BESIII Studies of Exotic Quark States

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On behalf of the BESIII Collaboration

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Outline

- The BESIII experiment
- Charmonium spectrum
  - The X, Y, Z states
- Conclusion
Beijing Electron Positron Collider II

BESIII Detector

Linac: 200 m

2004: BEPCII/BESIII Construction
Double ring
Beam energy: 1-2.3 GeV
Designed Luminosity $1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
2008: test run
2009-today: BESIII physics run
2014: Luminosity: $0.8 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$
The BESIII detector

- Magnet yoke
- RPC (9/8 layers Barrel/Endcaps)
- SC magnet, 1 Tesla
- TOF (scintillators), 90 ps
- Be beam pipe
- MDC, 120μm
- CsI(Tl) calorimeter, 2.5% at 1 GeV
Data samples

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#### Charmonium spectroscopy
Charmonium spectrum

- Below the $D\bar{D}$ threshold, all expected states have been observed, with properties in good agreement with theory.
- Many unexpected states have been reported above the $D\bar{D}$ threshold (XYZ). Several exotic hypotheses as to their nature: tetraquarks, hadronic molecules, hybrids, glueballs, hadro-quarkonia.

**X states:**
- charmonium-like states with $J^{PC} \neq 1^{--}$
- Observed in B decays, $pp$ and $p\bar{p}$ collisions

**Y states:**
- charmonium-like states with $J^{PC} = 1^{--}$
- Observed in direct $e^+e^-$ annihilation or in ISR

**Z states:**
- charmonium-like states carrying electric charge
- Must contain at least a $c\bar{c}$ and a light $q\bar{q}$ pair
Exotic charmonium-like states interpretation

**Molecular state:**
loosely bound state of a pair of mesons. The dominant binding mechanism should be pion exchange. Being weakly bound, mesons tend to decay as if they were free.

**Tetraquark:**
Bound state of four quarks, i.e. diquark-antidiquark. Strong decays proceed via rearrangement processes.

**Distinctive features of multi-quark picture with respect to charmonium:**
- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both.

**Charmonium hybrids**
States with an excited gluonic degree of freedom
Lattice and model predictions for the lowest lying hybrid:
\[ m \sim 4200 \text{ MeV} \]

**Conventional charmonium**

References:
- ES Swanson PLB 598,197 (2004)
- CY Wong PRC 69, 055202 (2004)

- D Ebert et al PLB 634, 214 (2006)
- ...

- P Lacock et al (UKQCD) PLB 401, 308 (1997)
- SL Zhu PLB 625, 212 (2005)
- ...

- C Meng & KT Chao PRD 75, 114002 (2007)
- W Dunwoodie & V Ziegler PRL 100 062006 (2008)
- O Zhang, C Meng & HQ Zheng arXiv:0901.1553
- ...

BESIII Studies of Exotic Quark States

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THE X STATES
Observation of $e^+e^- \rightarrow \gamma X(3872)$ - PRL 112, 092001(2014)

- The $X(3872)$ was discovered by Belle in $J/\psi \pi^+\pi^-$, PRL 110,252002(2013). $J^{PC} = 1^{++}$
- BESIII: Study of $e^+e^- \rightarrow \gamma X(3872)$, $X(3872) \rightarrow J/\psi \pi^+\pi^-$ at center of mass energies from 4.009 to 4.420 GeV.

- The $X(3872)$ is observed with significance $6.3\sigma$
- $m=3871.9\pm0.7\pm0.2$ MeV/c$^2$
- $\Gamma < 2.4$ MeV at 90% CL

- Study of the energy dependent cross section
- The fit with a $Y(4260)$ resonance gives a better description of the data ($\chi^2/ndf = 0.49/3$ at 90% CL)
- These observations strongly support the existence of the radiative transition process $Y(4260) \rightarrow \gamma X(3872)$
Observation of $e^+e^- \rightarrow \pi^+\pi^-X(3823)$ - Preliminary results

- The $X(3823)$ was discovered by Belle in $B \rightarrow \chi_{c1}\gamma K$, PRL 111,032001(2013). Mass and width consistent with the missing $\psi(1^3D_2)$ state
- BESIII: Study of $e^+e^- \rightarrow \pi^+\pi^-X(3823)$, $X(3823) \rightarrow \gamma\chi_{c1,c2}$ at center of mass energies from 4.19 to 4.6 GeV, with 4.67 fb$^{-1}$.

