Results on new particles from

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DPF, Santa Cruz, August 2013
Charged onia ($q\bar{q}q\bar{q}$)  
Parabottomonia  
D waves  
6q states

Outline

- B-decays
- Double Charmonium
- Annihilation at smaller energy
- Two photon production

Easy to study.
Low background.

$J^{PC}$ using angular studies.

Decays on Resonance Peak

CLEO
BABAR
BELLE

DPF 2013, Santa Cruz, 8/16/2013
R.Mussa, New particles from Belle
Belle has discovered two charged bottomonium-like resonances:

$Z_b(10610)$  \[ M = 10608.1 \pm 1.7 \text{ MeV} \]
\[ \Gamma = 15.5 \pm 2.4 \text{ MeV} \]

$Z_b(10650)$  \[ M = 10653.3 \pm 1.5 \text{ MeV} \]
\[ \Gamma = 14.0 \pm 2.8 \text{ MeV} \]

The states are observed in 5 final states, all with consistent masses, close to the $BB^*$ and $B^*B^*$ threshold.

Analysis of angular distributions suggests $J^P=1^+$ for these states.

PRL108,122001(2011)

For:
Search for the neutral partners $Z_b^0$
Search for decays to $BB^*$ and $B^*B^*$
Transitions to $Y(1D)$

See Santel's talk
Discovery of charged charmonium: \( Z_c(4430) \)

First charged charmonium observed by Belle in \( B \rightarrow K (\pi \psi') \), Babar controversy: data FULLY COMPATIBLE with Belle, but different interpretation: interference with \( K^* \) resonances?

\[
\begin{array}{cccc}
N_{\text{sig}} & N_{\text{cont}} & \text{BW Mass (GeV)} & \Gamma (\text{GeV}) \\
121 \pm 30 & 766 \pm 39 & 4.433 \pm 0.004 & 0.045^{+0.018}_{-0.013} \\
\end{array}
\]

\[
B(\bar{B}^0 \rightarrow K^- Z^+(4430)) \times B(Z^+(4430) \rightarrow \pi^+ \psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5},
\]
Two more charged charmonia observed by Belle in $B \to K (\pi \chi_{c1})$, disconfirmed by Babar: interference from $K^*$ resonances?

PRD80, 031104 (2009)

arXiv:1111.5919v2
New: $Z_c(4430)$ quantum numbers

ArXiV:1306.4894, $L dt = 711 \, fb^{-1}$ at Y(4S)

Full amplitude analysis in 4D: Dalitz Plot + angular distribution

$$B(\bar{B}^0 \rightarrow \psi' K^- \pi^+) = (5.80 \pm 0.36) \times 10^{-4},$$
$$B(\bar{B}^0 \rightarrow \psi' K^*(892)) = (5.20^{+0.28+1.45}_{-0.20-0.39}) \times 10^{-4},$$
$$B(\bar{B}^0 \rightarrow Z(4430)^+ K^-) \times B(Z(4430)^+ \rightarrow \psi' \pi^+) =$$
$$(3.5^{+1.2+0.4}_{-0.8-1.3}) \times 10^{-5} \text{ for } J^P = 1^+ \text{ or }$$
$$(1.5^{+0.7+0.7}_{-0.5-0.2}) \times 10^{-5} \text{ for } J^P = 0^-,$$

Fit after K* veto:
- phase space
- $1^+$ hypothesis

<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>4470 ± 20</td>
<td>4482 ± 4</td>
<td>4500 ± 12</td>
<td>4545 ± 2</td>
<td>4367 ± 2</td>
</tr>
<tr>
<td>Width, MeV</td>
<td>139 ± 36</td>
<td>10.9 ± 0.3</td>
<td>126 ± 20</td>
<td>11.2 ± 0.6</td>
<td>9.1 ± 0.6</td>
</tr>
<tr>
<td>Significance</td>
<td>4.4$\sigma$</td>
<td>1.2$\sigma$</td>
<td>6.1$\sigma$</td>
<td>2.3$\sigma$</td>
<td>2.6$\sigma$</td>
</tr>
</tbody>
</table>
Discovery of charged charmonia: Zc(3900)

Hints of deviations from phase space were observed by CLEO in data at 4170 MeV [PRL107,041803 (2011)]

