As is now well known, Japan suffered a terrible earthquake and tsunami on March 11, which has caused tremendous damage, especially in the Tohoku area. Fortunately, all KEK personnel and users are safe and accounted for. The injection linac did suffer significant but manageable damage, and repairs are underway. The damage to the KEKB main rings appears to be less serious, though non-negligible. No serious damage has been reported so far at Belle. Further investigation is necessary. We would like to convey our deep appreciation to everyone for your generous expressions of concern and encouragement.

DIS2011 April 10-15, 2011
Integrated luminosity at the B factories

On resonance:
\( \Upsilon(5S) : 121 \text{ fb}^{-1} \)
\( \Upsilon(4S) : 711 \text{ fb}^{-1} \)
\( \Upsilon(3S) : 3 \text{ fb}^{-1} \)
\( \Upsilon(2S) : 24 \text{ fb}^{-1} \)
\( \Upsilon(1S) : 6 \text{ fb}^{-1} \)

Off resonance/scan:
155 fb\(^{-1}\)
Charmonium / Exotic States
Exotic/charmonium spectroscopy

1974–1980:
\( J/\psi, \psi(2S), \eta_c, \chi_{c0}, \chi_{c1}, \chi_{c2}, \psi(3770), \psi(4040), \psi(4160), \psi(4415) \)

2002–now:
\( \eta_c(2S), \ h_c, \ X(3872), \ ... \)
**New states**

<table>
<thead>
<tr>
<th>State</th>
<th>$M$, MeV</th>
<th>$\Gamma$, MeV</th>
<th>$J^{PC}$</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>3871.52 ± 0.20</td>
<td>1.3 ± 0.6</td>
<td>$1^{++}/2^{--}$</td>
<td>$B \rightarrow K(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt; 2.2)</td>
<td></td>
<td>$p\bar{p} \rightarrow (\pi^+\pi^- J/\psi) + \ldots$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(\omega J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(D^{*0} D^0)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(\gamma J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K(\gamma(\psi)(2S))$</td>
</tr>
<tr>
<td>$X(3915)$</td>
<td>3915.6 ± 3.1</td>
<td>28 ± 10</td>
<td>0/2$^2+$</td>
<td>$\gamma\gamma \rightarrow (\omega J/\psi)$</td>
</tr>
<tr>
<td>$X(3940)$</td>
<td>3942$^{+9}_{-8}$</td>
<td>37$^{+27}_{-17}$</td>
<td>$??+$</td>
<td>$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow J/\psi(\ldots)$</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>4008$^{+121}_{-49}$</td>
<td>226 ± 97</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td>$Z_1(4050)^+$</td>
<td>4051$^{+24}_{-43}$</td>
<td>82$^{+51}_{-55}$</td>
<td>?</td>
<td>$B \rightarrow K(\pi^+\chi_{c1}(1P))$</td>
</tr>
<tr>
<td>$Y(4140)$</td>
<td>4143.4 ± 3.0</td>
<td>15$^{+11}_{-7}$</td>
<td>$??+$</td>
<td>$B \rightarrow K(\phi J/\psi)$</td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>4156$^{+29}_{-25}$</td>
<td>139$^{+113}_{-65}$</td>
<td>$??+$</td>
<td>$e^+e^- \rightarrow J/\psi(D\bar{D}^*)$</td>
</tr>
<tr>
<td>$Z_2(4250)^+$</td>
<td>4248$^{+185}_{-45}$</td>
<td>177$^{+321}_{-72}$</td>
<td>?</td>
<td>$B \rightarrow K(\pi^+\chi_{c1}(1P))$</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>4263 ± 5</td>
<td>108 ± 14</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow \gamma(\pi^+\pi^- J/\psi)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow (\pi^+\pi^- J/\psi)$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow (\pi^0\pi^0 J/\psi)$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow \gamma(\pi^+\pi^- \psi')$</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>4353 ± 11</td>
<td>96 ± 42</td>
<td>1$^{--}$</td>
<td>$B \rightarrow K(\pi^+\psi(2S))$</td>
</tr>
<tr>
<td>$Z(4430)^+$</td>
<td>4443$^{+24}_{-18}$</td>
<td>107$^{+113}_{-71}$</td>
<td>?</td>
<td>$e^+e^- \rightarrow \gamma(\Lambda_c^+\Lambda_c^-)$</td>
</tr>
<tr>
<td>$X(4630)$</td>
<td>4634$^{+9}_{-11}$</td>
<td>92$^{+41}_{-32}$</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow \gamma(\pi^+\pi^- \psi(2S))$</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664 ± 12</td>
<td>48 ± 15</td>
<td>1$^{--}$</td>
<td>$e^+e^- \rightarrow \gamma(\pi^+\pi^- \psi(2S))$</td>
</tr>
</tbody>
</table>
Exotic/charmonium production at B factories

