Heavy flavored hadron spectroscopy at Belle and prospect

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Outline

• Lessons from Belle experience
  – “XYZ” sensations
  – Quarkonium(-like) states
  – Charm baryons

• Extension and items to be tackled with Belle II
  – To go beyond sensations

• Summary
“XYZ” sensations at Belle

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

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

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

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

\[ \text{Two } Z_b^\pm \rightarrow \gamma(nS)\pi^\pm \]

\[ M_{l^+l^-\pi^+\pi^-} - M_{l^+l^-} \text{ (GeV)} \]

\[ M(\pi^+ \pi^- J/\psi) \text{ (GeV/c}^2\text{)} \]

\[ M_{\text{max}(\pi J/\psi)} \text{ (GeV/c}^2\text{)} \]

\[ M(\chi(3S))_{\text{max}}, \text{ (GeV/c}^2\text{)} \]
What made it possible?

From the experience of “XYZ” states,
We need to have 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.
Belle II Detector

$K_L$ and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (baseline)
(opt.) Pure CsI for end-caps

Central Drift Chamber
He(50%):C$_2$H$_6$(50%), Small cells, long lever arm, fast electronics

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

Beryllium beam pipe
2cm diameter

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Electron
(7GeV)

Positron
(4GeV)

Better or same performance under $\times 20$ beam background!
Variety of reactions; $X(3915) = \chi_{c0}(3915)$

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

$Y(3940) = X(3915) = \chi_{c0}(3915) \to J/\psi \omega$

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

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

$PRL94,182002(2005)$

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

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

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

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

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

$J^{PC}$ not yet determined.

(still need confirmation for PDG interpretation)
Information about X(3872)

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

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

PRD81, 031103(2010)

PRL110, 222001(2013)
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.
But no partner found

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.
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 $h_c$ then not familiar with $J/\psi$.

Hadronic decays $\rightarrow$ low branching fraction and S/N. Higher statistics needed $\rightarrow$ Belle II study item.
Two charged states, $Z_b(10610)^+ \text{ and } Z_b(10650)^+$

$\gamma(1S)\pi^\pm, \gamma(2S)\pi^\pm, \gamma(3S)\pi^\pm$

$\tau(1S)\pi^\pm$, $\gamma(2S)\pi^\pm$, $\gamma(3S)\pi^\pm$

$Y(nS)\rightarrow \mu^+\mu^-, h_b: MM(\pi^+\pi^-)$

$e^- \rightarrow \tau(5S)'', e^+$

$h_b(1P)\pi^\pm$, $h_b(2P)\pi^\pm$
Molecular picture works

Decays to $\Upsilon$ and $h_b$ can co-exist.
Signature in $B^*B^{(*)}$ partial recon. seen.

$J^P=1^+$ is supported by Dalitz analysis.
Partner states of $Z_b$

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”.

Various partner searches are a task for Belle II.
Z(4430)$^+$ 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)
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.
Short summary of quarkonium(-like) states

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

• Partner only found in $Z_{b}(10610)^0$ (and $Z(3900)^0$ in CLEO) so far.

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

• Argand diagram approach only possible with Belle II statistics.
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.
Excited states to $\Lambda_c$

Select $\Sigma_c(2455)\pi$ to see $\Lambda_c^{+}\pi^{+}\pi^{-}$

$\Lambda_c(2880)^+$

$\Lambda_c(2940)^+$

PRL98,262001(2007)

$\Lambda_c(2880)^+$

$J=5/2$

$J=3/2$

Parity determined to be +.

pion angular distribution
Reconstructed states with $\Lambda_c(\text{cont.}^2)$

For all these $\Xi_c(2980)$, $\Xi_c(3055)$ and $\Xi_c(3080)$, $J^P$ is not yet determined. $\Lambda_c^+K^-\pi^+$ final state. → Belle II make possible.
To go beyond

• To test di-quark picture, the states with rich information are necessary to be used.
  – $\Lambda_c(2880)^+ : J^P=(5/2)^+$
  – $\Xi_c(3080)^+$ seen in $\Sigma_c(2445)^{++} K^-$, $\Sigma_c(2520)^{++} K^-$, and $\Lambda D^+$.
  – Among $\rho$ and $\lambda$ modes excitation, which can fit?
  – Partner states’ mass? width? Dominant decay modes?

• Determination of $J^P$ is not yet done for many states, important mission in Belle II data.

• Visit radiative decays, decays with $\pi^0$ would be also the mission.
To go beyond (cont.)

- Visit baryon-meson molecule candidate, $J^P=(1/2)^-$
  - Counterpart of $\Lambda(1405)$ in strange sector
  - Only CLEO measurement for $\Xi_c(2790)$, $J^P=(1/2)^-$ assigned
    but no measurement so far.
  - Belle/Belle II is very suitable for $\Xi_c(2790) \rightarrow \Xi_c', \pi$, $\Xi_c' \rightarrow \Xi_c \gamma$.
- Absolute branching fractions are still unknown for many states.
- Even $\text{Br} (\Lambda_c \rightarrow p K^- \pi^+)$, there were assumptions to quote PDG value.
Detect only these

$e^+ e^- \rightarrow c\bar{c} \rightarrow D^{(*)-} p\pi^+ \Lambda_c^+$

PDG was 5.0±1.3%, significant improvement.
Should be evolved to other case in Belle II.
$\rightarrow D^{(*)-} p K^+: (usc), D^{(*)-} \Lambda \pi^+: (dsc), D^{(*)-} \Lambda K^+: (ssc)$.
For strange baryons

- $\Xi(1690)$ is known not to well match quark model prediction, very narrow.
- Knowledge of $\Omega$ baryons still limited.

Are we missing radiative decays?
Competition with LHCb

LHCb lumi. ×2000
(for possible & identified items)

Accel. commissioning starts from early 2016

Novel idea (general search possible), quick publication

Goal of Belle II/SuperKEKB

Peak luminosity (cm⁻² s⁻¹)

Integrated luminosity (ab⁻¹)

Calendar Year

2015 2017 2019 2021 2023

Same size data as Belle

9 months/year
20 days/month

Shutdown for upgrade
Closing remarks

• For quarkonium(-like) XYZ states
  – Other decay modes and Partner searches need more data.
    • Because of anticipated decay modes.
  – Argand diagram only possible with Belle II statistics.
• Charmed baryons to test “di-quark” picture.
  – $J^P$ determination need more data.
  – Evolve absolute br. measurements with MM.
• Variety of recorded reactions and accessible decay modes continue to be exploited.
• All attempts with higher statistics data to give convincing and comprehensive understanding is a Belle II mission in hadron spectroscopy.