The charged and neutral Zc states
at BESIII
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(On behalf of the BESIII collaboration)
Outline

• Introduction

• The BESIII Experiment

• The $Z_c$ states

• Summary
Constitution of hadrons in QCD

Baryons are red-blue-green triplets
\[ \Lambda = u sd \]

Mesons are color-anticolor pairs
\[ \pi = \bar{u} d \]

Other possible combinations of quarks and gluons:

- **Pentaquark**
  - \( S = +1 \)
  - Baryon
  - Tightly bound 6 quark state

- **H di-Baryon**
  - Tightly bound 6 quark state

- **Glueball**
  - Color-singlet multigluon bound state

- **Tetraquark**
  - Tightly bound diquark & anti-diquark

- **Molecule**
  - Loosely bound meson-antimeson “molecule”

- **q\bar{q} -gluon hybrid mesons**

However, none of them are established and they are exotica!!!
beam energy: 1.0 – 2.3 GeV

- **1989-2004 (BEPC):**
  \[ L_{\text{peak}} = 1.0 \times 10^{31} / \text{cm}^2 s \]

- **2009-now (BEPCII):**
  \[ L_{\text{peak}} = 1.0 \times 10^{33} / \text{cm}^2 (4/5/2016) \]

- 2004: started BEPCII upgrade, BESIII construction
- 2008: test run
- 2009 - now: BESIII physics run
Features of the BEPC Energy Region

- Rich of resonances: charmonia(-like) and charmed hadrons
- Threshold characteristics (pairs of $\tau$, D, $D_s$, $\Lambda_c$ ...)
- Transition between smooth and resonances, perturbative and non-perturbative QCD
- Energy location of the new hadrons: glueballs, hybrids, multi-quark states
The Zc states

Z states: charmonium-like states carrying electric charge; must contain at least cc and a light qq pair
**Zc⁺(3900) discovery**

- Mass = $(3899.0 \pm 3.6 \pm 4.9)$ MeV
- Width = $(46 \pm 10 \pm 20)$ MeV

![Graph showing significance >8σ and mass distribution](https://via.placeholder.com/150)

- Couples to $c\bar{c}$
- Has electric charge 1
- Consists of at least four quarks of $c\bar{c}u\bar{d}$

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PRL110, 252001 (2013)

from APS/Alan Stonebraker

Pei-RongLi

Hadron2017, Salamanca, Spain
Confirmations from other experiments

Belle with ISR-return from Y(nS) data set
PRL110, 252002 (2013)

Mass = \(3894.5 \pm 6.6 \pm 4.5\) MeV
Width = \(63 \pm 24 \pm 26\) MeV

\(159 \pm 49\) events >5.2\(\sigma\)

CLEOc data at 4.17 GeV:
PLB 727, 366 (2013)

Mass = \(3885 \pm 5 \pm 1\) MeV
Width = \(34 \pm 12 \pm 4\) MeV

\(81 \pm 20\) events 6.1\(\sigma\)

Consistent results from other electron-positron annihilation experiments!
Nature of the exotic $\text{Zc}^+(3900)$

- Its mass lies close to the threshold of $m(D)+m(D^*)$
- $DD^*$ molecule?  tetraquark?  and other scenarios:
  - Cusp?
  - Threshold effect?
  - ...

- Other decay mode of the Zc(3900)?
- Partner(s) of the Zc?
\[ \sigma(e^+e^- \rightarrow \pi^-Z_c^+(3885) \rightarrow \pi^-(DD^*)^+) \text{ at } 4.26\text{GeV} \]

If \(Z_c(3885)\) is \(Z_c(3900)\):

\[ R = \frac{\Gamma(Z_c(3885) \rightarrow (\bar{D}D^*)^+)}{\Gamma(Z_c(3900) \rightarrow \pi^+J/\psi)} = 6.2 \pm 1.1 \pm 2.7 \]

Angular distribution favors \(1^+\) and disfavors \(1^-\) or \(0^-\)

\[ \sigma(e^+e^- \rightarrow \pi^-Z_c(3885)\), \quad Z_c(3885)\rightarrow (DD^*)^+ +\text{c.c.}) \]

\[ = (83.5\pm6.6\pm22.0) \text{ pb} \]
Reflection and possible $Z_c(3900)$ signal

