Results Of Hadron Spectroscopy From BESIII

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The 3rd Workshop on Hadron Physics in China and Opportunities in US
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Outline

- Introduction

- Latest Results On Hadron Spectroscopy
  - $p\bar{p}$ threshold enhancement in $J/\psi$ and $\psi'$ decays
  - Confirmation of $X(1835)$ and observation of $X(2120)$ and $X(2370)$ in $J/\psi \rightarrow \gamma(\eta'\pi^+\pi^-)$ decay
  - Observation of $X(1870)$ in $J/\psi \rightarrow \omega(\eta\pi^+\pi^-)$ decay
  - $a_0(980) - f_0(980)$ mixing

- Prospects & Summary
BEPCII Storage Ring

Beam energy: 1.0-2.3 GeV
Luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
Optimum energy: 1.89 GeV
Energy spread: $5.16 \times 10^{-4}$
No. of bunches: 93
Bunch length: 1.5 cm
Total current: 0.91 A
From BESII to BESIII

<table>
<thead>
<tr>
<th>BESII</th>
<th>BESIII</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MDC</strong></td>
<td>$\sigma(p)/p = 1.78% \cdot \sqrt{1 + p^2}$</td>
</tr>
<tr>
<td></td>
<td>$dE/dx_{\text{reso}} = 8%$</td>
</tr>
<tr>
<td><strong>TOF</strong></td>
<td>180 ps (for bhabha)</td>
</tr>
<tr>
<td><strong>EMC</strong></td>
<td>$\sigma(E)/E = 22% \cdot \sqrt{E}$</td>
</tr>
<tr>
<td><strong>MUC</strong></td>
<td>3 layers for barrel</td>
</tr>
</tbody>
</table>
BESIII Milestones

Mar. 2008: first full cosmic-ray event
Apr. 30, 2008: Move the BESIII to IP
Jul. 19, 2008: First e^+e^- collision event in BESIII
Nov. 2008: ~14M ψ(2S) events collected
Apr. 14, 2009: ~106M ψ(2S) events collected (×4 CLEOc)
May 30, 2009: 42 pb^{-1} at continuum collected
Jul. 28, 2009: ~225M J/ψ events collected (×4 BESIII)
2010 - 2011: 2.9fb^{-1} ψ(3770) events (× 3.5 CLEOc)
May 2011: 0.5fb^{-1} ψ(4010) events collected
Main Physics Topics @ BESIII

• Light hadron spectroscopy
  – Full spectra: normal & exotic hadrons \( \text{QCD} \)
  – How quarks form a hadron? \( \text{non-pQCD} \)

• Charm physics
  – CKM matrix elements \( \Rightarrow \text{SM and beyond} \)
  – \( D \bar{D} \) mixing and CPV \( \Rightarrow \text{SM and beyond} \)

• Charmonium physics
  – Spectroscopy and transition \( \Rightarrow \text{pQCD & non-pQCD} \)
  – New states above open charm thresholds \( \Rightarrow \text{exotic hadrons?} \)
  – pQCD: \( \rho \pi \) puzzle \( \Rightarrow \) a probe to \( \text{non-pQCD or?} \)

• Tau physics and QCD
  – Precision measurement of the tau mass and R value

• Search for rare and forbidden decays

Precision test of SM and search for new physics
Why Hadron Spectroscopy?

Study of spectroscopy is one of the major approaches to understand deeper structure and interaction of the matter.
Light Hadrons

- Ordinary hadrons are consists of 2 or 3 quarks

**quark model:**

- **Meson:** $q \bar{q}$
- **Baryon:** $qqq$

\[
\begin{align*}
(q \bar{q}) & : \quad \frac{2S+1}{2}L_J \quad J^{PC} \quad P=(-1)^L+1 \\
{^1S_0} & : \quad 0^- \\
{^3S_1} & : \quad 1^- \\
\pi^0 = \frac{u \bar{u} - d \bar{d}}{\sqrt{2}}
\end{align*}
\]
Exotic Hadrons

QCD allows different type of hadrons:

- Multiquark: quark $\geq 4$
- hybrids: $\bar{q}qg$, $qqqqg$ ...
- glueball: $gg$, $ggg$ ...

