New CLEO Results on Charmonium Decays

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on behalf of the CLEO Collaboration

6th International Workshop on Heavy Quarkonia
Nara, Japan December 2008
Radiative Charmonia Decays

- **Simplest onia decays**
  - $J/\psi \rightarrow \gamma \gamma \gamma$
  - $\eta_c \rightarrow \gamma \gamma$
  - $\chi_{cJ} \rightarrow \gamma \gamma$

- **Next simplest**
  - $J/\psi \rightarrow \gamma \, g\, g$
  - $\psi(2S) \rightarrow \gamma \, g\, g$
  - $\chi_{cJ} \rightarrow \gamma \,(\rho^0, \omega, \phi)$

- $\eta'$ Properties from $J/\psi \rightarrow \gamma \eta'$
**J/ψ → 3γ & η_c → γγ**

- **Measure or limit the decay J/ψ → 3γ**
- **Expect B( J/ψ → 3γ) ~ 10^{-6} – 10^{-5}**
  - B < 5.5 × 10^{-5} Crystal Ball (1980)
  - No ‘particle’ ever observed in a 3γ decay!
    - B( ω → 3γ) < 1.9 × 10^{-4}
    - B( Z → 3γ) < 1 × 10^{-5}
    - However, ortho-positronium (o-Ps), the $^3S_1$ e^+e^- atom, decays nearly 100% to 3γ. Also, B(o-Ps → 5γ) ≈ 2 × 10^{-6}

- **Seek η_c → γγ in radiative J/ψ decays & measure**
  
  B( J/ψ → γ η_c ) × B( η_c → γγ )
  - E760 & E835 have observed η_c → γγ in pp → γγ
  - Belle: 4.1σ evidence in B(± → K± γγ)

  \[
  B( \eta_c → γγ ) = (2.4^{+0.9}_{-0.8}^{+0.7}_{-0.4}) × 10^{-4}
  \]

[PLB 662 (2008) 323]
$J/\psi \rightarrow 3\gamma$

**Unique topology:**
- 2 tracks provide a tag of the $J/\psi$
- 3 showers with no resonant substructure

**Impose 4-momentum conservation**

**$\chi^2$ of kinematic fit**
- a key variable
- Suppress feed-down from other decays

**Also seek**
$J/\psi \rightarrow \gamma \eta_c, \eta_c \rightarrow \gamma \gamma$
J/ψ → 3γ

Plot has χ^2<3 cut in place

Veto on masses inside 0.10-0.16, 0.50-0.60, 0.90-1.00, & >2.8 GeV

37 events remain in the data outside these regions

Smallest photon pair mass

Largest photon pair mass
J/ψ → γ π^0 π^0 feed-down

- Only happens if BOTH π^0's decay asymmetrically
- Demand 4-momentum conservation to suppress: \( \chi^2/dof < 3 \) for signal
- BRs for various J/ψ → γ \( f_J \) not well known
- Notice that SHAPES of all 5γ \( \chi^2 \) distribution are similar
- The data can be used at large \( \chi^2/dof (5-20) \) for bkgd normalization
- Mix of bkgd sources does not to matter much for leakage into \( \chi^2<3 \)
Result for $J/\psi \rightarrow 3\gamma$

- Normalize $\gamma f_j$ background in $\chi^2=5$-20 region
- Small non-$J/\psi$ bgd from $\pi^+\pi^-$ recoil sidebands
- After normalized bgd subtraction
- Signal shape required to describe data at small $\chi^2$
- Net yield $24.2^{+7.2}_{-6.0}$ evts
- $B = (12 \pm 3 \pm 2) \times 10^{-6}$
- $6\sigma$ significance

PRL 101, 101801 (2008)
\eta_c \rightarrow \gamma \gamma
$\eta_c \rightarrow \gamma \gamma \gamma$ Selection

- 2 signal events
- 0.8 events
- bgd total
- Eff=10.9%

<table>
<thead>
<tr>
<th>Source</th>
<th># bgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \eta$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\gamma \eta'$</td>
<td>0.2</td>
</tr>
<tr>
<td>$3\gamma$</td>
<td>0.3</td>
</tr>
<tr>
<td>Total</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Largest photon pair mass