Simultaneous fit to 4.23/4.26/4.36 GeV data and 16 $\eta_c$ decay modes: $8.9\sigma$

$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7$ MeV; $\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6$ MeV

$\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- h_c) < 13\text{ pb @}4.23\text{GeV}$

$< 11\text{ pb @}4.26\text{GeV}$

No significant $Z_c(3900)$ signal is observed
assume it as a particle, $Z_c(4025)$, and fit to the $\pi^-$ recoil mass distribution

**resonance parameter:**

$$m(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV}/c^2,$$
$$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}.$$  

401$\pm$47 $Z_c(4025)$ events

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

$$\frac{\sigma(e^+e^- \rightarrow Z_c^{\pm}(4025)\pi^\mp \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp)}{\sigma(e^+e^- \rightarrow (D^*\bar{D}^*)^\pm \pi^\mp)} = 0.65 \pm 0.09 \pm 0.06$$

**Z_c(4020)=Z_c(4025)?**

Coupling to $D^*D^*$ is much larger than to $\pi^-h_c$ if they are the same state
Discoveries of the charged $Z_c^\pm$'s by 2014

- Searching for isospin partners of these states are important to identify the nature
- Measurement of their quantum numbers
Search for $Z_c(3900)^0$ in $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$

$M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c$^2$
$\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV

Search for $Z_c(4020)^0$ in $e^+e^- \rightarrow \pi^0\pi^0 h_c$

$M = (4023.6 \pm 2.2 \pm 3.9)$ MeV/c$^2$
Width fixed to the $Z_c(4020)^+$

Evidence for neutral isospin partner!

[T. Xiao et al., PLB 727, 366 (2013)]

Isospin triplet is established: $Z_c(3900)^{\pm/0}$ & $Z_c(4020)^{\pm/0}$
Search for $Z_c(3885)^0$ in $e^+e^- \rightarrow \pi^0(D\bar{D}^*)^0$

PRL 115, 222002 (2015)

\[ D^+ \rightarrow K^-\pi^+\pi^+, K^-\pi^+\pi^0, Ks\pi^+, Ks\pi^-\pi^+\]
\[ D^0 \rightarrow K^-\pi^+, K^-\pi^0, K^-\pi^-\pi^+ \]

$e^+e^- \rightarrow D^+D^*\pi^0 \rightarrow D^+\bar{D}^0\pi^-\pi^0$

\[ m_{\text{pole}} = (3885.7^{+4.3}_{-5.7} \pm 8.4) \text{ MeV/c}^2 \]
\[ \Gamma_{\text{pole}} = (35^{+11}_{-12} \pm 15) \text{ MeV} \]

Isospin triplet is established: $Z_c(3885)^\pm/0$ & $Z_c(4025)^\pm/0$

Search for $Z_c(4025)^0$ in $e^+e^- \rightarrow \pi^0(D^*\bar{D}^*)^0$

PRL115, 182002 (2015)

\[ D^0/D^+ \]
\[ \bar{D}^0/D^- \]
\[ D^+ \rightarrow K^-\pi^+\pi^+ \]
\[ D^0 \rightarrow K^-\pi^+, K^-\pi^0, K^-\pi^-\pi^+ \]

\[ m_{\text{pole}} = (4025.5^{+2.0}_{-4.7} \pm 3.1) \text{ MeV/c}^2 \]
\[ \Gamma_{\text{pole}} = (23.0\pm6.0\pm1.0) \text{ MeV} \]
$e^+e^- \rightarrow (D\bar{D}^*)^+\pi^- + \text{c.c.}$ (DT method)

Single tag

- $M = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}$
- $\Gamma = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}$
- $J^P = 1^+$

Double tag

- @ 4.23 GeV:
  - $M = 3881.7 \pm 1.6 \pm 2.1 \text{ MeV}$
  - $\Gamma = 26.6 \pm 2.0 \pm 2.3 \text{ MeV}$
  - $J^P = 1^+$