Belle ISR data at Y(4260) confirmed this in the e+e- → J/ψ ππ channel: this suggested a dedicated run on Y(4260) peak at BES-III (December 2013)
Discovery of charged charmonia: Zc(3900)

Significance >5.2σ

Belle: 927 fb⁻¹ of ISR data at $\Upsilon(nS)$ energy

- Mass = (3894.5±6.6±4.5) MeV
- Width = (63±24±26) MeV
- Fraction = (29.0±8.9)% (stat. error only)


BES-III: 525 pb⁻¹ @ $\Upsilon(4260)$ peak energy

- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

The high yield of $h_b(1,2P)$:

$$N[h_b(1P)] = (50.4 \pm 7.8 ^{+4.5}_{-1.9}) \times 10^3$$

$$N[h_b(2P)] = (84.4 \pm 6.8 ^{+23}_{-10}) \times 10^3$$

opens new perspectives
to study the $\eta_b(1,2S)$

Expected E1 rates:

*Godfrey & Rosner, PRD66 014012 (2002)*

$h_b(1P) \rightarrow \gamma \eta_b(1S) = 41\%$

$h_b(2P) \rightarrow \gamma \eta_b(1S) = 13\%$

$h_b(2P) \rightarrow \gamma \eta_b(2S) = 19\%$
Rediscovery of $\eta_b$

Babar 2008:

$\chi_b(1P) \rightarrow \gamma Y(1S)$

$\gamma_{\text{ISR}} Y(1S)$

$\gamma(2S) \rightarrow \gamma \eta_b(1S)$

$\chi_b(2P) \rightarrow \gamma Y(1S)^{(b)}$

$\gamma_{\text{ISR}} Y(1S)$

$Y(3S) \rightarrow \gamma \eta_b(1S)$

PRL 101,071801(2008)

PRL 103,161801(2009)
Rediscovery of $\eta_b$

Babar 2008:

- $\chi_b(2P) \rightarrow \gamma Y(1S)$
  - $\gamma_{ISR} Y(1S)$
  - $Y(3S) \rightarrow \gamma \eta_b(1S)$

- $\chi_b(1P) \rightarrow \gamma Y(1S)$
  - $\gamma_{ISR} Y(1S)$
  - $Y(2S) \rightarrow \gamma \eta_b(1S)$

PRL 101, 071801 (2008)
PRL 103, 161801 (2009)

PRL 109, 232002 (2012)
Evidence of $\eta_b(2S)$

Ldt = $121.4 \text{ fb}^{-1}(5S) + 12 \text{ fb}^{-1}(\text{scan})$

$h_b(2P) \rightarrow \eta_b(2S)\gamma$

$m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9} \text{ MeV}/c^2$

B.F. [$h_b(2P) \rightarrow \eta_b(2S)\gamma$] = $(47.5 \pm 10.5^{+6.8}_{-7.7})\%$

Significance: $4.2 \sigma$, including all systematics
The claim of: Dobbs et al   PRL109 (2012) 082001 (analysis of CLEO data by Seth's group)

\[ B(Y(2S) \rightarrow \eta_b(2S)\gamma)^* \sum_i B_i(\eta_b(2S) \rightarrow f_i) = 46.2^{+29.2}_{-14.2} \pm 10.6 \times 10^{-6} \]

@ M = 9974.6 ± 2.3 ± 2.1 MeV is inconsistent with Belle result from \( h_b(2P) \rightarrow \eta_b(2S)\gamma \)

M = 9999.0 ± 3.5 \( ^{+2.8}_{-1.9} \) MeV
Search for  \( \eta_b(2S) \) in exclusive modes

Exclusive reconstruction of 26 decay modes:

