XYZ states at BESIII

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Outline

- The BESIII experiment
- News from X, Y, Z states
  - The X(3872) — $J^{PC} = 1^{++}$
  - The Y states — $J^{PC} = 1^{--}$
  - The $Z_c$ states — $I = 1$ & decays into $c\bar{c}$
- Summary
BESIII Detector @ IHEP

BEPCII (Beijing Electron Positron Collider)

- Symmetric $e^+e^-$ collider, double rings, $2.0 < E_{cm} < 4.6$ GeV
- Design luminosity: $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ @ 1.89 GeV, achieved on 5th April, 2016!

BESIII Detector

- Has been in full operation since 2008!
- Total weight 730 ton, ~40,000 readout channels, Data rate: 5kHz, 50Mb/s

BESIII Collaboration

14 countries
64 institutions
~450 members
Data sets for XYZ study

- Ongoing data taking.

- 4190, 4200, 4210, 4220, 4236, 4245, 4270, 4280: 3.9 fb⁻¹

- 4040: 0.5 fb⁻¹

- 4180: 3.0 fb⁻¹

- 4230: 1.0 fb⁻¹

- 4260: 0.8 fb⁻¹

- 4360: 0.5 fb⁻¹

- 4420: 1.0 fb⁻¹

- 4600: 0.6 fb⁻¹

\( R \) scan 1.3 fb⁻¹ (130 points)
Charmonium-like spectroscopy

- Potential model is used to describe $c\bar{c}$ states.
- Below the $2M_D$ threshold the predicted masses of the charmonium states match.
- Above the $2M_D$ threshold there are many predicted states but only a few have been experimentally measured.

Godfrey & Isgur, PRD32, 189 (1985)
Charmonium-like spectroscopy

- Potential model is used to describe $c\bar{c}$ states.
- Below the $2M_D$ threshold the predicted masses of the charmonium states match.
- Above the $2M_D$ threshold there are many predicted states but only a few have been experimentally measured.
- An abundance of states that do not fit the prediction has been discovered.
- New type of hadron (multi-quark …)?

Godfrey & Isgur, PRD32, 189 (1985)
X states
Story from $X(3872)$

- $X(3872)$ discovered by Belle in $B \rightarrow K\pi^+\pi^-J/\psi$, confirmed by many other experiments (in B decays, hadron collisions)

\[
M(X) - M(D^0D^{*0}) = 0.01 \pm 0.18 \text{ MeV} \\
\Gamma < 12 \text{ MeV} \quad J^{PC} = 1^{++} \text{ (from LHCb)}
\]

- BESIII observed $e^+e^- \rightarrow \gamma X(3872)$, $X(3872) \rightarrow \pi^+\pi^-J/\psi$

- Support the existence of the radiative transition process $Y(4260) \rightarrow \gamma X(3872)$

- If $B(X(3872) \rightarrow \pi^+\pi^-J/\psi) \sim 5\%$ ($>2.6$ in PDG):

\[
\frac{\sigma(e^+e^-\rightarrow\gamma X(3872))}{\sigma(e^+e^-\rightarrow\pi^+\pi^-J/\psi)} \sim 10\% \quad \text{Large transition ratio!}
\]

Despite growing experimental facts, the nature of the $X(3872)$ remains unclear
The $X(3872) \rightarrow \pi^0 \chi_{cJ}$ decays are sensitive to the internal structure of the $X(3872)$, PRD77, 014013 (2008)

- Conventional $c\bar{c}$ state: transitions should be suppressed
- Tetraquark or molecular state: transitions are expected to be enhanced

BESIII observed $5.2\sigma$ evidence for $X(3872) \rightarrow \pi^0 \chi_{c1}$

The Branching ratios are measured as:

$$R_j = \frac{B(X \rightarrow \pi^0 \chi_{cJ})}{B(X \rightarrow \pi^+ \pi^- J/\psi)}$$

- $R_0 < 19$ (90% U.L.)
- $R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14$
- $R_2 < 1.0$ (90% U.L.)

