Recent results on charmonium and light hadron spectroscopy at BESIII

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Outline

- Introduction
- Study of $h_c$ in $\psi(2S) \to \pi^0 h_c$
- Precise measurement of $\eta_c$ mass and width
- Observation of $\eta_c'$ in $\psi' \to \gamma KK\pi$
- Spin-parity analysis of the ppbar mass threshold enhancement $X(\text{ppbar})$ in $J/\psi$ and $\psi'$ radiative decays
- $\eta(1405)$ in $J/\psi \to \gamma f_0(980)\pi^0, f_0(980) \to 2\pi$
- PWA of $J/\psi \to \gamma \eta\eta$ and $J/\psi \to \gamma \omega\phi$
- Summary
Bird view of BEPCII /BESIII

- **Storage ring**
- **Linac**
- **Beijing electron positron collider BEPCII**
- **BSRF**
- **BESIII detector**
- **IHEP, Beijing**

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

**Timeline**
- 2004: start BEPCII construction
- 2008: test run of BEPCII
- 2009-now: BEPCII/BESIII data taking
The BESIII Detector

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

μ Counter
8-9 layers RPC
\( \delta R\Phi = 1.4 \,\text{cm} \sim 1.7 \,\text{cm} \)

Super-conducting magnet (1.0 tesla)

NIM A614, 345 (2010)
The BESIII Detector

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The results in this talk are based on the data samples of
225M \( J/\psi \) events and 106M \( \psi' \) events

\( \mu \) Counter
8-9 layers RPC
\[ R = 1.4 \text{ cm} - 1.7 \text{ cm} \]

EMC: \[ \sigma_{E/\sqrt{E}} (0/0) = 2.5 \% \ (1 \text{ GeV}) \]
(Csl) \[ \sigma_{z,\phi} (\text{cm}) = 0.5 - 0.7 \text{ cm}/\sqrt{E} \]
$\psi' \rightarrow \pi^0 h_c$ @ BESIII

- Select inclusive $\pi^0 (\psi' \rightarrow \pi^0 h_c)$
- Select E1-photon in $h_c \rightarrow \gamma \eta_c$ (w/o E1 tagged)
- E1-tagged selection gives $M(h_c)=3525.40\pm0.13\pm0.18\text{MeV}$
  (\(\Delta M_{h}(1P)=0.10\pm0.13\pm0.18\text{MeV}/c^2\))
  \(\Gamma(h_c)=0.73\pm0.45\pm0.28\text{MeV}\)
  (first measurement)
  (<1.44MeV at 90\% CL)
  $\text{Br}(\psi' \rightarrow \pi^0 h_c) \times \text{Br}(h_c \rightarrow \gamma \eta_c) =$
  \((4.58\pm0.40\pm0.50) \times 10^{-4}\)
- E1-untagged selection gives $\text{Br}(\psi' \rightarrow \pi^0 h_c) = (8.4\pm1.3\pm1.0) \times 10^{-4}$
- Combining branching fractions leads to $\text{Br}(h_c \rightarrow \gamma \eta_c) =$
  \((54.3\pm6.7\pm5.2)\%\)
  (first measurement)

PRL104, 132002, (2010)
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
$M(h_c)=3525.21\pm0.27\pm0.14$ MeV/$c^2$
$N = 136\pm14$
PRL101, 182003(2008)
$\eta_c(1S)$

- Ground state of $c\bar{c}$ system, but its properties are not well known:
  - $J/\psi$ radiative transition: $M \sim 2978.0\text{MeV}/c^2$, $\Gamma \sim 10\text{MeV}$
  - $\gamma\gamma$ process: $M = 2983.1 \pm 1.0\text{MeV}/c^2$, $\Gamma = 31.3 \pm 1.9\text{MeV}$

- CLEOc found the distortion of the $\eta_c$ lineshape in $\psi'$ decays
- $c\bar{c}$ hyperfine splitting: $M(J/\psi) - M(\eta_c)$ is important experimental input to test the lattice QCD, but is dominated by error on $M(\eta_c)$
Relative phase $\phi$ values from each mode are consistent within 3\(\sigma\),

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

Interference with non-resonant is significant!

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Phase (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_sK\pi$</td>
<td>2984.3 (\pm 0.6 \pm 0.6)</td>
<td>32.0 (\pm 1.2 \pm 1.0)</td>
<td>2.40 (\pm 0.07 \pm 0.08)</td>
</tr>
<tr>
<td>$K_sK^0\pi^+\pi^0$</td>
<td>2.40 (\pm 0.07 \pm 0.08)</td>
<td>4.19 (\pm 0.03 \pm 0.09)</td>
<td></td>
</tr>
</tbody>
</table>
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.
Observation of $\psi' \rightarrow \gamma \eta_c(2S)$

- First “observation” by Crystal Ball in 1982 (M=3.592, B=0.2%-1.3% from $\psi' \rightarrow \gamma X$, never confirmed by other experiments.)