\[ J^{PC} = 0^{--}, 1^{--}, 1^{++} \]

\[ J^{PC} = 0^{\pm+}, 2^{\pm+} \]

\[ C = +1 \]

\[ J^{PC} = 1^{--} \]
New mass measurement for $\eta_c$ and $\eta_c(2S)$

$\eta_c$ properties from PDG 2010:

Large spread $\Rightarrow$ C.L. < 0.0001

$\Gamma \simeq 15$ MeV in $J/\psi$ and $\psi'$ radiative decays

$\Gamma \simeq 30$ MeV in $B$ decays
New mass measurement for $\eta_c$ and $\eta_c(2S)$

$\eta_c$ properties from PDG 2010:

Large spread $\Rightarrow$ C.L. $< 0.0001$

$\Gamma \simeq 15$ MeV in $J/\psi$ and $\psi'$ radiative decays

$\Gamma \simeq 30$ MeV in B decays
New mass measurement for $\eta_c$ and $\eta_c(2S)$

$\eta_c$ in $B^+ \rightarrow K^+(K_SK\pi)^0$ to be submitted to PLB

- 2D fit of $\angle(K^+ K_S)$ vs $M(K_SK\pi)$

$M = 2985.4 \pm 1.5 \pm 0.2 \pm 2.0 \text{ MeV}$

$\Gamma = 35.1 \pm 3.1 \pm 1.0 \pm 1.6 \text{ MeV}$

agree with BaBar’s 2010 measurement in $\gamma\gamma \rightarrow \eta_c$
New mass measurement for $\eta_c$ and $\eta_c(2S)$

$\eta_c(2S)$ in $B^+ \rightarrow K^+ (K_SK\pi)^0$ to be submitted to PLB

$M = 3636.1 \pm 3.9_{\pm 4.1} \pm 0.5_{\pm 2.0}$ MeV

$\Gamma = 6.6 \pm 8.4_{\pm 5.1} \pm 2.6_{\pm 0.9}$ MeV

Interference is important!

Refit with no interference: $\Gamma = 41.1 \pm 12.0 \pm 6.4_{\pm 10.9}$ MeV
New final states seen for $\eta_c(2S)$

- Only one exclusive mode ($K_S K \pi$) seen until recently
- Not seen in 4-prong final state: Belle EPJC 53, 1 (2008)
- Seen in 6-prong final states:

<table>
<thead>
<tr>
<th>$M$, MeV</th>
<th>$\Gamma$, MeV</th>
<th>Signif.</th>
<th>$\Gamma_{\gamma\gamma} B$, eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6\pi$</td>
<td>3638.9 ± 1.6 ± 2.3</td>
<td>10.7 ± 4.9</td>
<td>8.5$\sigma$ 20.1 ± 3.7 ± 3.2</td>
</tr>
<tr>
<td>$2K4\pi$</td>
<td>3634.7 ± 1.6 ± 2.8</td>
<td>&lt; 13 @ 90%CL</td>
<td>6.2$\sigma$ 10.2 ± 2.3 ± 3.4</td>
</tr>
<tr>
<td>$K_SK3\pi$</td>
<td>3636.5 ± 1.8 ± 2.4</td>
<td>15.9 ± 5.7</td>
<td>8.7$\sigma$ 30.7 ± 3.9 ± 3.7</td>
</tr>
</tbody>
</table>

$M(\eta_c(2S)) = 3636.9 \pm 1.1 \pm 2.5 \pm 5.0 \text{ MeV}$
$\Gamma(\eta_c(2S)) = 9.9 \pm 3.2 \pm 2.6 \pm 2.0 \text{ MeV}$