The large value for $R_1$ disfavors the $\chi_{c1}(2P)$ interpretation of the $X(3872)$
Y states
Y states from Initial State Radiation

Some history

- The $Y(4260)$ has been discovered by BaBar in the mass spectrum $M(\pi^+\pi^- J/\psi)$ via initial state radiation, then confirmed by Belle.

- Belle also claimed the discovery of another resonance labeled $Y(4008)$.

- BaBar and Belle saw two resonances in the mass spectrum $M(\pi^+\pi^- \psi(2S))$: $Y(4360)$ and $Y(4660)$.

Inconsistent with all $1^{--}$ quark model states?
Greatly suppressed open charm decays
Candidates for exotic matter:

Hybrids? Tetraquark? Hadronic molecules?

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Y states: $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$

Precise measurement by BESIII

- The most precise cross section measurement to date from BESIII
- The "Y(4008)" not needed to describe data
- Cross-section in-consistent with a single peak for the Y(4260)!
- Two peaks favored over one by $> 7\sigma$

Y(4220): $M = 4222.0 \pm 3.1 \pm 1.4$ MeV
$\Gamma = 44.1 \pm 4.3 \pm 2.0$ MeV

Y(4320): $M = 4320.0 \pm 10.4 \pm 7.0$ MeV
$\Gamma = 101.4 \pm 25.3 \pm 19.7$ MeV

Y(4320) has been seen for the first time in this channel and it is compatible with Y(4360) measured by Belle and BaBar in $\pi^+ \pi^- \psi(2S)$.

PRL118, 092001 (2017)
Y states: $e^+ e^- \rightarrow \pi\pi\psi(2S)$

- BESIII confirms the line shape for $Y(4360)$ and measures with much higher precision:
  \[ M = 4383.8 \pm 4.2 \pm 0.8 \text{ MeV} \]
  \[ \Gamma = 84.2 \pm 12.5 \pm 2.1 \text{ MeV} \]

- The $Y(4220)$ is necessary (significance = $5.8\sigma$):
  \[ M = 4209.5 \pm 7.4 \pm 1.4 \text{ MeV} \]
  \[ \Gamma = 80.1 \pm 24.6 \pm 2.9 \text{ MeV} \]

Cross section measurements in charge and neutral channels show results that validate the isospin symmetry:

\[
R(\pi^+\pi^-\psi(2S)) = \frac{\sigma(e^+e^-\rightarrow\pi^0\pi^0\psi(2S))}{\sigma(e^+e^-\rightarrow\pi^+\pi^-\psi(2S))} = 0.48 \pm 0.04 \pm 0.02
\]

Y states: $e^+ e^- \rightarrow \pi^+ \pi^- h_c$

First precise cross section measurement from threshold to 4.6 GeV

- The data cannot be fitted with a single peak.
- Significance of two structures assumption over one structure 10σ!
- Y(4220) is compatible with the state found in $\pi^+ \pi^- J/\psi$ at 4222 MeV.

PRL118, 092002 (2017)
**e^+ e^- → π^+ D^0 D^{*-} + c. c.**

- Based on data samples from $E_{cms} = 4.05$ to 4.6 GeV.
- Reconstructed: $D^0 \rightarrow K^- \pi^+$.
- Using $RM(D^0 \pi^+) + M(D^0) - m(D^0)$ to select $D^{*-}$ signal. Peaking bkgd from isospin partner $e^+ e^- \rightarrow \pi^+ D^- D^{*0}$
- Fit of coherent sum of 3-body PHSP and 2 BW functions.
- Significance of two over one structure: $> 10\sigma$.

**Y(4220):**

- $M = (4228.6 \pm 4.1 \pm 5.9)$ MeV/$c^2$
- $\Gamma = (77.1 \pm 6.8 \pm 6.9)$ MeV/$c^2$

- Consistent with structure observed in $\pi\pi J/\psi, \pi\pi h_c, \pi\pi\psi(2S)$
- The resonance parameters for the enhancement around 4.40 GeV are strongly dependent on the model assumptions, necessitating further studies

*arxiv:1808.02847*
Y Puzzle, Y(4260) → Y(4220): what is it?

