A Review of Heavy Exotic States

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Hadrons: normal & exotic

• In the quark model, hadrons are dominantly bound states of \(qq\bar{q}\) (mesons) or \(qqq\) (baryons)
• But QCD allows hadrons with \(N_{\text{quarks}} \neq 2, 3\)
  – Glueball: \(N_{\text{quarks}} = 0\) (\(gg, ggg, \ldots\))
  – Hybrid: \(N_{\text{quarks}} = 2 + \) excited gluon
  – Multiquark state: \(N_{\text{quarks}} > 3\)
  – Molecule: bound state of 2 or more hadrons
  – …
• It is a long history of searches for these exotic hadrons, however, no solid experimental evidence was found until recent breakthroughs in the charmonium region.
Charmonium spectroscopy

Below open-charm threshold, all states have been observed. Charm anti-charm potential models describe spectrum very well.

Many missing states above open-charm threshold.
There are lots of XYZ states

A number of new states above open-charm threshold. Charmonium in the final state, but not an obvious charmonium state (charmoniumlike or XYZ)

What are they?
- Charmonium?
- Tetraquark?
- Molecule?
- Hybrid?
- Hadrocharmonium?
- …
**XYZ and Experiments**

- **X**: neutral, in B decays and hadron machines.
- **Y**: neutral, vectors in $e^+e^-$ colliders.
- **Z±**: charged quarkonium-like

*+CLEO-c, CDF, CMS...*
What is the $X(3872)$?

- First observed charmonium-like exotic state is $X(3872)$.
- Observed at Belle in 2003 in the mode $\pi^+\pi^- J/\psi$, confirmed by CDF, D0, BaBar, CMS and LHCb.
- Mass: Very close to $D^0D^{*0}$ threshold.
- Width: Very narrow (< 1.2 MeV).
- Mass and decay modes are in disagreement with charmonium.
- Produced in
  - $pp$ collision
  - $B$ decay ($B \rightarrow KX$)
  - $Y(4260) \rightarrow \gamma X(3872)$

BELLE [PRL 91, 26 (2003)]
Determination of the $X(3872)$ quantum numbers.

- CDF measurement [PRL 98 132002 (2007)] excluded all $J^{PC}$ except $2^{-+}$ and $1^{++}$.
- LHCb measurement [PRL 110, 222001 (2013)], established $J^{PC}=1^{++}$.

D-wave charmonium?
Molecular state?
Tetraquark?
Molecule + charmonium mixture?

Monica Pepe Altarelli @ LHCP2014
Radiative decays of $X(3872)$

LHCb result [NPB886, 665 (2014)]

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi \gamma)} = 2.46 \pm 0.64 \pm 0.29$$

BaBar result [PRL102 132001 (2009)]

$$R_{\psi\gamma} = 3.4 \pm 1.4$$

Belle did not see signal [PRL107, 091803 (2011)]

$$R_{\psi\gamma} < 2.1 \text{ @ 90}\% CL$$

D-wave charmonium?  
Molecular state?  
Tetraquark?  
Molecule + charmonium mixture?
Y-family states

- A family of vectors ($J^{PC}=1^{-}$) observed in $e^+e^-$ colliders.
- In the process $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$, the BaBar experiment observed the $Y(4260)$, then confirmed by CLEO and Belle.
- Properties are different from $1^{-}-$ charmonium: strong coupling to $\pi\pi J/\psi$, no significant enhancement in open charm production.

BaBar: [PRL95, 142001] 273fb-1

Belle [PRL99, 182004 (2005)] 548fb-1
Several Y states were observed by Belle and BaBar in $\pi^+\pi J/\psi$, $\pi^+\pi \psi(2S)$ and $\Lambda_c\Lambda_c$ after the discovery of $Y(4260)$.

$Y(4008)$ (Belle)
$Y(4260)$ (BaBar, Belle, CLEO)
$Y(4360)$ (BaBar, Belle)
$Y(4660)$ (Belle, BaBar)
$Y(4630)$ (Belle)
With larger data samples $Y(4260)$, $Y(4360)$ and $Y(4660)$ were confirmed by Belle and BaBar in ISR process.
# List of Y-family states

| State | Mass (MeV/c²)     | Width (MeV/c²) | Decay mode                  | Experiment |
|-------|-------------------|----------------|-----------------------------|------------|
| $Y(4008)$ | $4008^{+121}_{-49}$ | 226±97         | $\pi^+\pi J/\psi$          | Belle      |
| $Y(4260)$ | 4250±9            | 108±12         | $\pi^+\pi J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$ | BaBar, CLEO, Belle |
| $Y(4360)$ | 4361±13           | 74±18          | $\pi^+\pi \psi(2S)$        | Belle, BaBar |
| $Y(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $\Lambda_c^+\Lambda_c^-$  | Belle      |
| $Y(4660)$ | 4664±12           | 48±15          | $\pi^+\pi \psi(2S)$        | Belle, BaBar |
What do we know about Y?

