Charmonium production in two-photon processes at Belle

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Belle Collaboration

Measurements of $\gamma\gamma \rightarrow \pi^0\pi^0$
and other charmonium production processes

Resonance formation from two-photon collisions

Two-photon collisions at an $e^+e^-$ collider

(Quasi-real; $|q^2|<0.001\text{GeV}^2$, with zero-tag condition)

with $\gamma\gamma$ c.m. energy $W \equiv W_{\gamma\gamma} = 0.6 - 4.5\ \text{GeV}$ at KEKB/Belle

Quantum numbers

Charge = 0, Charge conjugation = + (even)
Spin-parity -- 0+, 0-, 2+, 2-, 3+, 4+, 4-, 5+ .... (real photon)

$$\pi, \eta, f_J, a_J, \eta_c, \chi_{cJ} \ J \neq 1$$

Measurement

Cross section $\sim$ Two-photon decay width $\times$ Branching fraction

Two-photon coupling – internal quark structure to the final state

Decay properties --- ratio of branching fractions

(Low background, “totally exclusive” measurement)
KEKB Accelerator and Belle Detector

- **Asymmetric e⁻ e⁺ collider**
  - 8 GeV e⁻ (HER) x 3.5 GeV e⁺ (LER)
  - $\sqrt{s}=10.58$ GeV $\Leftrightarrow \Upsilon(4S)$
  - Beam crossing angle: 22 mrad

- **Continuous injection**

- **Luminosity**
  - $L_{\text{max}} = 1.71 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - $\int L \, dt \sim 870 \text{ fb}^{-1}$ (2008-Nov)

- **High momentum/energy resolutions**
  - CDC+Solenoid, CsI(Tl)
  - Vertex measurement – Si strips
  - Particle identification
    - TOF, Si-aerogel, CDC-dE/dx,
    - RPC for $K_L$/muon

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\[ \gamma \gamma \rightarrow \pi^0 \pi^0 \]

Measurement of Differential Cross Section

in $0.6 \text{ GeV} < W < 4.1 \text{ GeV}$, $|\cos \theta^*| < 0.8$

Belle, P.R.D 78, 052004 (2008) $95 \text{ fb}^{-1}$

Physics

$W = 0.9 – 2.4 \text{ GeV}$ -- Light-quark resonances
$W > 2.4 \text{ GeV}$ -- Charmonia and QCD

Comparison with $\pi^+ \pi^-$, $K\bar{K}$

Isospin (or SU(3)) invariance in resonance decays and QCD

Interference effects
Trigger and Selection

**Trigger**

Purely neutral

\[ E_{\text{total}}(\text{ECL}) > 1.1 \text{ GeV} \]

4 or more clusters

\[ (>120 \text{ MeV}) \]

**Selection**

- Only 4 photons visible
  - Triggered by CsI calorimeter
  - No reconstructed track with \( p_t > 0.1 \text{ GeV/c} \)

- Just 2 \( \pi^0 \)s with \( E_\gamma > 70 \text{ MeV} \),
  \( p_t > 0.15 \text{ GeV/c} \)

- Transverse-momentum\((p_t)\)-balance of
  the two \( \pi^0 \)s  
  \[ |\Sigma p_t| < 0.05 \text{ GeV/c} \]

Candidate events of

\[ \gamma \gamma \rightarrow f_2(1270) \rightarrow \pi^0 \pi^0 \]
Cross sections

Consistent with Crystal-Ball Measurement (red: Belle, black: Crystal-Ball)

Angular dependence of Differential Cross Section

Preliminary
Charmonium extraction

Fits with and without interference between $\chi_{c0}$ and the continuum

Angular dependence of Observed cross section in the charmonium region
Forward peak – non-resonant (QCD)

Estimated $\chi_{cJ}$ contribution

Statistical significances
$\chi_{c0}: 7.3\sigma, 7.6\sigma$; $\chi_{c2}: 1.3\sigma, 2.6\sigma$
Results and comparison with $\pi^+\pi^-$

Fit function

\[
Y(W) = |\sqrt{\alpha k W^{-\beta}} + e^{i\phi} \sqrt{N_{\chi_{c0}} BW_{\chi_{c0}}(W)}|^2 + N_{\chi_{c2}} |BW_{\chi_{c2}}(W)|^2 + \alpha(1-k)W^{-\beta}
\]

Free parameters: $k$ – interfering fraction between $\chi_{c0}$ and continuum
$\phi$ – relative phase of the above interference
$\alpha, \beta$ -- normalization and slope parameters of the continuum
$N_{\chi_{c0}}, N_{\chi_{c2}}$ – charmonia yields

