Charmonium Spectroscopy Below Open Flavor Threshold

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There are 8 bound states of charmonium below the $D\bar{D}$ breakup threshold.

- Spin triplets - $J/\psi(1^3S_1)$, $\psi(2^3S_1)$, $\chi_{0,1,2}(1^3P_{0,1,2})$;
- Spin singlets - $\eta_c(1^1S_0)$, $\eta_c(2^1S_0)$, $h_c(1^1P_1)$.

Only $J/\psi$, $\psi(2S)$ can be produced directly in $e^+e^-$ annihilation.

A lot is known about these triplet states.

Spin singlet states population via radiative transitions from the vector states is either very weak ($M1$ for $\eta_c(1S)$, $\eta_c(2S)$), or C- forbidden ($h_c(1^1P_1)$).

Little is known about these singlet states.
**STATUS OF CHARMONIUM STATES**

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV) PDG07</th>
<th>Width (MeV) PDG07</th>
<th>Number of Decays (PDG) 2002</th>
<th>2004</th>
<th>2007*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>J/ψ</strong></td>
<td>3096.92(1)</td>
<td>93.4(21)(keV)</td>
<td>134</td>
<td>135</td>
<td>162</td>
</tr>
<tr>
<td><strong>ψ(2S)</strong></td>
<td>3686.09(3)</td>
<td>327(11) (keV)</td>
<td>51</td>
<td>62</td>
<td>115</td>
</tr>
<tr>
<td><strong>χc0</strong></td>
<td>3414.75(35)</td>
<td>10.4(7)</td>
<td>17</td>
<td>17</td>
<td>51</td>
</tr>
<tr>
<td><strong>χc1</strong></td>
<td>3510.66(7)</td>
<td>0.89(5)</td>
<td>12</td>
<td>13</td>
<td>35</td>
</tr>
<tr>
<td><strong>χc2</strong></td>
<td>3556.20(9)</td>
<td>2.05(12)</td>
<td>18</td>
<td>19</td>
<td>37</td>
</tr>
</tbody>
</table>

**SPIN SINGLETS**

| ηc(1S)         | 2979.8(12)       | 26.5(35)          | 20                          | 21   | 31    |
| ηc(2S)         | 3637(4)          | 14(7)             | 3                           | 4    | 4     |
| h_c(1^1P_1)    | 3525.93(27)      | <1                | 3                           | 3    | 4     |

- The 2007 PDG entries include some of the developments I am going to talk about.
- Notice the marked improvements after 2004.
Introduction cont’d.

- Charm quark has large mass (~1.5 GeV), compared to the masses of u, d, s quarks;
- Velocity of the charm quarks in hadrons is not too relativistic \((v/c)^2 \sim 0.2\);
- Strong coupling constant \(\alpha_s(m_c)\) is small \((\sim 0.3)\).

Therefore:

Charmonium spectroscopy is a good testing ground for the theories of strong interactions:
- QCD in both perturbative and nonperturbative regimes;
- QCD inspired purely phenomenological potential models;
- NRQCD and Lattice QCD.

I will review some new and recent experimental results on charmonium spectroscopy below open flavor threshold.
Observation of $\eta_c(2S)$

- Prior to 2002 there were several unsuccessful attempts to identify $\eta_c(2S)$ in $p\bar{p}$, $\gamma\gamma$ fusion, inclusive photon analysis.

- Most potential model calculations predicted $M(\eta_c(2S)) = 3594 - 3626$ (MeV).

- It is important to identify the singlets in order to determine the hyperfine or spin-spin interaction, which is responsible for singlet-triplet splitting of $q\bar{q}$ states.

- Identification of $\eta_c(2S)$ is important to know the possible variation of spin-spin interaction from Coulombic ($J/\psi$, $\eta_c(1S)$) to Confinement ($\psi(2S)$, $\eta_c(2S)$) regions of the $q\bar{q}$ interaction.
Observation of $\eta_c(2S)$ cont’d.