- Published results about $\eta_c(2S)$ observation:

<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>$B^\pm \rightarrow K^\pm \eta_c(2S), \eta_c(2S) \rightarrow K^-K^+\pi^-$</td>
</tr>
<tr>
<td>CLEO [2]</td>
<td>3642.9 ± 3.1 ± 1.5</td>
<td>6.3 ± 12.4 ± 4.0</td>
<td>$\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K^-K^+\pi^-$</td>
</tr>
<tr>
<td>BaBar [3]</td>
<td>3630.8 ± 3.4 ± 1.0</td>
<td>17.0 ± 8.3 ± 2.5</td>
<td>$\gamma\gamma \rightarrow \eta_c(2S) \rightarrow K^-K^+\pi^-$</td>
</tr>
<tr>
<td>BaBar [4]</td>
<td>3645.0 ± 5.5±4.9</td>
<td>—</td>
<td>$e^+e^- \rightarrow J/\psi cc$</td>
</tr>
<tr>
<td>PDG [5]</td>
<td>3638 ± 4</td>
<td>14 ± 7</td>
<td>—</td>
</tr>
</tbody>
</table>

Combined with the results based on two-photon processes from BaBar and Belle reported at ICHEP 2010, the world average $\Gamma(\eta_c(2S)) = 12 ± 3$ MeV

- The M1 transition $\psi' \rightarrow \gamma \eta_c(2S)$ has not been observed.
  (experimental challenge: search for real photons ~50 MeV, )

- Better chance to observe $\eta_c(2S)$ in $\psi'$ radiative transition with ~106M $\psi'$ data at BESIII.

- Decay mode studied: $\psi' \rightarrow \gamma \eta_c(2S) \rightarrow \gamma KsK\pi$ & K$^+K^-\pi^0$
Observation of $\eta_c(2S)$ in $\psi' \to \gamma \eta_c(2S)$, $\eta_c(2S) \to K_s K\pi$, $K^+ K^0\pi$$^0$.

**simultaneous fit results:**

- $M(\eta_c(2S)) = (3637.6 \pm 2.9 \pm 1.6) \text{ MeV}$
- $\Gamma(\eta_c(2S)) = (16.9 \pm 6.4 \pm 4.8) \text{ MeV}$

Statistical significance larger than 10.2$\sigma$.

$\text{Br}(\psi' \to \gamma \eta_c(2S) \to \gamma KK\pi) = (1.30 \pm 0.20_{\text{stat}} \pm 0.30_{\text{sys}}) \times 10^{-5}$

$+ \text{Br}(\eta_c(2S) \to KK\pi) = (1.9 \pm 0.4 \pm 1.1)\%$

From BABAR (PRD78, 012006)

$\text{Br}(\psi' \to \gamma \eta_c(2S)) = (6.8 \pm 1.1_{\text{stat}} \pm 4.5_{\text{sys}}) \times 10^{-4}$

CLEO-c: $<7.6 \times 10^{-4}$

PRD81, 052002 (2010)

Potential model: $(0.1 - 6.2) \times 10^{-4}$

PRL89, 162002 (2002)
Observed at BESII in 2003 (PRL,022001) agree with spin zero expectation
$M = 1860_{-10}^{+3}^{+5} - 25$ MeV, $\Gamma < 38$ MeV (90% CL)

Confirmed at BESIII in 2010
(CPC 34,421 (2010))
$M = 1859_{-13}^{+6}^{+6} - 26$ MeV, $\Gamma < 30$ MeV (90% CL)

Many possibilities:
normal meson/ p$\bar{p}$ bound state/multiquark/glueball/Final state interaction effect (FSI) ......

Spin-parity analysis
is essential for determining place in the spectrum and possible nature.
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 $\Delta \ln L = 51$ (7.1 $\sigma$)
- Different FSI models $\rightarrow$ Model dependent uncertainty

- Spin-parity, mass, width and B.R. of $X(pp\bar{p})$:
  - $J^{PC} = 0^{+}$ $\rightarrow$ $> 6.8 \sigma$ better than other $J^{PC}$ assignments
  - $M = 1832^{+19}_{-15} (\text{stat})^{+18}_{-17} (\text{syst}) \pm 19 (\text{mod})\text{MeV/c}^2$
  - $\Gamma = 13 \pm 20 (\text{stat})^{+11}_{-12} (\text{syst}) \pm 4 (\text{mod})\text{MeV/c}^2$ or $\Gamma < 76\text{MeV/c}^2$ @90\% C.L.
  - $B(J/\psi \rightarrow \gamma X(p\bar{p}))B(X(p\bar{p}) \rightarrow p\bar{p}) = (9.0^{+0.4}_{-1.1} (\text{stat})^{+1.5}_{-5.0} (\text{syst}) \pm 2.3 (\text{mod})) \times 10^{-5}$
Obviously different line shape of ppbar mass spectrum near threshold from that in J/ψ decays

PWA results:
- Significance of X(ppbar) is > 6.9σ.
- The production ratio R:
  \[ R = \frac{B(\psi' \rightarrow \gamma X(p\bar{p}))}{B(J/\psi \rightarrow \gamma X(p\bar{p}))} \]
  \[ = (5.08^{+0.71}_{-0.45} \text{ (stat)}^{+0.67}_{-3.58} \text{ (syst)} \pm 0.12 \text{ (mod)})\% \]
- It is suppressed compared with “12% rule”.

