First evidence of $B \rightarrow h_c K$ and Recent Results on X and Y from Belle

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On the behalf of Belle collaboration
HADRON 2019
Introduction

Quark model: M. Gell-Mann, Phys.Lett. 8, 214 (1964)
Classification scheme for hadrons in terms of valance quarks. Hadrons are composed of mesons (q\bar{q}, qq\bar{q}, ...) and baryons (qqq, qq\bar{q}q\bar{q}, ....).

- Charmonium consists of two heavy c quarks and allows to study strong interactions.
- Charmonium-like states are not predicted by potential models.

X(3872), Y(4260), Z_c(3900), Z^+(4430), X(3915)... were found in last decade. Still their properties are not well understood.

Not observed in conventional matter. However, they should be allowed.
The second generation of B-factories has been launched, and Belle II recorded the first collision on April, 2018

Contribution to charmonium like states:
X(3823), X(3872), Z(3895)$^+$, X(3915), Z(3930), X(3940), Y(4260), X(4350), X(4630), Y(4660), Z(4430)$^+$, \(Z_1(4050)^+\), \(Z_2(4250)^+\),...
B → Y(4260)K

Y(4260) was firstly discovered in ISR by BaBar in 2005.

Confirmed by Belle and CLEO.

<table>
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<th>BaBar</th>
<th>CLEO</th>
<th>Belle</th>
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<tbody>
<tr>
<td>Mass (MeV/c²)</td>
<td>4244±5</td>
<td>4284^{+17}_{-16}</td>
<td>4295±10</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>114^{+16}_{-15}</td>
<td>73^{+39}_{-25}</td>
<td>133±26</td>
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- BESIII suggest that there are two peaks at Y(4260) [Y(4260) and Y(4360)].
- Measured by BESIII:
  - Mass: (4222.0±3.1) MeV/c², Width: (44.1±4.3) MeV

Theory predicts Y(4260) to be charmonium-hybrid, tetraquark and admixture state. 

S. L. Zhu PLB 625 (2005)
\( B \rightarrow Y(4260)K \)

Measured by Belle: \[ \frac{B(Y(4260) \rightarrow Z_c(3900)^\pm \pi^\mp)}{B(Y(4260) \rightarrow J/\psi \pi \pi)} = (29.0 \pm 8.9)\% \]

Measured by BESIII: \[ \frac{B(Y(4260) \rightarrow Z_c(3900)^\pm \pi^\mp)}{B(Y(4260) \rightarrow J/\psi \pi \pi)} = (21.5 \pm 3.3)\% \]

  - \( 3.0 \times 10^{-8} < |\mathcal{B}(B \rightarrow K Y(4260), Y(4260) \rightarrow J/\psi \pi \pi)| < 1.8 \times 10^{-6} \)
  - Suggest \( Y(4260) \) is not pure charmonium state. It is an admixture state(?)

BaBar, PRD 73, 011101 (R) (2006)

\[ \mathcal{B}(B^- \rightarrow K Y(4260), Y(4260) \rightarrow J/\psi \pi \pi) < 2.9 \times 10^{-5} \]

Updated results using Belle data.

\[ 967 \text{ fb}^{-1} \]

Invariant mass of \( Z_c(3900)^\pm \)
**B→Y(4260)K**

**Selection criteria:**
- Y(4260) reconstructed in $J/\psi\pi\pi$ mode
- $|dz|< 3.5\text{cm}$ & $|dr| < 1.0 \text{ cm}$
- $J/\psi$ reconstruction: $3.07 \ (3.05)< M_{\mu\mu}(M_{ee}) < 3.13 \text{ GeV}/c^2$
- $\gamma$s added within 0.5 mrad to $J/\psi\to e^+e^-$ mode

Mass-constrained fit to $J/\psi$ candidates to improve resolution.

- B → $\psi\ K$ and B → X(3872) K are good control sample.
- Have same final state: $J/\psi\pi\pi$.

