XYZ resonances at Belle experiment

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Outline

• KEKB/Belle
• Production mechanisms of hadrons.
• $X(3872)$; how we get its interpretation.
• $Z_{b}^{+}$s at $\Upsilon(10860)$ and $\Upsilon(11020)$
• $Z_{c}(3900)^{+}$ at $Y(4260)$ and similar states
• $Z_{c}(4430)^{+}$ and similar states found in B decays
• Challenges at SuperKEKB/Belle II
• Summary
KEKB/Belle : world highest luminosity $e^+e^-$ collider

KEKB
8GeV×3.5GeV@ϒ(4S)

Belle
High resolution $4\pi$
spectrometer with particle identification capability
Integrated luminosity of B factories

Belle recorded more than 1 ab\(^{-1}\)!

\[ > 1 \text{ ab}^{-1} \]

On resonance:
\[ Y(5S): 121 \text{ fb}^{-1} \]
\[ Y(4S): 711 \text{ fb}^{-1} \]
\[ Y(3S): 3 \text{ fb}^{-1} \]
\[ Y(2S): 25 \text{ fb}^{-1} \]
\[ Y(1S): 6 \text{ fb}^{-1} \]

Off resonance/scan:
\[ \sim 100 \text{ fb}^{-1} \]

\[ \sim 550 \text{ fb}^{-1} \]

On resonance:
\[ Y(4S): 433 \text{ fb}^{-1} \]
\[ Y(3S): 30 \text{ fb}^{-1} \]
\[ Y(2S): 14 \text{ fb}^{-1} \]

Off resonance:
\[ \sim 54 \text{ fb}^{-1} \]
“XYZ” sensations at Belle

PRL91,261801(2003)

$X(3872) \rightarrow J/\psi \pi^+\pi^-$

$M_{l^+l^-\pi^+\pi^-} - M_{l^+l^-}$ (GeV)

PRL107,091803(2011)

$X(3872) \rightarrow J/\psi \gamma$

PRL110,252002(2013)

$Y(4260) \rightarrow J/\psi \pi^+\pi^-$

PRL100,142001(2008)

$Z(4430)^+ \rightarrow \psi(2S)\pi^+$

PRL110,252002(2013)

$Z(3900)^+ \rightarrow J/\psi \pi^+$

Two $Z_b^\pm \rightarrow \Upsilon(nS)\pi^\pm$

PRL108,122001(2012)
What made it possible?

First of all, the world highest luminosity by KEKB. High resolution $4\pi$ spectrometer = Belle. Those two brought us possibilities to access;

• Various production mechanisms
  – Each physics process has preferable states.
  – Interplay among several approaches is effective.

• Various decay modes
  – Each hypothesis; other decay modes, partner states.
  – Partner states have specific decay modes.
Variety of recorded reactions

Allowed/favored quantum numbers are different depending on production processes.
Everything started from this …

\[ X(3872) \]
Br(X(3872)\rightarrow D^0 D^{*0}) \text{ is about } Br(X(3872)\rightarrow J/\psi \pi^+\pi^-) \times 10.

J^{PC}=1^{++} (\text{Belle, BaBar, CDF, LHCb}) \text{ from } J/\psi \pi^+\pi^- \text{ angular distribution.}
More decay modes

X(3872) → J/ψ γ; C=+1

In $\chi_{c1} \pi^+ \pi^-$, neither X(3872) nor $\chi_{c1}^{(2P)}$ seen, though no explicit quantum number conflict.
Information from a friendly competitor

Pure molecule is unlikely ..
Admixture : most plausible interpretation for $X(3872)$

$D\bar{D}^*$ component is coupled with the same $J^{PC}$ $c\bar{c}$, $\chi_{c1}(2P)$ (unseen). → can explain $\text{Br}(X \rightarrow D^0\bar{D}^{*0})/\text{Br}(X \rightarrow J/\psi \pi^+\pi^-)$ is about 10. → pure molecule is too fragile to be produced in Tevatron/LHC. → another $\chi_{c1}(2P)$ dominant state would become broad. Reaching such an interpretation is remarkable progress.
Charged states in bottomonium sector.
As for bottomonium more, listen Y.J.Kwon’s talk on Friday

\[ Z_b(10610)^+ \text{ and } Z_b(10650)^+ \]
Seen in all bottomonium $\pi^\pm$ system at $\Upsilon(10860)$
\[ Z_b(10610)^+ \rightarrow B\bar{B}^*, \ Z_b(10650)^+ \rightarrow B^*\bar{B}^* \]