- Between 4 and 4.7 GeV, at most 5 $1^-$ states expected in charmonium family (3S, 2D, 4S, 3D, 5S), but 7 particles are observed.
- Hybrids? Molecular states? Hadrocharmonium? Threshold effect? FSI?
- $Y(4260)$, $Y(4360)$ and $Y(4660)$ are similar and narrow.
Cross sections around $Y$-states region

- Different decay modes have similar cross sections.
- The line shapes seem to be different.
- Correlation with $Y(4260)$ or $Y(4360)$ is unclear.
Cross sections around $Y$-states region

BESIII preliminary

$e^+e^- \rightarrow \omega \chi_{c0}$ are observed at 4230 MeV and 4260 MeV. Signal does not arise from the decays of the $Y(4260)$. 
BESIII observed $e^+e^-\rightarrow\gamma X(3872)$.

It seems that $X(3872)$ is from $Y(4260)$.

$R(B(e^+e^-\rightarrow\gamma X(3872))/B(e^+e^-\rightarrow\pi^+\pi J/\psi)) \sim 11\%$, large transition rate.

Together with $Y(4260)\rightarrow \pi Z_c(3900)$, indicates commonality in the nature of the exotics states $X(3872)$, $Y(4260)$, and $Z_c(3900)$. 
\( Z_c^{\pm} : \) charged charmonium-like states

- \( Z_c^{\pm} \) decay to charmonium demonstrates a ccbar pair.
- Electric charge demonstrates two or more light quarks:
  \[ N_{\text{quark}} \geq 4 \]
- A clear signature for an exotic hadronic state!

- Search in final states \( \pi J/\psi, \pi h_c, \pi \psi(2S) \pi \chi_{cJ}, \ldots \)
Observation of $Z_c(3900)^\pm$ in
\[ e^+e^- \rightarrow \pi^+\pi^- J/\psi \]

**BESIII**
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- 307 events, $>8\sigma$

**Belle**
- $M = 3894.5 \pm 6.6 \pm 4.5$ MeV
- $\Gamma = 63 \pm 24 \pm 26$ MeV
- 159 events, $>5.2\sigma$

**CLEO-c data**
- $M = 3886 \pm 4 \pm 2$ MeV
- $\Gamma = 37 \pm 4 \pm 8$ MeV
- 81 events, $>5\sigma$

- **$Z_c(3900)^\pm$:** first confirmed charged charmonium-like states observed in $\pi^+\pi^- J/\psi$ by BESIII, Belle and confirmed in CLEO-c data (NWU group).

- **Properties:**
  - Couple to ccbar.
  - Has electric charge.
  - At least 4 quarks.
  - Mass close to DD* threshold.
  - Molecular state?
  - Tetraquark?
  - Hadrocharmonium?
  - Threshold effect?...
$Z_c(3900)^0$ in $e^+e^- \rightarrow \pi^0 \pi^0 J/\psi$

BESIII preliminary, 2809 pb$^{-1}$

- $Z_c(3900)^0$ is observed clearly at $E_{cm} = 4230, 4260, 4360$ MeV by BESIII.
- BESIII preliminary result:
  - $M = 3894.8 \pm 2.3$ MeV
  - $\Gamma = 29.6 \pm 8.2$ MeV
  - Significance = 10.4 $\sigma$
  - Interpretation: neutral isospin partner, $Z_c(3900)^0$ observed

CLEO-c data [PLB 727, 366-370 (2013)]
586Pb-1 @ 4.17GeV
\(e^+e^- \rightarrow \pi^\pm (DD^*)^\pm \ @ 4.26 \text{ GeV}\)

\(Z_c(3885) \rightarrow D^0 D^{*-}\)

\(Z_c(3885) \rightarrow D^+ \bar{D}^{*-0}\)

\(\pi^0\) angular distribution indicates that \(J^P\) favors 1+

\(M[Z_c(3885)] = 3883.9 \pm 1.5 \pm 4.2 \text{ MeV}\)

\(\Gamma[Z_c(3885)] = 24.8 \pm 3.3 \pm 11.0 \text{ MeV}\)

2\(\sigma/1\sigma\) below those of \(Z_c(3900)\)

Assuming \(Z_c(3885)\) is \(Z_c(3900)\): \(\Gamma(DD^*)/\Gamma(\pi J/\psi) = 6.2 \pm 2.9\)