Smallest photon pair mass
\[ \eta_c \rightarrow \gamma \gamma \] Result

\[ B( J/\psi \rightarrow \gamma \eta_c ) \times B( \eta_c \rightarrow \gamma \gamma ) = (1.2^{+2.7}_{-1.1} \pm 0.3) \times 10^{-6} \]

or

\[ < 5.3 \times 10^{-6} \text{ @90\%CL} \]

Using CLEO's

\[ B( J/\psi \rightarrow \gamma \eta_c ) = (1.98 \pm 0.09 \pm 0.30)\% , \]

\[ B( \eta_c \rightarrow \gamma \gamma ) = (0.6^{+1.3}_{-0.5} \pm 0.1) \times 10^{-4} \]

\[ < 2.6 \times 10^{-4} \text{ @90\%CL} \]

• PDG08 value = (2.4^{+1.1}_{-0.9}) \times 10^{-4} \]

\( \text{Consistent within } 1.1\sigma \)
$\psi(2S) \rightarrow \gamma_1 \chi_{cJ}, \chi_{cJ} \rightarrow \gamma \gamma$
\( \psi(2S) \to \gamma_1 \chi_{cJ}, \chi_{cJ} \to \gamma \gamma \)

- Shown@QWG5: H. Mahlke
- Striking experimental signature: only 3\( \gamma \)!
- In \( R = \frac{\Gamma_2(\gamma\gamma)}{\Gamma_0(\gamma\gamma)} \) many theo. & exp. uncertainties will cancel
  - 1st decay-based msmt
  - Lowest order: \( R = 0.27 \)
  - 1st order \( \alpha_s \): \( R = 0.12 \)

**Table: Decay Amplitudes**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>( \chi_{c0} )</th>
<th>( \chi_{c2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_1 \times B_2 \times 10^5 )</td>
<td>2.17( \pm 0.32 \pm 0.10 )</td>
<td>2.68( \pm 0.28 \pm 0.15 )</td>
</tr>
<tr>
<td>( B_2 \times 10^4 )</td>
<td>2.31( \pm 0.34 \pm 0.10 \pm 0.10 )</td>
<td>3.23( \pm 0.34 \pm 0.18 \pm 0.16 )</td>
</tr>
<tr>
<td>( \Gamma_{\gamma\gamma} ) (keV)</td>
<td>2.36( \pm 0.35 \pm 0.11 \pm 0.19 )</td>
<td>0.66( \pm 0.07 \pm 0.04 \pm 0.05 )</td>
</tr>
<tr>
<td>( R )</td>
<td>0.278( \pm 0.050 \pm 0.018 )</td>
<td>0.031</td>
</tr>
</tbody>
</table>

**Graph: Experimental Data**

- \( e^+e^- \to \gamma\gamma \)
- \( \psi(2S) \to \gamma_1 \chi_{cJ}, \chi_{cJ} \to \gamma \gamma \)

**Reference Table**

<table>
<thead>
<tr>
<th>Reference</th>
<th>( \Gamma_{\gamma\gamma}(\chi_{c2}) ) (eV)</th>
<th>( \Gamma_{\gamma\gamma}(\chi_{c0}) ) (eV)</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barbieri</td>
<td>930</td>
<td>3500</td>
<td>0.27</td>
</tr>
<tr>
<td>Godfrey</td>
<td>459</td>
<td>1290</td>
<td>0.36</td>
</tr>
<tr>
<td>Barnes</td>
<td>580</td>
<td>1560</td>
<td>0.36</td>
</tr>
<tr>
<td>Bodwin</td>
<td>820( \pm 230 )</td>
<td>6700( \pm 2800 )</td>
<td>0.12( \pm 0.15 )</td>
</tr>
<tr>
<td>Gupta</td>
<td>570</td>
<td>6380</td>
<td>0.09</td>
</tr>
<tr>
<td>Münz</td>
<td>440( \pm 140 )</td>
<td>1390( \pm 160 )</td>
<td>0.32( \pm 0.12 )</td>
</tr>
<tr>
<td>Huang</td>
<td>490( \pm 150 )</td>
<td>3720( \pm 1100 )</td>
<td>0.13( \pm 0.06 )</td>
</tr>
<tr>
<td>Ebert</td>
<td>500</td>
<td>2900</td>
<td>0.17</td>
</tr>
<tr>
<td>Schuler</td>
<td>280</td>
<td>2500</td>
<td>0.11</td>
</tr>
</tbody>
</table>
$J/\psi \rightarrow \gamma \, gg$
Select clean primary $\gamma$'s
- $z_\gamma = E_\gamma / E_{\text{beam}} : z_\gamma > 0.3$
- veto $\gamma$'s that pair with another to form $\pi^0$
- do not veto $\eta \rightarrow \gamma\gamma$ (too much signal killed)

