Hadronic Physics at CLEO-c

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Indiana University

(on behalf of the CLEO Collaboration)

HADRON 07 / Frascati
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The CLEO-c Detector

- 6 layer inner stereo and 47 layer stereo+axial drift chambers ($\sigma_p/p \approx 0.6\%$ at 1 GeV/c)
- Ring Imaging Cherenkov (RICH)
- CsI Calorimeter ($\sigma_E/E \approx 2.2\%$ at 1 GeV)
- 1 T solenoidal field
- Located at the Cornell Electron Storage Ring (CESR)
- $e^+e^-$ at $E_{CM} = 3.6 - 4.3$ GeV
The CLEO-c Physics Program

- Very diverse physics program includes:
  - Scans of open charm cross section from 3.97 GeV to 4.26 GeV
  - Large data samples at $E_{CM} = 3770$ MeV and $E_{CM} = 4170$ MeV for $D$ and $D_s$ physics
  - CKM driven: precision tests of LQCD through form factor measurements, precision measurements of hadronic branching fractions
  - D Dalitz Analyses: hadronic physics and CPV (P. Naik - yesterday)
  - Relatively small amount (<5%) of luminosity taken at $E_{CM}=M(\psi')$.
  - The study of our pilot sample of $3M \psi'$ decays has already produced many interesting hadronic physics results.
  - *This talk focuses on results from our new sample of ~25M $\psi'$ decays.*
The Charmonium System: An Outline

- Hadronic and Electromagnetic Decays of the $\chi_c$
- $\eta$ meson properties, in $\psi' \rightarrow \eta J/\psi$
- $\eta_c(1S)$ production in hindered M1 transitions
- Properties of the $h_c$
$\chi_c J \rightarrow 2$ hadrons

- Accurate prediction of 2 hadron decay rates of $^3P_J$ states rely on understanding of the role of the color octet contribution
- $\chi_c$ produced in electromagnetic transitions from the $\Psi'$
- Search for 13 hadronic two-body decay modes of $\chi_c$

Analysis relies on identification of all decay products and kinematic fit to initial $\Psi'$ four-momentum.
$\chi_{cJ} \rightarrow 2 \text{ hadrons}$

**Baryon Modes**

- $x_c^0$
- $x_c^1$ (forbidden)
- $x_c^2$
- $\Lambda \bar{\Lambda}$
- $\Sigma^+ \Sigma^-$
- $\Sigma^0 \Sigma^0$
- $\Xi^- \Xi^-$
- $\Xi^0 \Xi^0$

**Meson Modes**

- $\pi^+ \pi^-$
- $\pi^0 \pi^0$
- $K^+ K^-$
- $K_S K_S$

**Invariant Mass**

- $\chi_{c0}$
- $\chi_{c1}$
- $\chi_{c2}$
- $\Lambda \bar{\Lambda}$
- $\Sigma^+ \Sigma^-$
- $\Sigma^0 \Sigma^0$
- $\Xi^- \Xi^-$
- $\Xi^0 \Xi^0$

**Events / 3 MeV**
**Branching Fraction Results:**

<table>
<thead>
<tr>
<th>B.F. (x10^{-3})</th>
<th>$\pi^+\pi^-$</th>
<th>$\pi^0\pi^0$</th>
<th>$K^+K^-$</th>
<th>$K_SK_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0}$</td>
<td>4.9±0.6</td>
<td>3.1±0.6</td>
<td>6.0±0.9</td>
<td>2.8±0.7</td>
</tr>
<tr>
<td>PDG</td>
<td>6.3±0.11</td>
<td>2.94±0.077</td>
<td>6.47±0.11</td>
<td>3.49±0.01</td>
</tr>
<tr>
<td>Our value</td>
<td>6.3±0.11</td>
<td>2.94±0.077</td>
<td>6.47±0.11</td>
<td>3.49±0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B.F. (x10^{-5})</th>
<th>$p\bar{p}$</th>
<th>$\Lambda\bar{\Lambda}$</th>
<th>$\Sigma^0\Sigma^0$</th>
<th>$\Sigma^+\Sigma^+$</th>
<th>$\Xi\Xi$</th>
<th>$\Xi^0\Xi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0}$</td>
<td>22.5±2.7</td>
<td>47±16</td>
<td>44.1±5.6</td>
<td>32.5±5.7</td>
<td>&lt;103</td>
<td>&lt;103</td>
</tr>
<tr>
<td>PDG</td>
<td>25.7±1.5</td>
<td>33.8±3.6</td>
<td>47±16</td>
<td>32.5±5.7</td>
<td>&lt;103</td>
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</tr>
</tbody>
</table>

Errors: (stat.) ± (syst.) ± (B($\psi'\rightarrow\gamma\chi_{cJ}$))
\[ \chi_{cJ} \rightarrow \eta(\prime)\eta(\prime) \]

- It is interesting that \( B(J/\psi \rightarrow \omega f_0(1710)) \) is larger than \( B(J/\psi \rightarrow \phi f_0(1710)) \) given \( f_0(1710) \) is thought to be largely strange.