$Z_c(4020) \rightarrow \bar{D}D^*$ is not observed

$\frac{\Gamma(Z_c(4020) \rightarrow \bar{D}D^*)}{\Gamma(Z_c(3885) \rightarrow \bar{D}D^*)} < 0.13$

Good agreement between ST & DT method
### The Zc Family at BESIII

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV)</th>
<th>Decay</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zc(3900)⁺</td>
<td>3899.0 ± 3.6 ± 4.9</td>
<td>46 ± 10 ± 20</td>
<td>π⁺⁻ J/ψ</td>
<td>e⁺⁻ → π⁺⁻ J/ψ</td>
</tr>
<tr>
<td>Zc(3900)⁰</td>
<td>3894.8 ± 2.3 ± 2.7</td>
<td>29.6 ± 8.2 ± 8.2</td>
<td>π⁰ J/ψ</td>
<td>e⁺⁻ → π⁰ J/ψ</td>
</tr>
<tr>
<td>Zc(3885)⁺</td>
<td>3883.9 ± 1.5 ± 4.2</td>
<td>24.8 ± 3.3 ± 11.0</td>
<td>(D⁻ D⁺)⁺</td>
<td>e⁺⁻ → (D⁻ D⁺)⁺ π⁺⁻</td>
</tr>
<tr>
<td>Zc(3885)⁰</td>
<td>3881.7 ± 1.6 ± 2.1</td>
<td>26.6 ± 2.0 ± 2.3</td>
<td>(D⁻ D⁺)⁺</td>
<td>e⁺⁻ → (D⁻ D⁺)⁺ π⁺⁻</td>
</tr>
<tr>
<td>Zc(3885)⁻</td>
<td>3885.7 ± 4.3 ± 8.4</td>
<td>35 ± 11 ± 15</td>
<td>(D⁻ D⁺)⁰</td>
<td>e⁺⁻ → (D⁻ D⁺)⁰ π⁺⁻</td>
</tr>
<tr>
<td>Zc(4020)⁺</td>
<td>4022.9 ± 0.8 ± 2.7</td>
<td>7.9 ± 2.7 ± 2.6</td>
<td>π⁺⁻ h_c</td>
<td>e⁺⁻ → π⁺⁻ h_c</td>
</tr>
<tr>
<td>Zc(4020)⁰</td>
<td>4023.9 ± 2.2 ± 3.8</td>
<td>fixed</td>
<td>π⁰ h_c</td>
<td>e⁺⁻ → π⁰ h_c</td>
</tr>
<tr>
<td>Zc(4025)⁺</td>
<td>4026.3 ± 2.6 ± 3.7</td>
<td>24.8 ± 5.6 ± 7.7</td>
<td>D⁺⁻ D⁺</td>
<td>e⁺⁻ → (D⁺⁻ D⁺)⁺ π⁺⁻</td>
</tr>
<tr>
<td>Zc(4025)⁰</td>
<td>4025.5 ± 2.⁰ ± 3.1</td>
<td>23.0 ± 6.0 ± 1.0</td>
<td>D⁺⁻ D⁺</td>
<td>e⁺⁻ → (D⁺⁻ D⁺)⁰ π⁺⁻</td>
</tr>
</tbody>
</table>

Which is the nature of these states? Different decay channels of the same observed states? Other decay modes?
Spin-parity determination of the $Z_c^+(3900)$

- $Z_c$ line shape parameterized with Flatte-like formula

$$BW(s) = \frac{1}{s - M^2 + \frac{i}{2} (g_1^2 \rho_{J/\psi}(s) + g_2^2 \rho_{D^*D}(s))}$$

$4.23\text{GeV}$

$J^P = 1^+$

$4.26\text{GeV}$

$J^P$ is measured to be $1^+$ with significance larger than $7.6\sigma$ by perform amplitude analysis of $e^+e^- \to \pi^+\pi^- J/\psi$
Study of $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$

**Data samples:**
- 16 energy points from $\sqrt{s}=4.008$ to 4.600 GeV.
- The total integrated luminosity ($L_{\text{int}}$) is 5.1 fb$^{-1}$.