- Study of the energy dependent cross section
- The fit with the $Y(4360)$ and $\psi(4415)$ gives a good description of the data

- The $X(3823)$ is a good candidate for the $\psi(1^3D_2)$ charmonium state
THE Y STATES
Observation of $e^+e^- \rightarrow \omega \chi_{c0}$ - arXiv:1410.6538 (accepted by CPC)

- Study of $e^+e^- \rightarrow \omega \chi_{cJ}$ at center of mass energies from 4.21 to 4.42 GeV ($L=1\, fb^{-1}$ at 4.23 GeV; $0.8\, fb^{-1}$ at 4.26 GeV).
- $\omega \rightarrow \pi^+\pi^-\pi^0$; $\chi_{c0} \rightarrow \pi^+\pi^-$ and $K^+K^-$; $\chi_{c1,2} \rightarrow \gamma J/\psi$

- The process $e^+e^- \rightarrow \omega \chi_{c0}$ is observed for the first time
  - $\sigma(e^+e^- \rightarrow \omega \chi_{c0}) = 55.4 \pm 6.0 \pm 5.9 \, pb$ at 4.23 GeV
  - $\sigma(e^+e^- \rightarrow \omega \chi_{c0}) = 23.7 \pm 5.3 \pm 3.5 \, pb$ at 4.26 GeV
  - $e^+e^- \rightarrow \omega \chi_{c1,c2}$ signals are not significant

- Study of the energy dependent cross section
- Inconsistent with the line shape of the Y(4260) observed in $e^+e^- \rightarrow J/\psi\pi^+\pi^-$
- Assuming the $\omega \chi_{c0}$ signal comes from a single resonance:
  - $m=4230\pm8\pm6 \, MeV/c^2$; $\Gamma=38\pm12\pm2 \, MeV$
  - Significance $>9\sigma$
The Y(4140) was discovered by CDF in $B^+ \rightarrow \phi J/\psi K^+$, PRL102,242002 (2009). Not observed by Belle and LHCb.

BESIII: Search for Y(4140) decays into $\phi J/\psi$ through the process $e^+e^- \rightarrow \gamma\phi J/\psi$ with 1094 pb$^{-1}$ at 4.23 GeV, 827 pb$^{-1}$ at 4.26 GeV and 545 pb$^{-1}$ at 4.36 GeV.
\[ \sigma^B \cdot B = \sigma(e^+ e^- \rightarrow \gamma Y(4140)) \cdot B(Y(4140) \rightarrow \phi J/\psi) : \]

at 4.23 GeV: \(<0.35\) pb at 90% CL  
at 4.26 GeV: \(<0.28\) pb at 90% CL  
at 4.36 GeV: \(<0.33\) pb at 90% CL

Compared with X(3872) production PRL 112, 092001:

\[ \sigma^B \cdot B = \sigma(e^+ e^- \rightarrow \gamma X(3872)) \cdot B(X(3872) \rightarrow \pi^+ \pi^- J/\psi) : \]

at 4.23 GeV: \(0.27 \pm 0.09 \pm 0.02\) pb  
at 4.26 GeV: \(0.33 \pm 0.12 \pm 0.02\) pb

They are of the same order of magnitude!

Considering \(B(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = 5\%\) arXiv:0910.3138  
and \(B(Y(4140) \rightarrow \phi J/\psi) = 30\%\) PRD80, 054019 (molecular calculation)

\[ \frac{\sigma^B(e^+ e^- \rightarrow \gamma Y(4140))}{\sigma(e^+ e^- \rightarrow \gamma X(3872))} \leq 0.1 \text{ at 4.23 and 4.26 GeV} \]
Discovery of the $Z_c(3900)^\pm$ - PRL 110, 252001 (2013)

- Study of the $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ process at the center of mass energy of 4.260 GeV using a 525 pb$^{-1}$
- Measured Born cross section is $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb
- Dalitz plot of events in the $J/\psi$ signal region shows structures in the $\pi^+\pi^-$ system and evidence for an exotic charmoniumlike structure in the $\pi^\pm J/\psi$ system at 3.9 GeV
Discovery of the $Z_c(3900)^\pm$ - PRL 110, 252001 (2013)

- Choosing the heavier $J/\psi$ combination per events removes reflection at 3.45 GeV/c$^2$
- Unbinned maximum likelihood fit to the $\pi^\pm J/\psi$ invariant mass distribution
  - Significance greater than 8$\sigma$
  - $m=(3899.0\pm3.6\pm4.9)$ MeV/c$^2$
  - $\Gamma=(46\pm10\pm20)$ MeV
- Mass close to the $D\bar{D}^*$ threshold
- Decays to $J/\psi \rightarrow$ contains $c\bar{c}$
- Electric charge $\rightarrow$ contains $ud$
- 4-quark state?!

$$\sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi)$$
= $$(21.5\pm3.3\pm7.2)\%$$