(possible interference with background)
$X(3872)$ properties

• $M_X - (m_{D^0} + M_{D^{*0}}) = -0.32 \pm 0.35$ MeV

• In $X \rightarrow \pi^+\pi^- J/\psi$, $M_{\pi\pi}$ is consistent with $\rho$
  $\Rightarrow$ large isospin violation; suggests $C = +1$

• In $X \rightarrow \pi^+\pi^- \pi^0 J/\psi$, $M_{\pi\pi\pi^0}$ is consistent with $\omega$, different isospin than $\rho J/\psi$. $J^{PC} = 1^{++}$ or $2^{--}$ from an angular analysis.

• An $S$–wave $D^0 \bar{D}^{*0}$ molecular state?

E.S. Swanson, PLB 588, 189 (2004)
Exotic charmonium-like states

Tetraquark: four tightly bound quarks

Molecular state: two loosely bound mesons

Hybrid: states with excited gluonic degrees of freedom

Hadrocharmonium: charmonium state, “coated” by excited light-hadron matter

Exotics signature: \[ J^{PC}, \text{ forbidden for charmonium} \]
Extremely narrow width for a state above \( D\bar{D} \)
Non-zero charge, strangeness
$X(3872) \rightarrow J/\psi \gamma$ determines $C = +1$ assignment

- First seen by Belle in 2005 hep-ex/0505037
- New Belle measurement:

$$N = 30.0 \pm 8.2 \quad 7.4$$

$$S = 4.9 \sigma$$

$$B(B^+ \rightarrow K^+X) \times B(X \rightarrow J/\psi \gamma) = (1.8 \pm 0.5) \times 10^{-6}$$

$C = +1$

$B(E)LLE$ to be submitted to PRL

$B^0$

$N = 5.7 \pm 3.5 \quad 2.8$

$S = 2.4 \sigma$

$B(E)LLE$

$B^0$

$\text{cf BaBar} \ (2.8 \pm 0.8) \times 10^{-6} \ PRL \ 102, \ 132001 \ (2009)$
$X(3872) \to \psi' \gamma$ is not seen by Belle

- but seen by BaBar  
  PRL 102, 132001 (2009)
- New Belle measurement:

  to be submitted to PRL

\[ N = 5.0 \pm 11.9^{+11.0}_{-11.0} \]

\[ N = 1.5 \pm 4.8^{+3.9}_{-3.9} \]

\[
\frac{\mathcal{B}(X \to \psi' \gamma)}{\mathcal{B}(X \to J/\psi \gamma)} < 2.0 \text{ @ 90\% CL}
\]

cf BaBar 3.4 \pm 1.4
Other exotics near 3940 MeV: $X$, $Y$, and $Z$

- $X(3940)$ in $e^+e^- \rightarrow J/\psi D\bar{D}$
- $Y(3940)$ in $B \rightarrow K\omega J/\psi$
- $Z(3930)$ in $\gamma\gamma \rightarrow D\bar{D}$
- $X(3915)$ in $\gamma\gamma \rightarrow \omega J/\psi$

$M(X(3915)) = 3915 \pm 3 \pm 2$ MeV
$\Gamma(X(3915)) = 17 \pm 10 \pm 3$ MeV

- $X(3915) = Y(3940)$? hypothesis is compatible with data
- $X(3915) = Z(3930) = \chi_{c2}'$? Then
  $\mathcal{B}(\chi_{c2}' \rightarrow \omega J/\psi) > 0.08 \mathcal{B}(\chi_{c2}' \rightarrow D\bar{D})$ ... huge!?!
Null search for charmonium in $\Upsilon(1S)$ radiative decays

