Quarkonium at Belle II

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Outline of the talk

❖ Motivation for spectroscopy

❖ Spectroscopy at $B$ factories

❖ Belle to Belle II

❖ Prospects of charmonium spectroscopy in Belle II

❖ Bottomonium spectroscopy prospects

❖ Summary
QCD: real particles are color singlet

- Baryons are red-blue-green triplets 
  \[ \Lambda = u s d \]
- Mesons are color-anticolor pairs 
  \[ \pi = \bar{u}d \]

Other possible combinations of quarks and gluons: exotic

- **Pentaquark**
  \[ S = +1 \]
  Baryon: \[ u d d \bar{s} \]

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

- **Glueball**
  Color-singlet multi-gluon bound state

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

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

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

- **q\bar{q}** spectroscopy with heavy quark (mostly \( c \) or \( b \)) are best place to study quark model.
- Simple two body system, non-relativistic and narrow (with OZI suppression).
- Further, one can search for exotics with them.
Production of $q \bar{q}$ (-like) \@ B-factories

B-decays

$B^- \rightarrow W^- j/\psi, \psi', \eta_c, \chi_c, ...$

Double charmonium

Reconstruct $J/\psi$ and look at recoil mass

Two photon production

c\bar{c} states produced without additional hadrons.

Initial state radiation

Quarkonium decay/transitions

Annihilation at smaller energy.
$q\bar{q}$ (-like) states till now

- 17 years have passed after the discovery of first $c\bar{c}$-like [$X(3872)$] by the Belle collaboration.
- Plenty of states have been found.
- Several states found in one process (not easy to understand).
- States have non-zero charge, suggesting them to be tetraquark/molecule-like state.
- Instead of conventional spectroscopy, it is now \textit{exotic spectroscopy}.
- However, the limited statistics always come as the evil limiting factor.

Belle II (with ability to accumulate 50 times* more data in comparison to Belle) can play crucial role in understanding these states.

*Thanks to super KEKB
Belle to Belle II
Belle to Belle II

Vertex detector
4 SVD layer → 2 layers
DEPFET + 4 layers DSSD
Expected resolution of
~25μm while in Belle ~50μm

arXiv:1011.0352
Belle to Belle II

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CDC
Larger volume drift chamber, smaller drift cell. Faster electronics

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Belle to Belle II

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Expected resolution of $\sim$25μm while in Belle $\sim$50μm

CDC
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PID
More compact. Time of Propagation (barrel) and prox. foc. ARICH (Endcap) is used. Provide better K/π separation with worse background condition.

arXiv:1011.0352
Vertex detector
4 SVD layer $\rightarrow$ 2 layers
DEPFET + 4 layers DSSD
Expected resolution of
$\sim 25 \mu m$ while in Belle $\sim 50 \mu m$

CDC
Larger volume drift chamber, smaller drift cell. Faster electronics

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ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

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Resistive place counter (Barrel)
Scintillation + WLSF + MCCP (endcap)

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ECL
Old crystals are used with modified waveform sampling electronics to reject pile-up events.

ECL crystals and part of KLM sub-detector are re-used.
SuperKEKB: asymmetric $e^-(7\text{GeV}) - e^+(4\text{ GeV})$ Collider

Tsukuba, Japan

Goal > $\sim 30 \times$ KEKB instantaneous luminosity $\mathcal{L} = 6 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$

Luminosity record:

$3.1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

SuperKEKB breaks the world record for integrated luminosity in a single month and integrates $40.3 \text{ fb}^{-1}$ in May 2021.

### Belle II Online luminosity

Exp: 7-18 - All runs

- Integrated luminosity
- Recorded Weekly
- $\int \mathcal{L}_{\text{recorded}} \, dt = 213.49 \text{[fb}^{-1}]$

### Luminosity record

- $\mathcal{L} = 0.5 - 1 \text{ ab}^{-1}$ 2022
- $\mathcal{L}_{\text{peak}} = 6 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$ 2029
- $\mathcal{L} = 10 \text{ ab}^{-1}$ 2026
- $\mathcal{L} = 50 \text{ ab}^{-1}$ 2031

Updated on 2021/07/05 17:20 JST
Starting from the start: $X(3872)$

Most probable explanation:
Molecule with admixture of charmonium (seems to be choice for now, others not ruled out yet).

Precise Mass and Width studies.

- Expected yield of $B^+ \rightarrow X(3872)(\rightarrow J/\psi\pi\pi)K^+ \sim 1500$ events (with 10 ab$^{-1}$).
- Current yield of $B^+ \rightarrow \psi'(\rightarrow J/\psi\pi\pi)K^+$ is $\sim 3600$ events (at Belle).

