Charmonium Decays in CLEO

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I will concentrate on the recent results.
Separate talk covering Y(4260).
CLEO-c Data Samples

- By far the largest $\psi(3770)$ sample
- The $\psi(2S)$ sample not the largest, but still unique because of the CLEO detector capabilities (excellent tracking, EM calorimeter and PID)
Photon transitions: $\psi(3770) \rightarrow \gamma \chi_{cJ}$

- Rare because $\Gamma_{E1} \sim 10^0\text{--}10^2 \text{ keV}$ while $\Gamma_{\psi(3770) \rightarrow DD} = 25 \text{ MeV}$

- Interesting because of well grounded potential model predictions for $\Gamma_{E1}[\psi(1^3D_1) \rightarrow \gamma \chi(1^3P_J)]$:
  
  - Is $\psi(3770)$ a regular $cc$ state?
  - Effects due to $1^3D_1 - 2^3S_1$ mixing?
  - Reliability of the $\Gamma_{E1}$ predictions for states above the open charm threshold?

- Two complementary methods:
  
  - $\chi_{cJ} \rightarrow \gamma J/\psi, J/\psi \rightarrow e^+e^-, \mu^+\mu^-$
    - Excellent background suppression but poor sensitivity to $\chi_{c0}$
  - $\chi_{cJ} \rightarrow K^+K^-, K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^+\pi^-\pi^+\pi^-$
    - More backgrounds but good sensitivity to $\chi_{c0}$
  - Total energy-momentum constraints suppress the backgrounds and improve the photon energy resolution

- $\psi(2S) \rightarrow \gamma \chi_{cJ}$ as control sample
Photon transitions: $\psi(3770) \rightarrow \gamma \chi_{cJ}$

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$B(\psi(3770) \rightarrow \gamma \chi_{cJ})$

$J = 0 \quad (0.73 \pm 0.07 \pm 0.06)\%$

$J = 1 \quad (0.29 \pm 0.05 \pm 0.04)\%$

$J = 2 \quad < 0.09\% \quad (90\% \text{ C.L.})$
Photon transitions: $\psi(3770) \rightarrow \gamma \chi_{cJ}$

$$\Gamma_{E1} = \frac{4}{3} e_Q^2 \alpha C_{J_f L_f J_i L_i S} E_\gamma^3 \langle n_f | L_{f J_f} | r | n_i | L_{i j_i} \rangle^2$$

$$C_{J_f L_f J_i L_i S} = \max(L_1, L_f)(2J_f + 1) \left\{ \begin{array}{ccc} L_f & J_f & S \\ J_i & L_i & 1 \end{array} \right\}^2$$

In non-relativistic limit
no $J$-dependence of the E1 matrix element

Dominant $J$-dependence

for $2^3S_1 \rightarrow 1^3P_J \; C_{J1111} \equiv C_J \; C_0 = \frac{1}{9} \; C_1 = \frac{3}{9} \; C_2 = \frac{5}{9}$

for $1^3D_1 \rightarrow 1^3P_J \; C_{J1121} \equiv C_J \; C_0 = \frac{2}{9} \; C_1 = \frac{1}{6} \; C_2 = \frac{1}{90}$

signature of the $1^3D_1$ state

$$\begin{array}{ccc} \Gamma_0 : & \Gamma_1 : & \Gamma_2 \\ \text{non-relativistic prediction} & 1 & 0.31 & 0.01 \\ \text{CLEO-c data} & 1 & 0.4 \pm 0.1 & <0.13 \end{array}$$

- $\psi(3770)$ photon transition rates fit the pattern expected for the $1^3D_1$ $c\bar{c}$ state
2³S₁ − 1³D₁ Mixing?