- No evidence for excited charmonium states below 4.8 GeV

<table>
<thead>
<tr>
<th>State ($R$)</th>
<th>$\mathcal{B}(10^{-5})$ Theor.</th>
<th>UL (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi_{c0}$</td>
<td>3</td>
<td>$&lt; 65$</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>1</td>
<td>$&lt; 2.3$</td>
</tr>
<tr>
<td>$\chi_{c2}$</td>
<td>0.6</td>
<td>$&lt; 0.76$</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>5</td>
<td>$&lt; 5.7$</td>
</tr>
<tr>
<td>$X(3872) \to \pi\pi J/\psi$</td>
<td></td>
<td>$&lt; 0.16$</td>
</tr>
<tr>
<td>$X(3872) \to \pi\pi\pi^0 J/\psi$</td>
<td></td>
<td>$&lt; 0.28$</td>
</tr>
<tr>
<td>$X(3915) \to \omega J/\psi$</td>
<td></td>
<td>$&lt; 0.30$</td>
</tr>
<tr>
<td>$Y(4140) \to \phi J/\psi$</td>
<td></td>
<td>$&lt; 0.22$</td>
</tr>
</tbody>
</table>
Observation of $h_b(1P)$ and $h_b(2P)$
Motivation for the $h_b$ search

Enhancement of $\sigma(h_c\pi\pi)$

@ $Y(4260)$

... suggests $\sigma(h_b\pi\pi)$ might be enhanced at $Y_b$, the B analog of $Y(4260)$

- Search for the $h_b$ in our $\Upsilon(5S)$ data
Expectations for the $h_b$ and $h_b(2P)$ masses
Use the missing-mass technique to find $h_b$ and $h_b(2P)$

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

From CM energy and boost (accelerator information)

\[ M(h_b) = \text{MM}(\pi^+ \pi^-) \]

reconstructed pion pair
Calibration: $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$, $\Upsilon((nS) \rightarrow \mu^+\mu^-$
Use the missing-mass technique to find $h_b$ and $h_b(2P)$
Use the missing-mass technique to find $h_b$ and $h_b(2P)$

\[
\begin{array}{|c|ccc|}
\hline
 & \text{Yield, } 10^3 & \text{Mass, MeV}/c^2 & \text{Signif.} \\
\hline
\Upsilon(1S) & 105.2 \pm 5.8 \pm 3.0 & 9459.42 \pm 0.53 \pm 1.02 & 18.2 \sigma \\
h_b(1P) & 50.4 \pm 7.8^{+4.5}_{-9.1} & 9898.25 \pm 1.06^{+1.03}_{-1.07} & 6.2 \sigma \\
3S \to 1S & 55 \pm 19 & 9973.01 & 2.9 \sigma \\
\Upsilon(2S) & 143.4 \pm 8.7 \pm 6.8 & 10022.25 \pm 0.41 \pm 1.01 & 16.6 \sigma \\
\Upsilon(1D) & 22.1 \pm 7.8 & 10166.2 \pm 2.4 & 2.4 \sigma \\
h_b(2P) & 84.4 \pm 6.8^{+23.7}_{-10.2} & 10259.76 \pm 0.64^{+1.43}_{-1.03} & 12.4 \sigma \\
\hline
\end{array}
\]
Results for $h_b$ and $h_b(2P)$

- $M(h_b(1P)) = 9898.25 \pm 1.06 \pm \frac{1.03}{1.07}$ MeV
- $M(h_b(2P)) = 10259.76 \pm 0.64 \pm \frac{1.43}{1.03}$ MeV

- Deviations from centre-of-gravity of $\chi_{bJ}$ masses is consistent with zero, as expected

- Why are these not $\chi_{b1}(nP)$?
  - The strong decay $\Upsilon(5S) \rightarrow \chi_{b1}(nP)\pi^+\pi^-$ would violate isospin conservation
  - The masses are significantly different:
    \[
    \Delta M(1P) = -5.47 \pm 1.56 \quad (3.5\sigma) \\
    \Delta M(2P) = -4.30 \pm 1.35 \quad (3.2\sigma) 
    \]

$\Rightarrow$ observed states are $h_b(nP)$
Summary

• New precise measurements of masses and widths of $\eta_c$ and $\eta_c(2S)$ with interference effects included in fits.

• Nature of the $X(3872)$, the first observed exotic state, remains unclear; $X(3872) \rightarrow \omega J/\psi$ confirmed

• No $c\bar{c}$ states observed in $\Upsilon(1S)$ radiative decays

• The $h_b(1P)$ and $h_b(2P)$ have been seen with no suppression of production rate for the spin-flip modes

B factories have made surprising studies of new states in charmonia / bottomonia, but more studies and more data are needed to reveal their true nature.