- BESIII measured \[ \frac{B(X(3872) \rightarrow \chi_{c1}\pi^0)}{B(X(3872) \rightarrow J/\psi\pi^+\pi^-)} = 0.88^{+0.33}_{-0.27} \pm 0.10 \]
  \[ \text{BESIII, PRL 122, 202001 (2019)} \]

- Belle measured same ratio as $<0.97$ (@90%).

- If $X(3872)$ structure is dominated by $\chi_{c1}'$ component, we expect $X(3872) \rightarrow \chi_{c1}\pi^+\pi^-$ to be there.

- Belle II should be able to observe $X(3872)$ or $\chi_{c1}' \rightarrow \chi_{c1}\pi^+\pi^-$. Informative to study $X(3872) \rightarrow \overline{D}^0 D^*$ in Belle II data.

- Mass $\rightarrow 3872.9^{+0.6}_{-0.4} \pm 0.4$ MeV/c$^2$.

  \[ \text{Belle, PRD 93, 052016 (2016)} \]

  \[ \text{Belle, PRD 81, 031103 (2010)} \]

- At Belle II, possible to study $J/\psi\pi^+\pi^-$ and $DD^*$, the coupling will provide information about the $X(3872)$ nature.

$1/5$ of total data
“Measuring absolute” $B (B \rightarrow X(3872)K^+)$ will help in measuring $B (X(3872) \rightarrow \text{final state})$. Measurement is “only possible at B factories” (operating at center-of-mass energy of $\Upsilon(4S)$ which decays into $B\overline{B}$ pairs)

$B (B^+ \rightarrow X(3872)K^+) < 2.6 \times 10^{-4}$ (@ 90% CL)

$B (B^+ \rightarrow X(3872)K^+) = (2.6 \pm 0.6 \pm 0.5) \times 10^{-4}$

Belle II might measure this value.

➢ Not only for $X(3872)$, but also for other states.

❖ Able to measure by $7\sigma$ (naïve estimation).

Improved “hadronic tagging” software at Belle II!
Rediscovery of $X(3872)$ with $14.4 \pm 4.6$ signal events ($4.6\sigma$) at Belle II.

$B \to X(3872)K\pi$ decay

$K^*(892)^0$ component in $(K\pi)$ system in $X(3872)$ does not dominate, "in marked contrast" to $\psi'$ case.

With 10 ab$^{-1}$, Belle II will measure this precisely.

**Events will be similar to what we have now for $\psi'$.**
Decays of $X(3872)$

Measuring ratios of radiative decays

$$\frac{\mathcal{B}(X(3872) \to \psi' \gamma)}{\mathcal{B}(X(3872) \to J/\psi \gamma)} = 3.5 \pm 1.4$$

$$< 2.1 \text{ (at 90\% CL)}$$

$$= 2.46 \pm 0.64 \pm 0.29$$

$$< 0.59 \text{ (at 90\% CL)}$$

Expected yield of $B^+ \to X(3872)(\to J/\psi \gamma)K^+$ : $\sim 400$ events (with $10 \text{ ab}^{-1}$)

Need to resolve the conflict. Belle II should be able to do this and measure the above mention ratio precisely in order to constraint the admixture.

Charged partner of $X(3872)$

Negative search

$$\frac{\mathcal{B}(B^0 \to X(3872)^+ K^-)}{\mathcal{B}(X(3872)^+ \to J/\psi \pi^+ \pi^-)} < 4.2 \times 10^{-6}$$

If found, will be very promising for the tetraquark picture.

Absence of charged partner suggest $X(3872)$ to be an iso-singlet state.

Suggests $X(3872) \to J/\psi \pi^+ \pi^-$ is iso-spin violating decay?

Belle, BaBar, BES III measured the allowed $X(3872) \to J/\psi \pi^+ \pi^- \pi^0$

$$\frac{\mathcal{B}(X(3872) \to J/\psi \omega (\to \pi^+ \pi^- \pi^0))}{\mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-)} = 0.8 \pm 0.3 , \ 1.43 \pm 0.28$$

Belle II should measure this ratio.

➢ One can also measure $\mathcal{B}(B^+ \to X(3915) K^+)$.  
➢ Searching for the molecular/tetraquark partners are important tasks that can be done at the Belle II.
Two photon processes
Study of $\chi_{c2}(3930)$ using $\gamma\gamma \rightarrow Z(3930) \rightarrow DD$
Mass and width precision study.

$X(3915)$ (thought to be $\chi_{c0}(2P)$) was discovered in two photon process.
Currently, $\chi_{c0}(2P)$ has been suggested to be recently found $X(3860)$ in $J/\psi D\overline{D}$.