- \( 2(\pi^+\pi^-) \), 3(\pi^+\pi^-), 4(\pi^+\pi^-),
- \( 5(\pi^+\pi^-), K^+K^-\pi^+\pi^- \), \( K^+K^-2(\pi^+\pi^-) \), \( K^+K^-3(\pi^+\pi^-) \), \( K^+K^-4(\pi^+\pi^-) \), \( 2(K^+K^-) \),
- \( 2(K^+K^-)\pi^+\pi^- \), \( 2(K^+K^-)\pi^+\pi^- \), \( 2(K^+K^-)3(\pi^+\pi^-) \), \( \pi^+\pi^-p\bar{p} \), \( 2(\pi^+\pi^-)p\bar{p} \), \( 3(\pi^+\pi^-)p\bar{p} \),
- \( 4(\pi^+\pi^-)p\bar{p} \), \( \pi^+\pi^-K^+K^-p\bar{p} \), \( 2(\pi^+\pi^-)K^+K^-p\bar{p} \), \( 3(\pi^+\pi^-)K^+K^-p\bar{p} \), \( K_s^0K^\pm\pi^\mp \), \( K_s^0K^\pm\pi^\mp \),
- \( \pi^+\pi^- \), \( K_s^0K^\pm\pi^\mp \), \( K_s^0K^\pm\pi^\mp \), \( K_s^0K^\pm\pi^\mp \), \( 2(\pi^+\pi^-) \), \( 2K_s^0(\pi^+\pi^-) \), \( 2K_s^02(\pi^+\pi^-) \), \( 2K_s^03(\pi^+\pi^-) \).

The claim of:

\[
\mathcal{B}(Y(2S) \to \eta_b(2S)\gamma) \Sigma_i \mathcal{B}_i(\eta_b(2S) \to f_i) = 46.2^{+29.2}_{-14.2} \pm 10.6 \times 10^{-6}
\]

@ M = 9974.6 ±2.3 ±2.1 MeV

**IS DISCONFIRMED BY BELLE:**

Using our record data sample:

- on peak 25 fb\(^{-1}\) (157.8M Y(2S) decays, 16x CLEO)
- bkg: 87 fb\(^{-1}\) @ 10.52 GeV

**We set the UL @ 90% CL:** < 4.9x10\(^{-6}\) (including syst.)
Parabottomonia vs theory

$\eta_b(2S) vs \eta_b(1S)$

Some tension with the most accurate NRQCD prediction, but very close to lattice QCD (Meinel) predictions.

Spin averaged 1P-1S splitting seems not to depend on scale!!
Parabottomonia vs theory

η_b(2S) vs η_b(1S)

Spin averaged 1P-1S splitting seems not to depend on scale: only 1% relative difference with charmonium

DPF 2013, Santa Cruz, 8/16/2013
Tetraquark model: C-odd partner of X3872 decays in $\gamma \chi_{c1,2}$

No signal of “X(3872)” → $\gamma \chi_{c1,2}$

... but another peak .... with a significance : 4.2 $\sigma$

Preliminary: $M(3D_2) = 3823.5\pm2.8$ MeV/$c^2$

90% CL UL on $\Gamma(3D_2 \rightarrow \gamma \chi_{c2})/\Gamma(3D_2 \rightarrow \gamma \chi_{c1}) < 0.42$ (Th: ~ 0.2)

M$^{\chi_{c1\gamma}}$ distribution

- Narrow peak observed around 3820 MeV/$c^2$.
- No strong evidence for any discrepancy between data/MC, except this narrow peak.

B$^{+} \rightarrow \psi(\rightarrow \chi_{c1\gamma}) K^{+}$

M$_{bc} > 5.27$ GeV/$c^2$

M$_{bc} > 5.27$ GeV/$c^2$

No strong evidence for any narrow peak between data/MC at current statistics.
Evidence of the long sought $^3D_2$ state of charmonium J=2 partner of the $\psi(3770)$
Search for H dibaryon

Observation (ARGUS,CLEO) of:
- enhanced production of hyperons in bottomonium decays
- sizable BR (~3x10^-5) of production of antideuteron in Y(1,2S) decays

Suggested the idea to search for exotic 6 quark states, such as the H dibaryon, suggested by Jaffe in 1977. Controversial claims from expts. E522 and STAR.

Belle has searched for H dibaryon in the following channels:
- $\Lambda\pi p$ (+cc)
- $\Lambda\Lambda$ (+cc)
[published:PRL 110, 222002 (2013)]
- $\Xi^+ p$ (+cc)
[aiming for a longer paper including also pentaquark searches, inclusive production of $\Xi_c$ and $\Xi^*$ from Y decays]
In the last years, Belle has discovered a large number of conventional and exotic states, accumulating increasing evidences that hadrons are not simply made of 2 (mesons) or 3 (baryons) quarks.

In heavy meson systems, the first hints for the existence of 4 quark states (tetraquarks or hadro molecules) came from B decays, the controversy between Belle and Babar on the interpretation of the $Z_c(4430)$ is still unsettled.

