Recent results on quarkonium(-like) states at B-factories

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OUTLINE:

\[ X(3872), \ Z^+ \]
\[ X(4140/4270) \rightarrow J/\psi \ \phi \]
\[ \Upsilon (4/5S) \rightarrow h_b \ \eta \]
Predictions for conventional charmonia

Theory described well the observed spectrum of cc states → The charmonium system is ideal place to search for exotic states = deviations from conventional charmonium spectroscopy.

Until the B-factories – no evidence for such deviations

\[ \eta_c(1S) \equiv 1^1S_0 \]
\[ J/\psi \equiv 1^3S_1 \]
\[ \chi_{cJ}(1P) \equiv 1^3P_J \]
In sum $L > 1552 \ fb^{-1}$

For 9 years the B-factories have observed a number of states that do not admit a conventional quarkonium interpretation. These states could be made of more than 2 quarks. So, unworried heavy quarkonium picture is broken!
A number of unexpected exotic states above $D\bar{D}(\ast)$ thresholds that do not fit into available $c\bar{c}$ slots were found.
**X(3872): a mixture of**

- 'Peripheral' part dominant at large distance
- 'Core' part localized at short distance, e.g. $2^3P_1$ and 'others'...

Decays into $DD^*$ and $J/\psi \rho^0$, $J/\psi \omega$

- Isospin mixed pionic transitions

Production and decays into $J/\psi \gamma$ and $\psi(2S) \gamma$

Searches for new X decay modes are needed to explore in detail its properties and internal structure.

**X(3872) was confirmed by all players in heavy flavours**
Recent results on $X(3872)$ decays:
Search for $X(3872) \rightarrow \chi_{c1}\pi^+\pi^- \text{ in } B^+ \rightarrow \chi_{c1}\pi^+\pi^- K^+$

Observation of $B^\pm \rightarrow \chi_{c1}\pi^+\pi^- K^\pm$ (1597 ± 76 events).
Search for $X(3872) / \chi_{c1}(2P)$: no resonances found.
$B(B \rightarrow \chi_{c1}\pi^+\pi^- K) = (3.94 \pm 0.19 \pm 0.30) \times 10^{-4}$.

Preliminary
The X(4140), X(4270) → J/ψφ story

CDF reported the study of the decay mode B⁺→J/ψφ K⁺

LHCb didn’t confirm these peaks, 2.4σ disagr. with CDF

CMS confirmed two resonances

D0 published evidence for these resonances
Search for X(4140) in $B^+ \rightarrow J/\psi \phi K^+$ decays at BaBar

![BaBar preliminary graph]

<table>
<thead>
<tr>
<th>Experiments</th>
<th>$f(4140)$ [%]</th>
<th>$f(4270)$ [%]</th>
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<tbody>
<tr>
<td>CDF</td>
<td>$14.9 \pm 2.9 \pm 2.4$</td>
<td>-</td>
</tr>
<tr>
<td>LHCb</td>
<td>$&lt;7$</td>
<td>$&lt;8$</td>
</tr>
<tr>
<td>D0</td>
<td>$19 \pm 7 \pm 4$</td>
<td>-</td>
</tr>
<tr>
<td>CMS</td>
<td>$13.4 \pm 3.0$ (*)</td>
<td>$18.0 \pm 7.3$ (*)</td>
</tr>
</tbody>
</table>

Fit fractions with the assumption of two resonances
- $f(4140) = (7.3 \pm 2.5 \pm 3.8)$%; Upper Limit (90% CL) = 12.1%
- $f(4270) = (7.7 \pm 3.7 \pm 5.2)$%; Upper Limit (90% CL) = 16.4%

No clear conclusion from BaBar on these resonances
- Lack of statistics
- Need a full Dalitz plot analysis
Charged Charmonium-like States

$Z(4430)^+, Z(4050)^+, Z(4250)^+$ at Belle

$B^0 \rightarrow \pi^+\psi(2S)K^-$

$B^0 \rightarrow \pi^+\chi_{c1}K^-$

Total significance: $6.5\sigma$ and $>5\sigma$ for each $Z^+$

These states have no chance to be a pure $cc$ (unlike neutral $XYZ$)

PRL 100, 142001 (2008)

PRD 78, 072004 (2008)
Belle updated $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ analysis

$M = 4485^{+22+28}_{-22-11}$ MeV/$c^2$,
$\Gamma = 200^{+41+26}_{-46-35}$ MeV.