**Reconstructed modes:**
- **Mode I:** $\Psi(3686) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow l^+l^-$ ($l=e/\mu$)
- **Mode II:** $\Psi(3686) \rightarrow$ neutrals+$J/\psi$,
  $\text{neutrals}=(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$ $J/\psi \rightarrow l^+l^-$ ($l=e/\mu$)

Clean signals at e.g., 4.416 GeV

Looking at the Dalitz plots in large data set $\rightarrow$ quite different behaviors
Simple fit to the resonant structure of $\pi^+\psi(3686)$ at 4.416 GeV

- A prominent narrow structure is observed in $\pi\psi(3686)$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$
  \[
  \frac{p \cdot q/c^2}{(M_R^2 - x)^2 + M_R^2 \cdot \Gamma^2/c^4} + \frac{p \cdot q/c^2}{(M_R^2 - y)^2 + M_R^2 \cdot \Gamma^2/c^4}
  \]
- The fit yields a mass of $M=4032.1\pm2.4$ MeV/c$^2$ and a width of $\Gamma=26.1\pm5.3$ MeV, with a significance of 9.2$\sigma$

However, the fitting quality is not good.

Constrain $M(\pi^+\pi^-)$ in higher region, fitting quality is improved

$M=4030.3\pm0.1$ MeV/c$^2$

$\Gamma=5.1\pm0.2$ MeV
Check on the resonance structures at other energy points

- Similar fits are carried out to data at $\sqrt{s} = 4.258$ and 4.358 GeV.
- No fit is applied at $\sqrt{s} = 4.226$ GeV due to its different behavior on the Dalitz plot and anomalous spectrum in $M^2(\pi^+\pi^-)$.

In the fits to data of 4.258 and 4.358 GeV, the $\pi^+\psi(3686)$ resonance parameters are fixed to that at 4.416 GeV. The resonances are confirmed with stat. significances of 9.6 $\sigma$ and 3.6 $\sigma$ at 4.258 and 4.358 GeV, respectively.

At 4.226 GeV, the resonance structures are close to the kinematic boundary.
Study of $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$

Decay channel:
$e^+e^- \rightarrow \pi^0\pi^0\psi(3686), \psi(3686) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow l^+l^- (l = e/\mu)$.

Data sample
- 16 energy point from $\sqrt{s} = 4.008$ to 4.600 GeV.
- The total luminosity ($\mathcal{L}$): 5.2 fb$^{-1}$.

Clear Signals in data

Broad bumps are from backgrounds of the charged mode $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$
Exploration of the intermediate structure

(a) 4.226 GeV,

\( \mathcal{L} = 1091.74 \text{ pb}^{-1} \)

825.67 pb\(^{-1}\)

(b) 4.258 GeV,

539.84 pb\(^{-1}\)

(c) 4.358 GeV,

1073.56 pb\(^{-1}\)

(d) 4.416 GeV
Simple fits to the $\pi^0\psi(3686)$ resonance

- A possible intermediate state is also observed in the $\pi^0\psi(3686)$ spectrum at 4.416 GeV.
- A 2D fit with a fixed width to charged structure observed in $e^+e^- \rightarrow \pi^+\pi^-\psi(3686)$ is performed on the Dalitz distribution of $M^2(\pi^0\psi(3686))$ vs $M^2(\pi^0\psi(3686))$.

$$\frac{p_1 \cdot q_1/c^2}{(x - M_R^2)^2 + M_R^2 \cdot \Gamma/c^4} + \frac{p_2 \cdot q_2/c^2}{(y - M_R^2)^2 + M_R^2 \cdot \Gamma/c^4}$$

- The fit yields a mass $(4038.7 \pm 6.5)$ MeV/c$^2$ (Prel.) with a significance $6.0\sigma$.
  - consistent with the resonance in the charged mode $\pi^+\psi(3686)$
- Similar fits with fixed width and mass are carried out to the data sample at 4.258 and 4.358 GeV.
Comparison to the study of $Z' \rightarrow \pi^+ \psi(3686)$ at Belle

The charged $\pi^+ \psi(3686)$ structure is about 4.030 GeV/$c^2$ at BESIII

- $M = 4030.3 \pm 0.1$ MeV/$c^2$
- $\Gamma = 5.1 \pm 0.2$ MeV

BESIII's result deviates from that of the structure observed by Belle by over 3$\sigma$.