Belle observed $X(4350)$ in $\gamma\gamma \rightarrow J/\psi \phi$.
Recently, LHCb did amplitude analysis of $B \rightarrow J/\psi \phi K$, found several structures $Y(4140)$, $Y(4274)$, $X(4500)$, $X(4700)$ but not $X(4350)$ (?)
Belle II should revisit with more data.

Double charmonium production, another interesting process through which Belle II can access $C=+\text{ even states.}$
Initial state radiation

\[ J^{PC} = 1^{--} \]

\[ \gamma \rightarrow q\bar{q} \]

\[ e^- \quad \gamma \quad e^+ \]

\[ \gamma > 5.2\sigma \]

\[ BR[\gamma(4260) \rightarrow Z(3895)^{\pm}\pi^\mp] = (29.0 \pm 8.9\%) \]

Measured properties
- Mass = (3894.5 ± 6.6 ± 4.5) MeV
- Width = (63 ± 24 ± 26) MeV

Belle II will compliment BESIII here.
- Expects improvement in mass resolution due to longer CDC
- One possible study \( e^+e^- \rightarrow \gamma(J/\psi\pi^0\pi^0)\gamma I_{SR} \) for neutral partner

**e^+e^- \rightarrow \psi'\pi^+\pi^- study**

Belle, PRD 91, 112007 (2015)

\[ 3.5 \sigma \]

Mass = (4054 ± 3 ± 1) MeV
Width = (45 ± 11 ± 6) MeV

Any relation to \( Z(4050)^+ \rightarrow \chi_{c1}\pi^+ \)?
Search \( Z(4430)^+ \rightarrow \psi\pi^+ \) as in \( B^0 \rightarrow \psi\pi^+K^- \)?

- One can also search for \( Z_{cs}^+ \) in \( e^+e^- \rightarrow J/\psi KK \).
- Further, interesting to study \( e^+e^- \rightarrow D^0D^-\pi^+ \) and \( e^+e^- \rightarrow \Lambda_c^+\Lambda_c^- \).
ISR preliminary results

\[ e^+ e^- \gamma_{ISR} \rightarrow \pi^+ \pi^- J/\psi (\rightarrow \ell^+ \ell^-) \]

- Clear observation of ISR $J/\psi$ and $\psi(2S)$ signal
- Soon, we can expect $Y(4260)$ rediscovery (~60 events per 100 fb⁻¹)
**Z : “with a charge”**

Belle observed a peak like structure, $Z_c^+ (4430)$, in $B \to [\psi (2S) \pi^+] K^-$ in 2008 with 6.5σ. They observed the charged state

$M = (4433 \pm 4 \pm 2) \text{ MeV}$

$\Gamma = (45^{+18}_{-13}^{+30}_{-13}) \text{ MeV}$

For long time, there was a conflict. Belle re-performed the analysis with more data (with amplitude analysis) and came with similar conclusion

- It was only after BESIII, Belle discovery of $Z_c^+ (3900)$ in 2014 tetra-quark was taken seriously.
- Further, same year LHCb confirmed the discovery of $Z_c^+ (4430)$.
- That lead to a new revolutionary change.

4D fit $(M\Psi_{(2S)\pi^+}, M_{K\pi}, \cos\Theta_{\psi(2S)}$ and $\phi)$ by LHCb confirm the Existence of $Z^+ (4430)$

$M = (4475 \pm 7^{+15}_{-25}) \text{ MeV}$

$\Gamma = (109 \pm 13^{+37}_{-34}) \text{ MeV}$
Perform Dalitz analyses with more statistics: help in measuring and understanding these states with precision.

- At Belle II, search for new states using $B^0 \rightarrow (\chi_{c2}\pi)K^+$ decay mode.
  - At 10 ab$^{-1}$, yield comparable to current Belle yield of $B^0 \rightarrow (\chi_{c1}\pi)K^+$
- Possible study of $B^0 \rightarrow (c\bar{c})\pi^0K^+$ in search for neutral partners.
Bottomonium at Belle

Bottomonium spectrum is significantly different from charmonium spectrum. $Z_b$ states were found in the $\Upsilon(5S)$ decays and were clear signature of exotic state.

Production ratio

$$\frac{\Gamma(\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.45 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

Decay to $h_b$ should be suppressed due to spin flip! $\Upsilon(5S) \rightarrow h_b(nP)\pi^+\pi^-$ decay mechanism seems to be eXotiC

Fit MM(\pi) in M(h_b\pi) bins

Belle, PRL 108, 122001 (2012)

Resonant structure of $\Upsilon(5S) \rightarrow \Upsilon(nS) \pi^+\pi^-$

Belle, PRL 108, 032001 (2012)

More precise measurements.
More on $Z_b$

$\Upsilon(5S) \rightarrow B^* B^{(*)}\pi$

Masses of $Z_b(10610)^+$ and $Z_b(10650)^+$ close to $B B^*$ and $B^* B^*$ threshold

One $B$ is fully reconstructed

$B$ is combined with $\pi$ and recoil mass to $(B\pi)$ combination is calculated

$$rM(B\pi) = \sqrt{E_{\text{cms}}^2 - P_{B\pi}^2}$$

$B^{(*)}$B* dominant mode of $Z_b$ decays.