Eliminate $e^+e^-$ “continuum” bgd, partly ISR, by using $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$
- Makes analysis much simpler than $\Upsilon \rightarrow \gamma\gamma$
  [PRD74, 012003 (2006)]
- Small non-$J/\psi$ bgd directly subtracted with $\pi^+\pi^-$ recoil mass sidebands

Model remaining bgd in 3 systematically complementary ways
- Two are data-driven, one MC-only
  - See paper for details
- Spread among them indicative of syst. error

Model signal as
- Three 2-body processes: $\gamma\eta$, $\gamma\eta'$, $\gamma\eta(1440)$
- Theoretical shape validated with CLEO $\gamma \rightarrow \gamma\gamma$ measurements
  - NEW: also include $z_\gamma\cos\theta_\gamma$ correlation & shape a la Koller-Walsh
  [NP B140, 449 (1978)].
These are spectra developed for $\Upsilon \rightarrow \gamma gg$

Found to work adequately for $J/\psi \rightarrow \gamma gg$

PRD 69, 114006 (2004); PRD 72, 054014 (2005); PRL 96, 111801 (2006).

J/ψ Direct Photon Spectrum

After correcting for angular acceptance & efficiency, this spectrum gives
# J/ψ → γgg events
# J/ψ→ggg from

- # π⁺π⁻ J/ψ
- # J/ψ → γgg
- J/ψ → e⁺e⁻, μ⁺μ⁻ (PDG)
- J/ψ → γ⁺ → q̅q (PDG)

\[ R_γ = \frac{B_{ggg}}{B_{ggg}^*} = \frac{N_{ggg}}{N_{ggg}^*} \]

Experiment | \( R_γ \)
---|---
MARK-II [14] | 0.041 ± 0.008 (\( z_γ > 0.6 \) only)
 | 0.146 ± 0.028 (all \( z_γ \), estimated)
This measurement | \( R_γ = 0.137 ± 0.001 ± 0.016 ± 0.004 \)

Garcia-Soto hep-ph/0701030
Prediction for J/ψ→γgg
Large Color Octet ME
Small Color Octet ME

Do not describe CLEO data

Data with 3 different bgd subtractions

γ(1S) shape with arbitrary normalization

PRD 78, 032012 (2008)
Measured $R_\gamma$ & QCD

- **Systematic error (11%)** dominated by
  - Background subtraction uncertainty
  - Signal shape uncertainty

Brodsky, Lepage, Mackenzie PRD 28, 228 (1983) predict

$$R_\gamma = \frac{36}{5} q_c^2 \alpha_{em} \left[ 1 + (2.2 \pm 0.6) \alpha_s / \pi \right]$$

Also can be expressed as $B(J/\psi \rightarrow \gamma gg) = (9.0 \pm 1.0)\%$
  - Somewhat larger than Voloshin [PPNP 61, 455 (2008)] estimate of **6.7%** based on $\alpha_s(m_c)=0.19$ & known $\Gamma_{ee}(J/\psi)$
$\psi(2S) \rightarrow \gamma gg$
$\psi(2S) \rightarrow \gamma gg$