Belle: 42 fb$^{-1}$ [$B \rightarrow K(K_S K \pi)$]  
BaBar: 124 fb$^{-1}$ ($e^+ e^- \rightarrow J/\psi + cc$)  
Belle: 357 fb$^{-1}$ ($e^+ e^- \rightarrow J/\psi + cc$)

CLEO II+III: 27 fb$^{-1}$ ($\gamma\gamma \rightarrow K_S K \pi$)  
BaBar: 86 fb$^{-1}$ ($\gamma\gamma \rightarrow K_S K \pi$)
**Observation of \( \eta_c(2S) \) cont’d.**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( M(\eta_c(2S)) )</th>
<th>( \Gamma(\eta_c(2S)) )</th>
<th>Events(reaction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle(2002)</td>
<td>( 3654 \pm 10 )</td>
<td>&lt; 55</td>
<td>( 39 \pm 11 ) ([B \rightarrow K(K_S K\pi)])</td>
</tr>
<tr>
<td>CLEO(2004)</td>
<td>( 3643.9 \pm 3.4 )</td>
<td>( 6.3 \pm 13.0 )</td>
<td>( 61 \pm 15 ) ((\gamma \gamma \rightarrow K_S K\pi))</td>
</tr>
<tr>
<td>BaBar(2004)</td>
<td>( 3630.8 \pm 3.5 )</td>
<td>( 17.0 \pm 8.7 )</td>
<td>( 112 \pm 24 ) ((\gamma \gamma \rightarrow K_S K\pi))</td>
</tr>
<tr>
<td>BaBar(2005)</td>
<td>( 3645.0 \pm 8.4 )</td>
<td>( 22 \pm 14 )</td>
<td>( 121 \pm 27 ) ((e^+e^- \rightarrow J/\psi + cc))</td>
</tr>
<tr>
<td>Belle(2007)</td>
<td>( 3626 \pm 8 )</td>
<td>-</td>
<td>( 311 \pm 42 ) ((e^+e^- \rightarrow J/\psi + cc))</td>
</tr>
</tbody>
</table>

Spread in \( M(\eta_c(2S)) \) is uncomfortably too large.

- The **PDG07** weighted average is \( M(\eta_c(2S)) = 3637 \pm 4 \) (MeV);
- This leads to the hyperfine splitting \( \Delta M_{hf}(2S) = 49 \pm 4 \) (MeV) \([\Delta M_{hf}(1S) = 117 \pm 1 \) (MeV)];
- Explaining large difference between \( \Delta M_{hf}(2S) \) and \( \Delta M_{hf}(1S) \) is a challenge for theorists;
- Width of \( \eta_c(2S) \) is essentially unmeasured (PDG07 value \( \Gamma(\eta_c(2S)) = 14 \pm 7 \) (MeV)). Measurement of the width is a challenge to the experimentalists.
- \( \eta_c(2S) \) decay is observed only in one decay channel, \( \eta_c(2S) \rightarrow K_S K\pi \).

A lot remains to be done about \( \eta_c(2S) \).

Attempts are being made to identify \( \eta_c(2S) \) in the decay \( \psi(2S) \rightarrow \gamma \eta_c(2S) \) from 54 \( \text{pb}^{-1} \) CLEOc \( \psi(2S) \) data. Expect news from CLEOc.
The observation and the measurement of the parameters of $h_c(1^1P_1)$ are important to determine the hyperfine splitting of P-states, which is expected from simple pQCD to be:

$$\Delta M_{hf}(1P) = M(3P_J) - M(1P_1) = 0$$

**CLEO** has analyzed data for 3.08x10^6 $\psi(2S)$ events

$$\psi(2S) \rightarrow \pi^0 h_c, \ h_c \rightarrow \gamma \eta_c$$

**Inclusive analysis:** two independent analysis, different in details of event selection. One constrained the photon energy, and the other the $\eta_c$ mass (recoil against $\pi^0\gamma$).

**Exclusive analysis:** Instead of constraining $E_\gamma$ or $M(\eta_c)$, seven known $\eta_c$ channels with a total branching fraction of $\sim 10\%$ were measured.

Results of inclusive and exclusive analysis are consistent.
CLEO observation of $h_c(1^{1}P_1)$, cont’d.

