Physics at BESIII

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Birds view of BEPCII /BESIII

South

BESIII detector

LINAC

2004: started BEPCII upgrade, BESIII construction
2008: test run
2009 - now: BESIII physics run
A long history of $e^+e^-$ colliders at the Tau-Charm energy region
<table>
<thead>
<tr>
<th></th>
<th>Previous data</th>
<th>BESIII present &amp; future</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>BESII 58M</td>
<td>1.2 B 20* BESII</td>
<td>10 B</td>
</tr>
<tr>
<td>$\psi'$</td>
<td>CLEO: 28 M</td>
<td>0.5 B 20* CLEOc</td>
<td>3B</td>
</tr>
<tr>
<td>$\psi''$</td>
<td>CLEO: 0.8 /fb</td>
<td>2.9 /fb 3.5*CLEOc</td>
<td>20 /fb</td>
</tr>
<tr>
<td>$\psi(4040)/\psi(4160)/\psi(4260)/\psi(4360)$</td>
<td>CLEO: 0.6 /fb @ $\psi(4160)$</td>
<td>2011:0.4 /fb @ $\psi(4040)$ 2013: 1 /fb@4260, 4360</td>
<td>5-10 /fb</td>
</tr>
<tr>
<td>R scan &amp; Tau</td>
<td>BESII</td>
<td>2012: 12/pb@2.23,2.4,2.8,3.4 25/pb tau 2013, 2014: high mass R, tau</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing data points and labels](image)
BESIII results

• Charmonium physics
  – Charmonium spectroscopy
  – Transitions and decays

• Light hadron spectroscopy
  – Meson & baryon spectroscopy
  – Search for unconventional hadrons – glueballs, hybrids, multi-quark states

• Charm physics
  – Decay constant $f_D$
  – CKM matrix elements: $V_{cd}$, $V_{cs}$

38 papers published/submitted
Charmonium states

$\psi', \, h_c(1P), \, \eta_c(1S), \, \eta_c(2S)$

Properties not well known

Problems with mass and width measurements
Y.P. Kuang’s contribution to BES: heavy quarkonium transitions and decays:

1. Hadronic transition – QCD multipole expansion
2. Coupled channel effect
3. 2S-1D mixing for ψ(3770) – non-DDbar decays
4. Improved potential model for charmonium decays

- In fact, Prof. Kuang is the main player in early days of BES for charmonium physics
- Theoretical support for the study at BES on charmonium transitions
- BESIII yellow book on hadronic transitions of charmonium
- Proposed the study of $\chi_{c1} \rightarrow \eta_c \pi \pi$ at BESIII
- Many other suggestions to BESIII...
Incomplete list of Kuang’s papers on the BESIII physics

\( h_c^{(1P_1)} \)

- Physics motivation even at BES I
- Prof. Kuang gave the first calculation of \( \psi' \rightarrow \pi^0 h_c \) in 1988, updated in 2002
- Unfortunately, BES I and BESII did not have the capability due to the poor energy resolution (\(~20\%) of EM calorimeter
- After 20 years, CLEOc observed the signal for the first time right before the BESIII, thanks to its crystal EM calorimeter (\(~2.5\%)
Impossible at BES I, nor at BESII

Search for $h_c(1P_1)$ at BESII

LU Feng, DU ShuXian
June 14, 2005

BESII Memo

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1 Introduction
2 BESII Detector
3 $h_c$ search by $\eta_c \rightarrow \pi^+\pi^-\eta^+\eta^-$ channel
3.1 Signal topology and yield expectation
3.2 Signal preselection
3.3 Final selection
4 $h_c$ search by $\eta_c \rightarrow K^0\bar{K}^0\pi^+\pi^-$ channel
5 Summary

Abstract

$h_c$, P-wave spin singlet charmonium state ($1P_1$), due to the $c\bar{c}$ system relativistic and other effects are less important than the light quarkonia system because of heavy charm quark mass, is extremely important to determine spin-dependent component of the $q\bar{q}$ confinement potential by $1P_1$-$2P_0$ mass splitting for lattice QCD and NRQCD. With scalar confinement, $h_c$ should be degenerate in mass with the center of gravity of the $X_{cc}(2P_1)$ states [1]:

$$M_{cc} = \frac{m(x_{cc}) + 3m(x_{cc}) + 5m(x_{cc})}{9} = (3525.30^{+0.12}_{-0.12}) \text{MeV}/c^2$$

The measurement of the deviation of the $h_c$ mass from $M_{cc}$ is a good test of Lorentz nature of the confining potential. Therefore searching $h_c$ and measuring its

1 Introduction

Search for $h_c$ via $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow 4\pi/\eta_c \rightarrow k_s k\pi$ from 14M $\Psi'$ at BESII:

$$\text{Br}(\psi' \rightarrow \pi^0 h_c) \times \text{Br}(h_c \rightarrow \gamma \eta_c) < 3.3 \times 10^{-3} \text{ (90% C.L.)}$$

A memo was written but no paper was published since CLEO-c observed the signal
First BESIII PRL paper: $\psi(2S) \rightarrow \pi^0 h_c$ 

BESIII: PRL 104, 132002 (2010) 
Mass: 3525.40$\pm$0.13$\pm$0.18 MeV 
Width: 0.73$\pm$0.45$\pm$0.28 MeV 
(<1.44 MeV @ 90% C.L.)