- Similar approach, but…
- Must subtract spectrum from below-$\psi(2S)$ continuum data to suppress ISR effects
- Must subtract contribution from $J/\psi \rightarrow \gamma gg$ & its bgd
  - Use shape from dipion tags: $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$
  - Correct for $\varepsilon$, $B(\text{any } J/\psi) / B_{++}$
- FSR from MC
- Model remaining backgrounds 3 different ways (both MC and data-driven methods)
Results for $\psi(2S) \to \gamma \, gg$

Integrate data for $z_\gamma > 0.4$
- spread among bgd methods indicates systematics
- Correct for $\varepsilon$
- Correct for $z_\gamma < 0.4 / z_\gamma > 0.4$

$\sum B(\psi(2S) \to$
- $e^+e^-, \mu^+\mu^-, \tau^+\tau^- (PDG)$
- $\gamma* \to q\bar{q} (PDG)$
- $\pi^+\pi^-J/\psi, \pi^0\pi^0J/\psi, \eta/\pi^0J/\psi$
- $\gamma \chi_cJ, \gamma \eta_c, \pi^0 h_c$

$\approx 87\%$
- Leaves $\sim 13\%$ for $\gamma gg, 3g$
- We know total $#\psi(2S)$
- $B(\gamma gg) \approx 0.9\%$
- $B(\, ggg ) \approx 12\%$

$\Rightarrow R_{\gamma} = 0.065 \pm 0.010 \pm 0.023$
- $\approx$ Half of $J/\psi \, R_{\gamma}$ ($\sim 3\sigma$ below)

Reminder: for $\Upsilon(1S,2S,3S) \to \gamma gg$, CLEO measurements yielded $R_{\gamma} \approx 0.03$ within $\sim 10$-15% errors
[PRD74 (2006) 012003]
Charmonium Annihilation Summary
Many measured annihilation rates!

- CLEO has measured several important & fundamental rates
- Various ratios can be taken to cancel out wave function terms & other common factors
- Lowest order PQCD predictions known, up to choice of the mass scale at which to evaluate $\alpha_s$
- 1st order $\alpha_s$ corrections to these ratios are also known
  - Most are large (>~20%)
  - Some are unphysical
- Fodder for postdictions!
### Charmonium Annihilation $\Gamma$ Ratios

<table>
<thead>
<tr>
<th>System</th>
<th>Ratio</th>
<th>Lowest order</th>
<th>L.O. Value</th>
<th>Msd by CLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>$\gamma \gamma / gg$</td>
<td>$(8 / 9) (\alpha / \alpha_s)^2$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$&lt; 2.6 \times 10^{-4}$ (90%CL)</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$\gamma \gamma \gamma / e^+e^-$</td>
<td>$[64(\pi^2-9) / (243\pi)] \alpha$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$(2.0 \pm 0.7) \times 10^{-4}$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$\gamma \gamma \gamma / \gamma gg$</td>
<td>$(8 / 27) (\alpha / \alpha_s)^2$</td>
<td>$1.8 \times 10^{-4}$</td>
<td>$(1.3 \pm 0.4) \times 10^{-4}$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$\gamma \gamma \gamma / ggg$</td>
<td>$(128 / 135) (\alpha / \alpha_s)^3$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$(1.8 \pm 0.4) \times 10^{-5}$</td>
</tr>
<tr>
<td>$J/\psi, \psi(2S)$</td>
<td>$\gamma gg / ggg$</td>
<td>$(16 / 5) (\alpha / \alpha_s)$</td>
<td>$0.078$</td>
<td>$0.137 \pm 0.017$ $0.065 \pm 0.025$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$\gamma \gamma / gg$</td>
<td>$(8 / 9) (\alpha / \alpha_s)^2$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$(2.3 \pm 0.4) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>$\gamma \gamma / gg$</td>
<td>$(8 / 9) (\alpha / \alpha_s)^2$</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$(4.3 \pm 0.6) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\chi_{c0,2}$</td>
<td>$\gamma \gamma_2 / \gamma \gamma_0$</td>
<td>$4 / 15$</td>
<td>$0.27$</td>
<td>$0.28 \pm 0.06$</td>
</tr>
</tbody>
</table>