**INCLUSIVE**
Significance = 3.8σ

**EXCLUSIVE**
Significance = 5.2σ

\[
\text{Br}(\psi(2S)\rightarrow \pi^0 h_c) \times \text{Br}(h_c \rightarrow \gamma c) = (4.0 \pm 0.8 \pm 0.7) \times 10^{-4}
\]
\[
M(h_c) = (3524.4 \pm 0.6 \pm 0.4) \text{ MeV}
\]
\[
\Delta M_{hf}(1P) = M(\chi_{cJ}) - M(h_c) = (+1.0 \pm 0.6 \pm 0.4) \text{ MeV}
\]
using \( <M(\chi_{cJ})> = (3525.4 \pm 0.1) \text{ MeV} \)

Two conclusions follow:

- Simple pQCD expectation, \( \Delta M_{hf}(1P) = 0 \), is not violated;
- The magnitude and sign of \( \Delta M_{hf}(1P) \) is not yet well determined.
More on CLEO $h_c(1^1P_1)$

- CLEOc now has new 48 pb$^{-1}$ $\psi(2S)$ data (24 million $\psi(2S)$ events).

- With these data greatly improved results from both inclusive and exclusive analysis are expected.

- Preliminary analysis show that these expectations will be fully met:
  - $\sim 1000$ $h_c$ are expected in inclusive analysis;
  - $\sim 250$ $h_c$ are expected in exclusive analysis.

- These should lead to $M(h_c)$ and $\Gamma(h_c)$ determinations with uncertainties at the level of $\sim \pm 0.3$ MeV and $\sim \pm 0.5$ MeV respectively.

Monte Carlo simulations for 24 million $\psi(2S)$ based on analysis of 3 million $\psi(2S)$. 
**Data**

45 pb\(^{-1}\) of \(p\bar{p}\) annihilation scan data in the \(h_c\) region, collected by Fermilab E835 in 1997 and 2000.

**Channel**

\(pp\rightarrow h_c\rightarrow \gamma \eta_c, \eta_c\rightarrow \gamma \gamma\)

**Method**

Extract resonance parameters from a maximum-likelihood fit to the cross section curve.

\[
M(h_c) = (3525.8 \pm 0.2 \pm 0.2) \text{ MeV}
\]

\[
\Gamma(h_c) < 1 \text{ MeV}
\]

\[
\Delta M_{hf}(1P) = M(\chi_{cJ}) - M(h_c) = (-0.4 \pm 0.2 \pm 0.2) \text{ MeV}
\]

A lot remains to be done about \(h_c\). Expect news from CLEOc soon.
New Measurements of the $\psi(2S)$ Width

**Data**

1.64 pb$^{-1}$ of $\bar{p}p$ annihilation scan data in the $\psi(2S)$ region, collected by Fermilab E835 in 2000.

**Channels**

- $\bar{p}p \rightarrow e^+e^-$
- $\bar{p}p \rightarrow J/\psi + X \rightarrow e^+e^- + X$

**Advantage to measurements at $e^+e^-$ experiments**

$p$ beams with FWHM energy spreads of 0.4-0.5 MeV.

**Method**

new technique of “complementary scans”, based on precise beam revolution-frequency and orbit-length measurements.

Extract resonance parameters from a maximum-likelihood fit to the excitation curves.

Most precise measurements to date:

$$\Gamma_{\text{tot}} [(\psi(2S)] = [290 \pm 25(\text{sta}) \pm 4(\text{sys})] \text{ keV}$$

$$\Gamma_{ee} \frac{\Gamma_{pp}}{\Gamma_{\text{tot}}} = [579 \pm 38(\text{sta}) \pm 36(\text{sys})] \text{ meV}$$
Measurements of the $\psi(2S)$ Width cont'd

Data
The $e^+e^-$ annihilation scan data in the $\psi(2S)$ and $\psi(3770)$ regions, collected by BES II in 2003.