|ψ(3770)⟩ = \cos \varphi |1³D₁⟩ + \sin \varphi |2³S₁⟩
|ψ(2S)⟩ = − \sin \varphi |1³D₁⟩ + \cos \varphi |2³S₁⟩

\[ \frac{M_{\psi(3770)}^2 \Gamma_{\psi(3770)\rightarrow ee}}{M_{\psi(2S)}^2 \Gamma_{\psi(2S)\rightarrow ee}} \]

\[ \tilde{\Gamma}_0 \quad or \quad \tilde{\Gamma}_2 \quad \tilde{\Gamma}_1 \]

\[ \tilde{\Gamma}_J = \frac{\Gamma_J}{C_J E_\gamma^3} \]

- No consistent solution can be obtained in the non-relativistic approach
- Mixing angle is small
Importance of relativistic corrections

- Non-relativistic calculations overestimate photon transition rates for the charmonium.
- Qualitatively, potential model predictions work for the $1^3D_1$ state equally well as for the $2^3S_1$ state.

Based on CLEO-c results (J-averaged)

$|\langle 1^3P| r|2^3S_1 \rangle|$

$|\langle 1^3P| r|1^3D_1 \rangle|$

Non-relativistic

Relativistic

Rosner hep-ph/0411003
Ding, Qin, Chao PRD44, 3562(91)

Eichten, Lane, Quigg PRD69, 094019(04)

Barnes, Godfrey, Swanson PRD72, 054026(05)
non-\(D\bar{D}\) decays of \(\psi(3770)\)

<table>
<thead>
<tr>
<th>CLEO</th>
<th>BR [%]</th>
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<tbody>
<tr>
<td>(\gamma\chi_{c0})</td>
<td>0.73(\pm)0.07(\pm)0.06</td>
</tr>
<tr>
<td>(\gamma\chi_{c1})</td>
<td>0.29(\pm)0.05(\pm)0.04</td>
</tr>
<tr>
<td>(\gamma\chi_{c2})</td>
<td>&lt;0.09</td>
</tr>
<tr>
<td>(\pi^+\pi^-J/\psi)</td>
<td>0.19(\pm)0.02(\pm)0.02</td>
</tr>
<tr>
<td>(\pi^0\pi^0J/\psi)</td>
<td>0.08(\pm)0.02(\pm)0.02</td>
</tr>
<tr>
<td>(\eta J/\psi)</td>
<td>0.09(\pm)0.03(\pm)0.02</td>
</tr>
<tr>
<td>(\pi^0J/\psi)</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>(\phi\eta)</td>
<td>0.03(\pm)0.01</td>
</tr>
<tr>
<td>(K^0_SK^0_L)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Detected so far</td>
<td>1.41(\pm)0.10(\pm)0.16</td>
</tr>
</tbody>
</table>

\[
\sigma(\psi(3770) \rightarrow hadrons) = (6.38 \pm 0.08^{+0.41}_{-0.30}) \text{ nb}
\]

\[
\sigma(e^+e^- \rightarrow D\bar{D}) = (6.39 \pm 0.10^{+0.17}_{-0.08}) \text{ nb}
\]

The difference

\[
(\sigma(\psi(3770) \rightarrow hadrons) - \sigma(e^+e^- \rightarrow D\bar{D})) = (-0.01 \pm 0.12^{+0.40}_{-0.33}) \text{ nb}
\]

\[
\Rightarrow B(\psi(3770) \rightarrow \text{non-}D\bar{D}) < 9 \%
\]

- No evidence for anomalously large non-\(D\bar{D}\) component

(CLEO PRL,96,082004 (06))

(CLEO PRL,95,121801 (05))

(CLEO PRL,96,092002 (06))

(CLEO PRD,73,012002 (06))

(many upper limits presented in this paper too)

(CLEO hep/ex-0603026 CLEO-CONF-06-7)

\[
\Gamma_{\text{tot }\psi(2S)}/\Gamma_{\text{tot }\psi(3770)} \sim 1.1\%
\]

(CLEO PRL,95,121801 (05))