Mass: 3525.28$\pm$0.19$\pm$0.12 MeV 
Width: fixed to 0.9 MeV 

$\Delta M_{hf} = \langle M(3P_J) \rangle - M(1P_1)$ 
Agrees with zero within $\sim$0.5 MeV

Information on spin-spin interaction.

Combined inclusive and E1-photon-tagged spectrum (First measurements) 

$B(\psi' \rightarrow \pi^0 h_c) = [8.4 \pm 1.3 \text{(stat.)} \pm 1.0 \text{(syst.)}] \times 10^{-4}$

$B(h_c \rightarrow \gamma \eta_c) = [54.3 \pm 6.7 \text{(stat.)} \pm 5.2 \text{(syst.)}] \%$

Agree with predictions of Kuang, Godfrey, Dudek, et al.
没有钱是万万不行的！
$h_c(1P1)$ in $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$, $\eta_c \rightarrow X_i$ (exclusive)

Simultaneous fit to $\pi^0$ recoiling mass in 106MeV $\psi'$ sample (preliminary results):

$M(h_c) = 3525.31 \pm 0.11_{(\text{stat})} \pm 0.15_{(\text{sys})}$ MeV/c$^2$

$\Gamma(h_c) = 0.70 \pm 0.28_{(\text{stat})} \pm 0.25_{(\text{sys})}$ MeV

$N = 832 \pm 35$

$\chi^2/\text{d.o.f.} = 32/46$

Accepted for publication at PRD

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

- The lowest lying S-wave spin singlet charmonium, discovered in 1980 by MarkII. Confusion properties:

  *Charmonium 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 \( \eta_c \) line shape in \( \psi' \) decays.

- \( c\bar{c} \) hyperfine splitting \( M(J/\psi) - M(\eta_c(1S)) \) is the important exp. input to test LQCD, but is dominated by error on \( M(\eta_c(1S)) \).

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**Mass**

- \( \gamma\gamma, \ pp, \ B \) decays

- \( \psi(1S, 2S) \rightarrow \gamma \eta_c \)

**Width**

- \( C.L. = 0.0014 \)

- \( C.L. < 0.0001 \)
Asymmetric lineshape in $J/\psi$ decay

Symmetric lineshape in $\gamma\gamma$ production

Symmetric $\eta_c$ lineshape from $\psi' \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$

CLEO-c
$J/\psi(1S) \rightarrow \gamma \eta_c(1S)$

Belle
$\gamma\gamma \rightarrow \eta_c(1S); \eta_c(1S) \rightarrow K_S K \pi$

BESIII
arXiv:1209.4963

BESIII
(arXiv:1209.4963)
Relative phase $\phi$ values from each mode are consistent within $3\sigma$.

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

$\eta_c$ resonance parameters from $\psi' \rightarrow \gamma \eta_c$ at BESIII

Interference taken into account

mass: $2984.3 \pm 0.6_{\text{stat}} \pm 0.6_{\text{sys}}$ MeV/c$^2$
width: $32.0 \pm 1.2_{\text{stat}} \pm 1.0_{\text{sys}}$ MeV
$\phi$: $2.40 \pm 0.07_{\text{stat}} \pm 0.08_{\text{sys}}$ rad (constructive)
$\Rightarrow$ or $4.19 \pm 0.03_{\text{stat}} \pm 0.09_{\text{sys}}$ rad (destructive)
Comparison of the mass and width for $\eta_c(1S)$

Mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/c$^2$
Width = $32.0 \pm 1.2 \pm 1.0$ MeV

- The most precise measurement
- Agree well with LQCD calculation.
**$\eta_c(2S)$**

- Crystal Ball’s “first observation” of $\psi' \rightarrow \gamma X$ never been confirmed
  
  PRL 48 70 (1982)

- Observed in different production mechanisms
  
  - $B \rightarrow K\eta_c(2S)$
  - $\gamma\gamma \rightarrow \eta_c(2S) \rightarrow KK\pi$
  - double charmonium production

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>Process</th>
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<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</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>
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- CLEOc did not find signals in 25M $\psi'$ M1 transition $\psi' \rightarrow \gamma\eta_c(2S)$
  
