Overview of the BESIII results

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For BESIII Collaboration

Institute of High Energy Physics

Meson2012, 31st May-5th June, Krakow, Poland
Outline

• Status of BEPCII/BESIII

• Highlight of BESIII results
  – Light hadrons spectroscopy
  – Charmonium transitions and decays
  – Charm decays

• Summary
Bird view of BEPCII/BESIII

- Linac
- Storage ring
- BESIII detector
- BSRF
- Beijing electron positron collider BEPCII
- Beam energy 1.0-2.3 GeV
  Energy spread: $5.16 \times 10^{-4}$
- Design luminosity
  $1 \times 10^{33}/\text{cm}^2/\text{s} @ \psi(3770)$

IHEP, Beijing

2004: start BEPCII construction
2008: test run of BEPCII
2009-now: BEPCII/BESIII data taking
Drift Chamber (MDC)
\( \sigma_{P/P} (0/0) = 0.5\% (1 \text{GeV}) \)
\( \sigma_{dE/dx} (0/0) = 6\% \)

Time Of Flight (TOF)
\( \sigma_T : 90 \text{ ps Barrel} \)
\( 110 \text{ ps endcap} \)

EMC:
\( \sigma_{E/\sqrt{E}} (0/0) = 2.5 \% (1 \text{ GeV}) \)
(Csl)
\( \sigma_{z,\phi} (\text{cm}) = 0.5 - 0.7 \text{ cm/VE} \)

Super-conducting magnet (1.0 tesla)
\( \mu\text{Counter} \)
8-9 layers RPC
\( \delta R\Phi=1.4 \text{ cm} \sim 1.7 \text{ cm} \)
The BESIII Collaboration

>300 physicists
50 institutions from 10 countries

http://bes3.ihep.ac.cn

US (6)
Univ. of Hawaii
Univ. of Washington
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (11)
Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINF Novosibirsk
Italy: Univ. of Torino, Frascati Lab
Netherlands: KVI/Univ. of Groningen
Turkey: Turkey Accelerator Center

Korea (1)
Seoul Nat. Univ.

Japan (1)
Tokyo Univ.

Pakistan (1)
Univ. of Punjab

China (30)
IHEP, CCAST, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ.,
Zhongshan Univ., Nankai Univ.
Shanxi Univ., Sichuan Univ
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Hong Kong Univ., Hong Kong Chinese Univ.

Univ. of South China, GUCAS.
BESIII commissioning

- July 19, 2008: first $e^+e^-$ collision event in BESIII
- Nov. 2008: ~14M $\psi(2S)$ events for detector calibration
- 2009: 106M $\psi(2S)$ 4×CLEOc
- 225M $J/\psi$ 4×BESII
- 2010: 900 pb$^{-1}$ $\psi(3770)$
- 2011: 2000 pb$^{-1}$ $\psi(3770)$
- 470 pb$^{-1}$ @ 4.01 GeV
- 2012: tau mass measurement
  $\psi(2S)$: 0.3 billion; $J/\psi$: from ~April 1

World’s largest samples of $J/\psi$, $\psi(2S)$ and $\psi(3770)$ (and still growing)

Peak luminosity reached $6.5 \times 10^{32}$ @3770 MeV
Physics Programs @ BESIII

**Light hardron physics**
- meson & baryon spectroscopy
- threshold effects
- multiquark states
- glueballs & hybrids
- two-photon physics
- form-factors

**Charm physics:**
- (semi-)leptonic form factors
- $f_D$ & $f_{Ds}$ decay constants.
- CKM matrix: $V_{cd}$, $V_{cs}$
- $D^0$-$D^0$ mixing and CPV
- strong phases

**Charmonium physics:**
- precision spectroscopy
- transitions and decays

**QCD & τ -physics:**
- precision $R$-measurement
- τ mass / τ decays

**XYZ meson physics:**
- $Y(4260)$ππ$\eta_c$ decays
Recent Results on Light Hadron Spectroscopy

• $p\bar{p}$ mass threshold structure in $J/\psi \rightarrow \gamma p\bar{p}$
• $X(1835)$ and two new structures in $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$
• $\eta(1405)$ in $J/\psi \rightarrow \gamma f_0(980)\pi^0, f_0(980) \rightarrow 2\pi$
• PWA of $J/\psi \rightarrow \gamma \eta\eta$
• PWA of $J/\psi \rightarrow \gamma \omega\phi$
Observation of $X(p\bar{p})$ @ BESII

\[ J / \psi \rightarrow \gamma p\bar{p} \]

Theoretical interpretation:
- conventional meson?
- $p\bar{p}$ bound state/multiquark
- glueball
- Final state interaction (FSI)
- ...

