SELECTED SPECTROSCOPY RESULTS FROM THE BABAR EXPERIMENT

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J-Lab

Theory Seminar, March 7, 2012
OUTLINE

I. The BaBar Experiment

II. Selected Baryon Spectroscopy Results

III. Selected Meson Spectroscopy Results

IV. Summary
Bunches are accelerated in the SLAC Linear Accelerator and injected into the storage rings in order to collide at the BaBar detector.
Instrumented Flux Return for muon and neutral hadron identification

Electromagnetic calorimeter: 6580 CsI crystals in ~projective geometry

Charged particle ID by means of velocity measurement

Angles and positions of charged tracks just outside the beam pipe

DCH

Charged tracks momentum dE/dx for PID

9.03 GeV [Y(4S)]
8.65 GeV [Y(3S)]
8.10 GeV [Y(2S)]
BaBar integrated luminosity since startup

BaBar Run 1-7

As of 2008/04/11 00:00

PEP II Delivered Luminosity: 553.48/ff
BaBar Recorded Luminosity: 531.43/ff
BaBar Recorded Y(4s): 432.89/ff
BaBar Recorded Y(3s): 30.23/ff
BaBar Recorded Y(2s): 14.45/ff
Off Peak Luminosity: 53.85/ff
# Largest Y(nS) Data Sets

<table>
<thead>
<tr>
<th>Samples</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
<th>$\Upsilon(4S)$</th>
<th>$\Upsilon(5S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td></td>
<td>14 fb$^{-1}$</td>
<td>30 fb$^{-1}$</td>
<td>433 fb$^{-1}$</td>
<td>3.2 fb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(scan)</td>
</tr>
<tr>
<td>Belle</td>
<td>6 fb$^{-1}$</td>
<td>24 fb$^{-1}$</td>
<td>3 fb$^{-1}$</td>
<td>711 fb$^{-1}$</td>
<td>121 fb$^{-1}$</td>
</tr>
</tbody>
</table>

**e$^+e^-$ Cross Section Scan**

Precision scan in $E_{cm}$ from 10.54 GeV to 11.20 GeV
- 5 MeV steps with 25 fb$^{-1}$ at each step ($\int L \approx 3.3$ fb$^{-1}$)
- 8 steps at $\Upsilon(6S)$ ($\int L \approx 0.6$ fb$^{-1}$)

Interesting new results

PRL 102, 012001 (2009)
BaBar as a Charm Baryon Factory

Present data sample contains:

- $> 450 \text{ M } Y(4S) \rightarrow B\bar{B}$ events ($\sigma = 1.05 \text{ nb}$)
- $> 1600 \text{ M } e^+e^- \rightarrow q\bar{q}$ events ($\sigma = 3.39 \text{ nb}$)
- $> 610 \text{ M } e^+e^- \rightarrow c\bar{c}$ events ($\sigma = 1.30 \text{ nb}$)

Provides access to rare decay modes & High precision studies of charm baryon properties ...
Charm Baryon Spectroscopy

Observation of new decay modes

First observation of charm baryon to charm meson decay

Evidence for new states
Charm Baryon to Charm Meson Decay

- Observation of two states decaying to $D^0 p$
  - previously observed $\Lambda_c(2880)^+ \ (in \ \Lambda_c \ \pi^+ \ \pi^-) \ [Q \sim 317 \text{ MeV/c}^2$]
  - BaBar measurements from $D^0 p \ [Q \sim 79 \text{ MeV/c}^2 \rightarrow \text{much greater precision}]$:
    \[
    M = 2881.9 \pm 0.1 \text{(stat)} \pm 0.5 \text{(syst)} \text{ MeV/c}^2 \\
    \Gamma = 5.8 \pm 1.5 \text{(stat)} \pm 1.1 \text{(syst)} \text{ MeV} \quad [\text{First measurement}]
    \]
  - new state:
    \[
    M = 2939.8 \pm 1.3 \text{(stat)} \pm 1.0 \text{(syst)} \text{ MeV/c}^2 \\
    \Gamma = 17.5 \pm 5.2 \text{(stat)} \pm 5.9 \text{(syst)} \text{ MeV}
    \]
    First observation of a charm baryon decaying to a charm meson

- No evidence in $D^+ p$ of doubly charged partners
  - Signals correspond to observation of excited $\Lambda_c$ states, not $\Sigma_c$ states

\[
\begin{align*}
\text{PRL 98, 012001 (2007)}
\end{align*}
\]
The Search for *charm* Cascades Decaying to \( \Lambda_c^+K^-(K_S)\pi^+(-) \) and \( \Lambda_c^+K^-(K_S)\pi^-\pi^+ \) Final States

- Confirmation of the existence of the \( \Xi_c(2980)^+, \Xi_c(3077)^+ \) and \( \Xi_c(3077)^0 \)
- Evidence for the \( \Xi_c(3055)^+ \) and \( \Xi_c(3123)^+ \)
  \( \Rightarrow \) natural widths consistent with strongly decaying states

Excited Cascade charm baryons
\( \Xi_c'^(*) \) observed to decay to G.S.
\( \Xi_c \) by pion or photon emission

The \( \Xi_c(2980)^+,0 \) and \( \Xi_c(3077)^+,0 \) seen in decays in which the \( s \) and \( c \) quark are in separate hadrons
\( \Rightarrow \) implications for the internal quark interactions inside these states

