) hadronic transitions

The \( \psi(2S) \rightarrow \gamma \chi_{cJ}, \psi(2S) \rightarrow \gamma J/\psi, J/\psi \rightarrow \mu^+ \mu^-, e^+ e^- \) decays can also be used to measure the processes \( \psi(2S) \rightarrow \pi^0 J/\psi \) and \( \pi^0 J/\psi \). These and \( \psi(2S) \rightarrow \pi \pi J/\psi \) results are shown in Table 4 [13–16]. Note that isospin is conserved in the CLEOc \( \pi^+ \pi^- J/\psi \) to \( \pi^0 \pi^0 J/\psi \) ratio. Using CLEOc + BESII, we determine

\[
R = \frac{\Gamma(\psi(2S) \rightarrow \pi^0 J/\psi)}{\Gamma(\psi(2S) \rightarrow \eta J/\psi)} = 0.042 \pm 0.004
\]

\( R \) is much larger than expected using PCAC [17] and may indicate mixing between \( \pi^0, \eta, \) and \( \eta' \) [18].

### 4. Hadronic decays of charmonium

Decays of \( J/\psi, \eta_c, \chi_{cJ}, \) and \( \psi(2S) \) with definite \( J \) and \( I \) are ideal to study meson and baryon spectroscopy. In particular, radiative decays of \( J/\psi \) are ideal for glueball searches [19]. As an example, Fig. 1 shows Dalitz plots, projections, and the result of a partial wave analysis fit for the decay \( \chi_{c0} \rightarrow \pi^+ \pi^- K^+ K^- \). The Dalitz plots show rich structure, and these decays are ideal for studying scalar states [20].

The pQCD 12% rule [21,22] states that single \( J/\psi \) and \( \psi(2S) \) hadronic decays to final state \( X \) proceed via the annihilation of the \( CC \) pair into three gluons or a virtual photon, and the decay

| Decay | PDG04 (%) | BESII (%) | CLEOc [14] (%) |
|-------|-----------|-----------|----------------|
| \( \chi_{c0} \) | 1.18 ± 0.14 | - | 2.0 ± 0.3 |
| \( \chi_{c1} \) | 31.6 ± 3.3 | 31.0 ± 3.2 | 37.9 ± 2.2 |
| \( \chi_{c2} \) | 20.2 ± 1.7 | 17.4 ± 1.8 | 19.9 ± 1.3 |

Table 2

Product branching fractions: (BESII [13], CLEOc [14])

Table 3

\( \chi_{cJ} \rightarrow \gamma J/\psi \) branching fractions. BESII calculated using the BES results of Table 2 and the CLEOc results of Table 1.
Table 4
Hadronic transitions: $\psi(2S)$ Branching fractions.

| Decay          | PDG04        | BES            | CLEOc [14] |
|----------------|--------------|----------------|------------|
| $\pi^+ J/\psi$ | $0.10 \pm 0.02\%$ | $0.14 \pm 0.01 \pm 0.01\%$ | $0.13 \pm 0.01 \pm 0.01\%$ |
| $\eta J/\psi$  | $3.16 \pm 0.22\%$ | $2.98 \pm 0.09 \pm 0.23\%$ | $3.25 \pm 0.06 \pm 0.11\%$ |
| $\pi^+\pi^- J/\psi$ | $31.7 \pm 1.1\%$ | $32.3 \pm 1.4\%$ | $33.54 \pm 0.14 \pm 1.10\%$ |
| $\pi^0\pi^0 J/\psi$ | $18.8 \pm 1.2\%$ | $-$ | $16.52 \pm 0.14 \pm 0.58\%$ |
| $\pi^0\pi^- J/\psi$ | $1.69 \pm 0.12$ | $1.75 \pm 0.03 \pm 0.08$ | $2.03 \pm 0.04$ |

Figure 1. Dalitz plots, projections, and the result of a partial wave analysis fit for the decay $\chi_{c0} \rightarrow \pi^+ \pi^- K^+ K^-$. 

rate should be determined by the wave function at the origin squared ($|\psi(0)|^2$), which is measured by the decay rate into leptons, and therefore 

$$Q_h = \frac{B(\psi(2S) \rightarrow X)}{B(J/\psi \rightarrow X)} = \frac{B(\psi(2S) \rightarrow e^+ e^-)}{B(J/\psi \rightarrow e^+ e^-)} \sim 12\%$$

MARK-II found that a number of decays obeyed this rule but that it was badly violated for $VP$ decays to $\rho \pi$ and $K^* K$, the so called $\rho \pi$ puzzle [23]. The suppression was confirmed by BESI with higher sensitivity, and BESI also found the VT mode to be suppressed [24].

There have many attempts at theoretical explanations [25]. Together BESII, CLEOc, and BaBar have all made many new $J/\psi$ and $\psi(2S)$ branching fraction measurements [26]. A summary of a few new $Q_h$ values from BESII is shown in Fig. 2. There is no obvious rule to categorize the suppressed, the enhanced, and the normal decay modes of the $J/\psi$ and $\psi(2S)$. Hopefully the many new measurements will help in understanding this problem.

5. $\psi(3770)$

The $\psi(3770)$ is just above $D \bar{D}$ threshold so it decays mostly to correlated $D \bar{D}$ pairs. Its importance for charm physics has been stressed by many speakers. BESII has 34 pb$^{-1}$ at and around the $\psi(3770)$, and CLEOc has 281 pb$^{-1}$ at the $\psi(3770)$. These samples not only allow precision charm decay measurements, they also better our understanding of the $\psi(3770)$.

The $\psi(3770)$ is thought to be a mixture of $S$ and $D$ wave (mostly $D$), but since the $\psi(3770)$ is above DD-bar threshold it is expected to decay mostly to $D \bar{D}$. BESII found evidence (see Fig. 3) for non $D \bar{D}$ decay in
ψ(3770) → π⁺π⁻ J/ψ [27] with a branching fraction $B(\psi(3770) \to π⁺π⁻ J/ψ) = (0.34 \pm 0.14 \pm 0.09)\%$ and a width of $\Gamma(\psi(3770) \to π⁺π⁻ J/ψ) = (80 \pm 33 \pm 23)$ keV, to be compared to a prediction of 26 to 147 keV [10]. CLEOc with a larger data sample confirmed this with $B(\psi(3770) \to π⁺π⁻ J/ψ) = (0.189 \pm 0.020 \pm 0.020)\%$ [28].

**ψ(3770) Evidence for non DD-bar decay:**

![Figure 3. Evidence for non DD bar decay through ψ(3770) → π⁺π⁻ J/ψ by BESII and CLEOc.](image)

CLEOc has also found evidence for non DD bar decays in the hadronic transitions, $\psi(3770) \to π^0 π^0 J/ψ$ and $\psi(3770) \to η J/ψ$ [28] and in radiative decays $\psi(3770) \to γχ_{c1}[29,30]$. However, they have found that hadronic decays at the $\psi(3770)$ are mostly consistent with continuum production [31].

6. Future

We can expect further progress from B factories, BESII, and CLEOc. However, BaBar and CLEOc will stop running in 2008. BEPCII with a design luminosity of $1 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ and a brand new BESIII detector will start commissioning in summer of 2007 [32]. With B factories, CLEOc, and BESIII, the future of charm and charmonium physics is very bright.

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