Recent results in (exotic) charmonium spectroscopy from BESIII

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BESIII collaboration

Dark Matter, Hadron Physics and Fusion Physics — Sep. 2014 Messina
Charmonium physics

- Charmonium in QCD is like positronium in QED
  - Presents an ideal laboratory for testing the interplay between perturbative and nonperturbative QCD.

- Theory tools:
  - Lattice simulation and Effective Field Theories: HQEFT, NRQCD, pNRQCD…

- Experiment methods:
  - **Spectroscopy**, Decay, Production…
  - *Existence, quantum number, masses and width of charmonium bound states*
Charmonium Spectroscopy

- Below open charm threshold
  - Experiment and theory agree well
Charmonium Spectroscopy

Below open charm threshold
• Experiment and theory agree well

Above open charm threshold
• Many predicted states have not yet been observed
• Some unpredicted states have been found with properties that are not consistent with conventional charmonium states
• Exotic charmonium states: X, Y, Z
XYZ physics

- **X states**
  - Iso-spin $I=0$ with quantum number other than $1^-$

- **Y states**
  - Iso-spin $I=0$ with quantum number $1^-$

- **Z states**
  - Iso-spin other than $0$
XYZ physics

X states
- Iso-spin \( l = 0 \) with quantum number \( \text{other than } 1^- \)

Y states
- Iso-spin \( l = 0 \) with quantum number \( 1^- \)

Z states
- Iso-spin \( \text{other than } 0 \)

This talk will focus on
XYZ physics

Why exotic?

- **X states**
  - Iso-spin $I=0$ with quantum number other than $1^-$

- **Y states**
  - Iso-spin $I=0$ with quantum number $1^-$

- **Z states**
  - Iso-spin other than 0

**Why exotic?**

- **X:** Narrow resonance
- **Y:** Absence of a corresponding enhancement in open-charm production
- **Z:** Can’t be formed with 1 quark and 1 anti-quark
Opportunity for BESIII

- $\tau$-Charm factory $\sqrt{s} : 2\sim 5$ GeV.
- Produce Y states directly.
- Good data quality.

Focus on:
- Search for new exotic states in the decays of Y states, especially for charged states.
- Investigate the hidden and open charm decays of XYZ states to clarify their natures.
Discovery of charged Z(3900)\(^{\pm/-}\)

- Investigate the structure in the reaction:
  \[ e^+ e^- \rightarrow \pi^\pm \pi^{\mp} J/\psi \]
  at 4260 MeV

Clear charged charmonium-like state has been observed!

\[ M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV} \]
\[ \Gamma = 46 \pm 10 \pm 20 \text{ MeV} \]
\[ 307 \pm 48 \text{ events, } >8\sigma \]
Confirmed by Belle and CLEO-c

The first Z state observed by more than 1 experiments! They provide strong evidence that more types of bound states than just mesons and baryons exist!
Discovery of neutral $Z(3900)^0$

- How about the iso-spin partner of $Z(3900)^\pm$?
- Just look at: $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$
- Answer from CLEO-c: May be
- Answer from BESIII: Yes

**BESIII preliminary**

Mass = 3894.8$\pm$2.3 MeV
Width = 29.6$\pm$8.2 MeV
Significance = 10.4 $\sigma$
Discovery of neutral Z(3900)$^0$

- Take account of the charged $Z(3900)^\pm$
  \[ M = 3899.0\pm3.6\pm4.9 \text{ MeV} \]
  \[ \Gamma = 46\pm10\pm20 \text{ MeV} \]
  \[ 307 \pm 48 \text{ events, } >8\sigma \]
- The iso-spin triplet $Z(3900)$ state has been established!

**BESIII preliminary**

<table>
<thead>
<tr>
<th>Mass</th>
<th>Width</th>
<th>Significance</th>
</tr>
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<tbody>
<tr>
<td>$3894.8\pm2.3 \text{ MeV}$</td>
<td>$29.6\pm8.2 \text{ MeV}$</td>
<td>$10.4 \sigma$</td>
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Discovery of neutral $Z(3900)^0$

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- The iso-spin triplet $Z(3900)$ state has been established!

**Are there more members in Z family?**
Look at $\pi\pi\chi_{cJ}, \pi\pi h_c, \pi\pi\psi(2S)\ldots$

**BESIII preliminary**

Mass = 3894.8$\pm$2.3 MeV
Width = 29.6$\pm$8.2 MeV
Significance = 10.4 $\sigma$
Observation of charged $Z(4020)^{\pm/-}$

$$e^+ e^- \rightarrow \pi^\pm \pi^\mp h_c$$

$M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}$

$\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$

Significance : $8.9\sigma$
Observation of neutral $Z(4020)^0$

\[ e^+ e^- \rightarrow \pi^\pm \pi^\mp h_c \]

\[ e^+ e^- \rightarrow \pi^0\pi^0 h_c \]

PRL 111, 242001

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV

$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

Significance : $8.9\sigma$

Mass = 4023.9 ± 2.2 ± 3.8 MeV,
Width is fixed at that of its charged partner.