- predicted excited charm baryons with \( J^P = 1/2^\pm, 3/2^\pm \)
  - \( J^P = 5/2^+ \)
  - radial excitations

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Results on excited charm Cascades
decaying to $\Lambda_c^+ K \pi$

Mode

$\Lambda_c^+ \rightarrow p K^- \pi^+$
$\Lambda_c^+ \rightarrow p K_S^0$
$\Lambda_c^+ \rightarrow p K_S^0 \pi^+ \pi^-$
$\Lambda_c^+ \rightarrow \Lambda \pi^+$
$\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^- \pi^+$

• Fit to two-dimensional invariant mass
distribution $M(\Lambda_c^+ K^- \pi^+)$ versus $M(\Lambda_c^+ \pi^+)$
  ➢ incorporate intermediate resonances $\Sigma_c(2520)^{++}$ and $\Sigma_c(2455)^{++}$ in the fit
  ➢ show the $M(\Lambda_c^+ K^- \pi^+)$ distribution for $M(\Lambda_c^+ \pi^+)$ ranges w/in 3-$\sigma$ of the $\Sigma_c(2455)^{++}$
  and 2-$\sigma$ of the $\Sigma_c(2520)^{++}$
Results on excited charm Cascades decaying to $\Lambda_c^+ K \pi$

Very close to threshold $\Rightarrow$ very important to take account of phase space

<table>
<thead>
<tr>
<th></th>
<th>$\Xi_c(2980)^+$</th>
<th>$\Xi_c(2980)^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c^2)</td>
<td>2969.3 ± 2.2 ± 1.7</td>
<td>2972.9 ± 4.4 ± 1.6</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>27 ± 8 ± 2</td>
<td>31 ± 7 ± 8</td>
</tr>
<tr>
<td>Yield</td>
<td>756 ± 178 ± 104</td>
<td>67 ± 33 ± 29</td>
</tr>
<tr>
<td>Resonant (%)</td>
<td>55 ± 7 ± 13</td>
<td>1.7σ</td>
</tr>
<tr>
<td>Significance</td>
<td>&gt;9.0σ</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>$\Xi_c(3077)^+$</th>
<th>$\Xi_c(3077)^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c^2)</td>
<td>3077.0 ± 0.4 ± 0.2</td>
<td>3079.3 ± 1.1 ± 0.2</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>5.5 ± 1.3 ± 0.6</td>
<td>5.9 ± 2.3 ± 1.5</td>
</tr>
<tr>
<td>Yield</td>
<td>403 ± 54 ± 27</td>
<td>90 ± 22 ± 15</td>
</tr>
<tr>
<td>Resonant (%)</td>
<td>&gt;80</td>
<td>78 ± 21 ± 5</td>
</tr>
<tr>
<td>$\Sigma_c(2455)$ (%)</td>
<td>45 ± 5 ± 5</td>
<td>44 ± 12 ± 7</td>
</tr>
<tr>
<td>Significance</td>
<td>&gt;9.0σ</td>
<td>4.5σ</td>
</tr>
</tbody>
</table>

<table>
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<th>$\Xi_c(3055)^+$</th>
<th>$\Xi_c(3123)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c^2)</td>
<td>3054.2 ± 1.2 ± 0.5</td>
<td>3122.9 ± 1.3 ± 0.3</td>
</tr>
<tr>
<td>Width (MeV)</td>
<td>17 ± 6 ± 11</td>
<td>4.4 ± 3.4 ± 1.7</td>
</tr>
<tr>
<td>Yield</td>
<td>218 ± 53 ± 79</td>
<td>101 ± 34 ± 9</td>
</tr>
<tr>
<td>Significance</td>
<td>6.4σ</td>
<td>3.6σ (3.0σ)</td>
</tr>
</tbody>
</table>

- Similar results for $M(\Lambda_c^+ K_S \pi^+)$ versus $M(\Lambda_c^+ \pi^+)$ although more statistically limited
- No evidence for structure in $(\Lambda_c^+ K_S \pi^+ \pi^+)$ nor $(\Lambda_c^+ K^- \pi^+ \pi^+)$
- No evidence for $\Xi_{cc}$ seen by SELEX in $\Lambda_c^+ K^- \pi^+ (\pi^+)$
The Search for the $\Omega_c^*$ ($J^P=3/2^+$)

- All $L=0$ singly-charm baryons discovered, $J^P=3/2^+$ $\Omega_c^* (css)$ state missing
- Splitting $M(\Omega_c^*) - M(\Omega_c)$ predictions range from $\sim 70 - 100$ MeV/c$^2$
- Search for $\Omega_c^*$ in $e^+e^- \rightarrow \Omega_c^* X$ processes

\[ \begin{align*}
\Omega_c^0 & \rightarrow \Omega^- \pi^+, \ \Omega^- \rightarrow \Lambda K^- \\
\Omega_c^0 & \rightarrow \Omega^- \pi^+ \pi^0, \ \Omega^- \rightarrow \Lambda K^- \\
\Omega_c^0 & \rightarrow \Omega^- \pi^+ \pi^- \pi^+, \ \Omega^- \rightarrow \Lambda K^- \\
\Omega_c^0 & \rightarrow \Xi^- K^- \pi^+ \pi^+, \ \Xi^- \rightarrow \Lambda \pi^-
\end{align*} \]
Observation of $\Omega_c^* \rightarrow \Omega_c^0 \gamma$