What is the role of threshold

Many new observations near thresholds: $D^*D, D^*D^*, D_1D, \ldots$

* Phase variations appear in many processes: not unique for resonance

To have a complete picture, more findings are desired

- Energy-dependence
- Patterns in productions and decays

For XYZ, the picture is still unclear

World-wide experimental efforts

Models

LQCD
Summary

• **BESIII is successfully operating since 2008**
  – Continue taking data beyond 2020 in the $\tau$-charm mass region

• Observations of the $Zc$ states in the final states of $\pi^+ J/\psi$, $\pi^+ h_c$, $\pi^+ \psi(3686)$, $DD^*$ and $D^*D^*$

• **Amplitude analysis on the $Zc(3900)$ gives $J^P=1^+$**
  → more similar works on other $Zc$ candidate states are ongoing

• We find complex behavior in Dalitz plots in the charged mode $e^+e^- \rightarrow \pi^+\pi^0\psi(3686)$ and the neutral mode $e^+e^- \rightarrow \pi^0\pi^0\psi(3686)$
  ✓ A resonance structure of $\pi\psi(3686)$ around 4.030 GeV is observed
  ✓ Still unresolved discrepancies between the fit model and data.
  ✓ This deviates from that of the structure observed by Belle
Thank you!
谢谢！
Amplitude analysis of $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

In the process $e^+e^- \rightarrow \gamma^* \rightarrow \pi^+\pi^-J/\psi$

- The helicity value of $\gamma^*$ is taken as $\lambda_0 = \pm 1$ due to from e+e- annihilation
- $\gamma^* \rightarrow Z_c^\pm \pi^m$, $Z_c^\pm \rightarrow J/\psi \pi^\pm$, we try $J^p$ for X: $0^-$, $1^-$, $1^+$, $2^-$, $2^+$, and $0^+$ is not allowed
- $Z_c^+$ and $Z_c^-$ states are assumed as isospin partner, with the same mass and coupling constant
- Six processes are included in fitting to data: $\sigma_0$, $f_0(980)$, $f_2(1270)$, $f_0(1370)$, $Z_c^\pm$, and $\pi^+\pi^-J/\psi$
Determined properties of the $Z_c^+(3900)$

- If $Z_c$ is parameterized with a Flatte-like formula
  
  \[ M_{\text{pole}} = 3881.2 \pm 4.2 \pm 52.7 \text{ MeV}, \quad \Gamma_{\text{pole}} = 51.8 \pm 4.6 \pm 36.0 \text{ MeV} \]
  
  \[ g_1' = 0.075 \pm 0.006 \pm 0.025 \text{GeV}^2 \]
  
  \[ g_2' / g_1' = 27.1 \pm 2.0 \pm 1.9 \]

  (consistent with the previous published results)

- Born cross section for $e^+e^- \to Z_c^+\pi^- + c.c. \to \pi^+\pi^- J/\psi$

  \[ 21.8 \pm 1.0 \pm 4.4 \text{ pb at 4.23 GeV} \]
  
  \[ 11.0 \pm 1.2 \pm 5.4 \text{ pb at 4.26 GeV} \]

- Search for $e^+e^- \to Z_c^+(4020)\pi^- + c.c. \to \pi^+\pi^- J/\psi$ gives upper limits at 90% C.L.:

  \[ <0.9 \text{ pb at 4.23 GeV}; \quad <1.4 \text{ pb at 4.26 GeV} \]

  then

  \[ \frac{\sigma(e^+e^- \to Z_c^+(4020)\pi^- + c.c \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to Z_c^+(3900)\pi^- + c.c \to \pi^+\pi^- J/\psi)} < 4\% \text{ at 4.23 GeV} \]

  \[ < 13\% \text{ at 4.26 GeV} \]