$M=1859 \pm 3 \pm 5$ MeV/$c^2$
$\Gamma < 30$ MeV/$c^2$ (90% CL)

PRL 91 (2003) 022001
Confirmation @ BESIII and CLEOc

Fit with one resonance at BESII did:

\[ \psi' \rightarrow \pi^+ \pi^- J/\psi, J/\psi \rightarrow \gamma p\bar{p} \]

M = 1861^{+6}_{-13} {+7}_{-26} \text{ MeV/c}^2

\[ \Gamma < 38 \text{ MeV/c}^2 \text{ (90\% CL)} \]

Several non-observations

$\gamma(1S) \rightarrow \gamma \, p\bar{p}$ @ CLEO

$J/\psi \rightarrow \omega \, p\bar{p}$ @ BESII

$\psi' \rightarrow \gamma \, p\bar{p}$ @ BESII

$\psi(2S) \rightarrow \gamma \, p\bar{p}$ @ CLEO

Pure FSI interpretation is disfavored
PWA of $J/\psi \rightarrow \gamma p\bar{p}$ @ BESIII

- PWA of $J/\psi \rightarrow \gamma p\bar{p}$ was first performed
- The fit with a BW and S-wave FSI($I=0$) factor can well describe ppb mass threshold structure.
- It is much better than that without FSI effect, and $\Delta 2\ln L = 51$ ($7.1\sigma$)
- Different FSI models $\rightarrow$ Model dependent uncertainty

- Spin-parity, mass, width and B.R. of $X(pp\bar{p})$: $J^{pc} = 0^{-+}$

\[ M = 1832_{-5}^{+19} \text{ (stat)}_{-17}^{+18} \text{ (syst)} \pm 19 \text{(mod) MeV}/c^2 \]
\[ \Gamma = 13 \pm 20 \text{ (stat)}_{-33}^{+11} \text{ (syst)} \pm 4 \text{(mod) MeV}/c^2 \text{ or } \Gamma < 76 \text{ MeV}/c^2 \text{ @ } 90\% \text{ C.L.} \]
\[ B(J/\psi \rightarrow \gamma X(pp\bar{p}))B(X(pp\bar{p}) \rightarrow pp\bar{p}) = (9.0_{-1.1}^{+0.4} \text{ (stat)}_{-5.0}^{+1.5} \text{ (syst)} \pm 2.3 \text{(mod)}) \times 10^{-5} \]
M_{p\bar{p}} threshold structure of $\psi' \rightarrow \gamma p\bar{p}$ @ BESIII

Obviously different line shape of $p\bar{p}$ mass spectrum near threshold from that in $J/\psi$ decays.

PWA results:
- Significance of $X(p\bar{p})$ is > 6.9\(\sigma\).
- The production ratio $R$:

$$R = \frac{B(\psi' \rightarrow \gamma X(p\bar{p}))}{B(J/\psi \rightarrow \gamma X(p\bar{p}))} = \frac{5.08^{+0.71}_{-0.45} \text{(stat)}^{+0.67}_{-3.58} \text{(syst)} \pm 0.12 \text{(mod)}}{\%}$$

- It is suppressed compared with “12% rule”.

PWA Projection:

PRL 108,112003(2012)
Observation of X(1835) at BESII

**BESII results** (Statistical significance \( \sim 7.7\sigma \)):

\[ M = 1833.7 \pm 6.1\,(\text{stat}) \pm 2.7\,(\text{syst})\text{MeV} / c^2 \]

\[ \Gamma = 67.7 \pm 20.3\,(\text{stat}) \pm 7.7\,(\text{syst})\text{MeV} / c^2 \]

\[ B(J / \psi \rightarrow \gamma X(1835)) B(X(1835) \rightarrow \pi^+ \pi^- \eta') = (2.2 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{syst})) \times 10^{-4} \]

**Theoretical interpretation:**

- pp\(\bar{p}\) bound state
- \(\eta\) excitation
- ....
- Whether are X(pp\(\bar{p}\)) and X(1835) from the same source?
X(1835) in $J/\psi \rightarrow \gamma \pi^+\pi^-\eta'$ at BESIII

<table>
<thead>
<tr>
<th>resonance</th>
<th>$M$ (MeV/c²)</th>
<th>$\Gamma$ (MeV/c²)</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1835)</td>
<td>1836.5 ± 3.0</td>
<td>190.1 ± 9.0</td>
<td>$&gt;&gt; 20\sigma$</td>
</tr>
<tr>
<td>X(2120)</td>
<td>2122.4 ± 6.7</td>
<td>84 ± 16</td>
<td>$&gt; 7.2\sigma$</td>
</tr>
<tr>
<td>X(2370)</td>
<td>2376.3 ± 8.7</td>
<td>83 ± 17</td>
<td>$&gt; 6.4\sigma$</td>
</tr>
</tbody>
</table>

For the X(1835):

$$BR(J/\psi \rightarrow \gamma X(1835)) \cdot BR(X(1835) \rightarrow \pi^+\pi^-\eta') = (2.87 \pm 0.09(stat)^{+0.49}_{-0.52}(syst)) \times 10^{-4}$$

The polar angle of the photon in J/psi center of mass system is consistent with expectation for a pseudoscalar

PWA is needed, inference among the resonances needs to be considered.
Why are $X(2120)/X(2370)$ interesting?

- It is the first time in $J/\psi$ radiative decays resonant structures are observed in the 2.4 GeV/$c^2$ region, it is interesting since:
  - LQCD predicts that the lowest lying pseudoscalar glueball: around 2.4 GeV/$c^2$.
  - $J/\psi \rightarrow \gamma \pi\pi\eta'$ decay is a good channel for finding $0^{-+}$ glueballs.

- Nature of $X(2120)/X(2370)$ pseudoscalar glueball?
  - $\eta/\eta'$ excited states?
  - $\Delta\Delta$ bound state?