- Splitting $M(\Omega_c^*) - M(\Omega_c^0) = 70.8 \pm 1.0\,(stat) \pm 1.1\,(syst)\,\text{MeV}/c^2$
  - consistent with pQCD predictions
  - $M(\Omega_c^*) = 2768.3 \pm 3.0\,\text{MeV}/c^2$

- Ratio of the inclusive production cross sections
  $$R = \frac{\sigma(e^+e^- \rightarrow \Omega_c^*X, x_p (\Omega_c^* > 0.5))}{\sigma(e^+e^- \rightarrow \Omega_c^0X, x_p (\Omega_c^0 > 0.5))} = 1.01 \pm 0.23\,(stat) \pm 0.11\,(syst)$$
Charm Baryon Spectroscopy

Insight into Light Baryon Spectroscopy

Study of Cascade baryons
Relevance of Cascades to Baryon Spectroscopy

- Quark content (u or d, s, s)
  - QCD calculations easier to handle
  - Developments in fast algorithms raised expectations from Lattice QCD

- Narrow widths
  - reduces potential overlap with neighboring states

- Predictions of mass, width, spin/parity rely on model-based calculations
  - Experimental validations are essential
  - Very little known about Ξ states which might populate the [70, 1]_1 and [56, 2^+]_2 of SU(6) × O(3)
  - Properties of Ξ(1690) are crucial:
    - first excited state not used as input in predictions
Cascade Physics from Charm
Baryon Decay
Spin measurement of $\Omega^-$ from $\Xi_c^0 \to \Omega^- K^+, \Omega^- \to \Lambda K^-$ decays

Helicity Formalism

- Examine implications of $\Omega$ spin hypotheses for angular distribution of $\Lambda$ from $\Omega$ decay

- Initial helicity, $\lambda_i = \lambda(\Omega) = \pm 1/2$
- Final state helicity, $\lambda_f = \lambda(\Lambda) - \lambda(\text{pseudoscalar}) = \pm 1/2$
- Decay amplitude for $\Omega^- \to \Lambda K^-$: $A_{\lambda_i \lambda_f}^J = D_{\lambda_i \lambda_f}^{J*} (\phi, \theta, 0) A_{\lambda_f}$

$$I \propto \frac{1}{2} \sum_{\lambda_i, \lambda_f} \rho_{\lambda_i} |A_{\lambda_i \lambda_f}^J|^2 = \frac{1}{2} \sum_{\lambda_i, \lambda_f} \rho_{\lambda_i} |D_{\lambda_i \lambda_f}^{J*} (\phi, \theta, 0) A_{\lambda_f}|^2$$

[density matrix element for $\Omega$ spin projection $\lambda_i$ = density matrix element for charm baryon parent]

$\Omega^- \to \Lambda K^+$ quantization axis

-$\Omega^- \to \Lambda K^+$ spin projection $\pm 1/2$ only
-$\Lambda$ decay angular distr' different for each assumed spin, $J$

Background-Subtracted Efficiency-Corrected

$\sim 116$ fb$^{-1}$

$\cos \theta(\Lambda)$

- $J_\Omega = 1/2$  $\Rightarrow I \propto 1$  $\Rightarrow$ Fit Prob = $10^{-17}$
- $J_\Omega = 3/2$  $\Rightarrow I \propto (1 + 3 \cos^2 \theta)$  $\Rightarrow$ Fit Prob = $0.64$
- $J_\Omega = 5/2$  $\Rightarrow I \propto (1 - 2 \cos^2 \theta + 5 \cos^4 \theta)$  $\Rightarrow$ Fit Prob = $10^{-7}$

$J_\Omega \geq 7/2$ also excluded: angular distribution increases more steeply near $\cos \theta \sim \pm 1$ and has (2 $J_\Omega - 2$) turning points.
The $\Xi(1530)^0$ From $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ Decay
Reconstructed $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$, $\Xi^- \rightarrow \Lambda \pi^-$ Events

- Uncorrected $N \sim 13800$ events
- HWHM $\sim 6$ MeV/c²
- $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$
- $\Xi^- (1530)^0 \rightarrow \Xi^- \pi^+$

- PID Information
  - Proton
  - Kaon
  - $\pi^+$, $\pi^-$
  - dE/dx & Cherenkov info (DIRC)

- 3-σ mass cut on intermediate states
- Intermediates $m$ mass-constrained $[\Lambda, \Xi]$
- $p^* > 2.0$ GeV/c [reduces background]
- $L_\Lambda > 2.0$ mm $r_\Xi > +1.5$ mm [outgoing]

- $m(\Xi^- \pi^+) \leftrightarrow \Lambda_c^+$ mass-signal region
- $m(\Xi^- \pi^+) \leftrightarrow \Lambda_c^+$ mass-sideband region
- $m(\Xi^- \pi^+) \leftrightarrow (\Lambda_c^+)$ mass-sideband-subtracted

- PDG mass
Resonant Structures in the $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ Signal Region

Only **obvious** structure:

$\Xi(1530)^0 \rightarrow \Xi^- \pi^+$

**Note:** $m^2(\Xi^- K^+)$ depends linearly on $\cos\theta_\Xi$
Using Legendre Polynomial Moments to Obtain $\Xi(1530)$ Spin Information

Spin 3/2 Test

- $P_L$ moments ($L \geq 6$) give no signal

$\Rightarrow$ spin 3/2 clearly established

$\Rightarrow$ spin 5/2 ruled out

Schlein et al. showed $J^P = 3/2^+$ or $J^P = 5/2^-$, and claimed $J > 3/2$ not required.