<table>
<thead>
<tr>
<th>Interference</th>
<th>$\Gamma_{\gamma\gamma} B(\chi_{c0})$ (eV)</th>
<th>$\Gamma_{\gamma\gamma} B(\chi_{c2})$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>without</td>
<td>$9.7 \pm 1.5 \pm 1.0$</td>
<td>$0.18^{+0.15}_{-0.14} \pm 0.03$</td>
</tr>
<tr>
<td>with</td>
<td>$9.9^{+5.8}_{-4.0} \pm 1.0$</td>
<td>$0.48 \pm 0.18 \pm 0.05 \pm 0.14$</td>
</tr>
</tbody>
</table>

Preliminary

Uncertainty from interference

Isospin invariance in $\chi_{cJ} \rightarrow \pi\pi$ decays is OK

$\pi^+\pi^-$ mode

\[
\begin{align*}
\Gamma_{\gamma\gamma} B(\chi_{c0}) & (eV) \\
\Gamma_{\gamma\gamma} B(\chi_{c2}) & (eV)
\end{align*}
\]

\[
\begin{align*}
15.1 \pm 2.1 \pm 2.3 \\
0.76 \pm 0.14 \pm 0.11
\end{align*}
\]

Ratio 1:2 for $\pi^0\pi^0/\pi^+\pi^-$ predicted

Belle, PLB 615, 39 (2005)
Light-quark resonances: $f_4(2050)\\?$: J=4

Decomposition to an orthogonal system

$$\frac{d\sigma}{d|\cos \theta^*|} \approx S Y_0^0 + D_0 Y_2^0 + G_0 Y_4^0 + D_2 Y_2^2 + G_2 Y_4^2$$

Including a tensor ($f_2(1950)$) and a J = 4 ($f_4(2050)$) etc.

**Preliminary**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>With $f_2(Z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All included</td>
</tr>
<tr>
<td>Mass($f_4(2050)$)</td>
<td>1935$^{+12}_{-14}$</td>
</tr>
<tr>
<td>$\Gamma_{\pi\pi}(f_4(2050))$</td>
<td>369$^{+17}_{-22}$</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma}(f_4(2050))$</td>
<td>45$^{+11}_{-19}$</td>
</tr>
<tr>
<td>mass($f_2(1950)$)</td>
<td>1852$^{+23}_{-20}$</td>
</tr>
<tr>
<td>$\Gamma_{\pi\pi}(f_2(1950))$</td>
<td>347$^{+23}_{-20}$</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma}(\pi^0\pi^0)$</td>
<td>9.2$^{+4.8}_{-2.6}$</td>
</tr>
<tr>
<td>mass($f_2(Z)$)</td>
<td>1526$^{+19}_{-9}$</td>
</tr>
<tr>
<td>$\Gamma_{\pi\pi}(f_2(Z))$</td>
<td>121$^{+9}_{-1}$</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma}(\pi^0\pi^0)$</td>
<td>17.5$^{+2.8}_{-2.6}$</td>
</tr>
<tr>
<td>$B_{f_2(1525)}(\gamma\gamma)$</td>
<td>1.11</td>
</tr>
<tr>
<td>$\chi^2/(ndf)$</td>
<td>485.0 (450)</td>
</tr>
</tbody>
</table>

Importance of G-wave in 1.7-2.3 GeV range
Is $f_0(980)$ a $q\bar{q}$ meson? ← Seems to be unlikely

Two-photon decay width is one of the most important physics observables

Observed in each of $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow \pi^0\pi^0$ as a small but significant peak

Smaller than $uu/dd$-meson predictions

Consistent with $ss$ and some exotic hypotheses
Charmonia production in decays to four-meson final states

$\gamma \gamma \to \text{charmonium} \to 4 \text{ mesons}$

$\pi^+\pi^-\pi^+\pi^-$
including $\rho \pi \pi$, $f_2 f_2$ etc.

$K^+K^-\pi^+\pi^-$
including $K^*\bar{K}^*$, $f_2 f'_2$ etc.