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References:

- PRD73,014516 (2006) Y.Chen et al
- PRD82,074026,2010 (J.F. Liu, G.J. Ding and M.L.Yan)
- PRD83:114007,2011 (J.S. Yu, Z.-F. Sun, X. Liu, Q. zhao), and more...
Anomalous line shape of $f_0(980)$ in $J/\psi \rightarrow \gamma 3\pi$

\[ M = 989.9 \pm 0.4 \text{MeV}/c^2 \]
\[ \Gamma = 9.5 \pm 1.1 \text{MeV}/c^2 \]

Surprising result:

very narrow $f_0(980)$ width: $< 11.8 \text{MeV}/c^2$ at 90% C.L.
much narrower than the world average (PDG 2010: 40-100 MeV/c^2)

A possible explanation is $KK^*$ loop, Triangle Singularity (TS) (J.J. Wu et al, PRL 108, 081803(2012))
First observed: $\eta(1405) \rightarrow f_0(980)\pi^0$ (Large isospin breaking):

$$\frac{BR(\eta(1405) \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{BR(\eta(1405) \rightarrow a_0(980)\pi^0 \rightarrow \pi^0\pi^0\eta)} \approx (17.9 \pm 4.2)\%$$

$\xi_{af} = \frac{Br(\chi_{c1} \rightarrow f_0(980)\pi^0 \rightarrow \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \rightarrow a_0(980)\pi^0 \rightarrow \eta\pi^0\pi^0)} < 1\% (90\% C.L.)$

$a_0$-$f_0$ mixing alone can not explain the branching ratio of $\eta(1405)$
New results on $\eta' \rightarrow 3\pi$

Comparison: Isospin violations in $\eta' \rightarrow \pi\pi\pi$

\[
\frac{BR(\eta' \rightarrow \pi^+\pi^-\pi^0)}{BR(\eta' \rightarrow \pi^+\pi^-\eta)} \approx 0.9\%, \quad \frac{BR(\eta' \rightarrow \pi^0\pi^0\pi^0)}{BR(\eta' \rightarrow \pi^0\pi^0\eta)} \approx 1.6\%
\]

New results:

$Br(\eta' \rightarrow \pi^+\pi^-\pi^0) = (3.83 \pm 0.15 \pm 0.39) \times 10^{-3}$ (PDG2010: $(3.6_{-0.93}^{+1.1}) \times 10^{-3}$)

$Br(\eta' \rightarrow \pi^0\pi^0\pi^0) = (3.56 \pm 0.22 \pm 0.34) \times 10^{-3}$ (PDG2010: $(1.68\pm0.22) \times 10^{-3}$)

For the decay $\eta' \rightarrow \pi^0\pi^0\pi^0$, it is two times larger than the world average value.

PRL 108, 182001 (2012)
Study of \( \eta \eta \) system

- First observed \( f_0(1710) \) from \( J/\psi \) radiative decays to \( \eta \eta \) by Crystal Ball in 1982.
- LQCD predicts:
  \[
  0^{++} : 1710 \pm 50 \pm 80
  \]

- Crystal Barrel Collaboration (2002) analyzed the three final states \( \pi^0\pi^0\pi^0 \), \( \eta\pi^0\pi^0 \) and \( \pi^0\eta\eta \) with K matrix formalism. Found a \( 2^{++} \) (~1870), but no \( f_0(1710) \).
- E835 (2006): \( pp\overline{p} \rightarrow \pi^0\eta\eta \), found \( f_0(1500) \) and \( f_0(1710) \).
- WA102 and GAMS all identified \( f_0(1710) \) in \( \eta\eta \).
Preliminary PWA results of $J/\psi \rightarrow \gamma \eta \eta$ @BESIII

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV/c²)</th>
<th>$B(J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta)$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(1500)$</td>
<td>$1468^{+14}_{-15}$</td>
<td>$136^{+41}_{-26}$</td>
<td>$(1.61^{+0.29}_{-0.32} \times 10^{-5})$</td>
<td>$8.2 \sigma$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$1759^{+6}_{-6}$</td>
<td>$4.10^{+13}_{-13}$</td>
<td>$(2.35^{+0.07}_{-0.07} \times 10^{-6})$</td>
<td>$25.0 \sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
<td>$2081^{+13}_{-13}$</td>
<td>$273^{+27}_{-21}$</td>
<td>$(9.99^{+0.57}_{-0.52} \times 10^{-5})$</td>
<td>$13.9 \sigma$</td>
</tr>
<tr>
<td>$f_2'(1525)$</td>
<td>$1513^{+5}_{-5}$</td>
<td>$75^{+12}_{-18}$</td>
<td>$(3.41^{+0.43}_{-0.50} \times 10^{-5})$</td>
<td>$11.0 \sigma$</td>
</tr>
<tr>
<td>$f_2(1810)$</td>
<td>$1822^{+29}_{-24}$</td>
<td>$229^{+29}_{-25}$</td>
<td>$(5.38^{+0.60}_{-0.67} \times 10^{-5})$</td>
<td>$6.4 \sigma$</td>
</tr>
<tr>
<td>$f_2(2340)$</td>
<td>$2362^{+31}_{-30}$</td>
<td>$33^{+31}_{-16}$</td>
<td>$(5.58^{+0.61}_{-0.65} \times 10^{-5})$</td>
<td>$7.6 \sigma$</td>
</tr>
</tbody>
</table>

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars
- $f_0(1500)$ exists (8.2 $\sigma$)
- $f_2'(1525)$ is the dominant tensor
M_{ωΦ} threshold enhancement in J/ψ→γωΦ

\[ \text{BESII} \]