“Spin-parity 3/2$^+$ is favored by the data” [PDG (2006)]

- Present analysis by establishing $J=3/2$ also establishes positive parity by implication [i.e. P-wave resonance]

• Other interesting aspects of Dalitz plot – not as simple as it first appears!
The $\Xi(1690)^0$ From $\Lambda_c^+ \rightarrow \Lambda \bar{K}^0 K^+$ Decay
Reconstructed $\Lambda_c^+ \rightarrow \Lambda K_S K^+$ Events

Selection Criteria:

- PID Information
  - Proton
  - Kaon
  - $\pi^+$, $\pi^-$

- 3-$\sigma$ mass cut on intermediate states

- interm$^d$. states mass-constrained [$\Lambda$, $K_S$]

- $p^*(\Lambda_c^+) > 1.5$ GeV/c (reduces background)

- $L_\Lambda$, $L_{K_S} > +2.0$, +1.0 mm [sign ⇒ outgoing].
The $\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda K_S) K^+$ Decay

$\Delta c^+ K_S$ mass-signal region

$\Delta c^+ K_S$ mass-sideband region

$\Delta c^+ (\Lambda K_S)$ mass-sideband-subtracted

- $N \sim 2900$ events
- HWHM $\sim (3.1 \pm 0.5)$ MeV/c

Note skewing
Using Legendre Polynomial Moments to Obtain $\Xi(1690)$ Spin Information

- Efficiency-corrected, background-subtracted unweighted $m(\Lambda K_S)$ distribution in data

$\Xi(1690)^0 \rightarrow$

$w_j = \sqrt{10} \, P_2(\cos\theta)$ from $\Lambda_c^+$ signal region

Spin 3/2 Test

$\Xi(1690) = 1/2$

Suggest $J(\Xi(1690)) = 1/2$

Efficiency-corrected, bckgr. subtracted dist. in data for $1.665 < m(\Lambda K_S) < 1.705$ GeV/c$^2$

Efficiency-corrected $P_4$ Moment Dist.

Spin 5/2 Test

...however $\cos\theta_\Lambda$ clearly not flat as expected for $J = 1/2$

WHY?
Dalitz plot for $\Lambda_c^+ \rightarrow \Lambda K_SK^+$

Accumulation of events in $K_SK^+$ near threshold ⊳ evidence of $a_0(980)^+$

\[ m = 1682.9 \pm 0.9 \text{(stat)} \pm 0.8 \text{(syst)} \text{ MeV/c}^2 \]
\[ \Gamma = 9.3^{+2.0}_{-1.7} \text{(stat)} \pm 0.4 \text{(syst)} \text{ MeV} \]
\[ J = 1/2 \text{ favored} \]

- Background-subtracted, efficiency-corrected data
- Integrated signal function smeared by mass resolution [Histogram]
- Signal function with no resolution smearing
- $|A(a_0(980)|^2$ contribution
- $|A(\Xi(1690)|^2$ contribution
- Interference term contribution

For $J(\Xi(1690)) = 1/2$
Evidence for the $\Xi(1690)$ in $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$


S-P interference – dip at 1690 MeV/c

Speculation:
Dip ($\sim 1680$ MeV/$c^2$) may be due to resonant $\Xi(1690)^0$ S-wave

$\Rightarrow$ negative parity for $\Xi(1690)$

Implications for Lattice calculations and models of level structure of $\Xi$ excited states
Remarks

• Lots of progress in charm baryon spectroscopy
• Insight into charm baryon production
• Measurements of charm baryon spin from exclusive B decay processes
• Insight into light quark spectroscopy from hyperon resonances produced in charm baryon decay
Possible Similar $\Xi$ Studies in Photoproduction

- **Exclusive t-channel** (i.e. meson exchange) Processes
  - Production of two-body systems with a $\Xi$
    - e.g. $\gamma p \rightarrow K^+ (\Xi^- K^+)$
    - $\rightarrow K^+ (\Xi^0 K^0)$
    - $\rightarrow K^0 (\Xi^0 K^+)$

  would enable the study of high mass $\Lambda^*$ and $\Sigma^*$ states decaying via these $\Xi$ modes.
Possible Similar $\Xi$ Studies in Photoproduction (ctd.)