- Y(4220) appeared in $\pi^+\pi^- J/\psi$, $\pi^+\pi^- \psi(2S)$, $\pi^+\pi^- h_c$, $\pi^+D^0D^{*-}$, and $\omega\chi_{c0}$, but absent in $K_S^0 K^+\pi^-$ and $K_S^0 K\pi\pi^0/\eta$

- No evidence of the Y(4220) decays into light hadrons yet
- Mass ~ 4220 MeV, Width ~ 60 MeV!
- What is it? More data and more theoretical work needed
Belle collaboration observed the baryonic decay of $Y(4660)$

Furthermore
\[ Y(4660) \rightarrow \psi(3686)\pi^+\pi^- \quad \sigma_{\text{peak}} \sim 0.04 \text{ nb} \]
\[ Y(4660) \rightarrow \Lambda_c \bar{\Lambda}_c \quad \sigma_{\text{peak}} \sim 0.55 \text{ nb} \]

$Y(4660)$ baryonic coupling $\geq 10$ mesonic coupling!

$Y(4660)$ likely is a charmed baryonium
(a confirmation by BESIII is needed)

As pointed out by Faccini et al., Maiani et al.: If hidden charm tetraquarks exist their main decay should be mostly by a light quark pair popping up from the vacuum and then falling apart as a charmed baryon pair (Rossi, Veneziano)

But BESIII and Belle data do not agree so much... (arxiv1710.03142)
BESIII $\sigma(e^+e^- \rightarrow \Lambda_c \bar{\Lambda}_c)$ reminds $\sigma(e^+e^- \rightarrow p\bar{p})$: flat with a step at threshold

BESIII is going to increase BEPCII maximum energy, so BESIII will confirm (or not) if $Y(4660)$ is a charmed baryonium

More data at threshold and above 4.6 GeV will be collected!
Z states
**Z states:** \( e^+ e^- \rightarrow \pi^+ (\pi^- J/\psi) \)

- Discovery of \( Z_C(3900)^\pm \rightarrow \pi^\pm J/\psi \):
  - Decay \( J/\psi \rightarrow \) contains \( c\bar{c} \)
  - Electrically charged \( \rightarrow \) contains \( u\bar{d} \)
  - Candidate for 4-quark state(?!)

\[
\begin{align*}
M &= (3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2 \\
\Gamma &= (46 \pm 10 \pm 20) \text{ MeV}
\end{align*}
\]

- Seen by Belle too and confirmed by CLEOc
- Discovered in the neutral mode at different energies with a significance > 10\(\sigma\)
- Establishes an isospin triplet \( Z_C(3900) \)
Several $Z$ decays have been measured in $c\bar{c}$ and open charm states.

Isospin triplet is established for all of them.

Masses and widths are comparable.
More Z states: $e^+e^- \rightarrow \pi^+(\pi^-\psi')$

- A prominent narrow structure is observed in $\pi^\pm\psi'$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi')$ versus $M^2(\pi^-\psi')$

$$\frac{p \cdot q / c^2}{(M_K^2 - x)^2 + M_K^2 \cdot \Gamma^2 / c^4} + \frac{p \cdot q / c^2}{(M_K^2 - y)^2 + M_K^2 \cdot \Gamma^2 / c^4}$$

Stat. err. ONLY!

- The fit yields: $M = (4032.1 \pm 2.4)$ MeV/$c^2$ and $\Gamma = (26.1 \pm 5.3)$ MeV/$c^2$, with a significance of $9.2\sigma$
- The behavior of the structure is very different between the high and the low $M(\pi^-\pi^+)$ region

PRD 96, 032004 (2017)
A neutral charmoniumlike structure is observed in $\pi^0 \psi'$ invariant mass.