PRL 96(2006) 162002

For X(1810):

\[ M = 1812^{+19}_{-26} \pm 18 \text{ MeV/c}^2 \]
\[ \Gamma = 105 \pm 20 \pm 28 \text{ MeV/c}^2 \]

\[ J^{pc} \text{ favors } 0^{++} \text{ over } 0^{-+} \text{ and } 2^{++} \]

\[ J / ψ → γωΦ \text{ (DOZI)} \]
Preliminary PWA results of $J/\psi \rightarrow \gamma \omega \Phi$ @BESIII

<table>
<thead>
<tr>
<th>Meson</th>
<th>$J^{PC}$</th>
<th>$M$(MeV/$c^2$)</th>
<th>$\Gamma$(MeV/$c^2$)</th>
<th>Events</th>
<th>$\Delta S$</th>
<th>$\Delta ndf$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(1810)$</td>
<td>$0^{++}$</td>
<td>1795 $\pm$ 7</td>
<td>95 $\pm$ 10</td>
<td>1319 $\pm$ 52</td>
<td>783</td>
<td>4</td>
<td>$&gt;30\sigma$</td>
</tr>
<tr>
<td>$f_2(1950)$</td>
<td>$2^{++}$</td>
<td>1944</td>
<td>472</td>
<td>665 $\pm$ 40</td>
<td>211</td>
<td>2</td>
<td>$&gt;10\sigma$</td>
</tr>
<tr>
<td>$f_0(2020)$</td>
<td>$0^{++}$</td>
<td>1992</td>
<td>442</td>
<td>715 $\pm$ 45</td>
<td>100</td>
<td>2</td>
<td>$&gt;10\sigma$</td>
</tr>
<tr>
<td>$\eta(2225)$</td>
<td>$0^{--}$</td>
<td>2240</td>
<td>190</td>
<td>70 $\pm$ 30</td>
<td>23</td>
<td>2</td>
<td>6.4$\sigma$</td>
</tr>
<tr>
<td>Phase space</td>
<td>$0^{--}$</td>
<td>2400</td>
<td>5000</td>
<td>319 $\pm$ 24</td>
<td>45</td>
<td>2</td>
<td>$&gt;8\sigma$</td>
</tr>
</tbody>
</table>

Is $X(1810)$ the $f_0(1710)/f_0(1790)$ or new state?
Recent results on Charmonium spectroscopy

• Properties of $h_c$

• Mass and width of $\eta_c$

• Observation evidence of $\psi'\rightarrow\gamma\eta_c(2S)$

• First observation of $\psi'\rightarrow\gamma\gamma J/\psi$

• Multipole in $\psi'\rightarrow\gamma\chi_{c2}$
First evidence:
E835 in pp → h_c → γη_c (PRD72, 092004(2005))

CLEO-c observed h_c in ee → ψ' → π^0 h_c, h_c → γη_c
ΔM_{hf}(1P)=0.08±0.18±0.12 MeV/c^2
(PRL104, 132002(2010))

Study isospin forbidden transition:

Measure as well the E1 transition:

M(h_c) gives access to hyperfine splitting of 1P states:
ΔM_{hf}(1P)=M(h_c)−1/9(M(χ_c0)+3M(χ_c1)+5M(χ_c2))
\( \psi' \to \pi^0 h_c \) @ BESIII

- Select inclusive \( \pi^0 (\psi' \to \pi^0 h_c) \)
- Select E1-photon in \( h_c \to \gamma \eta_c \) (w/o E1 tagged)
- E1-tagged selection gives
  \[ M(h_c) = 3525.40 \pm 0.13 \pm 0.18 \text{MeV} \]
  \[ (\Delta M_{hf}(1P) = 0.10 \pm 0.13 \pm 0.18 \text{MeV/c}^2) \]
  \[ \Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28 \text{MeV} \] (first measurement)
  \(< 1.44 \text{MeV} \) at 90% CL

- \( \text{Br}(\psi' \to \pi^0 h_c) \times \text{Br}(h_c \to \gamma \eta_c) = (4.58 \pm 0.40 \pm 0.50) \times 10^{-4} \)

- E1-untagged selection gives
  \[ \text{Br}(\psi' \to \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \times 10^{-4} \]

- Combining branching fractions leads to
  \[ \text{Br}(h_c \to \gamma \eta_c) = (54.3 \pm 6.7 \pm 5.2)\% \]
  (first measurement)

*PRL104, 132002, (2010)*
$\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$, $\eta_c$ exclusive decays @ BESIII

Simultaneous fit to $\pi^0$ recoiling mass
$\chi^2$/d.o.f. = 32/46
Mass = $3525.31 \pm 0.11 \pm 0.15$ MeV/c$^2$
Width = $0.70 \pm 0.28 \pm 0.25$ MeV

Consistent with BESIII inclusive results PRL104, 132002(2010)
CLEOc exclusive results
$M(h_c) = 3525.21 \pm 0.27 \pm 0.14$ MeV/c$^2$
$N = 136 \pm 14$
PRL101, 182003(2008)
\( \eta_c(1S) \)

- The lowest lying S-wave spin singlet charmonium, discovered in 1980 by MarkII
- Parameters:
  - \( J/\psi, \psi' \) radiative transition: \( M \sim 2978.0 \text{MeV}/c^2, \quad \Gamma \sim 10 \text{MeV} \)
  - \( \gamma\gamma \) process: \( M = 2983.1 \pm 1.0 \text{MeV}/c^2, \quad \Gamma = 31.3 \pm 1.9 \text{MeV} \)
Relative phase $\phi$ values from each mode are consistent within $3\sigma$,

$\Rightarrow$ use a common phase value in the simultaneous fit.