- Production of three-body systems with a $\Xi$, or a $\Xi^*$ system with two-body decay:

  with a forward $K^0$:

  e.g. $\gamma p \rightarrow K^0 (\Xi^- \pi^+) K^+, K^0 (\Xi^0 \pi^0) K^+, K^0 (\Xi^0 K^0)$

  - can observe in a totally different context

  with a forward $K^+$:

  e.g. $\gamma p \rightarrow K^+ (\Xi^- \pi^+) K^0, K^+ (\Xi^- \pi^0) K^+$
  $\rightarrow K^+ (\Xi^0 \pi^-) K^+, K^+ (\Xi^0 \pi^0) K^0$
  $\rightarrow K^+ (\Lambda K^-) K^+$

- Interesting four-body possibilities when add pion

  e.g. $\gamma p \rightarrow K^+ (\Lambda K^- \pi^+) K^+$,

  - accessible at BaBar via $\Xi_c^0 \rightarrow \Lambda K^- \pi^+$, complicated Dalitz plot
Quarkonium Spectroscopy

Insight into Bottomonium Spectroscopy

Searches for missing states
Radiative bottomonium transitions from $Y(3S)$ events using $\gamma \rightarrow e^+e^-$ conversions

Significantly improves energy resolution [see later]

$\rightarrow$ Precise BF Measurements

Efficiency $\sim (0.1 - 1)\%$
Inclusive photon energy regions for Y(3S) events

\[ E_\gamma^{(i)} = \frac{m_i^2 - m_f^2}{2m_i} \in [207, 243] \text{ MeV} \]

- Resolution dominated
- Small Doppler broadening

<table>
<thead>
<tr>
<th>Transition</th>
<th>( E_\gamma^{(i)} ) (MeV)</th>
<th>Yield</th>
<th>( \epsilon ) (%)</th>
<th>Derived Branching Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi_{b0}(2P) \rightarrow \gamma Y(2S) )</td>
<td>205.0</td>
<td>(-347 \pm 209)</td>
<td>0.105</td>
<td>(-4.9 \pm 2.9) ((&lt; 2.9))</td>
</tr>
<tr>
<td>( \chi_{b1}(2P) \rightarrow \gamma Y(2S) )</td>
<td>229.7</td>
<td>(4294 \pm 251)</td>
<td>0.152</td>
<td>(19.5 \pm 1.1)</td>
</tr>
<tr>
<td>( \chi_{b2}(2P) \rightarrow \gamma Y(2S) )</td>
<td>242.3</td>
<td>(2462 \pm 243)</td>
<td>0.190</td>
<td>(8.6 \pm 0.9)</td>
</tr>
</tbody>
</table>
Inclusive photon energy regions for Y(3S) events

\[ E_\gamma^{(i)} = \frac{m_i^2 - m_j^2}{2m_i} \in [430, 484] \text{ MeV} \]

\[ E_\gamma^{(i)} = \frac{m_i^2 - m_j^2}{2m_i} \in [391, 442] \text{ MeV} \]

<table>
<thead>
<tr>
<th>Transition</th>
<th>( E_\gamma^* ) (MeV)</th>
<th>Yield ( \epsilon ) (%)</th>
<th>Derived Branching Frac ( \text{BABAR} ) ( \times 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y(3S) \rightarrow \gamma \chi_{b2}(1P) )</td>
<td>433.1</td>
<td>9699 ± 318</td>
<td>0.794</td>
</tr>
<tr>
<td>( Y(3S) \rightarrow \gamma \chi_{b1}(1P) )</td>
<td>452.2</td>
<td>483 ± 315</td>
<td>0.818</td>
</tr>
<tr>
<td>( Y(3S) \rightarrow \gamma \chi_{b0}(1P) )</td>
<td>483.5</td>
<td>2273 ± 307</td>
<td>0.730</td>
</tr>
</tbody>
</table>

from Y(3S) to Y(1S)
Inclusive photon energy regions for $Y(3S)$ events

Search for the Bottomonium Ground State $\eta_b(1S)$

$\eta_b(1S)$ observed in inclusive $\gamma$ spectrum

$Y(3S) \rightarrow \gamma \eta_b(1S)$ photons from calorimeter

With converted photons $\eta_b$ significance $< 3\sigma$
The BaBar Observation of the $\eta_b$

- $\chi_{bJ}$ Peak Yield: $821841 \pm 2223$
- $\gamma_{\text{ISR}}$ Y(1S) Yield: 25153 (fixed)
- $\eta_b$ Yield: $19152 \pm 2010$

- $R(\text{ISR}/\chi_{bJ}) \sim 1/33$
- $R(\eta_b/\chi_{bJ}) \sim 1/43$

19152 ± 2010 events

All backgrounds subtracted
Comparison of $E_\gamma$ Spectra for $Y(3S)$ and $Y(2S)$ Events

Results from $Y(2S)$ and $Y(3S)$ analyses are consistent!
BF measurements:

\[ B(\Upsilon(3S) \rightarrow \Upsilon \eta_b(1S)) = (5.1 \pm 0.7) \times 10^{-4} \]

\[ B(\Upsilon(2S) \rightarrow \Upsilon \eta_b(1S)) = (3.9 \pm 1.5) \times 10^{-4} \]

Compatible with predictions

Combined values of mass and HF splitting:

- \( m_{\eta_b(1S)} = 9390.9 \pm 2.8 \) MeV/c\(^2\) \( \Gamma_{\eta_b(1S)} \approx 10 \) MeV
- \( (m_{\Upsilon(1S)} - m_{\eta_b(1S)}) = 69.3 \pm 2.8 \) MeV/c\(^2\)

Unquenched lattice QCD calculations (~50-60 MeV/c\(^2\)) agree better than NRQCD predictions (~40 MeV/c\(^2\))

Tension with Belle measurement in \( \Upsilon(5S) \rightarrow \pi \pi \ h_b(1P) \rightarrow \Upsilon \eta_b(1S) \):

\( (m_{\Upsilon(1S)} - m_{\eta_b(1S)}) = 59.3 \pm 1.9^{+2.4}_{-1.4} \) MeV/c\(^2\)
Searches for the $h_b(1P)$ State of Bottomonium at BaBar

- Essential to measure the hyperfine mass splitting for $P$-wave states to understand the spin dependence of $qq\bar{q}$ potentials for heavy quarks.