Preferred $J^P$ hypothesis: $1^+$. Exclusion levels (0$^-$, 1$^-$, 2$^-$ and 2$^+$ hypotheses): 3.4$\sigma$, 3.7$\sigma$, 4.7$\sigma$ and 5.1$\sigma$.

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>0$^-$</th>
<th>1$^-$</th>
<th>1$^+$</th>
<th>2$^-$</th>
<th>2$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV/$c^2$</td>
<td>4479 $\pm$ 16</td>
<td>4477 $\pm$ 4</td>
<td>4485 $\pm$ 20</td>
<td>4478 $\pm$ 22</td>
<td>4384 $\pm$ 19</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>110 $\pm$ 50</td>
<td>22 $\pm$ 14</td>
<td>200 $\pm$ 40</td>
<td>83 $\pm$ 25</td>
<td>52 $\pm$ 28</td>
</tr>
<tr>
<td>Significance</td>
<td>4.5$\sigma$</td>
<td>3.6$\sigma$</td>
<td>6.4$\sigma$</td>
<td>2.2$\sigma$</td>
<td>1.8$\sigma$</td>
</tr>
</tbody>
</table>

Amplitude analysis of $B \rightarrow J/\psi \pi K$

4D amplitude analysis (similar to $Z(4430)^+$)

Search for $Z(4430)^+$ and another additional $Z^+$ decaying into $J/\psi \pi^+$

New $Z_c^+$ is found ($J^P = 1^+$) [$Z_c(4200)^+$, 7.2σ with syst. error].

$$M = 4196^{+31+17}_{-29-6} \text{ MeV/c}^2, \quad \Gamma = 370^{+70+70}_{-70-85} \text{ MeV}.$$

$J^P = 1^+$

Exclusion levels ($J^P = 0^-, 1^-, 2^-, 2^+$): 6.7σ, 7.7σ, 5.2σ, 7.6σ.

$Z(4430)^+$ is also found (4σ) $\Rightarrow$ new decay mode of $Z(4430)^+$

$B(B^0 \rightarrow Z_c(4430)^+K^-) \times B(Z_c(4430)^+ \rightarrow J/\psi \pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$

$B(B^0 \rightarrow Z_c(4200)^+K^-) \times B(Z_c(4200)^+ \rightarrow J/\psi \pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$

$$\frac{B(Z_c(4430)^+ \rightarrow \psi(2S)^{\pi^+})}{B(Z_c(4430)^+ \rightarrow J/\psi \pi^+)} \sim 10$$

It could be a sign of a complex structure of $Z(4430)^+$ wavefunction.
Since 2007 Belle remained confident that their analysis is sound and the peaks in $\pi^+\psi'$ and $\pi^+\chi_{c1}$ masses are not due to the reflections from the dynamics in $K\pi$ system.

Last year new charged charmonium-like state, $Z(3900)^+ \rightarrow J/\psi \pi^+$, was observed by BES III and Belle.

Very recently the first charmonium-like charged state, $Z(4430)^+ \rightarrow \psi(2S) \pi^+$, discovered by Belle in 2007 was finally confirmed by LHCb.

<table>
<thead>
<tr>
<th>LHCb</th>
<th>Belle</th>
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<tbody>
<tr>
<td>$M(Z)$ [MeV]</td>
<td>$4475 \pm 7^{+15}_{-25}$</td>
</tr>
<tr>
<td>$\Gamma(Z)$ [MeV]</td>
<td>$172 \pm 13^{+37}_{-34}$</td>
</tr>
<tr>
<td>$f_Z$ [%]</td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$</td>
</tr>
<tr>
<td>$f_{Zf}$ [%]</td>
<td>$16.7 \pm 1.6^{+2.6}_{-3.2}$</td>
</tr>
<tr>
<td>Significance</td>
<td>&gt; 13.9$\sigma$</td>
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</table>
Interpretation of $Z^+$

A variety of interpretations
(not a complete list...):

- D*$D_1$ molecular state
  (X. Liu and Y.R. Liu, 0711.0494);

- radially excited tetraquark
  (L. Maiani, A.D. Polosa, V. Riquer,
   0708.3997);

- hadro-charmonium
  (S. Dubinskiy, M.B. Voloshin, 0803.2224)
The transitions between Upsilonons with \( \eta \) emission are suppressed in comparison with \( \pi\pi \) in QCD multipole expansion models. \( S \rightarrow S\eta \) requires spin flip (E1 M1 transition).