$M: 2984.4 \pm 0.5 \pm 0.6$ MeV

$\Gamma: 30.5 \pm 1.0 \pm 0.9$ MeV

$\phi: 2.35 \pm 0.05 \pm 0.04$ rad
Comparison of the mass and width for $\eta_c$

The world average in PDG2010 was using earlier measurements

Hyperfine splitting: $\Delta M(1S) = 112.6 \pm 0.8$ MeV

Consistent with B factory results in other production mechanisms. Agree with lattice QCD calculations of the charmonium hyperfine splitting.
**$\eta_c (2S)$**

Crystal Ball’s “first observation” of $\psi' \rightarrow \gamma X$ (M=3.592, B=0.2%-1.3%) never been confirmed. *PRL 48 70 (1982)*

“Seen” $\eta_c (2S)$ from inclusive photon spectrum of $\psi'$ decays.

Branch ratios and parameters are far from modern measurements.

**Observed in different processes other than radiative transition**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [1]</td>
<td>3654 ± 6 ± 8</td>
<td>—</td>
<td>$B^\pm \rightarrow K^\pm \eta_c(2S), \eta_c(2S) \rightarrow K_S K^{\pm} \pi^\mp$</td>
</tr>
<tr>
<td>CLEO [2]</td>
<td>3642.9 ± 3.1 ± 1.5</td>
<td>6.3 ± 12.4 ± 4.0</td>
<td>$\gamma \gamma \rightarrow \eta_c(2S) \rightarrow K_S K^{\pm} \pi^\mp$</td>
</tr>
<tr>
<td>BaBar [3]</td>
<td>3630.8 ± 3.4 ± 1.0</td>
<td>17.0 ± 8.3 ± 2.5</td>
<td>$\gamma \gamma \rightarrow \eta_c(2S) \rightarrow K_S K^{\pm} \pi^\mp$</td>
</tr>
<tr>
<td>BaBar [4]</td>
<td>3645.0 + 5.5$^{+4.9}_{-7.8}$</td>
<td>—</td>
<td>$e^+e^- \rightarrow J/\psi c\bar{c}$</td>
</tr>
<tr>
<td>PDG [5]</td>
<td>3638 ± 4</td>
<td>14 ± 7</td>
<td>—</td>
</tr>
</tbody>
</table>

**M1 transition $\psi' \rightarrow \gamma \eta_c (2S)$**

CLEO found no signals in 25M $\psi'$.

$BF(\psi' \rightarrow \gamma \eta_c (2S)) < 7.6 \times 10^{-4}$

CLEO: *PRD 81 052002 (2010)*

**Experimental challenge: search for photons of 50 MeV**
Observation of $\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma (K^0_sK\pi)$ @BESIII

$\eta_c(2S)$ signal:

$\left(E_\gamma^3 \times BW(m) \times damping(E_\gamma)\right) \otimes Gauss(0, \sigma)$

$M_{K^0_sK\pi}^{3C}$ (GeV/c$^2$)

$Br(\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma K^0_sK\pi) = (2.98\pm0.57\pm0.48) \times 10^{-6}$

$Br(\eta_c(2S) \rightarrow KK\pi) = (1.9\pm0.4\pm1.1)\%$

BaBar: PR D78 012006 (2008)

$Br(\psi' \rightarrow \gamma \eta_c(2S)) = (4.7\pm0.9\pm3.0) \times 10^{-4}$

CLEO-c: $<7.6\times10^{-4}$

PRD81 052002 (2010)

Potential model predicts

$(0.1\sim 6.2) \times 10^{-4}$

PRL 89 162002 (2002)

M1 transition

Width fixed to 12 MeV (world ave.)

Events: 50.6±9.7; Significance >6.0σ!

Mass = 3638.5±2.3±1.0 MeV/c$^2$
$\psi' \rightarrow \gamma \gamma J/\psi$

- Two photon transitions are well known in excitations of molecules, atomic hydrogen, and positronium.
  \[ \text{[F. Bassani et al, PRL 39, 1070 (1977); A. Quattropani et al, PRL 50, 1258 (1983)]} \]
- Never been observed in the quarkonium system.
  CLEOc: upper limit of $Br(\psi' \rightarrow \gamma \gamma J/\psi)$ is $1 \times 10^{-3}$ (PRD 78,011102(2008))
- Observation helpful to understand heavy quarkonium spectrum & strong interaction

**Theoretically:**
- Potential models give discrete spectra
  \( \psi(2S) \rightarrow \gamma \chi_{cJ}, \chi_{cJ} \rightarrow \gamma J/\psi \)
- Possibility of testing the hadron-loop effect
- Coupled channel: the hadron-loop effect also may play a important role in the continuous spectra
First evidence of $\psi' \rightarrow \gamma\gamma J/\psi$ @BESIII

- Select $\psi(2S) \rightarrow \gamma\gamma J/\psi$, $J/\psi \rightarrow e^+e^-$ and $\mu^+\mu^-$ events

- Global fit of the two-photon process and cascade $\chi_{cJ}$ processes
- See clear excess over BG + continuum
- $Br(\psi' \rightarrow \gamma J/\psi) = (3.3 \pm 0.6^{+0.8}_{-1.1}) \times 10^{-4}$ (both $ee$ and $\mu\mu$)
- Significance: $3.8\sigma$ including systematics
- $Br(\psi' \rightarrow \gamma\chi_{cJ}, \chi_{cJ} \rightarrow \gamma J/\psi)$ are also measured

5/31/12
Meson2012
Higher-order Multipole in $\psi' \rightarrow \gamma \chi_{c2}$, $\chi_{c2} \rightarrow \pi^+\pi^-, K^+K^-$

- $\psi' \rightarrow \gamma \chi_{c2}$ is dominated by electric dipole (E1) transition, but expect some magnetic quadrupole component (M2).