- Hyperfine splitting between $h_b(1P)$ mass & spin-weighted center of gravity of the $\chi_{bJ}(1P)$ states ($9899.87\pm0.27$ MeV/$c^2$) expected to be $\sim0$ [confirmed for $h_c$].

- Hyperfine mass splitting larger than 1 MeV/$c^2$ might be indicative of a vector component in the confinement potential.

- BaBar searched for the $h_b(1P)$ meson in the transitions:
  - $Y(3S)\to\pi^+\pi^- h_b(1P)$
  - $Y(3S)\to\pi^0 h_b(1P)$ (requiring a photon consistent with subsequent $h_b\to\gamma \eta_b(1S)$ decay)
Expected Mass of the $h_b(1P)$ State

Hyperfine splitting for $L=1$ states $\Delta M_{HF}(nL) = \left\langle M(n^3L_J) \right\rangle - M(n^1L_J=L) \sim 0$

\[ \frac{\sum_j (2J+1)M_j / \sum_j (2J+1)}{M(1^1P_1) \sim \left( M(1^3P_0) + 3M(1^3P_1) + 5M(1^3P_2) \right) / 9} = 9899.87 \pm 0.27 \text{ MeV/c}^2 \]

Search for a peak in invariant mass of system recoiling against $\pi^+\pi^-$ or $\pi^0$

\[ m_{\text{recoil}}(X) \equiv \sqrt{(E_{Y(3S)}^* - E_X^*)^2 - (p_X^*)^2} \]
Search for the $h_b(1P)$ in the decay $Y(3S) \rightarrow \pi^+\pi^-h_b$

**Background-subtracted result:**

- No $h_b$ observation: $-1106 \pm 2432$ (stat.) signal events (mass fixed at 9.9 GeV/c$^2$)
- $\text{BF}(Y(3S) \rightarrow \pi^+\pi^-h_b) < 1.0 \times 10^{-4}$ (@90% C.L.)
  -- suppressed by a factor $>3$ compared to $\pi^0$ mode (see later)
- First separate observation of $\chi_{b1,2}(2P) \rightarrow \pi^+\pi^- \chi_{b1,2}(1P)$ transitions and BF measurements:
  - $\text{BF}(\chi_{b1}(2P) \rightarrow \pi^+\pi^- \chi_{b1,2}(1P)) = (9.2 \pm 0.6 \pm 0.9) \times 10^{-3}$
  - $\text{BF}(\chi_{b2}(2P) \rightarrow \pi^+\pi^- \chi_{b1,2}(1P)) = (4.9 \pm 0.4 \pm 0.6) \times 10^{-3}$
Evidence for the $h_b(1P)$ in the decay $Y(3S) \rightarrow \pi^0 h_b$

- $10814 \pm 2813$ signal events
- $M(h_b) = 9902 \pm 4 \pm 2$ MeV/$c^2$ (C.G. = 9899.87 $\pm$ 0.27 MeV/$c^2$)
- Stat. Signif. = 3.8$\sigma$ ($\sqrt{\Delta \chi^2}$); including systematic errors = 3.3$\sigma$
- $B(Y(3S) \rightarrow \pi^0 h_b(1P)) = (4.1 \pm 1.1 \pm 0.9) \times 10^{-4}$
  $< 6.1 \times 10^{-4}$ (@ 90% CL)
- Existence subsequently confirmed by Belle in $Y(5S) \rightarrow \pi^+ \pi^- h_b(1P)$ [arXiv:1103.3419 ($^*$)] with combinatorial bkg. 2X BaBar Y(3S) search — also observe $h_b(2P)$

($^*$) La Thuille 2011

• $\chi^2$ fit of $m_{recoil}(\pi^0)$ distribution:
  - $h_b(1P)$ signal: Double Crystal Ball function
  - Background: 5th order polynomial
    - Parameters determined with $h_b$ signal region excluded (i.e. blind analysis strategy)

Phys.Rev. D84, 091101(2011)
Confirmation of the existence of the $h_b(1P)$ by Belle in $e^+e^{-}\rightarrow\pi^+\pi^-$ transitions at the $Y(5S)$

Observation of the $h_b(1P)$ and $h_b(2P)$ states

- Measured $h_b(1,2P)$ mass values consistent with predictions
- Observed $h_b$ production rate enhancement may be indicative of exotic process violating HQ spin-flip suppression
- Resonant structures in $h_b(1P, 2P)\pi$ seen in $Y(5S)\rightarrow h_b(1P, 2P)\pi^+\pi^-$ events (also in $Y(5S)\rightarrow Y(nS)\pi^+\pi^-$)