Kwong, et al., PRD 37, 3210 (1988)

Using $\alpha_s = 0.3$
\( \chi_{cJ} \rightarrow \gamma (\rho^0, \omega, \phi) \)
\( \chi_{cJ} \to \gamma (\rho^0, \omega, \varphi) \)

- Glue-rich system recoils against \( \gamma \)
- Clean experimental signatures
- ULs for \( B[\chi_{c0,2} \to \gamma (\rho^0, \omega, \varphi)] \)
- Observe \( B[\chi_{c1} \to \gamma (\rho^0, \omega)] \approx 10^{-4} \)
  - Factors of \( \approx (15, 50) \) higher than prediction of Gao, Zhang, & Chao, CPL 23, 2376 (2006)
- \( \chi_{c1} \to \gamma \rho^0 \) has \( \approx \text{full long. polarization} \)
  - Like \( f_1(1285) \to \gamma \rho^0 \) [VES, ZPC66, 71 (1995)]

\[
\begin{align*}
\chi_{c1} & \to \gamma \rho^0 & \text{Longitudinal} \\
\chi_{c1} & \to \gamma \omega & \text{Transverse}
\end{align*}
\]

PRL 101, 151801 (2008)
CLEO has studied $\eta'$ properties via $J/\psi \rightarrow \gamma \eta'$:

- Mass error improved by factor of 5
- Limits on rare hadronic modes
- 1st observation of $\eta' \rightarrow \pi^+ \pi^- \pi^0$, $\pi^+ \pi^- e^+ e^-$

Significance: $>6\sigma$

PRL101, 182002 (2008)
Summary & Conclusions

CLEO has measured a large number of charmonium annihilation rates

- \( B( J/\psi \to \gamma \gamma \gamma) = (12 \pm 3 \pm 2) \times 10^{-6} \)
- \( B( J/\psi \to \gamma \eta_c) \times B( \eta_c \to \gamma \gamma) = (1.2 \pm 2.7 \pm 1.1 \pm 0.3) \times 10^{-6} \)
- \( \chi_{cJ} : \Gamma_2(\gamma\gamma) / \Gamma_0(\gamma\gamma) = 0.278 \pm 0.050 \pm 0.018 \pm 0.031 \)
- \( J/\psi \to \gamma \gamma : R_\gamma = 0.137 \pm 0.001 \pm 0.016 \pm 0.004 \)
- \( \psi(2S) \to \gamma \gamma : R_\gamma = 0.065 \pm 0.010 \pm 0.023 \)

\( \chi_{cJ} \to \gamma (\rho^0, \omega, \phi) \) rates measured

- \( \chi_{c1} \to \gamma (\rho^0, \omega) \) BRs exceed prediction by factor of (15,50)

CLEO has studied \( \eta' \) properties via \( J/\psi \to \gamma \eta' \)

- Mass error improved by factor of 5
- Limits on rare hadronic modes
- 1\textsuperscript{st} observation of \( \eta' \to \pi^+\pi^-\pi^0, \pi^+\pi^-e^+e^- \)
Charmonium Decay Analyses in Progress

- $\eta_c$ exclusive branching fractions
- $h_c$ decays to light hadrons
- $J/\psi \to \gamma + \text{invisible}$
- $J/\psi \to \text{invisible}$
- $J/\psi, \psi(2S) \to \gamma/\pi^0$ pp
- $J/\psi, \psi(2S) \to \gamma f_J \to \gamma (\pi\pi, KK, \eta\eta)$ [glueball search]
- $J/\psi \to \pi\pi, KK, pp$
- $J/\psi, \psi(2S) \to \text{baryon-antibaryon}$
- $\psi(4160) \to \gamma \chi_c(2P)$ search
Backup Slides
$\eta'$ Properties
Some properties of $\eta'(958)$ are not so well known