Large non-DDbar coupling
Observation of $Z_c(4020)^\pm$ in $e^+e^-\rightarrow\pi^+\pi^-h_c(1P)$

Narrow $\pi^h_c$ structure observed
* $M = 4022.9\pm0.8\pm2.7$ MeV
* $\Gamma = 7.9\pm2.7\pm2.6$ MeV
* Significance : 8.9$\sigma$

Hint for $Z_c(3900)\rightarrow\pi^h_c$?
* Significance is only 2.1$\sigma$

\[ \sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- h_c) < 11 \text{ pb} \]

\[ \sigma(e^+e^- \rightarrow \pi^\pm Z_c(3900)^\mp \rightarrow \pi^+\pi^- J/\psi) = 13 \pm 5 \text{ pb} \]

Deviation from phase space decay
* $M = 4026.3\pm2.6\pm3.7$ MeV
* $\Gamma = 24.8\pm5.6\pm7.7$ MeV
* Significance : 10$\sigma$

Assuming $Z_c(4025)$ is $Z_c(4020)$
$\Gamma(DD^*)/\Gamma(\pi h_c) = 12\pm5$
Neutral partner of $Z_c(4020)$ in $e^+e^- \rightarrow \pi^0 \pi^0 h_c$

BESIII Preliminary Result:

$\frac{1}{2}$ X-sec of $\pi^0 \pi^0 h_c$ is about half of charged process, agree with expectation of isospin symmetry.

$M[Zc(4020)^0] = 4023.6\pm2.2\pm3.9$ MeV - $M[Zc(4020)^+] = 4022.9\pm0.8\pm2.7$ MeV

Width fixed to charged $Z_c(4020)$

Significance $>5\sigma$
$Z_b(10610)^\pm$ and $Z_b(10650)^\pm$

Belle [PRL108,122001 (2012)] 121.4 fb$^{-1}$

$e^+e^-\rightarrow \Upsilon(5S)\rightarrow \pi^+\pi^- \Upsilon(nS)$

Heavy flavor partners of $Z_c$?

$Z_c \rightarrow \pi J/\psi, (DD^*)$
$Z_c' \rightarrow \pi h_c(1P), (D^*D^*)$
$Z_b \rightarrow \pi \Upsilon(nS), \pi h_b(mP), (B B^*)$
$Z_b' \rightarrow \pi \Upsilon(nS), \pi h_b(mP), (B^*B^*)$
**Z(4430)**± in $B^0 \rightarrow \psi(2S)K\pi$

Seen by Belle
[PRL100, 142001 (2008)] 605fb⁻¹

Not seen by BaBar
[PRD 79, 112001 (2009)] 413fb⁻¹

Belle updated results confirmed its existence, $J^p = 1^+$ is favored
[PRD 88, 074026 (2013)] 711fb⁻¹

Belle Z(4430) was the first evidence of a fourquark state in the charmonium sector.
Fitted values of the $Z(4430)$ amplitude in six $m^{2}(\psi'\pi^{-})$ bins. Argand diagram is consistent with the behavior of resonance.
Belle observed a new charged charmonium-like state $Z_c(4200)^\pm$ in $\pi J/\psi K\pi$ with a significance of 6.2 sigma.

$$M = 4196^{+31+17}_{-29-13} \text{ MeV/c}^2,$$

$$\Gamma = 370^{+70+70}_{-70-132} \text{ MeV}.$$
## List of confirmed $Z_c$ states

| State   | Mass (MeV/$c^2$) | Width (MeV/$c^2$) | Decay mode       | $J^P_C$ | Experiment                  |
|---------|------------------|-------------------|------------------|---------|----------------------------|
| $Z_c(3900)^{\pm 0}$ | 3888.6±2.7       | 34.7±6.6          | $\pi^* J/\psi (D D^*)$ | 1$^+$   | BESIII, Belle CLEO-c data  |
| $Z_c(4020)^{\pm 0}$ | 4023.8±2.1       | 7.9±3.8           | $\pi^* h_c (D^* D^*)$ | 1$?$    | BESIII                     |
| $Z(4430)^{\pm}$   | 4478±21          | 181±33            | $\pi^* \psi(2S)$   | 1$^+$   | Belle LHCb                  |
Exotic particles, $XYZ$, are found both in charmonium and bottomonium sectors in the last decade. They don’t fit into the expected charmonium spectrum.

$J^{PC}$ of $X(3872)$ has been determined to be $1^{++}$.

Y-states: $Y(4260), Y(4360)$ and $Y(4660)$ are confirmed.

Four quark states are observed with certainty: $Z_c(3900), Z_c(4020), Z(4430), Z_b(10610)\pm$ and $Z_b(10650)$...
Thank you!