To identify signal:

- MC Control sample

**Signal is extracted from fit to the $s$-plot distribution of $M_{J/\psi\pi\pi}$**

**Control sample results:**
- $\mathcal{B}(B^+\to \psi(2S) K^+) = [6.54\pm0.18\text{(stat.)}] \times 10^{-4}$
- $\mathcal{B}(B^0\to \psi(2S) K^0) = [5.25\pm0.45\text{(stat.)}] \times 10^{-4}$
- $\mathcal{B}(B^+\to X(3872) K^+, X(3872)\to J/\psi\pi\pi) = [9.07\pm0.64 \text{ (stat.)}] \times 10^{-6}$
- $\mathcal{B}(B^0\to X(3872) K^0, X(3872)\to J/\psi\pi\pi) = [4.97\pm1.03 \text{ (stat.)}] \times 10^{-6}$

Agreement with Belle previous measurement.
$\mathcal{B}(B^+ \to Y(4260) K^+, Y(4260) \to J/\psi \pi \pi) < 1.4 \times 10^{-5} (90\% \text{ C.L.})$

$\mathcal{B}(B^0 \to Y(4260) K^0, Y(4260) \to J/\psi \pi \pi) < 1.7 \times 10^{-5} (90\% \text{ C.L.})$

No significant signal with current dataset

Signal significance: 2.1$\sigma$

Signal significance: 0.9$\sigma$

Consistent with BaBar limit but more precise

Given for the first time
B→X(3872,3915)(→χ_{c1}\pi^0)K

X(3872) was first observed by the Belle Collaboration in 2003.


Recently, new decay of X(3872) was observed by BESIII in e^+e^-→X(3872) (→χ_{c1}\pi^0)γ.

BESIII, PRL 122, 202001 (2019)

X(3915) was first observed by Belle collaboration in 2005.

Belle, PRL 94, 182002 (2005)

- J^{PC} = 1^{++} ⇒ may be χ_{c1}(2P), single pionic transition is suppressed due to isospin breaking.
- \( B(X(3872)→χ_{c1}\pi^0)/B(X(3872)→J/\psi\pi^+\pi^-) = 0.88^{+0.33}_{-0.27}\pm0.10 \) is larger than \( B(\psi(2S)→J/\psi\pi^0)/B(\psi(2S)→J/\psi\pi^+\pi^-) = 3.66 \times10^{-3} \)
- Disfavors the χ_{c1}(2P) interpretation of X(3872).

Worth checking this ratio using Belle data!

Belle, PRD 99, 111101(R) (2019)
Selection:
- $\chi_{c1}$ reconstructed in $J/\psi\gamma$ mode
- Photon selection: $E_\gamma > 100$ MeV, $\pi^0$ veto to reject $\gamma$ from $\pi^0$

Veto on $B^+ \rightarrow \chi_{c1} K^{*+}$:
$791.8 \text{ MeV} < M(K^+\pi^0) < 991.8 \text{ MeV}$.

UML fit to $\Delta E$ gives $(806 \pm 69)$ signal events (consistent with similar previous Belle study of $B^+ \rightarrow \chi_{c1}\pi^+\pi^-K^+$).

Belle, PRD 93, 052016 (2016)

$\mathcal{B}(B^+ \rightarrow X(3872)K^+) \times \mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ (90% C.L.)
$\mathcal{B}(B^+ \rightarrow X(3915)K^+) \times \mathcal{B}(X(3915) \rightarrow \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$ (90% C.L.)
$\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0) / \mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.)

Results are consistent with BESIII result.

Compatible with the interpretation of $X(3872)$ as an admixture of $D^0 D^{*0}$ molecule and $\chi_{c1}(2P)$ charmonium state.
$B \to h_c K$

- Charmonium state, mass=$(3525 \pm 0.11)$ MeV and width=$(0.7 \pm 0.4)$ MeV.
- $B^+ \to \chi_{c0} K^+$, $B^+ \to \chi_{c2} K^+$ and $B^+ \to h_c K^+$ are suppressed by factorization.
- $\mathcal{B}(B \to h_c K^+)$ is expected to be of same order as of $\mathcal{B}(B^+ \to \chi_{c0} K^+)$. However, not observed so far!

LHCb also provided the upper limit $\mathcal{B}(B \to h_c K^+) < 6.4 \times 10^{-8}$ @ 95% C.L.

LHCb, EPJ C73, 2462 (2013)

Belle set the upper limit on $\mathcal{B}(B \to h_c K^+) < 3.8 \times 10^{-5}$ using 253 fb$^{-1}$ [$h_c \to \eta_c (\eta_c \to K_S^0 K^\pm \pi^\mp, pp)\gamma$].