$K^+K^-K^+K^-$
including $\phi \phi$

Belle EPJ C53, 1 (2008)
$\gamma\gamma \rightarrow \eta_c\ (1S,\ 2S) \rightarrow K^0_S K\pi$

Interference between charmonium and continuum is not taken into account. B($\eta_c\ (2S) \rightarrow KsK\pi$) is assumed to be equal to B($\eta_c\ (1S) \rightarrow KsK\pi$).
Summary of $\eta_c$ production and its decays

U08: Belle EPJ C53, 1 (2008),

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma \gamma \gamma$ BF (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$40.7 \pm 3.7 \pm 5.3$</td>
<td>U08</td>
</tr>
<tr>
<td>$\pi^+ \pi^- K^+ K^-$</td>
<td>$25.7 \pm 3.2 \pm 4.9$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^+ K^- K^+ K^-$</td>
<td>$5.6 \pm 1.1 \pm 1.6$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^* K^*$</td>
<td>$32.4 \pm 4.2 \pm 5.8$</td>
<td>U08</td>
</tr>
<tr>
<td>$f_2 f_2$</td>
<td>$69 \pm 17 \pm 12$</td>
<td>U08</td>
</tr>
<tr>
<td>$f_2 f_2'$</td>
<td>$49 \pm 9 \pm 13$</td>
<td>U08</td>
</tr>
<tr>
<td>$\phi \phi$</td>
<td>$6.8 \pm 1.2 \pm 1.3$</td>
<td>U08</td>
</tr>
<tr>
<td>$\rho \rho$</td>
<td>$&lt; 39$</td>
<td>U08</td>
</tr>
</tbody>
</table>
\( \eta_c \) production and its decays (2)

K05: PL B621, 41 (2005), BC0673: hep-ex/0609048

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>( \Gamma_{\gamma\gamma} \text{ BF (eV)} )</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{p}p )</td>
<td>( 7.20 \pm 1.53 \pm 0.75 )</td>
<td>K05</td>
</tr>
<tr>
<td>( \Lambda\Lambda )</td>
<td>( 6.21 \pm 1.01 \pm 0.52 )</td>
<td>Preliminary BC0673</td>
</tr>
<tr>
<td>( \Sigma^0\bar{\Sigma}^0 )</td>
<td>( 9.80 \pm 2.50 \pm 1.03 )</td>
<td>Preliminary BC0673</td>
</tr>
<tr>
<td>( K^0_sK^-\pi^+ \text{ c.c.} )</td>
<td>( 142.1 \pm 3.8 \pm 11.2 )</td>
<td>Preliminary</td>
</tr>
</tbody>
</table>

Ratios among BF’s are not very consistent with previous BF measurements (mainly done with \( J/\psi \) decay experiments). Especially between the four-meson final states and the other modes. Interference effects are large?
Summary of $\chi_{c0}$ production and its decays

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma_{\gamma\gamma}$ BF (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>$44.7 \pm 3.6 \pm 4.9$</td>
<td>U08</td>
</tr>
<tr>
<td>$\pi^+\pi^-K^+K^-$</td>
<td>$38.8 \pm 3.7 \pm 4.7$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^+K^-K^+K^-$</td>
<td>$7.9 \pm 1.3 \pm 1.1$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^<em>K^</em>$</td>
<td>$&lt;18$</td>
<td>U08</td>
</tr>
<tr>
<td>$\phi\phi$</td>
<td>$2.3 \pm 0.9 \pm 0.4$</td>
<td>U08</td>
</tr>
<tr>
<td>$\rho\rho$</td>
<td>$&lt;12$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^*K^+K^- + c.c.$</td>
<td>$16.7 \pm 6.1 \pm 3.0$</td>
<td>U08</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>$15.1 \pm 2.1 \pm 2.3$</td>
<td>N05</td>
</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>$9.9 \pm 5.8 \pm 4.0 \pm 1.6$</td>
<td>Preliminary</td>
</tr>
<tr>
<td>$K^+K^-$</td>
<td>$14.3 \pm 1.6 \pm 2.3$</td>
<td>N05</td>
</tr>
<tr>
<td>$K^0_SK^0_S$</td>
<td>$7.00 \pm 0.65 \pm 0.71$</td>
<td>C07</td>
</tr>
</tbody>
</table>

These results are consistent with previous and recent BF measurements.