One B reconstructed

\[ \frac{\text{Br}(Z_b(10610)^+ \rightarrow B\bar{B}^*)}{\text{Br}(Z_b(10610)^+ \rightarrow bb)} = 5.93 \pm 0.99/-0.59 \pm 1.01/-0.73 \]

\[ \frac{\text{Br}(Z_b(10650)^+ \rightarrow B^*\bar{B}^*)}{\text{Br}(Z_b(10650)^+ \rightarrow bb)} = 2.80 \pm 0.69/-0.40 \pm 0.54/-0.36 \]

Found to be dominant!
Molecular picture works

\[ \bar{B}^* \rightarrow \bar{b} \bar{q} \pi \]

\[ B \rightarrow b \bar{q} \pi \]

\[ B^* \rightarrow b \bar{q} \pi \]

\[ \bar{B} \rightarrow b q \]

\[ \Upsilon \] and \[ h_b \]

\[ J^P=1^+ \]

Decays to \( \Upsilon \) and \( h_b \) can co-exist.

B*\( \bar{B}^{(*)} \) dominant Br.

A.E.Bondar et al., PRD84,054010(2011)

$Z_b(10610)^+, Z_b(10650)^+$ → $h_b(1P,2P)\pi^+$ at $\Upsilon(11020)$

Phase space hypothesis is excluded at 3.6$\sigma$ and 4.5$\sigma$ for $h_b(1P)$ and $h_b(2P)$, respectively.

arXiv:1508.06562 submitted to PRD
Analogous with $Z_b$s at $\Upsilon(10860)$

$Z_C(3900)^+ \text{ AT } \Upsilon(4260) \text{ AND SIMILAR STATES}$
$Z_c(3900)^+$ at $Y(4260) \rightarrow J/\psi \pi^+ \pi^-$

$Y(4260) \rightarrow J/\psi \pi^+ \pi^-$

$Z(3900)^+ \rightarrow J/\psi \pi^+$

$J^{PC}=1^-$ state decaying to quarkonium $\pi^+ \pi^-$ contains charged state as an intermediate!
$Z_c(4060)^+ \text{ at } Y(4360) \rightarrow \psi(2S)\pi^+\pi^-$

Excess at 4060 MeV for $\psi(2S)\pi^+$ in $Y(4360)$

Again charged state as an intermediate!
Note

- BES III reported charged charmonium-like states;
  - $Z_c(3885)\pm$ in (DD$^*$)$\pm$, $Z_c(4025)\pm$ in (D$^*$D$^*$)$\pm$ and $Z_c(4020)\pm$ in $h_c\pi\pm$
  - Molecular picture look still working, however..

- In bottomonium-like case, $Z_b(10610)\pm$ and $Z_b(10650)\pm$ look explain all the observed features, while there seems to be more in charmonium-like case depending on the decay final state.

- Does such difference give a hint to reveal the proper degree of freedom to form heavy hadrons?
Charged charmonium-like states produced in B decays

$Z_c(4430)^+ \text{ and SIMILAR STATES}$
$Z(4430)^\pm$ in $\psi(2S)\pi^\pm$ final state

Reconstructing $B \rightarrow \psi(2S)\pi^\pm K$, $M(\psi(2S)\pi^\pm)$ is looked back. Confirmed by LHCb
PRL112, 222002(2014)

Clear peak at 4.43 GeV/c$^2$

References:
PRL100, 142001(2008)
PRD 80, 031104(2009)
PRD 88, 074026(2013)
Confirmation by LHCb

4D fit(M(\psi(2S)\pi^\pm), M(K\pi), \cos\theta_{\psi(2S)}, \phi), PRL112, 222002(2014)
Argand diagram gives a proof of resonance.
Such approach will be possible to study other states with Belle II statistics only.
How about $J/\psi \, \pi^{\pm}$ system?

In $B \to J/\psi \pi^{\pm} K$ decays

$Z_c(4430)^{\pm} \to J/\psi \pi^{\pm}$ seen, $Z_c(4200)^{\pm}$ observed.