<table>
<thead>
<tr>
<th>Transition</th>
<th>CLEO</th>
<th>BaBar</th>
<th>Belle</th>
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<tbody>
<tr>
<td>( \Upsilon(2S) \rightarrow \Upsilon(1S) \eta )</td>
<td>2.1( ^+0.7_{-0.6}\pm0.3 )</td>
<td>2.39( \pm0.31\pm0.14 )</td>
<td>3.57( \pm0.25\pm0.21 )</td>
</tr>
<tr>
<td>( \Upsilon(3S) \rightarrow \Upsilon(1S) \eta )</td>
<td>(&lt;0.1)</td>
<td>( &lt;0.1 )</td>
<td>( &lt;0.1 )</td>
</tr>
<tr>
<td>( \Upsilon(4S) \rightarrow \Upsilon(1S) \eta )</td>
<td>1.96( \pm0.06\pm0.09 )</td>
<td>( \times10^{-4} )</td>
<td>( \times10^{-4} )</td>
</tr>
<tr>
<td>( \Upsilon(5S) \rightarrow \Upsilon(1S) \eta )</td>
<td>2-3 orders of magnitude higher than theoretical expectations</td>
<td>7.3( \pm1.6\pm0.8 )</td>
<td>( \times10^{-4} )</td>
</tr>
<tr>
<td>( \Upsilon(5S) \rightarrow \Upsilon(2S) \eta )</td>
<td>( \times10^{-4} )</td>
<td>( \times10^{-4} )</td>
<td>( \times10^{-4} )</td>
</tr>
</tbody>
</table>

Coupled channels effects (hadronic loops) account for

**But what with \( \Upsilon(4/5S) \rightarrow h_b\eta \)?** (never observed so far)

\( \Upsilon(4S) \rightarrow h_b\eta \) is expected to be as large as \( 10^{-3} \) \[PRL 105 (2010) 162001\]
First observation of $\gamma(4S)\rightarrow h_b\eta$ at Belle

M(h_b) = “Missing mass” = $\sqrt{(P_{e^+e^-} - P_\eta)^2}$

$\text{Br}(\gamma(4S)\rightarrow h_b\eta) = (1.83 \pm 0.16 \pm 0.17) \times 10^{-3}$

Then additional photon is reconstructed

$\Delta M_M = M(\gamma\eta) - M(\eta) = M(\eta_b) - M(h_b)$

$M(\eta_b) = (9405.3 \pm 1.3 \pm 3.0)$ MeV

$\Delta M_{HF}(1S) = M(\gamma(1S)) - M(\eta_b(1S)) = (55.0 \pm 1.3 \pm 3.2)$ MeV

In a good agreement with the Belle measurement from $\gamma(5S) \rightarrow \pi^+\pi^-h_b(\rightarrow \gamma\eta_b)$ and LQCD but somewhat lower than BaBar and CLEO results from $\gamma(2/3S) \rightarrow \gamma\eta_b$.
The same analysis in $\Upsilon(5S)$ data:

$\Upsilon(5S) \rightarrow (b\bar{b}) \eta$

**NEW**

**BF**[$\Upsilon(5S) \rightarrow \eta \ Y(1D)] = (2.8 \pm 0.7 \pm 0.4) \times 10^{-3}$

**BF**[$\Upsilon(5S) \rightarrow \eta \ Y(2S)] = (2.1 \pm 0.7 \pm 0.3) \times 10^{-3}$

**BF**[$\Upsilon(5S) \rightarrow \eta \ hb(1P)] < 3.3 \times 10^{-3}$ (90% CL)

**BF**[$\Upsilon(5S) \rightarrow \eta \ hb(2P)] < 3.7 \times 10^{-3}$ (90% CL)

Unexpected behavior in comparison with $\Upsilon(4S)$

Effects that violate heavy spin symmetry may be important!
Summary

• Study of X(3872) continues, Belle searched for $\chi_{c1}\pi^+\pi^-$ mode;

• BaBar searched for $X(4140) \rightarrow J/\psi \phi$;

• NEW RESULTS on the first charged Z, $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ and $J/\psi\pi^+$ from Belle;

• New $Z(4200)^+ \rightarrow J/\psi\pi^+$ was found at Belle;

• New observations in bottomonia decays: $\eta$ transitions in $\Upsilon(4S)$ and $\Upsilon(5S)$ at Belle.

Current picture of quarkonium-like (≡exotic) states is rather scattered.

Today there is no unique theoretical model which coherently describes all experimental data.

$X,Y,Z$ states remain a mystery, especially charged $Z$; new efforts are needed to understand new states.

Contribution from high-statistics measurements is important: LHC, BES III and Belle II.