Searching for above hadron states is one of the important topics for many experiments. In past decades, although none of above states has been established, there do exist some open questions:

1) much more states than predicted exist in some mass region

2) some of states are hard to be understood as ordinary hadrons
$p\bar{p}$ Threshold Enhancement
$p\bar{p}$ Threshold Enhancement @ BESII

- BESII observed $p\bar{p}$ enhancement close to threshold

$$J/\psi \rightarrow \gamma p\bar{p}$$

**PRL 91 (2003) 022001**

- What it could be theoretically:
  - $p\bar{p}$ bound state
  - FSI effect

$$M=1859^{+3}_{-10}^{+5}_{-25} \text{ MeV/c}^2 \Gamma < 30 \text{ MeV/c}^2 \text{ (90\% CL)}$$
p\bar{p} Threshold Enhancement: None Observations

- Several none observations...

\( \psi(2S) \rightarrow \gamma p\bar{p} \) (BES-II)

\( \Upsilon(1S) \rightarrow \gamma p\bar{p} \) (CLEO)

\( J/\psi \rightarrow \omega p\bar{p} \) (BES-II)

No significant signal of \( X(1860) \) found (only 2\( \sigma \) significance)
Mass Spectrum Fitting

$J / \psi \rightarrow \gamma p\bar{p}$

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

$M = 1859 \pm 3^{+5}_{-10} \text{ MeV}/c^2$

$\Gamma < 30 \text{ MeV}/c^2 \text{ (90\% CL)}$

PRL 91 (2003) 022001

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

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

Chinese Physics C 34, 421 (2010)

Consistent with BESII observation, confirmed the enhancement !!
M(\(pp\bar{p}\)) threshold structure in \(J/\psi \rightarrow \gamma p\bar{p}\)

- Evident narrow \(M_{pp}\) threshold enhancement in \(J/\psi\) decays.

- Partial Wave Analysis (PWA):
  - Concentrate on dealing with the \(pp\) mass threshold structure, especially to determine the \(J^{PC}\).
Preliminary PWA Results for $J/\psi \rightarrow \gamma p\bar{p}$

<table>
<thead>
<tr>
<th>Component</th>
<th>$J^P$</th>
<th>$M$ (GeV)</th>
<th>$\Gamma$ (GeV)</th>
<th>Stat.sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(p\bar{p})$</td>
<td>$0^{-+}$</td>
<td>$1.832 \pm 0.005$</td>
<td>$0.013 \pm 0.020$</td>
<td>$\gg 30\sigma$</td>
</tr>
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<td>$f_0(2100)$</td>
<td>$0^{++}$</td>
<td>$2.103$</td>
<td>$0.209$</td>
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<td>$f_2(1910)$</td>
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</tr>
<tr>
<td>phase space</td>
<td>$0^{++}$</td>
<td>–</td>
<td>–</td>
<td>$6.3\sigma$</td>
</tr>
</tbody>
</table>

- The fit with a BW and S-wave FSI($l=0$) factor can well describe $p\bar{p}$ mass threshold structure.
- It is much better than that without FSI effect, and $\Delta 2\ln L=51 \Rightarrow 7.1\sigma$.
Preliminary PWA Results for $J/\psi \rightarrow \gamma p\bar{p}$

- PWA results are carefully checked from different aspects:
  - Contribution of additional resonances
  - Solution with different combinations
  - Different background levels and fitting mass ranges
  - Different BW formula
  - … …

All uncertainties are considered as systematic errors.

- Different FSI models $\rightarrow$ Model dependent uncertainty

- Spin-parity, mass, width and B.R. of $X(p\bar{p})$:

$J^{pc} = 0^{-+}$ $\rightarrow$ **>6.8σ better than other $J^{pc}$ assignments.**

$M = 1832 \pm 5^{+15}_{-17}\,(\text{stat}) \pm 19^{+15}_{-13}\,(\text{mod})\,\text{MeV}/c^2$

$\Gamma = 13 \pm 20^{+8}_{-26}\,(\text{stat}) \pm 4^{+1.5}_{-2.3}\,(\text{mod})\,\text{MeV}/c^2$ or $\Gamma < 45\,\text{MeV}/c^2$ @ 90% $C.L.$

$B(J/\psi \rightarrow \gamma X(p\bar{p}))B(X(p\bar{p}) \rightarrow p\bar{p}) = (9.0 \pm 0.7^{+1.5}_{-4.8}\,(\text{stat}) \pm 2.3^{+1.5}_{-2.3}\,(\text{mod})) \times 10^{-5}$
Preliminary PWA Results for $\psi' \to \gamma p\bar{p}$

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 larger than 6.9σ.
- The production ratio $R$:

  $$R = \frac{B(\psi' \to \gamma X(p\bar{p}))}{B(J/\psi \to \gamma X(p\bar{p}))}$$

  $= (5.08 \pm 0.56{\text{(stat)}}^{+0.64}_{-3.10}{\text{(syst)}} \pm 0.12{\text{(mod)})\%}}$