Establishes isospin triplet $Z(4020)^{\pm,0}$
Cross section of $e^+e^- \rightarrow \pi\pi h_c$

More data are needed to pin down the shape of structure. One resonance exist here or more?

Measured cross sections consist with isospin-spin conservation!
Investigation of open charm decays

- Z(3900) is just ~20 MeV/c² above the $D\bar{D}^*$ mass threshold.
- Z(4020) is also slightly higher than the threshold of $D^*\bar{D}^*$.
- One natural explanation is that these Zc states are S-wave $D\bar{D}^*$ and $D^*\bar{D}^*$ molecular states or molecular-type resonances.

loosely bound states composed of a pair of mesons, probably bound by the long-range color-singlet pion exchange

- Investigation of open charm decays of Zc may provide information that is useful for understanding its nature.
Observation of $Z(3885)^{+/−}$

- Study of $e^+e^- \rightarrow \pi^\pm (D\bar{D}^*)^\mp$ at $\sqrt{S} = 4.26$ GeV

Mass = 3883.9 ± 1.5 ± 4.2 MeV, (fit with BW function)

Width = 24.8 ± 3.3 ± 11.0 MeV

Fit to angular distribution favors $J^{PC}=1^+$ over $0^-, 1^-$
Observation of $Z(4025)^{+/−}$

- Search for the open charm decay of $Z$ states $e^+e^- \to (D^*\bar{D}^*)^{±}\pi^{∓}$ at $\sqrt{S} = 4.26$ GeV
- Clear enhancement in the threshold of $D^*\bar{D}^*$, named $Z(4025)$

$$\sigma(e^+e^- \to (D^*\bar{D}^*)^{±}\pi^{∓}) = 137 \pm 9 \pm 15 \text{ pb}$$

$$R = \frac{\sigma(e^+e^- \to Z_c^{±}(4025)\pi^{∓}\to(D^*\bar{D}^*)^{±}\pi^{∓})}{\sigma(e^+e^- \to (D^*\bar{D}^*)^{±}\pi^{∓})} = 0.65 \pm 0.09 \pm 0.06.$$
Summary of $Z$ states at BESIII

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass $m$ [MeV/c²]</th>
<th>Width $\Gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi\pi^+$</td>
<td>$3899.0 \pm 3.6 \pm 4.9$</td>
<td>$46 \pm 10 \pm 20$</td>
</tr>
<tr>
<td>$J/\psi\pi^0$</td>
<td>$3894.8 \pm 2.3$</td>
<td>$29.6 \pm 8.2$</td>
</tr>
<tr>
<td>$D^+\overline{D}^{*0}$</td>
<td>$3883.9 \pm 1.5 \pm 4.2$</td>
<td>$24.8 \pm 3.3 \pm 11.0$</td>
</tr>
<tr>
<td>$h_c\pi^+$</td>
<td>$4022.9 \pm 0.8 \pm 2.7$</td>
<td>$7.9 \pm 2.7 \pm 2.6$</td>
</tr>
<tr>
<td>$h_c\pi^0$</td>
<td>$4023.6 \pm 2.2 \pm 3.9$</td>
<td>fixed</td>
</tr>
<tr>
<td>$D_{s+}\overline{D}^{*0}$</td>
<td>$4026.3 \pm 2.6 \pm 3.7$</td>
<td>$24.8 \pm 5.6 \pm 7.7$</td>
</tr>
</tbody>
</table>

- $Z(3900)^{+/-,0} \ I=1$
- $Z(3885)^{+/-} \ I=1$
- $Z(4020)^{+/-,0} \ I=1$
- $Z(4025)^{+/-} \ I=1$

- Consist of at least 4 quarks.
- What is the configuration of quarks? Many theoretical interpretations.

Are the $Z(3900)/Z(4020)$ and $Z(3885)/Z(4025)$ the same states?

- Determine the $J^{PC}$ (Angular analysis).
- Search for more partner states.
- More decay pattern on both open/hidden charm channel.
Summary of Z states at BESIII

- Consist of at least 4 quarks.
- What is the configuration of quarks? Many theoretical interpretations.
- Are the Z(3900)/Z(4020) and Z(3885)/Z(4025) the same states?
  - Determine the \( J^{PC} \) (Angular analysis).
  - Search for more partner states.
  - More decay pattern on both open/hidden charm channel.
First observation of \( e^+ e^- \rightarrow \gamma X(3872) \)

- Study the radiative transition between Y and X states
- \( X(3872) : J^{PC}=1^{++} \), it should be able to be produced through the radiative transition of Y states.
  \[ \sqrt{S} = 4009, 4230, 4260, 4360 \text{ MeV} \]

Cross section \( e^+ e^- \rightarrow \gamma X(3872) \rightarrow \gamma \pi^+ \pi^- J/\psi \)