Summary of $\chi_{c2}$ production and its decays


<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma\gamma\gamma$ BF (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-\pi^+\pi^-$</td>
<td>$5.01 \pm 0.44 \pm 0.55$</td>
<td>U08</td>
</tr>
<tr>
<td>$\pi^+\pi^-K^+K^-$</td>
<td>$4.42 \pm 0.42 \pm 0.53$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^+K^-K^+K^-$</td>
<td>$1.10 \pm 0.17 \pm 0.27$</td>
<td>U08</td>
</tr>
<tr>
<td>$\phi\phi$</td>
<td>$2.4 \pm 0.5 \pm 0.8$</td>
<td>U08</td>
</tr>
<tr>
<td>$\rho\rho$</td>
<td>$0.58 \pm 0.18 \pm 0.16$</td>
<td>U08</td>
</tr>
<tr>
<td>$\rho^0\pi^+\pi^-$</td>
<td>$3.2 \pm 1.9 \pm 1.5$</td>
<td>U08</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>$0.76 \pm 0.14 \pm 0.11$</td>
<td>N05</td>
</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>$0.48 \pm 0.18 \pm 0.16$</td>
<td>Preliminary</td>
</tr>
<tr>
<td>$K^+K^-$</td>
<td>$0.44 \pm 0.11 \pm 0.07$</td>
<td>N05</td>
</tr>
<tr>
<td>$K^0_SK^0_S$</td>
<td>$0.31 \pm 0.05 \pm 0.03$</td>
<td>C07</td>
</tr>
<tr>
<td>$\gamma J/\psi$</td>
<td>$114 \pm 11 \pm 9$</td>
<td>A02</td>
</tr>
</tbody>
</table>

These results are consistent with previous and recent BF measurements.

\[ \gamma\gamma \rightarrow \rho^0\rho^0 \]

\[ \gamma\gamma \rightarrow \chi_{c2} \rightarrow \gamma J/\psi \]
$\eta_c(2S)$ and $\chi_{c2}(2P)$

U06: PRL 96, 082003 (2006)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Gamma_{\gamma\gamma}$ BF (eV)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^- \pi^+ \pi^-$</td>
<td>$&lt; 6.5$</td>
<td>U08</td>
</tr>
<tr>
<td>$\pi^+ \pi^- K^+ K^-$</td>
<td>$&lt; 5.0$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^+ K^- K^+ K^-$</td>
<td>$&lt; 2.9$</td>
<td>U08</td>
</tr>
<tr>
<td>$K^0_S K^- \pi^+ +$ c.c.</td>
<td>$11.2 \pm 2.4 \pm 1.3$</td>
<td>Preliminary</td>
</tr>
<tr>
<td>$D \bar{D}$</td>
<td>$180 \pm 50 \pm 30$</td>
<td>U06</td>
</tr>
</tbody>
</table>

$\eta_c(2S)$

$\chi_{c2}(2P) = \frac{Z(3930)}{Z(3930)}$

Fit giving a 90% CL upper limit for the $\eta_c(2S)$ yield
Summary

Recent measurement/publication from Belle

\[ \gamma \gamma \rightarrow \pi^0\pi^0 \text{ in } 0.6 - 4.1 \text{ GeV} \]

\[ \chi_{c0} \rightarrow \pi^0\pi^0 \text{ and } \]
\[ f_0(980) \rightarrow \pi^0\pi^0 \text{ are observed} \]

\[ \gamma \gamma \rightarrow \text{charmonium} \rightarrow 4 \text{ mesons} \]
(combination of charged pions and charged kaons)

Many decay modes of the \( \eta_c, \chi_{c0}, \chi_{c2} \) are measured.
No significant \( \eta_c(2S) \) signal is observed in these channels
(Only seen in \( K_S^0K\pi \) mode)

Belle provides products of two-photon decay width and branching fractions for numbers of decay modes
Systematic research on \( \Gamma_{\gamma\gamma} \) and Ratio of the BF’s are possible.
Hadron production from two quasi-real photons

(\(|q^2|<0.001\text{GeV}^2\), with zero-tag condition)

Exclusive processes with \(\gamma\gamma\) c.m. energy

\(W=0.6 - 4.5\text{ GeV}\) at KEKB/Belle

Wide energy region --- Various physics aspects can be studied simultaneously.

**Light-quark resonances, charmonia**

Perturbative /Non-perturbative QCD, Hadron production mechanism
Event display, efficiency

Candidate events of $\gamma\gamma \rightarrow f_2(1270) \rightarrow \pi^0\pi^0$

Event only consisting of four photons

Efficiently detected, well reconstructed and clearly identified

Energy and Angular dependence of efficiency
$\pi^0\pi^0$ mass spectra from other experiments (BES, GAMS)

Similar structures around 1.4 GeV - 2.3 GeV are seen in the BES measurement of the radiative $J/\psi$ decay to $\gamma\pi^0\pi^0$. BES, PL B 642, 441 (2006)

Any resonance attributes of the peak structure near 1.7 GeV is as $f_0(1710)$.

GAMS, $\pi^0\pi^0$ production from $\pi N$ scattering
The partial-wave analysis shows a $J=4$ meson near 1.9 GeV.

GAMS, EPJ A3, 361 (1998)
Two-body invariant-mass distributions in $\eta_c$ region

Black – peak region
Blue -- sideband region