- $M(\text{PDG08}) = 957.66 \pm 0.24$ MeV
  - Best msmt $1974$: MMS $957.46 \pm 0.33$ MeV
  - Compare to $\eta$ mass error of 24 keV:
    - $\eta'$ is less precise by a factor of 10

Rare BRs: many mode limits of order 1-5%

- $B(\eta' \rightarrow \pi^+\pi^-\pi^0) < 5\%$
  - Of interest because $B(\eta' \rightarrow \pi^+\pi^-\pi^0) \propto m_u - m_d$ (or not!)
  - Predictions vary from 0.1%-3%.
  - Rate sensitive to level of $\eta'\eta'\pi^0$ mixing, final state rescattering
- $B(\eta' \rightarrow \pi^+\pi^-e^+e^-) < 0.6\%$. Predicted to be $\sim 0.2\%$.
- $\eta' \rightarrow 2(\pi^+\pi^-)\pi^0$, $\eta' \rightarrow 3(\pi^+\pi^-)$, $\eta' \rightarrow 2(\pi^+\pi^-)$ each has a $B < 1\%$

Turns out that we can produce many $\eta'$ mesons in

$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \gamma \eta' : \sim 40K$ in CLEO-c data.

Use common decay modes for mass measurement & search for some rare modes

- Exclusive reconstruction & constrained fitting
$\eta'$ Mass

- $\sim 4K$ reconstructed decays
- $M_{\eta'} = 957.793 \pm 0.054 \pm 0.036$ MeV
- Factor of 5 in mass precision

PRL101, 182002 (2008)
### Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Variation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit mass window</td>
<td></td>
<td>11</td>
<td>9</td>
<td>31</td>
<td>7</td>
</tr>
<tr>
<td>$M_{\psi(2S)}$</td>
<td>34 keV</td>
<td>9</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>$M_{J/\psi}$</td>
<td>11 keV</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Bias</td>
<td>$(</td>
<td>\beta_i</td>
<td>+ \Delta \beta_i)/3$</td>
<td>27</td>
<td>51</td>
</tr>
<tr>
<td>$p_{\pi^\pm}$ scale</td>
<td>0.01%</td>
<td>28</td>
<td>17</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>$E_\gamma$ scale</td>
<td>0.6%</td>
<td>13</td>
<td>22</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>$M_\eta$</td>
<td>24 keV</td>
<td>44</td>
<td>63</td>
<td>57</td>
<td>36</td>
</tr>
<tr>
<td>Systematic sum</td>
<td></td>
<td>87</td>
<td>70</td>
<td>208</td>
<td>54</td>
</tr>
</tbody>
</table>
Rare $\eta'$ Decays

$\eta' \rightarrow \pi^+ \pi^- \pi^0$

Significance: $>6\sigma$

$\eta' \rightarrow \pi^+ \pi^- e^+ e^-$

Significance: $>6\sigma$

<table>
<thead>
<tr>
<th>Mode $X$</th>
<th>$\epsilon/\epsilon_0$</th>
<th>$N$</th>
<th>$B(10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>$0.55$</td>
<td>$20.2^{+6.1}_{-4.8}$</td>
<td>$37^{+11}_{-9} \pm 4$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- e^+ e^-$</td>
<td>$0.31$</td>
<td>$7.9^{+3.9}_{-2.7}$</td>
<td>$25^{+12}_{-9} \pm 5$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \mu^+ \mu^-$</td>
<td>$2.14$</td>
<td>$&lt;4.8$</td>
<td>$&lt;2.4$</td>
</tr>
<tr>
<td>$2(\pi^+ \pi^-)$</td>
<td>$1.02$</td>
<td>$&lt;2.3$</td>
<td>$&lt;2.4$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- 2\pi^0$</td>
<td>$0.18$</td>
<td>$&lt;4.1$</td>
<td>$&lt;27$</td>
</tr>
<tr>
<td>$2(\pi^+ \pi^-)\pi^0$</td>
<td>$0.21$</td>
<td>$&lt;3.6$</td>
<td>$&lt;20$</td>
</tr>
<tr>
<td>$3(\pi^+ \pi^-)$</td>
<td>$0.47$</td>
<td>$&lt;2.3$</td>
<td>$&lt;5.3$</td>
</tr>
<tr>
<td>Invisible</td>
<td>$0.74$</td>
<td>$&lt;5.8$</td>
<td>$&lt;9.5$</td>
</tr>
</tbody>
</table>

$\eta' \rightarrow$ invisible

Improved 1st Limits

1st Obs.