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

**PWA Projection:**

chi2/nbin=0.887100

- $106M\psi'$
- $X_c$
- $\eta_c$

![Graphs and Data](image)
Confirmation of X(1835) and Observation of X(2120) and X(2370) in $J/\psi \rightarrow \gamma (\eta' \pi^+ \pi^-)$ decay
LQCD predicts the glueball mass of $0^{-+}$ is ~2.3 GeV

For $0^{-+}$ glueball, it may have similar property as $\eta_c$ (mainly decay to $\pi\pi\eta'$)

$J/\psi \rightarrow \gamma\pi\pi\eta'$ is specially interested and was studied with 57M $J/\psi$ @BESII

**BESII result** (Stat. sig. ~ 7.7 $\sigma$):

\[
M = 1833.7 \pm 6.1 (\text{stat}) \pm 2.7 (\text{syst}) \text{MeV} \\
\Gamma = 67.7 \pm 20.3 (\text{stat}) \pm 7.7 (\text{syst}) \text{MeV}
\]

PRL 95,262001(2005)

Need to confirm it with BESIII ~225M $J/\psi$ data !!!
Invariant Mass of $\pi\pi\eta'$

- $\eta' \rightarrow \gamma\rho$
- Two additional structures are observed at $M \sim 2.1\text{GeV}$ and $2.3\text{GeV}$
- There maybe some $f_1(1510)$.

Combination for $\eta'$ to $\pi^+\pi^-\eta$ and $\gamma\rho$
X(1835) @ BESIII

$\eta' \rightarrow \gamma \rho$

$\eta' \rightarrow \pi\pi\eta$

Statistical Significance $\sim 18 \sigma$

Statistical Significance $\sim 9 \sigma$

Bump around 1835 MeV becomes much more clear from BESIII $\sim 225 M J/\psi$
Fitting With One Resonance

Fitting Results:

BESIII preliminary:

\[ M = 1842.4 \pm 2.8 \text{ (stat.) MeV} \]
\[ \Gamma = 99.2 \pm 9.2 \text{ (stat.) MeV} \]

Statistical significance: \(~ 21\sigma\)

BESII Results:

\[ M = 1833.7 \pm 6.1 \text{ (stat.)} \pm 2.7\text{(syst.) MeV} \]
\[ \Gamma = 67.7 \pm 20.3 \text{ (stat.)} \pm 7.7\text{(syst.) MeV} \]

Statistical significance: \(~ 7.7\sigma\)

X(1835) is confirmed in BESIII and the significance increases as statistics increases.
Fitting With 4 Resonances

- Fitting with four resonances (acceptance weighted BW \( \otimes \) gauss)
- Three background components:
  1. Contribution from non-\( \eta' \) events estimated by \( \eta' \) mass sideband
  2. Contribution from \( J/\psi \rightarrow \pi^0 \pi^+\pi^-\eta' \) with re-weighting method
  3. Contribution from “PS background”

\[
f_{\text{bg}}(x) = (x - m_0)^{1/2} + a_0(x - m_0)^{3/2} + a_1(x - m_0)^{5/2}, \quad m_0 = 2m_\pi + m_{\eta'}
\]

Red line: estimated contribution of ① + ②
Black line: total background

Stat. sig. is conservatively estimated:
fit range, background shape, contribution of extra resonances

PRL 106:072002, 2011
Fitting Results With 4 Resonances

<table>
<thead>
<tr>
<th>Resonance</th>
<th>M (MeV/c²)</th>
<th>Γ (MeV/c²)</th>
<th>Stat. sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(1835)</td>
<td>1836.5 ± 3.0±5.6</td>
<td>190.1 ± 9.0±38</td>
<td>&gt;20σ</td>
</tr>
<tr>
<td>X(2120)</td>
<td>2122.4 ± 6.7±4.7</td>
<td>83 ± 16±31</td>
<td>7.2σ</td>
</tr>
<tr>
<td>X(2370)</td>
<td>2376.3 ± 8.7±3.2</td>
<td>83 ± 17±44</td>
<td>6.4σ</td>
</tr>
</tbody>
</table>

For the X(1835):

\[
BR(J/ψ \to γX(1835)) \cdot BR(X(1835) \to π^+π^−η') = (2.87 ± 0.09(stat) ±0.49(syst)) \times 10^{-4}
\]

PRL 106:072002, 2011
Observation of $X(1870)$ in $J/\psi \rightarrow \omega (\eta \pi^+ \pi^-)$ decay
In addition to the well-known $\eta'$, $f_1(1285)$ and $\eta(1405)$, an unknown structure (denoted as $X(1870)$) around 1.87GeV/$c^2$ is observed.