Belle: $e^+e^- \rightarrow \gamma_{ISR} J/\psi\pi^+\pi^-$
- $m=(3894.5\pm6.6\pm4.5)$ MeV/c$^2$
- $\Gamma=(63\pm24\pm26)$ MeV

CLEO-c: $e^+e^- \rightarrow J/\psi\pi^+\pi^-$
at 4.17 GeV
- $m=(3886\pm4\pm2)$ MeV/c$^2$
- $\Gamma=37\pm4\pm8$ MeV

BESIII Studies of Exotic Quark States

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Search for a neutral $Z_c(3900)$ isospin partner - Preliminary results

- Observation of the $Z_c(3900)^0$ decaying into $J/\psi \pi^0$ in $e^− e^− \rightarrow \pi^0 \pi^0 J/\psi$ using 2.5 fb$^{-1}$ data sample
- Simultaneous fit to the $J/\psi \pi^0$ invariant mass distributions for the three data samples: $\sqrt{s} = 4.230$ GeV, 4.260 GeV, 4.360 GeV
- $m = 3894.8 ± 2.3 ± 2.7$ MeV/c$^2$; $\Gamma = 29.6 ± 8.2 ± 8.2$ MeV; Significance greater than 10$\sigma$

- First evidence by CLEO-c
  - $e^+ e^- \rightarrow J/\psi \pi^+ \pi^-$ at 4.17 GeV
  - $m = 3904 ± 4 ± 5$ MeV/c$^2$
  - $\Gamma = 37$ (Fixed) MeV
  - Significance 3.7$\sigma$

Isospin triplet is established!
Observation of $Z_c(3885)\pm$ in $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)\mp$ using single D tag method - PRL 112, 022001 (2014)

- Study of the $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)\mp$ at $\sqrt{s}=4.26$ GeV using a 525 pb$^{-1}$
- Single D tag method: Reconstruction of the $\pi$ and one final state D meson; the presence of the $\bar{D}^*$ is inferred from energy-momentum conservation.
- $D^0 \rightarrow K^-\pi^+$; $D^+ \rightarrow K^-\pi^+\pi^-$

- Enhancement at $D\bar{D}^*$ threshold in both channels - Significance $\sigma > 18$ - Fit function: Breit-Wigner + smooth threshold function
- $m = (3883.9 \pm 1.5 \pm 4.2)$ MeV/c$^2$
- $\Gamma = (24.8 \pm 3.3 \pm 11.0)$ MeV
- $\sigma \times B = (83.5 \pm 6.6 \pm 22.0)$ pb

Parameters similar to $Z_c(3900)$. A $J^P$ quantum number determination for the $Z_c(3900)$ needed

Fit to angular distribution favours $J^P = 1^+$
If this is $Z_c(3900)\pm$, the ratio of partial decay widths is:
$$\frac{\Gamma(Z_c(3885)\rightarrow D\bar{D}^*)}{\Gamma(Z_c(3900)\rightarrow \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$
This ratio is much smaller than typical values for decays of conventional charmonium states above the open charm threshold:
$$\frac{\Gamma(\psi(3770)\rightarrow D\bar{D})}{\Gamma(\psi(3770)\rightarrow \pi^+\pi^- J/\psi)} = 482 \pm 84$$
This suggests the influence of very different dynamics in the Y(4260)-$Z_c(3900)$ system
Confirmation of $Z_c(3885)^\pm$ in $e^+e^- \rightarrow \pi^\pm(D\bar{D}^*)^\mp$ using double D tag method - Preliminary results

- Combined study of the processes $e^+e^- \rightarrow \pi^+D^0\bar{D}^0$ ($\pi^+D^0\bar{D}^0$-tag.) and $e^+e^- \rightarrow \pi^+D^-\bar{D}^0$ ($\pi^+D^-D^0$-tag.) using $1090\ \text{pb}^{-1}$ at $\sqrt{s}=4.23\ \text{GeV}$ and $827\ \text{pb}^{-1}$ at $\sqrt{s}=4.26\ \text{GeV}$.
- Double tag method: reconstruction of the bachelor $\pi$ and $D\bar{D}$ pair: this allows to use more $D$ decays modes and effectively suppresses background.