$\Rightarrow$ charged exotic candidates $Z_{b1}$, $Z_{b2}$

<table>
<thead>
<tr>
<th>State</th>
<th>Yield, $10^3$</th>
<th>Mass, MeV/c$^2$</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(1S)$</td>
<td>105.2 ± 5.8</td>
<td>9459.42 ± 0.53</td>
<td>18.2 $\sigma$</td>
</tr>
<tr>
<td>$h_b(1P)$</td>
<td>50.4 ± 7.8</td>
<td>9898.25 ± 1.06</td>
<td>6.2 $\sigma$</td>
</tr>
<tr>
<td>$3S \rightarrow 1S$</td>
<td>55 ± 19</td>
<td>9973.01</td>
<td>2.9 $\sigma$</td>
</tr>
<tr>
<td>$\Upsilon(2S)$</td>
<td>143.4 ± 8.7</td>
<td>10022.25 ± 0.41</td>
<td>16.6 $\sigma$</td>
</tr>
<tr>
<td>$\Upsilon(1D)$</td>
<td>22.1 ± 7.8</td>
<td>10166.2 ± 2.4</td>
<td>2.4 $\sigma$</td>
</tr>
<tr>
<td>$h_b(2P)$</td>
<td>84.4 ± 6.8</td>
<td>10259.76 ± 0.64</td>
<td>12.4 $\sigma$</td>
</tr>
<tr>
<td>$2S \rightarrow 1S$</td>
<td>151.6 ± 9.7</td>
<td>10304.57 ± 0.61</td>
<td>15.7 $\sigma$</td>
</tr>
<tr>
<td>$\Upsilon(3S)$</td>
<td>44.9 ± 5.1</td>
<td>10356.56 ± 0.87</td>
<td>8.5 $\sigma$</td>
</tr>
</tbody>
</table>

\[\Rightarrow\text{Consistent with BaBar measmt.}\]
2011 Picture of the Bottomonium Spectrum

- $b\bar{b}$ states below $Y(3S)$ not yet discovered: 2 S-wave ($\eta_b(2S,3S)$), 3 D-wave & possibly 4 F-wave.
- Recently discovered states including the $h_b(1P)$ and $h_b(2P)$ states

\[ J^{PC} = \begin{array}{c}
0^+ \\
1^-
\end{array} \]

$\eta_b(1S)$

\[ \chi_b(2P) \]

\[ \chi_{b1}(2P) \]

\[ \chi_{b2}(2P) \]

\[ \chi_{b0}(1P) \]

\[ h_b(1P) \]

\[ h_b(2P) \]

\[ \gamma \]

$\eta_b(2S)$

$\eta_b(3S)$

$Y(1S)$

$Y(2S)$

$Y(3S)$

$Y(4S)$

$Y(5S)$

$Y(6S)$

$\eta_b(2S)$

$\eta_b(3S)$

$nL$ where $n$ is the principal quantum number and $L$ indicates the $b\bar{b}$ angular momentum in spectroscopic notation ($L=S, P, D,...$)

$BB$ threshold

[Orbital Ang. Momentum between quarks]
Quarkonium Spectroscopy

Insight into Charmonium Spectroscopy

Evidence for unconventional states
Charmonium properties were well understood up to $\psi (3770)$ (i.e. about the $D\bar{D}$ threshold) with some missing pieces (like the $\eta_c(2S)$).

- No new $c\bar{c}$ states were discovered between 1980 and 2002.
- $c\bar{c}$ states above open charm threshold are expected to have significant width values and to decay mainly to open charm Channels.

Contributions of B factories to charmonium spectroscopy...
In a few years the situation changed rapidly

There were discoveries of new charmonium states like the $h_c(1P)$, $\eta_c(2S)$ and $\chi_{c2}(2P)$

And several new “charmonium-like” states

Charmonium production mechanisms at the B-factories

B → c\bar{c} K(*) decay

States of any Quantum Number can be formed

Two-photon collision

C = +, J^P = 0^\pm, 2^\pm, ...

Initial state radiation

Recoil against J/ψ → C = +

Double charmonium production

J^{PC} = 1⁻⁻
Some *Unconventional* States

**B → c\bar{c} K(*) decay**

- **X(3872)**
  - Narrow state above \( \bar{D}D \) threshold
  - First Observed by Belle in \( J/\psi \pi \pi \)
  - Confirmed by BaBar, CDF, D0, LHCb
  - **Measured width much smaller than that expected for a conventional charmonium state**
  - Seen in \( J/\psi \gamma, \psi(2S) \gamma \) decay \( \rightarrow C=+ \)
  - Angular analyses inconclusive: \( J^P = 1^+, \text{ OR } 2^- \)
Some Unconventional States

$$B \rightarrow c\bar{c} K(*)$$ decay

- $X(3872)$
- $Y(3940)$
- $Z(4430)^-$
- $Z_1(4050)^-$
- $Z_2(4250)^-$
- $Y(4140)$

A state $Z^- \rightarrow \psi' \pi^-$ would have hidden charm & charge ☞ candidate for $\bar{c}c\bar{u}d$ tetraquark
Some Unconventional States

B → c ¯c K(*) decay

- X(3872)
- Y(3940)
- Z(4430) -
- Z_1(4050) -
- Z_2(4250) -
- Y(4140)

Initial state radiation

- Y(4260)
- Y(4008)
- Y(4350)
- Y(4660)

J^{PC} = 1--

Two-photon collision

- C = +, J^P = 0^±, 2^±,...
- Z(3930) (?=\chi_{c2}(2P))
- Y(3915)

Double charmonium production

- X(3940)