A simple fit with S-wave Breit-Wigner function is performed, and yield a mass with $(4038.7 \pm 6.5)$ MeV/$c^2$, which confirms the structure in the charged mode.

No obvious $Z_c(3900)^0$ state is observed.
**Determination of spin and parity for \( Z_c(3900) \)**

- Amplitude analysis
  - Five resonances are considered in the amplitude: \( \sigma(500), f_0(980), f_0(1270), f_0(1370) \rightarrow \pi\pi; \ Z_c(3900)\pm \).
  - Charge conjugate partner assumed: \( Z_c(3900)^+ \) & \( Z_c(3900)^- \) share same mass, width…
  - Five \( J^P \) assumptions: 0\(^-\), 1\(^-\), 1\(^+\), 2\(^-\) & 2\(^+\) are tested
  - \( J^P = 1^+ \) is favored over 0\(^-\), 1\(^-\), 2\(^-\) & 2\(^+\)

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>( \Delta(-2 \ln L) )</th>
<th>( \Delta(\text{ndf}) )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^+) over 0(^-)</td>
<td>94.0</td>
<td>13</td>
<td>7.6(\sigma)</td>
</tr>
<tr>
<td>1(^+) over 1(^-)</td>
<td>158.3</td>
<td>13</td>
<td>10.8(\sigma)</td>
</tr>
<tr>
<td>1(^+) over 2(^-)</td>
<td>151.9</td>
<td>13</td>
<td>10.5(\sigma)</td>
</tr>
<tr>
<td>1(^+) over 2(^+)</td>
<td>96.0</td>
<td>13</td>
<td>7.7(\sigma)</td>
</tr>
</tbody>
</table>
Determination of spin and parity for $Z_c(3900)$

- Amplitude analysis
- Five resonances are considered in the amplitude: $\sigma(500)$, $f_0(980)$, $f_0(1270)$, $f_0(1370) \rightarrow \pi\pi$; $Z_c(3900)^\pm$.
- Charge conjugate partner assumed: $Z_c(3900)^+ \& Z_c(3900)^-$ share same mass, width…
- Five $J^P$ assumptions: 0-, 1-, 1+, 2- & 2+ are tested
- Res. param. of $Z_c(3900)$ improved:

$$BW(s, M, g_1', g_2') = \frac{1}{s - M^2 + i[g_1'\rho_1(s) + g_2'\rho_2(s)]}$$

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>$(3901.5 \pm 2.7 \pm 38.0)$ MeV</td>
</tr>
<tr>
<td>$g_1'$</td>
<td>$(0.075 \pm 0.006 \pm 0.025)$ GeV$^2$</td>
</tr>
<tr>
<td>$g_2'/g_1'$</td>
<td>$27.1 \pm 2.0 \pm 1.9$</td>
</tr>
<tr>
<td>$M_{\text{pole}}$</td>
<td>$(3881.2 \pm 4.2 \pm 52.7)$ MeV</td>
</tr>
<tr>
<td>$\Gamma_{\text{pole}}$</td>
<td>$(51.8\pm 4.6\pm 36.0)$ MeV</td>
</tr>
</tbody>
</table>

$$\sigma(e^+e^- \rightarrow \pi^+Z_C^- + c.c.):$$

- $4.23$ GeV $\quad (21.8 \pm 1.0 \pm 4.4)$ pb
- $4.26$ GeV $\quad (11.0 \pm 1.2 \pm 5.4)$ pb