PWA Projection:

First measurement

PRL 108, 112003(2012)
Anomalous line shape of $f_0(980)$ in $J/\psi \rightarrow \gamma 3\pi$

$M = 989.9 \pm 0.4$ MeV/c$^2$
$\Gamma = 9.5 \pm 1.1$ MeV/c$^2$

**Surprising result:**
very narrow $f_0(980)$ width: $<11.8$ MeV/c$^2$ @90% C.L.
much narrower than the world average (PDG 2010: 40-100 MeV/c$^2$)

A possible explanation is $K K^*$ 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):

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

$\zeta_{\eta}$:

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

$a_0$-$f_0$ mixing alone cannot explain the branching ratio of $\eta(1405)$

ICHEP2012
New results on $\eta' \rightarrow 3\pi$

### New results:

\[
\begin{align*}
Br(\eta' \rightarrow \pi^+\pi^-\pi^0) &= (3.83 \pm 0.15 \pm 0.39) \times 10^{-3} \quad \text{(PDG2010: } (3.6^{+1.1}_{-0.93}) \times 10^{-3}\text{)} \\
Br(\eta' \rightarrow \pi^0\pi^0\pi^0) &= (3.56 \pm 0.22 \pm 0.34) \times 10^{-3} \quad \text{(PDG2010: } (1.68\pm0.22) \times 10^{-3}\text{)}
\end{align*}
\]

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

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

\[
\frac{BR(\eta' \rightarrow \pi^+\pi^-\pi^0)}{BR(\eta' \rightarrow \pi^+\pi^-\eta)} \approx 0.9\%, \quad \frac{BR(\eta' \rightarrow \pi^0\pi^0\pi^0)}{BR(\eta' \rightarrow \pi^0\pi^0\eta)} \approx 1.6\% 
\]
• 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 $2^{++}$ ($\sim 1870$ MeV), but no $f_0(1710)$.

• E835 (2006): $p\bar{p} \rightarrow \pi^0\eta\eta$, found $f_0(1500)$ and $f_0(1710)$.

• WA102 and GAMS all identified $f_0(1710)$ in $\eta\eta$. 

ICHET2012
Preliminary PWA results of $J/\psi \rightarrow \gamma \eta \eta$ @BESIII

- $f_0(1710)$ and $f_0(2100)$ are dominant scalars.
- $f_0(1500)$ exists (8.2 $\sigma$).
- $f_2'(1525)$ is the dominant tensor.
For X(1810):

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

\( J^{pc} \) favors 0++ over 0+ and 2++

\[ J/\psi \rightarrow \gamma \omega \phi \] (DOZI)
Is $X(1810)$ the $f_0(1710)/f_0(1790)$ or new state?
Summary

- A lot of interesting results on charmonium and light hadron spectroscopy have been obtained at BESIII, with new observations and measurements.

- BESIII just took 1 billion $J/\psi$ events and 0.4 billion $\psi'$ events this year ➔
  More and more exciting results from BESIII in the future
Thank you
Property of $h_c$

- First evidence: E835 in $pp \rightarrow h_c \rightarrow \gamma \eta_c$ (PRD72,092004(2005))
- CLEO-c observed $h_c$ in $ee \rightarrow \psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$
  $\Delta M_{hf}(1P) = 0.08 \pm 0.18 \pm 0.12$ MeV/c$^2$ (PRL104,132002(2010))
- Study isospin forbidden transition: $B(\psi' \rightarrow \pi^0 h_c)$
- Measure as well the E1 transition: $B(h_c \rightarrow \gamma \eta_c)$
- $M(h_c)$ gives access to hyperfine splitting of 1P states:
  $\Delta M_{hf}(1P) = M(h_c) - 1/9(M(\chi_{c0})+3M(\chi_{c1})+5M(\chi_{c2}))$
The $\eta_c$ lineshape is not distorted in the $h_c \rightarrow \gamma \eta_c$, non-resonant bkg is small. This channel will be best suited to determine the $\eta_c$ resonance parameters.
Is the X(1835) from the same source of X(ppbar)?

- The mass of X(ppbar) is consistent with X(1835)

- The width of X(ppbar) is much narrower.

Possible reasons:

- X(ppbar) and X(1835) come from different sources

- Interference effect in J/ψ → γ π π η’ 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 → γ π π η’ decays.
Confirmation @ BESIII and CLEOc

Fit with one resonance at BESII did:

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

\begin{align*}
M &= 1861^{+6}_{-13}^{+7}_{-26} \text{ MeV/c}^2 \\
\Gamma &< 38 \text{ MeV/c}^2 (90\% \text{ CL})
\end{align*}

Chinese Physics C 34, 421 (2010)  
PRD 82, 092002(2010)
Several non-observations

Pure FSI interpretation is disfavored