- M2 amplitude provides sensitivity to charm quark anomalous magnetic moment $\kappa$: $M2 = 0.029(1 + \kappa)$

- Use large clean samples of $\chi_{c2} \rightarrow \pi^+\pi^-$ and $\chi_{c2} \rightarrow K^+K^-$; $\chi_{c0}$ samples used as control since $M2 = 0$. 

5/31/12 Meson2012
Higher-order Multipole in $\psi' \rightarrow \gamma \chi_{c2}$, $\chi_{c2} \rightarrow \pi^+ \pi^-, K^+ K^-$

- Extract M2 using fit to full angular distribution
- Evidence of M2 contribution:
  \[ M2 = 0.046 \pm 0.010 \pm 0.013, \]
  \[ E3 = 0.015 \pm 0.008 \pm 0.018, \]

- Significant signal for M2 amplitude that is consistent with $\kappa = 0$

\[ M(c) = 1.5 \text{ GeV and } \kappa = 0 \]

\[ \chi_{c2} \rightarrow \pi^+ \pi^- \]
\[ \chi_{c2} \rightarrow K^+ K^- \]

PRD84, 092006 (2011)
Recent results on Charmonium Decays

• $\psi' \rightarrow \gamma\pi^0, \gamma\eta, \gamma\eta'$

• Search for $\eta_c(2S) \rightarrow VV$

• $\chi_{cJ}$ decays
$\psi' \to \gamma P(\pi^0, \eta, \eta')$, arise surprises

$\psi' \to \gamma P$ are important tests for various mechanisms:
Vector meson Dominance Model (VDM); Couplings & form factor;
Mixing of $\eta-\eta'(-\eta_c)$; FSR by light quarks; 12% rule and “$\rho$ $\pi$ puzzle”.

CLEO-c: $J/\psi$, $\psi'$, $\psi'' \to \gamma P$
$R_{J/\psi} = (21.1 \pm 0.9)\%$
No Evidence for $\psi' \to \gamma \pi^0$ or $\gamma \eta$
$Br(\psi' \to \gamma \eta') = (1.19 \pm 0.09)\%$
$R_{\psi'} < 1.8\%$ at 90% CL

$R_{\psi'} << R_{J/\psi}$
PRD 79, 111101 (2009)
$\psi' \rightarrow \gamma P(\pi^0, \eta, \eta') @ BESIII$

\[ \psi' \rightarrow \gamma \eta \]
(First evidence 4.3\sigma)

\[ \psi' \rightarrow \gamma \eta' \]
(First evidence 4.6 \sigma)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B(\psi') \times 10^{-6}$</th>
<th>$B(J/\psi) \times 10^{-4}$ (PDG)</th>
<th>Q (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\pi^0$</td>
<td>1.58±0.42</td>
<td>0.35±0.03</td>
<td>4.5±1.3</td>
</tr>
<tr>
<td>$\gamma\eta$</td>
<td>1.38±0.49</td>
<td>11.04±0.34</td>
<td>0.13±0.04</td>
</tr>
<tr>
<td>$\gamma\eta'$</td>
<td>126±9</td>
<td>52.8±1.5</td>
<td>2.4±0.2</td>
</tr>
</tbody>
</table>

$R_{\psi'} = (1.10±0.38±0.07)\% \ll R_{J/\psi}$

PRL105, 261801, (2010)
Search for $\eta_c(2S) \rightarrow VV$

Test for the ‘intermediate charmed meson loops’:

$\eta_c(2S) \rightarrow VV$ is highly suppressed by the helicity selection rule.

‘intermediate charmed meson loops’ can increase the production rate of $\eta_c(2S) \rightarrow VV$.

<table>
<thead>
<tr>
<th></th>
<th>$\text{Br}(\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma VV) \times 10^{-7}$</th>
<th>$\text{Br}(\eta_c' \rightarrow VV) \times 10^{-3}$ (using BESIII BF($\psi' \rightarrow \gamma \eta_c(2S)$))</th>
<th>$\text{Br}(\eta_c' \rightarrow VV) \times 10^{-3}$ (Theory: (arXiv:1010.1343))</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0 \rho^0$</td>
<td>$&lt; 12.7$</td>
<td>$&lt; 3.1$</td>
<td>$6.4 \sim 28.9$</td>
</tr>
<tr>
<td>$K^{*0} K^{*0}$</td>
<td>$&lt; 19.6$</td>
<td>$&lt; 5.4$</td>
<td>$7.9 \sim 35.8$</td>
</tr>
<tr>
<td>$\phi \phi$</td>
<td>$&lt; 7.8$</td>
<td>$&lt; 2.0$</td>
<td>$2.1 \sim 9.8$</td>
</tr>
</tbody>
</table>

• No signals observed in $\eta_c(2S) \rightarrow \rho \rho$, $K^{*0} K^{*0}$, $\phi \phi$;