PRL 119, 072001 (2017)
Search for $Z_c \to \rho \eta_c$

- Search for new decay mode of $Z_c(3900)$ and $Z_c(4020)$
- The ratios of $Z_c^{(i)} \to \rho \eta_c$ to $Z_c^{(i)} \to \pi J/\psi (\pi h_c)$ may provide an important hint to experimentally distinguish the **tetra-quarks (Type-1)** and **molecular** model

$$R_Z = \frac{Br(Z_c \to \rho \eta_c)}{Br(Z_c \to \pi J/\psi)}$$

Type-II neglect the spin-spin interaction outside the diquarks


- Also calculations predict very different values:
  $$R_Z = 10^{-3} \sim 10^2$$
  arXiv:1806.05651
  arXiv:1512.01938
  PRD 91, 034032 (2015)
  PRD 90, 054006 (2014)
  EPJC 73, 2561 (2013)
Search for $Z_c \to \rho \eta_c$

Preliminary result

- $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$
- $\eta_c \to 9$ hadronic decays

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c \to p\bar{p}$</td>
<td>~0.13%</td>
</tr>
<tr>
<td>$\eta_c \to 2(K^+K^-)$</td>
<td>~0.15%</td>
</tr>
<tr>
<td>$\eta_c \to \pi^+\pi^-K^+K^-$</td>
<td>~1.50%</td>
</tr>
<tr>
<td>$\eta_c \to K^+K^-\pi^0$</td>
<td>~1.20%</td>
</tr>
<tr>
<td>$\eta_c \to p\bar{p}\pi^0$</td>
<td>~0.18%</td>
</tr>
<tr>
<td>$\eta_c \to K_SK\pi$</td>
<td>~1.80%</td>
</tr>
<tr>
<td>$\eta_c \to \pi^+\pi^-\eta$</td>
<td>~1.60%</td>
</tr>
<tr>
<td>$\eta_c \to K^+K^-\eta$</td>
<td>~0.57%</td>
</tr>
<tr>
<td>$\eta_c \to \pi^+\pi^-\pi^0\pi^0$</td>
<td>~2.40%</td>
</tr>
</tbody>
</table>

- Strong evidence of $e^+e^- \to \pi Z_c, Z_c \to \rho \eta_c$ is observed at $\sqrt{s} = 4.23$ GeV, with statistical significance of 4.3$\sigma$
- $e^+e^- \to \pi Z_c', Z_c' \to \rho \eta_c$ is not seen (1$\sigma$)
- Measure Born cross section at 4.23 GeV
  
  $\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10 \) pb$
  
  $\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho \eta_c) = (47 \pm 11 \pm 11 \) pb$

\[
R_{Z_c^{(l)}} = \frac{Br(Z_c^{(l)} \to \rho \eta_c)}{Br(Z_c^{(l)} \to \pi J/\psi)}:
\]

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>Type-I</th>
<th>Type-II</th>
<th>Molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.23 GeV</td>
<td>2.1 $\pm$ 0.8</td>
<td>&lt; 6.4</td>
<td>...</td>
</tr>
<tr>
<td>4.26 GeV</td>
<td>6.6 $\pm$ 1.2</td>
<td>&lt; 1.0</td>
<td>0.010 $^{+0.006}_{-0.004}$</td>
</tr>
<tr>
<td>4.36 GeV</td>
<td>&lt; 1.9</td>
<td>&lt; 1.2</td>
<td>0.046 $^{+0.025}_{-0.017}$</td>
</tr>
</tbody>
</table>
Summary

• BESIII observed a series of vector charmonium-like states from various processes

• $Y(4260) \rightarrow Y(4220)$ with more decay modes now

• Observation of $Y(4220) \rightarrow \gamma X(3872)$ and $X(3872) \rightarrow \pi^0 \chi_{c1}$

• Observation of $Z_C$ states, a new structure in $\pi \psi'$, evidence for $Z_C(3900) \rightarrow \rho \eta_c$

• The $J^P$ of $Z_C(3900)$ is confirmed to be $1^+$

• $Y(4660)$ is a charmed baryonium, according to Belle data on $Y(4660) \rightarrow \Lambda_c \bar{\Lambda}_c$ as expected if XYZ are tetraquarks, but Belle and BESIII do not agree so much, soon BESIII new data above 4.6 GeV

• Data taking is on going on BESIII and more analyses are in progress

Thanks a lot for your attention!