Prospects in spectroscopy with 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:

**Pentaquark**
- S = +1
- Baryon

**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) \(\text{at B-factories}\)

**B-decays**
- $B$-decays
- $B\to W^-$
- $J/\psi, \psi', \eta_c, \chi_c, \ldots$
- $s\bar{u}$
- $c\bar{c}$

**Double charmonium**
- $c\bar{c}$
- $C = +1$
- $\gamma$
-+$e^-$ $e^+$

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

**Two photon production**
- $\gamma \to e^- e^+$
- $J$ even
- $C = +1$
- $c\bar{c}$ states produced without additional hadrons.

**Initial state radiation**
- $e^- e^+$
- $J^{PC} = 1^{--}$
- Annihilation at smaller energy.

**Quarkonium decay/transitions**
- $Z_b$
- $\pi^+$
- $\gamma^*$
- $u$, $\bar{u}$

Annihilation at smaller energy.

**Graphs**
- Various decay processes and productions of particles.
- Energy levels and transitions for specific states.
$q\bar{q}$ (-like) states till now

- A $\frac{1}{2}$ decade has 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 *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*
Vertex detector
4 SVD layer $\rightarrow$ 2 layers
DEPFET + 4 layers DSSD
Expected resolution of
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ECL crystals and part of KLM sub-detector are re-used.

arXiv:1011.0352
**Recent status**

Currently we are running Phase 2, all sub-detectors are in except full vertex detector.

**First collision on 26 April 2018**
Validation: Belle II is working
Re-discovery of "November revolution" in June

$J/\psi \to e^+e^-$

$J/\psi \to \mu^+\mu^-$
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).

Belle II should be able to observe
$X(3872)$ or $\chi_{c1}' \rightarrow \chi_{c1}\pi^+\pi^-$

Informative to study $X(3872) \rightarrow D^0\overline{D}^*0$ in Belle II data

Mass → $3872.9^{+0.4}_{-0.4}\ (0.4) \ \text{MeV}/c^2$

$1/5$ of total data
Decays of $X(3872)$

Measuring ratios of radiative decays

$$\frac{\mathcal{B}(X(3872)\to \psi' \gamma)}{\mathcal{B}(X(3872)\to J/\psi \gamma)} = 3.5 \pm 1.4 \quad \text{BaBar, PRL 102, 132001 (2009)}$$

$$< 2.1 \text{ (at 90\% CL)} \quad \text{Belle, PRL 107, 091803 (2011)}$$

$$= 2.46 \pm 0.64 \pm 0.29 \quad \text{LHCb, NPB 886, 665 (2014)}$$

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

Measure the above mention ratio precisely in order to constraint the admixture.

Charged partner of $X(3872)$

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

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 and BaBar measured the allowed $X(3872) \to J/\psi \pi^+ \pi^- \pi^0$

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

Belle II should measure this ratio.
Production of $X(3872)$

Measuring Absolute $\mathcal{B}(B \rightarrow X(3872)K^+)$ will help in measuring $\mathcal{B}(X(3872) \rightarrow \text{final state})$.

Measurement is “only possible at B factories” (operating at center-of-mass energy of $\Upsilon(4S)$ which decays into $B\bar{B}$ pairs).

Missing mass recoiling against $K^+$

$$M_{\text{miss}} = \sqrt{(p_{e^+e^-}^* - p_{\text{tag}}^* - p_h^*)^2}$$

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

Belle II might measure this value.

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

Belle, PRD 97, 012005 (2018)

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$B^0 \rightarrow \psi'K^+\pi^-$

$B^0 \rightarrow X K^* (892)^0$

$B^0 \rightarrow X (K\pi)_{NR}$

$B^0 \rightarrow X K_2^* (1430)^0$

$K^* (892)^0$ 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 $\psi'$.

Belle, PRD91, 051101 (R) (2015)
Two photon processes

Study of $\chi_{c2}(3930)$ using $\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$

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 $J/\psi D\bar{D}$.
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.
$e^+e^- \rightarrow J/\Psi\pi^+\pi^-$ study

$Y$ ISRs

$159\pm49\pm7$ events

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

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

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

$3.5 \sigma$

Belle, PRD 91, 112007 (2015)

Search for $Z_{cs}^+$ in $e^+e^- \rightarrow J/\Psi KK$.
Study $e^+e^- \rightarrow D^0D^-\pi^+$ and $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$. 

Any relation to $Z(4050)^+ \rightarrow \chi_{c1}\pi^+$ ?

Search $Z(4430)^+ \rightarrow \psi'\pi^+$ as in $B^0 \rightarrow \psi'\pi^+K^-$ ?
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

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

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

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

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

Belle, PRL 108 032001 (2012)

Belle, PRL 108, 122001 (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 $BB^*$ and $B^{*}B^{*}$ threshold

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

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

Belle, PRL116, 212001 (2016)

➢ $Z_b(10610)^+$ in $BB^*$ and $Z_b(10650)^+$ seen in $B\bar{B}^*/B^{*}\bar{B}^*$.

➢ $B^{(*)}B^*$ 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 $Z_b^0$

w/o $Z_b^0$

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

Data consist of five energy points in \( \Upsilon(6S) \)

- Evidence that proceed via intermediate \( Z_b \) state.
  - Only \( Z_b(10610) \) (excluded 3.3\( \sigma \))
  - Only \( Z_b(10650) \) produced not excluded significantly.

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

If \( Z_b \) molecular state, then Heavy Quark Spin symmetry suggest there should be \( 2/4 \) molecular partner bottomonium-like state (\( W_b \))
\( \Upsilon(5S,6S) \rightarrow W_{b0} \gamma \)
\( \Upsilon(6S) \rightarrow W_{b0} \pi^+\pi^- \)
\( W_{b0} \rightarrow \eta_b\pi, \chi_b\pi, \Upsilon \rho \)

Voloshin, 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