- Suggestive of large OZI violating effects in \( J/\psi \) decay? ....glueball mixing? (F. Close and Q. Zhao, PRD 71, 094002)

- Look for similar effects in \( \chi_c \) decays to the pseudoscalar the isoscalars

- Use the factorization scheme proposed by Q. Zhao (PRD 72, 074001)

\[ r = \text{relative strength between singly-OZI and doubly-OZI suppressed transition amplitudes} \]
Use similar analysis technique as used for other two-body modes

Update of previous CLEO analysis on 3M $\psi'$ (PRD 75, 071101(R)(2007))

**CLEO Preliminary**

<table>
<thead>
<tr>
<th>B.F. ($\times 10^{-3}$)</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \eta'$</td>
<td>$3.18 \pm 0.13 \pm 0.18 \pm 0.16$</td>
<td>$0.51 \pm 0.05 \pm 0.03 \pm 0.03$</td>
</tr>
<tr>
<td>$\eta' \eta'$</td>
<td>$&lt;0.25$ (90% CL)</td>
<td>$&lt;0.05$ (90% CL)</td>
</tr>
<tr>
<td>$\eta' \eta'$</td>
<td>$2.12 \pm 0.13 \pm 0.11 \pm 0.11$</td>
<td>$0.06 \pm 0.03 \pm 0.004 \pm 0.004 &lt; 0.10$ (90% CL)</td>
</tr>
</tbody>
</table>

Errors: (stat.) ± (syst.) ± (B($\psi' \rightarrow \gamma \chi_{c0}$))

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\( \chi_{cJ} \rightarrow \eta(\prime)\eta(\prime) \)

Predicted dependence of BR on \( r \) (DOZI/SOZI)
(from Q. Zhao (PRD 72, 074001))

Data suggest small if any contribution for DOZI decays in 0\(^+\) channel.
Two photon decays of $\chi_{cj}$ are pure QED in first approximation.

A measurement of decay rates allows one to probe relativistic and radiative corrections known to be significant in the charmonium system.

Experimental technique similar to that for $\chi_{cj}$ decays to 2 hadrons.

Fit E1 photon distribution after selecting $\chi_{cj} \rightarrow \gamma\gamma$.
• **CLEO Preliminary Results**

  • Errors: (stat.) ± (syst.) ± (PDG Input)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>This measurement</th>
<th>PDG 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1(\psi(2S)\to\gamma\chi_0)x B_2(\chi_0 \to \gamma\gamma)x 10^{-5}$</td>
<td>$2.32\pm0.33\pm0.15$</td>
<td></td>
</tr>
<tr>
<td>$B_1(\psi(2S)\to\gamma\chi_2)x B_2(\chi_2 \to \gamma\gamma)x 10^{-5}$</td>
<td>$2.82\pm0.29\pm0.21$</td>
<td></td>
</tr>
<tr>
<td>$B_2(\chi_0 \to \gamma\gamma)x 10^{-4}$</td>
<td>$2.52\pm0.36\pm0.16\pm0.11$</td>
<td>$2.76\pm0.33$</td>
</tr>
<tr>
<td>$B_2(\chi_2 \to \gamma\gamma)x 10^{-4}$</td>
<td>$3.20\pm0.33\pm0.24\pm0.18$</td>
<td>$2.58\pm0.19$</td>
</tr>
<tr>
<td>$\Gamma(\chi_0 \to \gamma\gamma)$ keV</td>
<td>$2.65\pm0.38\pm0.17\pm0.25$</td>
<td>$2.87\pm0.39$</td>
</tr>
<tr>
<td>$\Gamma(\chi_2 \to \gamma\gamma)$ keV</td>
<td>$0.62\pm0.07\pm0.05\pm0.06$</td>
<td>$0.53\pm0.05$</td>
</tr>
<tr>
<td>$R=\Gamma(\chi_0 \to \gamma\gamma) / \Gamma(\chi_2 \to \gamma\gamma)$</td>
<td>$0.235\pm0.042\pm0.005\pm0.030$</td>
<td>$0.184\pm0.030$</td>
</tr>
</tbody>
</table>

• Also limit the forbidden process:

$$B(\chi_1 \to \gamma\gamma) < 3.6\times10^{-5}, \; 90\% \; CL.$$
• Use the transition $\psi' \to \eta \psi$, with $\psi \to l^+l^-$, to study the properties of the $\eta$
• Kinematic fitting of both $\psi$ and $\psi'$ to known masses improves $\eta$ mass resolution:
  $M_\eta = 547.785 \pm 0.017 \pm 0.057$ MeV
  (PRL, 99, 122002 (2007))
• Apply similar technique to simultaneously measure all allowed branching fractions of $\eta$
• Systematics are well under control since all measurements are made with the same experiment
• Allows independent determination of absolute $\eta$ branching fractions

PRL 99, 122001 (2007)
\[ \psi' \rightarrow \gamma \eta_c \]

- Precision determination of the hindered M1 ($\psi' \rightarrow \gamma \eta_c$) and allowed M1 ($J/\psi \rightarrow \gamma \eta_c$) rates are critical for understanding radiative transitions in charmonium and measuring $\eta_c$ branching fractions.