Belle, PRL116, 212001 (2016)

- $Z_b(10610)^+$ in $BB^*$ and $Z_b(10650)^+$ seen in $BB^*/B*B^*$.
- $B^{(*)}B^*$ dominant mode of $Z_b$ decays.

Belle II can confirm $Z_b$ relation to $B^{(*)}B^*$.

Neutral $Z_b^0$ in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$

Belle, PRD88, 052016 (2013)

with $Z_b^0$

Belle II can study neutral $Z_b^0$ and confirm in other modes also.
Energy scan

- Many quarkonium-like states were found in energy scans in ISR, \( \Upsilon(4008) \) and \( \Upsilon(4260) \) in \( J/\psi \pi^+\pi^- \), \( \Upsilon(4360) \) and \( \Upsilon(4660) \) in \( \psi' \pi^+\pi^- \), \( \psi(4050) \) and \( \psi(4160) \) in \( J/\psi \eta \).
  - Peaks observed in the cross-section depend on final state.

- Recent energy scan of \( e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^- \) (\( n=1,2,3 \)) cross sections by Belle, show situation is different in bottomonium-like states.
  - All of cross-sections exhibits peaks at \( \Upsilon(10860) \) and \( \Upsilon(11020) \) resonances that are also seen in total hadronic cross sections.

Energy scan of \( e^+e^- \rightarrow h_b(nP)\pi^+\pi^- \) (\( n=1,2 \))

Belle observe a new structure in the energy dependence.
- The global significance is \( 5.2\sigma \)
- \( M = (10752.7 \pm 5.9^{+0.7}_{-1.1}) \) MeV/
- \( \Gamma = (35.5^{+17.6}_{-11.3}^{+3.9}_{-3.3}) \) MeV
- New structure could have a resonant origin and correspond to a signal for not yet observed \( \Upsilon(3D) \) state provided S-D mixing is enhanced or an exotic state.

Current statistics is limited and Belle II will play crucial role here.
Transition from $\Upsilon(5,6S)$ to molecular states

With unique data set at $\Upsilon(6S)$, Belle II can understand the $\Upsilon(6S) \rightarrow Z_b$ decay

$\Upsilon(6S) \rightarrow h_b(nP) \pi^+\pi^-, \Upsilon(mS) \pi^+\pi^- [n=1,2; m=1,2,3]$

If $Z_b$ molecular state, then Heavy Quark Spin symmetry suggest there should be $2/4$ molecular partner bottomonium-like state ($W_b$)

$\Upsilon(5S,6S) \rightarrow W_{b0} \gamma$

$\Upsilon(6S) \rightarrow W_{b0} \pi^+\pi^-$

$W_{b0} \rightarrow \eta_b \pi, \chi_b \pi, \Upsilon \rho$

Voreshin, PRD 84, 031502(R)(2011)
Future summary

➢ Quarkonium sector is not as simple as one expects.

➢ Many new states have been found with puzzling nature.

➢ Still not fully understood in spite of the best efforts by all the experiments.

➢ Belle II will play an important role along with LHCb and BESIII to understand them.

➢ Belle II detector already started collecting data and hope to provide fruitful results soon.
Thank you
This wizard helps in keeping track of BACK-UP slides

To continue press Next >
Search for $R^{++} \rightarrow D^+ D_{s}^{*+}$

By exchanging a kaon, a $D^+ D_{s0}^{*+}$ (2317) molecular state can be formed (regardless of whether $D_{s0}^{*+}$ (2317) is a $c\bar{s}$ state or a $DK$ molecule).

One expect to have the molecule state at 4140 MeV/c$^2$ as (denote as $R^{++}$)

A doubly-charged and doubly-charmed molecule $R^{++}$ expected to decay to $D^+ D_{s}^{*+}$ with modest rates.

Mass of $R^{++}$ is predicted to be in the range of 4.13-4.17 GeV/c$^2$ with width of (2.3-2.5) MeV.

$e^+ e^- \rightarrow D^+ D_{s}^{*+} + X$ \quad $D^+ \rightarrow K^- \pi^+\pi^+$ and $D^+ \rightarrow K_s^0 (\rightarrow \pi^+\pi^-)$ \quad $D_s^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow K^*(892)^0 K^+$

$R^{++}$ mass of 4.14 GeV/c$^2$ with a width of 2 MeV.

More precise search can be carried out at Belle II!