(CLEO PRL,96,092002 (06))

vs. (9 \(\pm\) 2 \(\pm\) 6)% BES-II Gang Rong’s talk
Results relevant for the interpretation of $X(3872)$

• Combining results from the previous slides:

\[
\frac{\Gamma(\psi(3770) \to \gamma \chi_{c1})}{\Gamma(\psi(3770) \to \pi^+ \pi^- J/\psi)} = 1.5 \pm 0.3 \pm 0.3
\]

\[
\downarrow \times (2 - 3.5) \quad \text{for } 1^3D_2 \text{ at } 3872 \text{ MeV}
\]

\[
\frac{\Gamma(\psi(1^3D_2) \to \gamma \chi_{c1})}{\Gamma(\psi(1^3D_2) \to \pi^+ \pi^- J/\psi)} > 2.0 \quad \text{vs.} \quad \frac{\Gamma(X(3872) \to \gamma \chi_{c1})}{\Gamma(X(3872) \to \pi^+ \pi^- J/\psi)} < 0.9 \quad (\text{Belle})
\]

– $X(3872)$ cannot be $1^3D_2$ cc state!
– A moot point by now, since Belle, CDF, BaBar have shown $X(3872)$ is $J^{PC}=1^{++}$
Results relevant for the interpretation of $X(3872)$

- **D^0 mass:**
  - $\psi(3770) \rightarrow \overline{D}^0 D^0 \rightarrow K_s \phi (\pi^+\pi^-)(K^+K^-)$

- Very small background
- $D^0, K_s, \phi$ have small momenta
  - $D^0$ mass scale well calibrated via $K_s, \phi$ masses
    - 1864.85±0.15±0.20 MeV CLEO PRELIMINARY
    - 1864.5±0.40 MeV PDG’06 fit
    - 1864.1±1.00 MeV PDG’06 average

- $M_{X(3872)} - M_{D^0\overline{D}^0} = M_{X(3872)} - (2M_{D^0} + \Delta M_{D^0* - D^0}) =$
  - +0.1±1.0 MeV PDG’06
  - −0.4±0.7 MeV PDG’06+CLEO

  - The error is now limited by the $X(3872)$ mass measurement

- Accidental mass coincidence even less likely. $\overline{D}^0 D^0*$ molecule, other 4-quark state with small binding energy, or a threshold cusp?
\( \psi(2S) \) as \( \chi_{cJ} \) factory

- \( e^+e^- \rightarrow \psi(2S) \)
  - 5pb\(^{-1}\), CLEO Ill+c, 3M \( \psi(2S) \)
  - by the end of the year \( \times 10 \)

- \( \psi(2S) \rightarrow \gamma \chi_{cJ}, \; J=0,1,2 \)
  - \( B \sim 9\% \) each \( J \), “\( \chi_{cJ} \) factory”
  - observed in inclusive analysis
  - \( B(\chi_{cJ} \rightarrow \text{hadrons}) \) are not well known

- Selected analyses of \( \chi_{cJ} \) hadronic decays:
  - Channels involving neutrals:
    - \( \chi_{cJ} \rightarrow \eta^{(')}\eta^{(')} \)
    - \( \chi_{cJ} \rightarrow h^+h^-h^0 \), 3-body decays, Dalitz plot analysis
Charmonium in CLEO ICHEP’06 Moscow Tomasz Skwarnicki

\[ \chi_{cJ} \rightarrow \eta' \eta' \]

\[ B(\chi_{c0} \rightarrow \eta \eta) = 0.31 \pm 0.05 \pm 0.04 \% \]
\[ B(\chi_{c0} \rightarrow \eta'/\eta') = 0.18 \pm 0.04 \pm 0.02 \% \]
\[ B(\chi_{c0} \rightarrow \eta \eta') < 0.05\% (90\% CL) \]
\[ B(\chi_{c2} \rightarrow \eta \eta) < 0.05\% (90\% CL) \]
\[ B(\chi_{c2} \rightarrow \eta'/\eta') < 0.03\% (90\% CL) \]
\[ B(\chi_{c2} \rightarrow \eta \eta') < 0.023\% (90\% CL) \]

\[ \chi_{c1} \] spin-parity forbidden

Theoretical model by: Qiang Zhao, PRD, 72, 074001 (05)