- Measure the rate by a fit to the inclusive photon spectrum in $\psi'$ decay.

- Background is smooth and well understood -- the signal line shape, however, is not!
ψ' → γη_c

- Tag η_c decay using 13 signal-rich decay modes (some new)
- Perform full event kinematic fit to sharpen photon resolution
- Backgrounds peaking outside of signal region are well understood
- The η_c line shape in hindered M1 transitions is nontrivial and cannot be easily fit by a Breit-Wigner (even when energy-dependent phase space and matrix element terms are included)
\( \eta_c \) Properties (PDG ‘06)

- \( \gamma\gamma \) or \( p+p^- \)
- \( \gamma\gamma \) or \( p+p^- \) (used for width, but not mass)
- \( \psi(1S,2S) \to \gamma\eta_c \)
Inclusive and tagged $\eta_c$ present a consistent picture of line-shape.

Hindered M1 transitions distort $\eta_c$ line-shape in a way not apparent in other production mechanisms ($\gamma\gamma$ fusion, pp, B decay).

A possible explanation for the experimental discrepancy in measurements of the mass and width of $\eta_c$?

Use and empirical function and “cut and count” techniques to extract yield in inclusive spectrum -- line-shape/background uncertainties dominate the systematic error.

$$B(\psi(2S) \rightarrow \gamma\eta_c(1S)) = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}$$

**CLEO Preliminary**

(PDG Ave.: $3.0\pm0.5 \times 10^{-3}$ based on 2 measurements)
E835 (2005): $3\sigma$
CLEO (2005): $5\sigma$
consistent but statistically limited $h_c$ properties

According to simple potential models one expects mass of $h_c (^1P_1)$ to be at the spin-averaged mass of the $\chi_c J (^3P_J)$ states.

Mass of $h_c$ yields information on the hyperfine splitting for P-wave states of charmonium

Study $h_c$ using the decay chain: $\psi' \rightarrow \pi^0 h_c; h_c \rightarrow \gamma \eta_c$

Two experimental approaches for reducing background:

**Inclusive $\eta_c$**
Identify a candidate $h_c \rightarrow \gamma \eta_c$ transition photon

**Exclusive $\eta_c$**
Identify the $h_c \rightarrow \gamma \eta_c$ transition photon and use 18 different hadronic decay modes of the $\eta_c$

$Extract h_c properties from a fit of the recoil mass against the \pi^0.$
• Inclusive $\eta_c$ decay

• Tag E1 photon by: $468 \text{ MeV} < E_\gamma < 538 \text{ MeV}$

• Background shape derived from data by relaxing the E1 photon requirement

• $M(h_c) = 3525.35 \pm 0.24 \pm 0.21 \text{ MeV}$

• $10\sigma$ significance
Exclusively reconstruct 18 hadronic decay modes of the $\eta_c$

Perform full event kinematic fit

$M(h_c) = 3525.35\pm0.27\pm0.20$ MeV

13$\sigma$ significance

Aside: not statistically sensitive to $\eta_c$ line-shape
Angular distribution is consistent with $^1P_1 \rightarrow ^1S_0$ transition

Accounting for statistical correlations in samples one obtains:

$$M(h_c) = 3525.35 \pm 0.19 \pm 0.15 \text{ MeV}$$

This is consistent at high precision with the spin averaged mass of the $^3P_J$ states 3525.30$\pm$0.11 MeV (PDG).

Is it surprising that the agreement is this good given the rather large spin orbit interaction in the $^3P_J$ states?
Summary

- Many new results with the CLEO-c ~25M $\psi'$ data set including:
  - Probing gluon dynamics through measurements of two-body $\chi_c$ decay
  - Precision measurements of $\eta$ mass and width
  - The $\eta_c$ line-shape in $\psi' \rightarrow \gamma \eta_c$ is non-trivial and needs understanding for extraction of mass and width of $\eta_c$

\[
B(\psi(2S) \rightarrow \gamma \eta_c(1S)) = (4.02 \pm 0.11 \pm 0.52) \times 10^{-3}
\]

- The hyperfine splitting in 1P charmonium appears to be very consistent with naive potential model predictions

\[
M(h_c) = 3525.35 \pm 0.19 \pm 0.15 \text{ MeV}
\]
\[
\Delta M_{hf}(1P) = -0.05 \pm 0.19 \pm 0.16 \text{ MeV}
\]

- The hadronic physics program at CLEO-c is vibrant – expect many more results in the future!

See Ryan Mitchell at next week

See Kam Seth at next week