  $\text{BF}(\psi' \rightarrow \gamma\eta_c(2S)) < 7.6 \times 10^{-4}$

  CLEOc: PRD 81 052002 (2010)

Experimental challenge: detect photons of 50 MeV
First observation of $\psi' \rightarrow \gamma \eta_c(2S)$

Statistical significance $>10 \sigma$

New discovery! Great effort since BESI

- Observed signal in $K_S K^+ \pi^- + c.c.$, found evidence in $K^+ K^- \pi^0$
- First measured $\text{Br}(\psi' \rightarrow \gamma \eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}$

Potential model expectation: $(0.1-6.2) \times 10^{-4}$  
CLEOc: $< 7.6 \times 10^{-4}$

BESIII: PRL109, 042003 (2012)

PRD 81 052002 (2010)
Kuang’s QCDME model: Heavy quakonium hadronic transition

\[\Gamma(\psi(3770) \rightarrow J/\psi \pi\pi) = |C_1|^2 \left[ \sin^2 \theta \, G(\psi') \left| f_{2010}^{11}(\psi') \right|^2 + \frac{4}{15} \left| \frac{C_2}{C_1} \right|^2 \cos^2 \theta \, H(\psi'') \left| f_{1210}^{11}(\psi'') \right|^2 \right] \]

Y.P. Kuang’s prediction: \[\Gamma[\psi(1^3D \rightarrow 1^3D \pi\pi)] = [11\sim160] \text{ keV} \]

M.B. Voloshin’s prediction: \[\Gamma[\psi(1^3D \rightarrow 1^3D \pi\pi)] < 0.1 \text{ keV} \]

PRD41 (1990) 155
Non-DD decay of $\psi(3770)$ : discovered at BESII

$$BF(\psi(3770) \rightarrow J/\psi \pi^+ \pi^-) = (0.34 \pm 0.14 \pm 0.09)\%$$

Kuang’s QCDME prediction:
$$BF[\psi(3770) \rightarrow J/\psi \pi^+ \pi^-] = (0.1--0.7)\%$$

M. Voloshin’s QCDME prediction:
$$BF[\psi(3770)/J/\psi \pi^+ \pi^-] < 0.001\%$$

Results from BES-II in agreement with Kuang’s prediction. Observation later confirmed by CLEOc
**D-wave charmonium hadronic transition at BES-III**

- Branching ratio and decay width of the following process:
  - $\psi(3770) \rightarrow J/\psi \, \pi^+\pi^- , J/\psi \, \pi^0\pi^0$
  - $\psi(3770) \rightarrow J/\psi \, \pi^0$
  - $\psi(3770) \rightarrow J/\psi \, \eta$
- S-D mixing angle $\theta_{\text{mix}}$
- $\pi\pi$ invariant mass spectrum from $\psi(3770) \rightarrow J/\psi \, \pi\pi$ for parameters $c_1$ and $c_2$ in the Kuang’s QCDME model
Light hadron physics
Confirmation of the BESII observation: pp threshold enhancement in J/ψ decays

BESIII

M=1859 +3 +5 MeV/c²
-10 -25
Γ < 30 MeV/c² (90% CL)

arXiv:1001.5328, accepted by Chinese Phys. C
PWA of $J/\psi \rightarrow \gamma p\bar{p}$ @ BESIII

$f_0(2100) / f_2(1910)$ fixed to PDG. Sig. of $X(p\bar{p}) >> 30\sigma$

- 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 $\Delta 2\ln L = 51 \Rightarrow 7.1\sigma$.

$J^{PC} = 0^{-+}$

$M = 1832^{+10}_{-5}^{+18}_{-17} \text{(stat.)}^{+18}_{-17} \text{(syst)} \pm 19 \text{(model)} \text{MeV/c}^2$

$\Gamma = 13 \pm 39 \text{(stat.)}^{+10}_{-13} \text{(syst)} \pm 4 \text{(model)} \text{MeV/c}^2 (\Gamma < 60\text{MeV/c}^2 @ 90\text{C.L.})$

$\text{Br}(J/\psi \rightarrow \gamma X)\text{Br}(X \rightarrow p\bar{p}) = (9.0^{+0.4}_{-1.1}^{+1.5}_{-5.0} \text{(stat.)}^{+18}_{-17} \text{(syst)} \pm 2.3 \text{(model)}) \times 10^{-5}$

Different FSI models $\Rightarrow$ Model dependent uncertainty
X(1835) and two new structures

- $X(1835)$ was observed in $J/\psi \rightarrow \gamma \eta' \pi \pi$ at BESII.
- $X(1835)$ is confirmed at BESIII with 225 MeV $J/\psi$.
- Two new structures are observed.