Channel
$e^+e^-\rightarrow$ hadrons

Method
Extract resonance parameters from simultaneous fit of cross section curves covering energy ranges of both $\psi(2S)$ and $\psi(3770)$ resonances.

\[ \Gamma_{ee}[(\psi(2S))] = [2.330 \pm 0.036(\text{sta}) \pm 0.110(\text{sys})] \text{ keV} \]

\[ \Gamma_{\text{tot}}[(\psi(2S))] = [331 \pm 58(\text{sta}) \pm 2(\text{sys})] \text{ keV} \]

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PDG 2006 average value is

\[ \Gamma_{\text{tot}}[(\psi(2S))] = (277 \pm 22) \text{ keV} \]

New average value including E835 and BES new results will be

\[ \Gamma_{\text{tot}}[(\psi(2S))] = (287 \pm 16) \text{ keV} \]
Measurements of the $J/\psi$ Widths

- Use 281 pb$^{-1}$ CLEOC $\psi(3770)$ data and look for radiative return events to $J/\psi$.

- Select $\mu^+\mu^-(\gamma)$ events with a $M(\mu^+\mu^-)=M(J/\psi)$.

- Resulting cross-section is proportional to $\text{Br}_{\mu\mu} \times \Gamma_{ee}(J/\psi)$.

- Divide by new CLEOC $\text{Br}_{\mu\mu}=(5.953\pm0.056\pm0.042)$% (PRD 71(2005)111103(R)) to get $\Gamma_{ee}(J/\psi)$.

- Assume lepton universality $\text{Br}_{ee}=\text{Br}_{\mu\mu}$, divide by CLEOC $\text{Br}_{\mu\mu}$ again to get $\Gamma_{\text{tot}}(J/\psi)$.

Most precise measurements to date:

$$\text{Br}_{\mu\mu} \times \Gamma_{ee}(J/\psi) = [0.3384 \pm 0.0058\,(\text{sta}) \pm 0.0071\,(\text{sys})]\text{ keV}$$

$$\Gamma_{ee}(J/\psi) = [5.68 \pm 0.11\,(\text{sta}) \pm 0.13\,(\text{sys})]\text{ keV}$$

$$\Gamma_{\text{tot}}(J/\psi) = [95.5 \pm 2.4\,(\text{sta}) \pm 2.4\,(\text{sys})]\text{ keV}$$
Measurements of $\eta_c(1S), \chi_{c0}(1P), \chi_{c2}(1P)$ in two-photon fusion processes at Belle

• Use 395 fb$^{-1}$ Belle data and look for $4\pi, 2K2\pi, 4K$ final states in two-photon fusion reactions.

• Signals of $\eta_c(1S), \chi_{c0}(1P), \chi_{c2}(1P)$ are observed.

• Measure Masses and Total Widths of $R = \eta_c(1S), \chi_{c0}(1P), \chi_{c2}(1P)$ in the channels $R \rightarrow 4\pi, 2K2\pi, 4K$.

• Measure $\Gamma_\eta \times Br$ for $\eta_c(1S), \chi_{c0}(1P), \chi_{c2}(1P)$. 
Mass and Width of $\eta_c(1S)$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>N(events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(1S)$</td>
<td>$2986.1\pm1.0\pm2.5$</td>
<td>$28.1\pm3.2\pm2.2$</td>
<td>7616±553</td>
</tr>
<tr>
<td>$\chi_{c0}(1P)$</td>
<td>$3414.2\pm0.5\pm2.3$</td>
<td>$10.6\pm1.9\pm2.6$</td>
<td>5459±319</td>
</tr>
<tr>
<td>$\chi_{c2}(1P)$</td>
<td>$3555.3\pm0.6\pm2.2$</td>
<td>-</td>
<td>2503±158</td>
</tr>
</tbody>
</table>

$M(\eta_c(1S))$ and $\Gamma(\eta_c(1S))$ are known with only ~1 MeV and ~3 MeV precision respectively.