The $f_1(1285)$, $\eta(1405)$ and $X(1870)$ decay primarily via $a_0(980)\pi$ mode.
Fitting Result of $X(1870)$

- Fitting with three resonances (acceptance weighted BW $\otimes$ Gauss)
- Background component described by Polynomial function

**Fit results:**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV/c$^2$)</th>
<th>Width (MeV/c$^2$)</th>
<th>Branch ratio ($10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1(1285)$</td>
<td>$1285.1 \pm 1.0^{+1.6}_{-0.3}$</td>
<td>$22.0 \pm 3.1^{+2.0}_{-1.5}$</td>
<td>$1.25 \pm 0.10^{+0.19}_{-0.20}$</td>
</tr>
<tr>
<td>$\eta(1405)$</td>
<td>$1399.8 \pm 2.2^{+2.8}_{-0.1}$</td>
<td>$52.8 \pm 7.6^{+0.1}_{-7.6}$</td>
<td>$1.89 \pm 0.21^{+0.21}_{-0.23}$</td>
</tr>
<tr>
<td>$X(1870)$</td>
<td>$1877.3 \pm 6.3^{+3.4}_{-7.4}$</td>
<td>$57 \pm 12^{+19}_{-4}$</td>
<td>$1.50 \pm 0.26^{+0.72}_{-0.36}$</td>
</tr>
</tbody>
</table>

The fit is performed under the assumption that the interference between the resonances and background can be ignored.

Whether the $X(1870)$ is the $X(1835)$ or $\eta_2(1870)$ ($\Gamma = 225 \pm 14$ MeV/c$^2$), or a new resonance? **Need further study.**

Submitted to PRL
Summary of X(1870) in J/ψ→ω(ππη)

- The resonant parameters of f_{1}(1285) and \eta(1405) agree quite well with PDG values.
- A structure with mass of ~1.87 GeV/c^2 and width of ~57 MeV/c^2 is observed with a significance of ~7.2σ.
- Whether X(1860) (J/ψ→γpp), X(1835) (J/ψ→γη′ππ) and X(1870) (J/ψ→ωηππ) are the same resonance still need both experimental and theoretical study.
$a_0(980) - f_0(980)$ mixing
a0(980)-f0(980) Mixing

- Mixing intensity provides important information to understand the nature of a0(980) and f0(980).
- Narrow peak (8 MeV) at around 980 MeV can be expected in ηπ (J/ψ → φf0 → φa0 → φηπ case) or π+π− (χc1 → a0π0 → f0π0 → π+π−π0 case) invariant mass spectra.

J. Wu, Q. Zhao, B. Zou PRD75 114012,
C. Hanhart etc. PRD76 074028,

J. Wu, B. Zou PRD78 074017
**a₀-f₀ Mixing: f₀ → a₀ transition**

![Graph showing events vs. M(ηπ⁰) (GeV/c²)](image)

**Significance:** 3.4σ

**N(mixing)=25.8±8.6(stat.)**

<39.7 (90% C.L.)

Br(J/ψ → φf₀ → φa₀ → φηπ⁰)

=(3.3±1.1(stat.)±0.4(sys.)±1.4(para.))×10⁻⁶

<5.4×10⁻⁶ (90% C.L.)

**Mixing intensity:**

\[ \xi_{fa} = \frac{\text{Br}(J/ψ → φf₀ → φa₀ → φηπ⁰)}{\text{Br}(J/ψ → φf₀ → φππ)^{[\text{BESII]}}} \]

=(0.60±0.20(stat.)±0.12(sys.)±0.26(para.))%

<1.1% (90% C.L.)

--- **Mixing signal**

--- **a₀(980) contribution from**

J/ψ → γ*/K*K → φa₀(980)

--- **Background polynomial**
**a₀-f₀ Mixing: a₀→f₀ transition**

**Significance: 1.9σ**

N(mixing)=6.4±3.2(stat.)

<13.0 (90% C.L.)

Br(ψ'→γχ₁χ₁→a₀π⁰→f₀π⁰→π⁺π⁻π⁰)

=(2.7±1.4(stat.)±0.7(sys.)±0.3(para.))×10⁻⁷

<6.0×10⁻⁷ (90% C.L.)