BESIII: PRL 106 (2011) 072002
X(1870) in J/ψ→ωX, X→a_0(980)ππ

New particle?  η_2(1870) ?  X(1835)?
$J/\psi \rightarrow \gamma 3\pi$

- First observed large isospin breaking: $\eta(1405) \rightarrow f_0(980)\pi^0$

- Observed narrow $f_0(980)$ – much narrower than PDG value

\[
\begin{align*}
M &= 989.9 \pm 0.4 \text{ MeV} \\
\Gamma &= 9.5 \pm 1.1 \text{ MeV} \\
M &= 987.0 \pm 1.4 \text{ MeV} \\
\Gamma &= 4.6 \pm 5.1 \text{ MeV}
\end{align*}
\]
General speaking, the isospin breaking in hadronic decays $< 1\%$ or at $0.1\%$ level.

For example:

$$\frac{\text{BR}(\psi' \rightarrow \pi^0 J / \psi)}{\text{BR}(\psi' \rightarrow \eta J / \psi)} = 0.2\% \times \frac{|P_\pi|^3}{|P_\eta|^3}, \quad \frac{\text{BR}(\eta' \rightarrow \pi^+ \pi^- \pi^0)}{\text{BR}(\eta' \rightarrow \pi^+ \pi^- \eta)} = 0.9\%$$

However:

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

How to understand? Stimulated many theoretical speculations.

Charm Physics
Preliminary study of $D^+ \rightarrow \mu \nu$ at BESIII

- 9 singly $D^-$ tag modes

$$\mathcal{N}_D^{\text{tag}} = (1.566 \pm 0.002) \times 10^6 \text{ in } 2.9 \text{ fb}^{-1}$$

The $K_L^0$ escape from the detector.

There are still some backgrounds
Results: \( N(D^+ \rightarrow \mu^+ \nu) = 377.3 \pm 19.4 \)
\( BF(D^+ \rightarrow \mu^+ \nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4} \)

\[
\Gamma(D^+ \rightarrow l^+ \nu_l) = \frac{G_F^2 f_{D^+}^2}{8\pi} |V_{cd}|^2 m_{D^+}^2 m_{l}^2 \left(1 - \frac{m_l^2}{m_{D^+}^2}\right)^2
\]

\( f_{D^+} = (203.91 \pm 5.72 \pm 1.97) \text{ MeV} \)
\( |V_{cd}| = (0.222 \pm 0.006 \pm 0.005) \)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( B(D^+ \rightarrow \mu^+ \nu_\mu) ) (( \times 10^{-4} ))</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO-c</td>
<td>( 3.82 \pm 0.32 \pm 0.09 )</td>
<td>( 3.76 \pm 0.18 )</td>
</tr>
<tr>
<td>BES-III(PRLMNRY)</td>
<td>( 3.74 \pm 0.21 \pm 0.06 )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( f_{D} ) (MeV)</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>CLEO-c</td>
<td>( 205.8 \pm 8.5 \pm 2.5 )</td>
<td>( 204.5 \pm 5.0 )</td>
</tr>
<tr>
<td>BES-III(PRLMNRY)</td>
<td>( 203.91 \pm 5.72 \pm 1.97 )</td>
<td></td>
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</tbody>
</table>

The error is still statistical dominated.
Preliminary study of $D^0 \rightarrow \pi e \nu$ and $K e \nu$

Fit U distribution: $U = E_{\text{miss}} - |\vec{P}_{\text{miss}}| \approx 0$

- $D^0 \rightarrow K e \nu$
  - $0.92 \text{ fb}^{-1}$
  - $N_{\text{sig}} = 18460 \pm 143$

- $D^0 \rightarrow \pi e \nu$
  - $0.92 \text{ fb}^{-1}$
  - $N_{\text{sig}} = 1677 \pm 45$

**Fit U distribution:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>measured branching fraction(%)</th>
<th>PDG</th>
<th>CLEO-c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{D}^0 \rightarrow K^+ e^- \bar{\nu}$</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>$\bar{D}^0 \rightarrow \pi^+ e^- \bar{\nu}$</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>

- Systematic uncertainties are preliminary
- Good consistency with CLEO-c, statistical precision comparable with only 1/3 data analyzed
Summary

- BESIII collected
  - 1 billion J/ψ, 0.5 billion ψ’ data
  - R scan between 2.4 – 3.6 GeV
  - tau mass measurement (25/pb)
  - Phase measurement and J/ψ lineshape

- Next physics run:
  - ~500 pb⁻¹ at 4260 MeV
  - ~500 pb⁻¹ at 4360 MeV
  - R scan at high mass region

- A lot of physics results. More are coming
Happy birthday, Prof. Kuang. I learned a lot from you since 1986. Thanks