PDG07 $\eta_c(1S)$ Mass

$M(\eta_c(1S)) = 2979.8 \pm 1.2$ (MeV)

PDG07 $\eta_c(1S)$ Width

$\Gamma(\eta_c(1S)) = 26.5 \pm 3.5$ (MeV)

Expect new results from CLEOc with its $(48+6)$ pb$^{-1}$ $\psi(2S)$ data studying the reactions $J/\psi \rightarrow \gamma \eta_c(1S)$ and $\psi(2S) \rightarrow \gamma \eta_c(1S)$.
Two photon widths of $\eta_c(1S)$, $\chi_{c2}(1P)$

$\Gamma_\gamma$ values are evaluated from measured $\Gamma_\gamma \times \text{Br}$ using Br from PDG07.
Results of $4\pi$, $2K2\pi$, $4K$ channels are combined.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\Gamma_\gamma$ (keV), Belle</th>
<th>$\Gamma_\gamma$ (keV), PDG07</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(1S)$</td>
<td>$2.46\pm{0.60}$</td>
<td>$6.7\pm{0.9}$</td>
</tr>
<tr>
<td>$\chi_{c0}(1P)$</td>
<td>$1.98\pm{0.24}$</td>
<td>$2.90\pm{0.43}$</td>
</tr>
<tr>
<td>$\chi_{c2}(1P)$</td>
<td>$0.438\pm{0.062}$</td>
<td>$0.539\pm{0.050}$</td>
</tr>
<tr>
<td>$R = \Gamma_\gamma(\chi_{c2})/\Gamma_\gamma(\chi_{c0})$</td>
<td>$0.221\pm{0.041}^*$</td>
<td>$0.186\pm{0.032}^*$</td>
</tr>
</tbody>
</table>

* These errors in the ratios are overestimated since they do not take account of correlations between the errors for the individual values.

- The ratio $R$ is an interesting quantity because it allows us to evaluate the reliability of the first order radiative corrections, which are often very large, by calculating $\alpha_s$ from them

$$R \equiv \frac{\Gamma_\gamma(\chi_{c2})}{\Gamma_\gamma(\chi_{c0})} = \frac{(4|\Psi'(0)|^2\alpha^2_{em}/m_c^4) \times (1-1.7\alpha_s)}{(15|\Psi'(0)|^2\alpha^2_{em}/m_c^4) \times (1+0.06\alpha_s)} = 0.267(1-1.76\alpha_s)$$

- The Belle value of $R=0.221\pm{0.040}$ leads to $\alpha_s=0.098\pm{0.085}$ which is obviously a gross underestimate of $\alpha_s(m_c)$, which is known to be $\sim 0.3$. This clearly illustrates that the nearly factor of two first order correction factor for $\Gamma_\gamma(\chi_{c2})$ is unreliable.
Measurement of $\Gamma_{\gamma\gamma}(\chi_{c0},\chi_{c2})$ at CLEO

- At CLEOc a measurement of $\Gamma_{\gamma\gamma}(\chi_{c0},\chi_{c2})$ has been undertaken by using data for $24 \times 10^6 \psi(2S)$. The reaction chosen is

$$\psi(2S) \rightarrow \gamma \chi_{c0,2}, \quad \chi_{c0,2} \rightarrow \gamma\gamma$$

- to take advantage of the very precisely known values of $\text{Br}[\psi(2S) \rightarrow \gamma \chi_{c0,2}]$.

- The CLEO results should be available soon by analysis of the spectra in which $\chi_{c0}$ and $\chi_{c2}$ are both excited.
Summary

- All charmonium states below open flavor threshold have now been firmly identified.

- The spectroscopy of spin-triplet states is now well in hand, but a lot still needs to be done for spin-singlet states. Masses, widths, particularly of $\eta_c(2S)$ and $h_c(1^1P_1)$ need to be better determined. Many more decay channels need to be investigated for each.

- A large number of investigations, based on the world’s largest sample of $\psi(2S)$ acquired by CLEOc, are currently in progress, and results are expected soon. These include:
  - Precision results for mass, width and branching fractions of $h_c(1^1P_1)$;
  - Results for many decay channels of $\eta_c(1S)$;
  - Results for attempt to identify $\eta_c(2S)$ in radiative decay of $\psi(2S)$;
  - Results of studies for $pp$ threshold enhancement in radiative decays of $J/\psi, \psi(2S)$;
  - Results of search for the tensor glueball, $\xi(2230)$;
  - Hadronic and radiative decays of $\psi(2S)$ and $J/\psi$;
  - Two-body and multi-body decays of $\chi_c(1P)$ states;
  - and others.