$M = 4196^{+31+17}_{-29-13}$ MeV/$c^2$ \hspace{1cm} $\Gamma = 370^{+70+70}_{-70-132}$ MeV.
Limitation with available statistics

\[ M(\chi_{c1}\pi^\pm), \text{ GeV/c}^2 \]

\[ Z(4050)^\pm \text{ and } Z(4250)^\pm \text{ in } \chi_{c1}\pi^\pm \text{ in } B\to\chi_{c1}\pi^\pm K; \]

Seen v.s. Unseen, only higher statistics e^+e^- data can give a clear answer.
Still many things we should attempt …

**CHALLENGES AT HIGHER STATISTICS**
Partner states; a key to go further

For $X(3872)$, no signature for
• Charged partner in $J/\psi \pi^+\pi^0$. $\rightarrow$ most likely, isospin=0.
• $C=-1$ partner in $J/\psi \eta$ and $\chi_{c1}\gamma$. $\rightarrow$ disfavor tetraquark hypothesis.

![Graphs showing J/ψ η mode and χ₁c γ mode](image-url)
What does it mean?

If $X(3872)$ is admixture of molecule and $\chi_{c1}(2P)$, its C-odd partner, $J^{PC}=1^{+-}$ state, is mixing with

Hadronic decays or radiative decay to $\eta_c \rightarrow \text{low br. and S/N.}$ $J^{PC}=1^{+-}$ is factorization disfavored, three-body $B \rightarrow h_c \ K \ \pi$ should be at first looked for. Higher statistics desirable.
Partner states of $Z_b$ case

PRD88, 052016 (2013)

- Partners may decay into $\chi_{bJ}$ (PRD86,014004(2012)).
  - $Z_b \rightarrow \chi_{bJ} \pi$, $Z_{b0} \rightarrow \chi_{bJ} \gamma$
- $\text{Br}(\chi_{bJ} \rightarrow \Upsilon(1,2,3S)\gamma)$ and $\gamma$ efficiency are multiplied, signal yield may be lower one order of magnitude.

$Z_b(10610)^0 \rightarrow \Upsilon(2S)\pi^0\pi^0$ seen 6.5$\sigma$ stat. significance

$I^G=1^+$, first isospin partner among “XYZ”.

Higher statistics needed.
Charm baryon to check “di-quark”

- Thought to be a good place to check if “di-quarks” is behaving as a good degree of freedom to form hadrons.
- One of the constituent quark is heavy, correlation between the remaining light quarks would become clear.
  - $L_1 : \rho$ mode, $L_2 : \lambda$ mode.

As for more detail, listen Y.Kato’s talk on Friday.
Competition with LHCb

LHCb lumi. $\times 2000$
(for possible & identified items)

Accelarator phase-1 commissioning done!

ShUTDOWN FOR UPGRADE

Same size data as Belle

9 months/year
20 days/month

Novel idea (general search possible), quick publication

Goal of Belle II/SuperKEKB

As for Belle II, listen
D. Liventsev’s talk on Saturday
Summary

• Molecular picture turned out to play important role near the threshold.
  – $X(3872) : D^0 \ D^{*0}$ and mixing with $\chi_{c1}(2P)$.
  – $Z_b(10610)^+ : B \ \overline{B}^*$, $Z_b(10650)^+ : B^* \ \overline{B}^*$

• $J^{PC}=1^-$ state decay contain a charged state as an intermediate in both charmonium-like and bottomonium-like cases.

• Searches for other partners states need more data.
  – Because of anticipated decay modes.

• Argand diagram approach only possible with Belle II statistics.
Backup
Variety of reactions; $X(3915) = \chi_{c0}(3915)$

In $B^\pm \rightarrow J/\psi \omega K^\pm$ decay

$Y(3940) = X(3915) = \chi_0(3915) \rightarrow J/\psi \omega$

$M = 3943 \pm 11 \text{(stat)} \pm 13 \text{(syst)} \text{ MeV}$

$\Gamma = 87 \pm 22 \text{(stat)} \pm 36 \text{(syst)} \text{ MeV}$

PRL94,182002(2005)

In $\gamma \gamma \rightarrow J/\psi \omega$ process

$X(3915) = \chi_{c0}(3915) \rightarrow J/\psi \omega$

$N_{\text{sig}} = 49 \pm 14 \text{(stat)} \pm 4 \text{ events.}$

$M = 3915 \pm 3 \text{(stat)} \pm 2 \text{(syst)} \text{ MeV}$

$\Gamma = 17 \pm 10 \text{(stat)} \pm 3 \text{(syst)} \text{ MeV}$

$J^{PC}$ not yet determined.

 stil need confirmation for PDG interpretation