• More stringent UL’s are set.
The $\chi_{cJ}$ decays provide good place to:

- **Study gluonium:** $\chi_c \rightarrow gg \rightarrow (qq)(qq)$
  

- **Test the Color Octet Mechanism (COM)**
  

  - First measurement of $\chi_{cJ} \rightarrow \omega\phi$, $\omega\omega$, $\phi\phi$
  
  - First measurement of $\chi_{cJ} \rightarrow \gamma\phi$
\( \chi_{cJ} \rightarrow VV \) (V: \( \omega, \phi \))

- \( \chi_{cJ} \rightarrow \phi\phi \) and \( \chi_{cJ} \rightarrow \omega\omega \) are Singly OZI suppressed
- \( \chi_{c1} \rightarrow \phi\phi \) and \( \chi_{c1} \rightarrow \omega\omega \) is suppressed by helicity selection rule.
- \( \chi_{cJ} \rightarrow \phi\omega \) is doubly OZI suppressed, not measured yet

PRL107, 091803 (2011)
Long distance transitions could contribute via the intermediate meson loops.

\[ \chi_{cJ} \rightarrow \gamma \ V \ (V: \rho, \omega, \phi) \]

Branching fractions for \( \chi_{cJ} \) radiative decays to a vector meson (in units of \( 10^{-6} \))

<table>
<thead>
<tr>
<th>Mode</th>
<th>CLEO (^1)</th>
<th>pQCD (^2)</th>
<th>QCD (^3)</th>
<th>QCD+QED (^3)</th>
<th>BESIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi_{c0} \rightarrow \gamma \rho^0 )</td>
<td>&lt; 9.6</td>
<td>1.2</td>
<td>3.2</td>
<td>2.0</td>
<td>&lt;10.5</td>
</tr>
<tr>
<td>( \chi_{c1} \rightarrow \gamma \rho^0 )</td>
<td>243 ± 19 ± 22</td>
<td>14</td>
<td>41</td>
<td>42</td>
<td>228±13±22</td>
</tr>
<tr>
<td>( \chi_{c2} \rightarrow \gamma \rho^0 )</td>
<td>&lt; 50</td>
<td>4.4</td>
<td>13</td>
<td>38</td>
<td>&lt;20.8</td>
</tr>
<tr>
<td>( \chi_{c0} \rightarrow \gamma \omega )</td>
<td>&lt; 8.8</td>
<td>0.13</td>
<td>0.35</td>
<td>0.22</td>
<td>&lt;12.9</td>
</tr>
<tr>
<td>( \chi_{c1} \rightarrow \gamma \omega )</td>
<td>83 ± 15 ± 12</td>
<td>1.6</td>
<td>4.6</td>
<td>4.7</td>
<td>69.7±7.2±6.6</td>
</tr>
<tr>
<td>( \chi_{c2} \rightarrow \gamma \omega )</td>
<td>&lt; 7.0</td>
<td>0.5</td>
<td>1.5</td>
<td>4.2</td>
<td>&lt;6.1</td>
</tr>
<tr>
<td>( \chi_{c0} \rightarrow \gamma \phi )</td>
<td>&lt; 6.4</td>
<td>0.46</td>
<td>1.3</td>
<td>0.03</td>
<td>&lt;16.2</td>
</tr>
<tr>
<td>( \chi_{c1} \rightarrow \gamma \phi )</td>
<td>&lt; 26</td>
<td>3.6</td>
<td>11</td>
<td>11</td>
<td>25.8±5.2±2.3</td>
</tr>
<tr>
<td>( \chi_{c2} \rightarrow \gamma \phi )</td>
<td>&lt; 13</td>
<td>1.1</td>
<td>3.3</td>
<td>6.5</td>
<td>&lt;8.1</td>
</tr>
</tbody>
</table>

First observation

Prediction by pQCD much lower than experiment
Polarization of $\chi_{cJ} \rightarrow \gamma V (V: \rho, \omega, \phi)$

Longitudinal polarization ($f_L$); Transverse polarization ($f_T$); Helicity angle ($\theta$)

$$
\frac{d\Gamma}{\Gamma d \cos \theta} \propto (1 - f_T) \cos^2 \theta + \frac{1}{2} f_T \sin^2 \theta
$$

$$
f_T = \frac{|A_T|^2}{|A_T|^2 + |A_L|^2}
$$

Longitudinal polarization dominates, consistent with theoretical prediction

$\chi_{cJ} \rightarrow \gamma \rho$

$\chi_{cJ} \rightarrow \gamma \omega$

$\chi_{cJ} \rightarrow \gamma \phi$

$\chi_{cJ} \rightarrow \gamma \rho$

$\chi_{cJ} \rightarrow \gamma \omega$

$\chi_{cJ} \rightarrow \gamma \phi$

$\chi_{cJ} \rightarrow \gamma \rho$

$\chi_{cJ} \rightarrow \gamma \omega$

$\chi_{cJ} \rightarrow \gamma \phi$

$\chi_{cJ} \rightarrow \gamma \rho$

$\chi_{cJ} \rightarrow \gamma \omega$

$\chi_{cJ} \rightarrow \gamma \phi$

$\chi_{cJ} \rightarrow \gamma \rho$

$\chi_{cJ} \rightarrow \gamma \omega$
Recent results on D analysis

- Leptonic Decays
- Semi-leptonic Decays
- Search for D0->γγ
Preliminary results of $D^+ \rightarrow \mu^+ \nu$ @BESIII