B. Heltsley QWG Decays
### Results for $J/\psi \rightarrow n\gamma$

<table>
<thead>
<tr>
<th></th>
<th>$2\gamma$</th>
<th>$3\gamma$</th>
<th>$4\gamma$</th>
<th>$5\gamma$</th>
<th>$\gamma\eta_c, \gamma\eta_c \rightarrow \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal candidates (events)</strong></td>
<td>9</td>
<td>37</td>
<td>5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td><strong>Background (events)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J/\psi$ backgrounds</td>
<td>6.2</td>
<td>11.9</td>
<td>3.2</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Non-$J/\psi$ backgrounds</td>
<td>0.9</td>
<td>0.9</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Background sum (events)</td>
<td>7.1</td>
<td>12.8</td>
<td>3.7</td>
<td>0.5</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Statistical significance ($\sigma$)</strong></td>
<td>1.1</td>
<td>6.3</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Net yield (68% C.L. interval) (events)</strong></td>
<td>1.9 $^{+4.7}_{-1.6}$</td>
<td>24.2 $^{+7.2}_{-6.0}$</td>
<td>1.3 $^{+2.4}_{-1.3}$</td>
<td>0 $^{+1.2}_{-0}$</td>
<td>1.2 $^{+2.8}_{-1.1}$</td>
</tr>
<tr>
<td>UL @ 90% C.L.</td>
<td>&lt;7.7</td>
<td>&lt;33.5</td>
<td>&lt;6.0</td>
<td>&lt;2.3</td>
<td>&lt;4.7</td>
</tr>
<tr>
<td><strong>Efficiency (%)</strong></td>
<td>19.2</td>
<td>21.8</td>
<td>8.71</td>
<td>1.90</td>
<td>10.9</td>
</tr>
<tr>
<td><strong>Systematic errors (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix element</td>
<td>0</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$J/\psi$ background</td>
<td>15</td>
<td>5</td>
<td>10</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>$\pi^+ \pi^- J/\psi$ counting</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Detector modeling</td>
<td>4.5</td>
<td>6.4</td>
<td>8.3</td>
<td>10</td>
<td>6.4</td>
</tr>
<tr>
<td>$\Gamma(\eta_c)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Quadrature sum (%)</td>
<td>16</td>
<td>17</td>
<td>20</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>$\mathcal{B}(J/\psi \rightarrow X)$ [$10^{-6}$]</td>
<td>12 ± 3 ± 2</td>
<td></td>
<td></td>
<td></td>
<td>1.2 $^{+2.7}_{-1.1}$ ± 0.3</td>
</tr>
<tr>
<td>UL on $\mathcal{B}(J/\psi \rightarrow X)$ @ 90% C.L. [$10^{-6}$]</td>
<td>&lt;5</td>
<td>&lt;19</td>
<td>&lt;9</td>
<td>&lt;15</td>
<td>&lt;6</td>
</tr>
</tbody>
</table>
Matrix element for $J/\psi \rightarrow 3 \gamma$

- Lowest order for ortho-positronium $3\gamma$ decay: 
  \[ \text{Ore & Powell, Phys. Rev. 75, 1696 (1949).} \]

\[ <|M|^2> = (512/3) \pi^2 \alpha^6 \sum_{i=1}^{3} \frac{1}{(x_j x_k)} \]

where $x_i = 2 E_i^*/M_{J/\psi}$, $E_i =$ c.o.m. $\gamma_i$ energy, $i \neq j, k$

- Weight the phase space events by this factor to sculpt the distributions
- Is a very gentle sculpting
- Makes $(0.2 \pm 0.1)%$ relative difference in efficiency compared to pure phase space
Belle evidence for $\eta_c \rightarrow \gamma \gamma$