**Mixing intensity:**

\[ ξ_{af} = \frac{\text{Br}(χ₁→a₀π⁰→f₀π⁰→π⁺π⁻π⁰)}{\text{Br}(χ₁→π⁺a₀→ηπ⁻π⁰) [PDG]} \]

=(0.31±0.16(stat.)±0.14(sys.)±0.03(para.))%

<1.0% (90% C.L.)

--- f₀(980) contribution from other processes

--- Background polynomial
Comparison with different predictions

- Mixing intensities can be derived from measured / predicted $f_0 \rightarrow K^+K^-$, $\pi\pi$, $a_0 \rightarrow K^+K^-$, $\eta\pi$ coupling constants
  (Wu et al. PRD75, 114012(2007) and references within)

- **BESIII upper limits** (90% CL)

- Coupling constants from theory models
- Coupling constants from experiments
- First direct measurement
BESIII has been in operation since 2008: $\sim 106M \psi(2S)$, $\sim 225M \ J/\psi$, $2.9fb^{-1} \ \psi(3770)$, $0.5fb^{-1} \ \psi(4010)$ events have been collected.

Following results obtained for hadron spectroscopy:

Confirmation of $p\bar{p}$ threshold enhancement and $X(1835)$
Observation of $X(2120)$ and $X(2370)$
Observation of $X(1870)$
a$0(980) - f0(980)$ mixing

*and more than a dozen analyses in progress*

More data and more exciting results are expected, stay tuned.
Acknowledgement

Thanks to all BESIII colleagues

for their helps on preparation of this talk
THANK YOU!
Backup
PWA projections in $J / \psi \rightarrow \gamma p \bar{p}$

Fit $p \bar{p}$ mass threshold structure with pure FSI effect

- It is hard to fit the $p \bar{p}$ threshold structure with pure FSI effect.
PWA results (without FSI) of $J/\psi \rightarrow \gamma p\bar{p}$

<table>
<thead>
<tr>
<th>Component</th>
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<th>$\Gamma$ (GeV)</th>
<th>Stat.sig.</th>
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<tbody>
<tr>
<td>$X(p\bar{p})$</td>
<td>$0^{--}$</td>
<td>$1.861 \pm 0.001$</td>
<td>$0.001 \pm 0.006$</td>
<td>$\gg 30\sigma$</td>
</tr>
<tr>
<td>$f_0(2100)$</td>
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<td>phase space</td>
<td>$0^{++}$</td>
<td>–</td>
<td>–</td>
<td>$6.4\sigma$</td>
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</table>
Measurement of $X(p\bar{p})$ without FSI

- Spin-parity, mass, width and B.R. of $X(p\bar{p})$:  
  \[ J^{pc} = 0^{-+} \]
  
  \[ M = 1861 \pm 1 \text{(stat)}^{+12}_{-4} \text{(syst)} \text{MeV/c}^2 \]
  \[ \Gamma = 1 \pm 6 \text{(stat)}^{+16}_{-0} \text{(syst)} \text{MeV/c}^2 \text{ or } \Gamma < 29 \text{MeV/c}^2 \text{ @ 90\% C.L.} \]
  
  \[ B(J / \psi \to \gamma X(p\bar{p}))B(X(p\bar{p}) \to p\bar{p}) = (8.6 \pm 0.3 \text{(stat)}^{+2.2}_{-3.1} \text{(syst)}) \times 10^{-5} \]

- Consistent with BESII and BESIII published results without FSI

\[ M = 1859^{+3}_{-10} \text{(stat)}^{+5}_{-25} \text{(syst)} \text{MeV/c}^2 \]
\[ \Gamma < 30 \text{MeV/c}^2 \text{ @ 90\% C.L.} \]
\[ B(J / \psi \to \gamma X(p\bar{p}))B(X(p\bar{p}) \to p\bar{p}) = (7.0 \pm 0.4 \text{(stat)}^{+1.9}_{-0.8} \text{(syst)}) \times 10^{-5} \]
PWA results (without FSI) of $\psi' \rightarrow \gamma p\bar{p}$

- Significance of $X(p\bar{p})$ is $> 10\sigma$.
- The production ratio $R$:
  \[
  R = \frac{B(\psi' \rightarrow \gamma X(p\bar{p}))}{B(J/\psi \rightarrow \gamma X(p\bar{p}))} = (4.80 \pm 0.47\text{(stat)})^{+2.20}_{-1.05}\text{(syst)})\%
  \]
- It is suppressed compared with "12% rule".