CLEO preliminary

Fits all  \( r = \text{Double-OZI/Single-OZI} \)

![Graph showing BR(×10^{-3}) vs. q1 for \( \chi_{c0} \rightarrow PP \)]
Analysis of $\chi_{cJ} \rightarrow h^0 h^+ h^-$

- See results on the next slide
### Analysis of $\chi_{cJ} \rightarrow h^0 h^+ h^-$

**CLEO-CONF-06-9**  
**CLEO PRELIMINARY**  
(in %)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\chi_{c0}$</th>
<th>$\chi_{c1}$</th>
<th>$\chi_{c2}$</th>
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</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-\eta$</td>
<td>$&lt; 0.021$</td>
<td>$0.52 \pm 0.03 \pm 0.03$</td>
<td>$0.051 \pm 0.011 \pm 0.004 \pm 0.003$</td>
</tr>
<tr>
<td>$K^+K^-\eta$</td>
<td>$&lt; 0.024$</td>
<td>$0.034 \pm 0.010 \pm 0.003 \pm 0.002$</td>
<td>$&lt; 0.033$</td>
</tr>
<tr>
<td>$p\bar{p}\eta$</td>
<td>$0.038 \pm 0.010 \pm 0.003 \pm 0.02$</td>
<td>$&lt; 0.015$</td>
<td>$0.019 \pm 0.007 \pm 0.002 \pm 0.002$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta'$</td>
<td>$&lt; 0.038$</td>
<td>$0.24 \pm 0.03 \pm 0.02 \pm 0.02$</td>
<td>$&lt; 0.053$</td>
</tr>
<tr>
<td>$K^+K^0\pi^0$</td>
<td>$&lt; 0.006$</td>
<td>$0.200 \pm 0.015 \pm 0.018 \pm 0.014$</td>
<td>$0.032 \pm 0.007 \pm 0.002 \pm 0.002$</td>
</tr>
<tr>
<td>$p\bar{p}\pi^0$</td>
<td>$0.059 \pm 0.010 \pm 0.006 \pm 0.004$</td>
<td>$0.014 \pm 0.005 \pm 0.001 \pm 0.001$</td>
<td>$0.045 \pm 0.007 \pm 0.004 \pm 0.003$</td>
</tr>
<tr>
<td>$\pi^+K^-\bar{K}^0$</td>
<td>$&lt; 0.010$</td>
<td>$0.84 \pm 0.05 \pm 0.06 \pm 0.05$</td>
<td>$0.15 \pm 0.02 \pm 0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$K^+\bar{p}\Lambda$</td>
<td>$0.114 \pm 0.016 \pm 0.009 \pm 0.007$</td>
<td>$0.034 \pm 0.009 \pm 0.003 \pm 0.002$</td>
<td>$0.088 \pm 0.014 \pm 0.07 \pm 0.006$</td>
</tr>
</tbody>
</table>

(upper limits at 90% C.L.)

- Most of them are the first observations!
- Statistics in $\chi_{c1} \rightarrow \eta\pi^+\pi^-, K^+K^-\pi^0, K^0_sK\pi$ sufficient for Dalitz plot analysis of resonant substructure (following slides)
Dalitz plot analysis of $\chi_{c1} \rightarrow \eta \pi^+ \pi^-$

- May offer the best way to determine $a_0(980)$ parameters in the future
- 10x increase in statistics expected this year