- Theoretical predictions:
  - $2.7 \times 10^{-5}$ from QCD factorization
  - $3.6 \times 10^{-5}$ from pQCD, X. Q. Li, et al. PRD 74 114029 (2006)
  - $(3.1 \times 10^{-5} - 5.7 \times 10^{-5})$ from QCD factorization including the charmonium bound-state scales, M. Beneke, et al. NPB 811 155 (2009)

- Theoretical predictions are slightly below the current experimental limits.

New $h_c \to pp\pi^+\pi^-$ is recently observed by BESIII.

BESIII, PRD 99, 072008 (2019)

Updated results using Belle full data.
Analysis feature:

- $h_c \rightarrow \eta_c \gamma$ and $pp\pi^+\pi^-$ are used.
- $\eta_c$ candidates are reconstructed in 10 decay channels ($K^+K_S^0\pi^-$, $K^+K^-\pi^0$, $K^0_\Sigma K^0_\Sigma\pi^0$, $K^+K^-\eta$, $K^+K^-K^-$, $\eta'\rightarrow \eta\pi^+\pi^-$, pp, $pp\eta$, $pp\pi^+\pi^-$, and $\Lambda\Lambda$).
- $\eta$ candidates are reconstructed in $\gamma\gamma$ and $\pi^+\pi^-\pi^0$.
- MVA is used for each channel to separate signal from bkg.
- Simultaneous UML fit to $h_c \rightarrow \eta_c \gamma$ signal and $h_c \rightarrow pp\pi^+\pi^-$ bkg and signal.

Evidence for $B^+ \rightarrow h_c K^+$

$\mathcal{B}(B^+ \rightarrow h_c K^+) = (3.7^{+1.0}_{-0.9} \pm 0.8) \times 10^{-5}$

No evidence is observed for $B^0 \rightarrow h_c K^0$

$\mathcal{B}(B^0 \rightarrow h_c K^0) < 1.4 \times 10^{-5}$ at 90% C.L.
Observation of the new $\eta_c(2S)$ decay channel: $\eta_c(2S) \to pp\pi^+\pi^-$!

Other charmonium signals are consistent with PDG.
Summary

B→Y(4260)K:  
- Upper limit on $\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.4 \times 10^{-5}$ is consistent with BaBar but more precise.
- Upper limit on $\mathcal{B}(B^0 \to Y(4260)K^0) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.7 \times 10^{-5}$ is given for the first time.

B→X(3872,3915)K:  
- Upper limits are set on the product branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ and $\mathcal{B}(B^+ \to X(3915)K^+) \times \mathcal{B}(X(3915) \to \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$.
- Compatible with the interpretation of X(3872) as an admixture of $D^0D^{*0}$ molecule and $\chi_{c1}(2P)$ charmonium state.
- Ratio $\mathcal{B}(X(3872) \to \chi_{c1}\pi^0) / \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ (90% C.L.) consistent with BESIII result.

B→$h_c K$:  
- Evidence of the decay $B^+ \to h_c K^+$ is found, and $\mathcal{B}(B^+ \to h_c K^+) = (3.7^{+1.0}_{-0.9} \pm 0.8) \times 10^{-5}$ is consistent with the existing limit and theoretical predictions.
- Upper limit is set on $\mathcal{B}(B^0 \to h_c K_s^0) < 1.4 \times 10^{-5}$ at 90% C.L.
- First observation of $\eta_c(2S) \to pp\pi^+\pi^-$ decay with 12.1σ significance.

Belle II is active and results can be measured more precisely.
Backup
B→hc K

A multivariate analysis is performed for each channel using the MLP from TMVA library.

- All channels: thrust angle of B daughters and remaining particles in the events, thrust angle of all tracks and photons, ratio of Fox-wolfram moment $F_2/F_0$, the B production angle, vertex fit quality.

- $hc→ηcγ$: $hc$ helicity angle, $ηc$ mass, number of $π^0$ candidates that include the $hc$ daughter photon as one of their daughters.

- $ηc→K^+K^0\pi^-$, $ηc→K^+K^0\pi^0$, $ηc→K^0_0K^0_0\pi^0$: invariant masses of (K, $π$) combinations.

- Channels with the corresponding particles in the final state: K and p particle identification likelihoods.

- Channels with $π^0$ and $η$: the $π^0$ ($η$) mass, the minimal energy of the $π^0$ ($η$) daughter photons in the lab frame, the number of $π^0$ candidates that includes $π^0$ ($η$) daughter photons as one of their daughters.

- Channels with $η→π^+\pi^-\pi^0$ or $η'→ηπ^+\pi^-$: the $η$ ($η'$) mass.