Results:

$N(D^+ \rightarrow \mu^+ \nu) = 377.3 \pm 19.4$

$BF(D^+ \rightarrow \mu^+ \nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4}$

$f_{D^+} = (203.91 \pm 5.72 \pm 1.97) \text{ MeV}$

$|V_{cd}| = (0.222 \pm 0.006 \pm 0.005)$
The most precise measurement is provided by BESIII. The error is still dominated by statistics, needing more data taken at 3773 GeV to reduce it.
Semi-leptonic Decays @ BESIII

- Systematics are preliminary
- Will improve using full (3X) data set in the near future
- Form factor measurement is ongoing

<table>
<thead>
<tr>
<th>Mode</th>
<th>measured branching fraction(%)</th>
<th>PDG</th>
<th>CLEOc</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{D}^0 \to K^+ e^- \bar{\nu}$</td>
<td>$3.542 \pm 0.030 \pm 0.067$</td>
<td>$3.55 \pm 0.04$</td>
<td>$3.50 \pm 0.03 \pm 0.04$</td>
</tr>
<tr>
<td>$\bar{D}^0 \to \pi^+ e^- \bar{\nu}$</td>
<td>$0.288 \pm 0.008 \pm 0.005$</td>
<td>$0.289 \pm 0.008$</td>
<td>$0.288 \pm 0.008 \pm 0.003$</td>
</tr>
</tbody>
</table>

BESIII Preliminary (~0.92 fb$^{-1}$)
Search for D0->γγ

• Forbidden FCNC transition (c ->u+γ);
• SM prediction: Br(D0->γγ)~10^{-8} or less;
• Results presented in Br(D_0->γγ)/Br(D_0->π^0π^0) < 5.8 \times 10^{-3} \text{ @ 90\% CL}, Br(D_0->γγ) < 4.6 \times 10^{-6} \text{ @ 90\% CL (preliminary)};
• PDG 2.7 \times 10^{-5}, CLEO-c preli. 8.63 \times 10^{-6}, BaBar 2.2 \times 10^{-6}
Summary

• BESIII has been successfully operated since 2008:
  – World largest data sample of $J/\psi$, $\psi’$, $\psi(3770)$, $\psi(4040)$ already collected, more data in future ($D_s^{*+}D_s^{-}$ at 4170MeV coming soon).

• A lot of results have been obtained:
  ➢ Light quark states:
    □ confirmation the enhancement at $pp$ threshold in $J/\psi \rightarrow \gamma pp$, $J_{pc} = 0-+$.  
    □ confirmation $X(1835)$ with two new structures in $J/\psi \rightarrow \gamma \pi \pi \eta’$. 
    □ First observation: $\eta(1405) \rightarrow f_0(980)\pi^0$ (isospin breaking).  
    □ $\omega \phi$ threshold enhancement in $J/\psi \rightarrow \gamma \omega \phi$  
    □ $\eta \eta$ system in $J/\psi \rightarrow \gamma \eta \eta$
  ➢ Charmonium transitions and decays:
    □ Precision measurements of $h_c$ and $\eta_c(1S)$ properties.  
    □ first observation of $\eta_c(2S)$ in $\psi’ \rightarrow \gamma \eta c(2S)$ decay.  
    □ First evidence of $\psi’ \rightarrow \gamma \gamma J/\psi$.  
    □ $\chi_{cJ} \rightarrow \omega \phi$, $\omega \omega$, $\phi \phi$, $\gamma \phi$.
  ➢ Charm decays:
    □ $D^+ \rightarrow \mu^+ \nu$, $D^0 \rightarrow K/\pi e \nu$, $D^0 \rightarrow \gamma \gamma$.

• Expect many more results from BESIII in the future
Thank you
Backup
The $\eta_c$ lineshape is not distorted in the $h_c \to \gamma \eta_c$, non-resonant bkg is small. This channel will be best suited to determine the $\eta_c$ resonance parameters.
Tag Mode Reconstruction

- Four tag modes picked
- Best tag mode based minimum $\Delta E$

$$\Delta E \equiv E - E_{beam}$$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Data Yield</th>
<th>Fraction of All Tags (%)</th>
<th>Tag Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^-\pi^+$</td>
<td>159,929 ± 413</td>
<td>20.7</td>
<td>62.08±0.07</td>
</tr>
<tr>
<td>$D^0 \to K^-\pi^+\pi^0$</td>
<td>323,348 ± 667</td>
<td>41.8</td>
<td>33.56±0.03</td>
</tr>
<tr>
<td>$D^0 \to K^-\pi^+\pi^0\pi^0$</td>
<td>78,467 ± 480</td>
<td>10.1</td>
<td>14.93±0.04</td>
</tr>
<tr>
<td>$D^0 \to K^-\pi^+\pi^-\pi^+$</td>
<td>211,910 ± 550</td>
<td>27.4</td>
<td>36.80±0.04</td>
</tr>
</tbody>
</table>
Is the X(1835) from the same source of X(pp̅)?

• The mass of X(pp̅) is consistent with X(1835)

• The width of X(pp̅) is much narrower.

Possible reasons:

– X(pp̅) and X(1835) come from different sources

– Interference effect in J/ψ-⟩γππη’ process should not be ignored in the determination of the X(1835) mass and width

– There may be more than one resonance in the mass peak around 1.83GeV in J/ψ-⟩γππη’ decays.