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Amplitude</th>
<th>Phase (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0(980)^{\pm} \pi^+$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$f_2(1270)\eta$</td>
<td>0.186 ± 0.017 ± 0.003</td>
<td>$-118 \pm 10 \pm 4$</td>
</tr>
<tr>
<td>$\sigma\eta$</td>
<td>0.68 ± 0.07 ± 0.05</td>
<td>$-85 \pm 18 \pm 15$</td>
</tr>
</tbody>
</table>

CLEO PRELIMINARY
Dalitz plot analysis of $\chi_{c1} \rightarrow K^+ K^- \pi^0$

- Analyzed together with $K^0_s K\pi$
- see the next slide for the fit results
Dalitz plot analysis of $\chi_{c1} \rightarrow K^0_S K\pi$

CLEO PRELIMINARY

**KK\pi fit results**

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Amplitude ($\pm$)</th>
<th>Phase ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)K$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$K^*_2(1430)K$</td>
<td>$0.50 \pm 0.09 \pm 0.12$</td>
<td>$-2 \pm 13 \pm 6$</td>
</tr>
<tr>
<td>$K^*_0(1430)K$</td>
<td>$5.3 \pm 1.0 \pm 0.1$</td>
<td>$77 \pm 12 \pm 16$</td>
</tr>
<tr>
<td>$K^*(1680)K$</td>
<td>$2.3 \pm 0.5 \pm 0.5$</td>
<td>$-38 \pm 12 \pm 12$</td>
</tr>
<tr>
<td>$a_0(980)\pi$</td>
<td>$10.8 \pm 1.2 \pm 1.2$</td>
<td>$-112 \pm 12 \pm 3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Fit Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)K$</td>
<td>$19.7 \pm 4.0 \pm 2.0$</td>
</tr>
<tr>
<td>$K^*_2(1430)K$</td>
<td>$18.0 \pm 6.6 \pm 3.2$</td>
</tr>
<tr>
<td>$K^*_0(1430)K$</td>
<td>$36.0 \pm 12.8 \pm 3.0$</td>
</tr>
<tr>
<td>$K^*(1680)K$</td>
<td>$11.2 \pm 5.4 \pm 2.7$</td>
</tr>
<tr>
<td>$a_0(980)\pi$</td>
<td>$29.5 \pm 7.1 \pm 2.6$</td>
</tr>
</tbody>
</table>

- $K^*(892)K, a_0(980)\pi$ clearly seen
- Need more data to sort out other contributions
Search for $\psi(2S) \rightarrow \eta_c(1S) \pi^+\pi^-\pi^0$

- $B(\psi(2S) \rightarrow \eta_c \pi^+\pi^-\pi^0) < 0.1\%$ (90% C.L.)
- Rules out “survival before annihilation” model by P. Artoisenet et al. PLB, 628, 211 (05) invented to explain the “$\rho\pi$ puzzle” (predicted $B > 1\%$)
Analysis of $\psi(2S) \rightarrow 2$ pseudo-scalars

- Confirm BES results
- The phase difference $\Delta$ between the EM and strong amplitudes around 90°, which is consistent with the J/$\psi$ value, contrary to some theoretical speculations that it might be very different
Summary

• Potential models predict $\Gamma_{E1}$ for $\psi(3770) \rightarrow \gamma \chi_{cJ}$ equally well as for $\psi(2S) \rightarrow \gamma \chi_{cJ}$
• No evidence for anomalously high $\psi(3770) \rightarrow \text{non-DD}$
• $\psi(3770)$ appears to be standard $1^3D_1$ cc state with a small admixture of $2^3S_1$
• Preliminary precision measurement of $D^0$ mass improves $M_{X(3872)} - M_{D^0D^{0*}}$ determination to $-0.4\pm0.7$ MeV
• Vast improvement in measurements of exclusive hadronic decay modes of the $\chi_{cJ}$ states.
• An order of magnitude increase in $\psi(2S)$ statistics (x10) expected soon. Significant improvement in $\psi(3770)$ statistics (x3) expected by 2008.