$B^\pm \rightarrow K^\pm \gamma\gamma$

$\mathcal{B}(\eta_c \rightarrow \gamma \gamma) = (2.4^{+0.9}_{-0.8}^{+0.7}_{-0.4}) \times 10^{-4}$
**TABLE 1.** Summary of the fitted yield, efficiency, and branching fraction ($\mathcal{B}$) or upper limit (U.L.) at 90% confidence level for each of the $\chi_{cJ} \rightarrow \gamma V$ transitions. Also listed is the total systematic error and the portion of the systematic error due to uncertainty in the backgrounds that might bias the signal yield. The efficiencies include the vector meson branching fractions [5] and the probability of detecting the $\psi(2S) \rightarrow \gamma \chi_{cJ}$ transition photon. Finally, we list the pQCD predictions of Ref. [1].

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield [Events]</th>
<th>Efficiency [%]</th>
<th>Bias Uncert. [%]</th>
<th>Syst. Error [%]</th>
<th>$\mathcal{B} \times 10^6$</th>
<th>U.L. [$10^{-6}$]</th>
<th>pQCD [$10^{-6}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0} \rightarrow \gamma \phi^0$</td>
<td>1.2 ± 4.5</td>
<td>20</td>
<td>...</td>
<td>±10</td>
<td>&lt;0.6</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \gamma \phi^0$</td>
<td>186 ± 15</td>
<td>22</td>
<td>±2</td>
<td>±9</td>
<td>243 ± 19 ± 22</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \gamma \phi^0$</td>
<td>17.2 ± 6.8</td>
<td>31</td>
<td>±30</td>
<td>±36</td>
<td>25 ± 10 ± 14</td>
<td>&lt;50</td>
<td>4.4</td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow \gamma \omega$</td>
<td>0.0 ± 2.8</td>
<td>17</td>
<td>...</td>
<td>±16</td>
<td>&lt;8.8</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \gamma \omega$</td>
<td>39.2 ± 7.1</td>
<td>20</td>
<td>±8</td>
<td>±15</td>
<td>83 ± 15 ± 12</td>
<td>&lt;70</td>
<td>1.6</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \gamma \omega$</td>
<td>0.0 ± 1.8</td>
<td>18</td>
<td>...</td>
<td>±16</td>
<td>&lt;7.0</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c0} \rightarrow \gamma \phi$</td>
<td>0.1 ± 1.6</td>
<td>15</td>
<td>...</td>
<td>±12</td>
<td>&lt;6.4</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c1} \rightarrow \gamma \phi$</td>
<td>5.2 ± 3.1</td>
<td>17</td>
<td>...</td>
<td>±12</td>
<td>12.8 ± 7.6 ± 1.5</td>
<td>&lt;26</td>
<td>3.6</td>
</tr>
<tr>
<td>$\chi_{c2} \rightarrow \gamma \phi$</td>
<td>1.3 ± 2.5</td>
<td>16</td>
<td>...</td>
<td>±12</td>
<td>&lt;13</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

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**B. Heltsley QWG Decays**

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J/ψ → γ gg

Small bgd subtraction from non-J/ψ photons

<table>
<thead>
<tr>
<th>Source</th>
<th>Assigned systematic error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon angular distribution</td>
<td>3%</td>
</tr>
<tr>
<td>Nonphoton showers</td>
<td>1.5%</td>
</tr>
<tr>
<td>Number of three-gluon events</td>
<td>2%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1%</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>7%</td>
</tr>
<tr>
<td>Photon-finding efficiency</td>
<td>2%</td>
</tr>
<tr>
<td>J/ψ signal/sideband definition</td>
<td>2%</td>
</tr>
<tr>
<td>π⁰ veto</td>
<td>3%</td>
</tr>
<tr>
<td>QED contamination</td>
<td>1%</td>
</tr>
<tr>
<td>Fitting systematics</td>
<td>6%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>11.2%</td>
</tr>
</tbody>
</table>