- Significance = 6.3\(\sigma\)
- \( N = 20.1 \pm 4.5 \) events
- \( M = 3871.9 \pm 0.7 \pm 0.2 \) MeV
- \( \rightarrow \) Suggests production in \( Y(4260) \) decays
First observation of $e^+ e^- \rightarrow \omega \chi_{c0}$

- Study the hadronic transition between Y and conventional charmonium.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$N_{\text{obs}}$</th>
<th>$N_{\text{bkg}}$</th>
<th>$\sigma_{\text{UL}}^B$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega \chi_{c1}$</td>
<td>4.31</td>
<td>1</td>
<td>0</td>
<td>$&lt; 18$</td>
</tr>
<tr>
<td></td>
<td>4.36</td>
<td>1</td>
<td>1</td>
<td>$&lt; 0.9$</td>
</tr>
<tr>
<td></td>
<td>4.39</td>
<td>1</td>
<td>0</td>
<td>$&lt; 17$</td>
</tr>
<tr>
<td></td>
<td>4.42</td>
<td>0</td>
<td>0</td>
<td>$&lt; 11$</td>
</tr>
<tr>
<td>$\omega \chi_{c2}$</td>
<td>4.36</td>
<td>5</td>
<td>1</td>
<td>$&lt; 11$</td>
</tr>
<tr>
<td></td>
<td>4.39</td>
<td>3</td>
<td>0</td>
<td>$&lt; 64$</td>
</tr>
<tr>
<td></td>
<td>4.42</td>
<td>2</td>
<td>0</td>
<td>$&lt; 61$</td>
</tr>
</tbody>
</table>

- Clear signals of $e^+ e^- \rightarrow \omega \chi_{c0}$ are observed at 4230 and 4260 MeV.

- No significant signals of $\omega \chi_{c1/2}$ are found.
First observation of $e^+ e^- \rightarrow \omega \chi_{c0}$

Statistical significance is determined to be $9.3\sigma$ by comparing resonance and phase space assumption.

The line shape of cross section is not consistent with $Y(4260)$. 
Summary

- Charmonium presents an ideal laboratory for testing the interplay between perturbative and non-perturbative QCD.

- The spectroscopy above open charm threshold is more interesting.
  - New class of charmonium-like states has been discovered. They have properties which cannot be understood in terms of conventional charmonium states.

- Charged charmonium-like states that must contain at least 2 quark / anti-quark pairs. They provide strong evidence that more types of bound states than just mesons and baryons exist.

- Most of XYZ states are not understood well so far, more experimental measurements and theory calculations are needed to solve the puzzle!

Thank you!
Backup
Charmonium

- **Bound states of charm/anti-charm quarks.**
  - Mass of low lying state: \( \sim 3 \) GeV.
  - Quantum number: \( J = L + S, \quad P = (-1)^{L+1}, \quad C = (-1)^{L+S} \)

- **Production mechanism:**
  - \( e^+ e^- \) direct formation
  - \( 2\gamma \) production
  - Initial state radiation
  - Double charmonium
  - \( B \) meson decay
  - \( p\bar{p} \) annihilation
First exotic state observed!

Production: \( B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi \)
\[ M = 3872 \pm 0.8 \text{ MeV}/c^2 \]
\[ \Gamma < 2.3 \text{ MeV} \ @90\% \ CL. \quad (\Gamma_{\psi(3770)} = 27.2 \text{ MeV}) \]

\( J^{PC} \) favor 1\(^{++} \) by Belle

Explanation: \( \chi_{c1}(2P) \) ?

molecule of \( D^0 D^{0*} \) ?

\( \text{BELLE Collaboration, PRL 91, 26 (2003)} \)

\( X(3872) \)
XYZ physics

- **X states**
  - Neutral states with quantum number **other than** $1^{--}$

- **Y states**
  - Neutral states with quantum number $1^{--}$

- **Z states**
  - Charged states

**First Y state!**

Production:
\[ e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi \]

- $M = 4259 \pm 8^{+2}_{-6}$ MeV
- $\Gamma = 88 \pm 23^{+6}_{-4}$ MeV
- $J^{PC} = 1^{--}$

Comparing to $\psi(3770)$ the ratio is 500!
XYZ physics

- **X states**
  - Neutral states with quantum number other than $1^{--}$

- **Y states**
  - Neutral states with quantum number $1^{--}$

- **Z states**
  - Charged states

**Z state**

Production: $B \rightarrow K \pi^+ \psi(2S)$

$M = 4433 \pm 4 \pm 2$ MeV

$\Gamma = 45^{+18+30}_{-13-13}$ MeV

Consist of at least 2 quarks and 2 anti-quarks!
Discovery of charged $Z(3900)^{+/-}$
Confirmed by Belle and CLEO-c

\[ e^+ e^- \rightarrow \gamma_{ISR} \pi^+ \pi^- J/\psi \]

\[ e^+ e^- \rightarrow \pi^+ \pi^- J/\psi \]

"APS highlight of year 2013"

New Particle Hints at Four-Quark Matter

Published 17 June 2013

Two experiments have detected the signature of a new particle, which may combine quarks in a way not seen before.