Belle's new analysis of $Z_c(4430)$ quantum numbers favors $J^P=1^+$

More solid evidence of 4-quark states comes from $Y(4260)$ and $\Upsilon(10860)$ where Zc and Zb states provide new pathways to bound quarkonia:
- $Z_b(10510,10560)$ led to Belle's discovery of 3 missing parabottomonia, $h_b(1,2P)$ and $\eta_b(2S)$, and to the best mass determination of $\eta_b(1S)$
- a similar mechanism seems at work in charmonium, where Zc states at 3900 (Belle and BES-III) and 4020 (BES-III) mediate transitions towards $J/\psi$ and $h_c(1P)$.

After completing the low lying S and P wave spectra, Belle is making progress on D-wave states: while searching for partners of $X(3872)$, Belle ran into the long sought $^3D_2$ state of charmonium, decaying to , at a mass of $3823.5\pm2.8$ MeV/$c^2$.

Belle does not see any evidence of inclusive production of H-dibaryon
Exclusive Reconstruction of $\eta_c$ in 12 decay modes:

- $\pi^+\pi^+\pi^-\pi^-$
- $\pi^+\pi^+\pi^-\pi^0\pi^0$
- $K^+K^-\pi^+\pi^-
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\pi^0$

Cross section DOES NOT peak at 4170

CLEO: PRL 107 (2011) 041803

- $e^+ e^- \rightarrow \pi^+\pi^-\eta_c \rightarrow \gamma\pi^+\pi^-\eta_c$
  @4170 MeV

- $e^+ e^- \rightarrow \eta\eta_c \rightarrow \gamma\eta\eta_c$
  @4170 MeV

- $e^+ e^- \rightarrow \pi^+\pi^-\eta_c \rightarrow \gamma\pi^+\pi^-\eta_c$
  @4260 MeV

DPF 2013, Santa Cruz, 8/16/2013 R.Mussa, New particles from Belle
R.Mussa, New particles from Belle

ΔM_{HF}(1P) = 1.6 ± 1.5 MeV/c²

ΔM_{HF}(2P) = 0.5^{+1.6}_{-1.2} MeV/c²

Significance after correcting for systematics effects:

h_b(1P) 5.5σ

h_b(2P) 11.2σ

Masses very close to the state COG of χ states, as expected from theory

\[ \Gamma[Y(5S) \rightarrow h_b(nP) \pi^+\pi^-] \]

\[ \Gamma[Y(5S) \rightarrow Y(2S) \pi^+\pi^-] \]

\[ \frac{0.46 \pm 0.08^{+0.07}_{-0.12}}{0.77 \pm 0.08^{+0.22}_{-0.17}} \]

for h_b(1P)

for h_b(2P)
Single $\pi$ recoil in $\Upsilon(5S) \rightarrow h_b(1,2P)&\Upsilon(1,2,3S) : Z_b$'s!

9.43 GeV $< \text{MM}(\pi^+\pi^-) < 9.48$ GeV

10.05 GeV $< \text{MM}(\pi^+\pi^-) < 10.10$ GeV

10.33 GeV $< \text{MM}(\pi^+\pi^-) < 10.38$ GeV
Bottomonium D wave

Already seen by Cleo and Babar from Y(3S)

Significance:
- Exclusive: 9σ
- Inclusive: 2.4σ

CLEO
\[ M = 10161.1 \pm 0.6 \pm 1.6 \text{ MeV} \]
\[ B[Y(3S) \rightarrow Y(1D) \gamma \gamma \rightarrow Y(1S) \gamma \gamma \gamma \gamma] = (2.5 \pm 0.5 \pm 0.5) \times 10^{-5} \]

Belle preliminary
\[ B[Y(5S) \rightarrow Y(1D) \pi^+ \pi^- \rightarrow Y(1S) \gamma \gamma \pi^+ \pi^-] = (2.0 \pm 0.4 \pm 0.3) \times 10^{-4} \]
First particle(s) found at LHC!

Mass of $\chi_{b} (3P)$ centroid:

**ATLAS**, 4.4 fb$^{-1}$ @7 TeV  
$M = 10539 \pm 4 \pm 8$ MeV/c$^2$

Confirmed by Tevatron:

**D0**, 1.3 fb$^{-1}$ @2 TeV  
$M = 10551 \pm 14 \pm 17$ MeV/c$^2$