- Simultaneous fit to the $M(D\bar{D}^*)$ distributions for the two processes.
- $m=3884.3\pm1.2\pm1.5\ \text{MeV}/c^2$; $\Gamma=23.8\pm2.1\pm2.5\ \text{MeV}$; Significance $>10\sigma$
- The angular distribution is consistent with $J^P=1^+$. 
- The measured mass, width and quantum numbers are consistent with single D tag results.
Observation of $Z_c(4020)^\pm$ in $e^+e^- \rightarrow \pi^+\pi^- h_c$ - PRL 111, 242001(2013)

- Study of $e^+e^- \rightarrow \pi^+\pi^- h_c$ at center of mass energies from 3.90 to 4.42 GeV.
  - $h_c \rightarrow \gamma\eta_c$; $\eta_c$ reconstructed in 16 hadronic decay modes

- Simultaneous fit to the $M_{\pi^\pm h_c}$ distributions at 4.23, 4.26 and 4.36 GeV using 2.46 fb$^{-1}$.
- A structure, $Z_c(4020)^\pm$ is observed with significance $> 8.9\sigma$
- $m=4022.9\pm 0.8\pm 2.7$ MeV/c$^2$
- $\Gamma=7.9\pm 2.7\pm 2.6$ MeV

\[ \sigma(e^+e^- \rightarrow \pi^\pm Z_c(4020)^\mp \rightarrow \pi^+\pi^- h_c) = 8.7 \pm 1.9 \pm 2.8 \pm 1.4 \text{ pb at 4.23 GeV} \]
\[ \sigma(e^+e^- \rightarrow \pi^\pm Z_c(4020)^\mp \rightarrow \pi^+\pi^- h_c) = 7.4 \pm 1.7 \pm 2.1 \pm 1.2 \text{ pb at 4.26 GeV} \]
\[ \sigma(e^+e^- \rightarrow \pi^\pm Z_c(4020)^\mp \rightarrow \pi^+\pi^- h_c) = 10.3 \pm 2.3 \pm 3.1 \pm 1.6 \text{ pb at 4.36 GeV} \]
Observation of $Z_c(4020)^0$ in $e^+e^- \rightarrow \pi^0\pi^0 h_c$ - PRL 113, 212002(2014)

- Study of $e^+e^- \rightarrow \pi^0\pi^0 h_c$ at center of mass energies of 4.23, 4.26 and 4.36 GeV using 2.46 fb$^{-1}$.
- $h_c \rightarrow \gamma\eta_c$; $\eta_c$ reconstructed in 16 hadronic decay modes

- Simultaneous fit to the $M^{\text{recoil}}_{\pi^0}$ distributions.
- A structure, $Z_c(4020)^0$ is observed with significance $> 5\sigma$
- $m=4023.9\pm2.2\pm3.8$ MeV/c$^2$
- Width is fixed to be the same as its charged partner
- Another isospin triplet is established!

The combined ratio $R_{Z_c(4020)} = \frac{\frac{\sigma(e^+e^- \rightarrow \pi^0 Z_c(4020)^0 \rightarrow \pi^0\pi^0 h_c)}{\sigma(e^+e^- \rightarrow \pi^0 Z_c(4020)^0 \rightarrow \pi^0\pi^0 h_c)}}{\frac{\sigma(e^+e^- \rightarrow \pi^0 Z_c(4020)^\pm \rightarrow \pi^0\pi^0 h_c)}{\sigma(e^+e^- \rightarrow \pi^0 Z_c(4020)^\pm \rightarrow \pi^0\pi^0 h_c)}}=0.99\pm0.31$ with is well within $1\sigma$ of the expectation of isospin symmetry 1.0
Observation of $Z_c(4025)\pm$ in $e^+e^- \rightarrow \pi^\pm (D^* \bar{D}^*)\mp$ - PRL 112, 132001(2014)

- Study of $e^+e^- \rightarrow \pi^\pm (D^* \bar{D}^*)\mp$ at 4.26 GeV using 827 pb$^{-1}$.
- Only the bachelor $\pi^-$, the $D^+$ decaying from $D^{**+} \rightarrow D^+\pi^0$ and at least one soft $\pi^0$ from $D^{**+} \rightarrow D^+\pi^0$ or $\bar{D}^{*0} \rightarrow \bar{D}^0\pi^0$ decay are reconstructed.

- Unbinned maximum likelihood fit to the $M_{\pi^-}^{\text{recoil}}$ distribution.
- A structure, $Z_c(4025)^+$ is observed with significance $13\sigma$
- $m=4026.3\pm2.6\pm3.7$ MeV/c$^2$
- $\Gamma=24.8\pm5.6\pm7.7$ MeV

To validate the establishment of $Z_c(4025)$ a rigorous spin analysis is required based on a larger data sample.
Conclusion

- Quarkonium spectroscopy is a very interesting field, many new exotic states have been discovered in recent years;

- Still many missing pieces need to be found to have the full picture;

- In 2012, BESIII has started a dedicated program toward understanding X, Y, Z states.

THANKS FOR YOUR ATTENTION!