Recoil against

J/ψ → C = +
## Topics not covered today

<table>
<thead>
<tr>
<th>State</th>
<th>$m$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (mode)</th>
<th>Experiment (#σ)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(2S)$</td>
<td>3537 ± 4</td>
<td>14±7</td>
<td>0−−</td>
<td>$B \to K(K^0\phi^−)$</td>
<td>Belle [49] (6.0)</td>
<td>2002</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>$e^+e^- \to e^+e^−(K^0\phi^−)$</td>
<td>BABar [50] (4.9), CLEO [51] (6.5),</td>
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<td></td>
<td></td>
<td></td>
<td>Belle [52] (6)</td>
<td></td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>3871.52±0.20</td>
<td>1.3±0.6</td>
<td>1++/2−+ (&lt;2.2)</td>
<td>$p\bar{p} \to (\pi^+\pi^-J/\psi) + \ldots$</td>
<td>CDF [88-90] (np), DØ [91] (5.2)</td>
<td>2003</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>$B \to K(\omega/\psi)$</td>
<td>Belle [92] (4.3), BABar [93] (4.0)</td>
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<td></td>
<td>$B \to K(D^*0D^0)$</td>
<td>Belle [34, 95] (8.4), BABar [66] (4.9)</td>
<td></td>
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<tr>
<td>$X(3915)$</td>
<td>3915.6 ± 3.1</td>
<td>28±10</td>
<td>0/2++</td>
<td>$B \to K(\omega/\psi)$</td>
<td>Belle [100] (5.1), BABar [101] (19)</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \to e^+e^−(\omega/\psi)$</td>
<td>Belle [102] (7.7)</td>
<td></td>
</tr>
<tr>
<td>$\chi_c(2P)$</td>
<td>3927.2 ± 2.0</td>
<td>24.1±0.1</td>
<td>2++</td>
<td>$e^+e^- \to e^+e^−(DD)$</td>
<td>Belle [55] (5.3), BABar [56] (5.8)</td>
<td>2005</td>
</tr>
<tr>
<td>$X(3840)$</td>
<td>3943.2±0.8</td>
<td>37.37</td>
<td>?++</td>
<td>$e^+e^- \to J/\psi(DD^*)$</td>
<td>Belle [103] (6.0)</td>
<td>2007</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>4008±121</td>
<td>226±97</td>
<td>1--</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$</td>
<td>Belle [104] (7.4)</td>
<td>2007</td>
</tr>
<tr>
<td>$Z_1(4050)^+$</td>
<td>4051±25</td>
<td>82±34</td>
<td>?</td>
<td>$B \to K(\pi^+\chi_c(1P))$</td>
<td>Belle [105] (5.0)</td>
<td>2008</td>
</tr>
<tr>
<td>$Y(4140)$</td>
<td>4143.4 ± 3.0</td>
<td>15±14</td>
<td>?+</td>
<td>$B \to K(\phi J/\psi)$</td>
<td>CDF [106, 107] (5.8)</td>
<td>2009</td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>4155±29</td>
<td>151±13</td>
<td>?</td>
<td>$\pi^+e^- \to J/\psi(DD^*)$</td>
<td>Belle [103] (5.5)</td>
<td>2007</td>
</tr>
<tr>
<td>$Z_2(4260)^+$</td>
<td>4248±185</td>
<td>177±10</td>
<td>?</td>
<td>$B \to K(\pi^+\chi_c(1P))$</td>
<td>Belle [105] (5.0)</td>
<td>2008</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>4263 ± 5</td>
<td>108±14</td>
<td>1--</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$</td>
<td>BABar [108, 109] (8.0)</td>
<td>2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \to (\pi^+\pi^-J/\psi)$</td>
<td>CLEO [110] (5.4)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \to (\pi^0\pi^0J/\psi)$</td>
<td>Belle [104] (15)</td>
<td></td>
</tr>
<tr>
<td>$Y(4274)$</td>
<td>4274.4±2.4</td>
<td>32±22</td>
<td>?++</td>
<td>$B \to K(\phi J/\psi)$</td>
<td>CDF [107] (3.1)</td>
<td>2010</td>
</tr>
<tr>
<td>$X(4350)$</td>
<td>4350.5±2.1</td>
<td>13.3±15.6</td>
<td>0,2++</td>
<td>$e^+e^- \to e^+e^−(\phi J/\psi)$</td>
<td>Belle [112] (3.2)</td>
<td>2009</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>4363 ± 11</td>
<td>96±42</td>
<td>1--</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$</td>
<td>BABar [113] (np), Belle [114] (8.0)</td>
<td>2007</td>
</tr>
<tr>
<td>$Z(4430)^+$</td>
<td>4443±10</td>
<td>107±14</td>
<td>?</td>
<td>$B \to K(\pi^+\psi(2S))$</td>
<td>Belle [115, 116] (0.4)</td>
<td>2007</td>
</tr>
<tr>
<td>$X(4630)$</td>
<td>4634±9</td>
<td>92±14</td>
<td>1--</td>
<td>$e^+e^- \to (\Lambda_c^+\Lambda_c^-)$</td>
<td>Belle [25] (8.2)</td>
<td>2007</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664±12</td>
<td>48±15</td>
<td>1--</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$</td>
<td>Belle [114] (5.8)</td>
<td>2007</td>
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<tr>
<td>$r_0(1S)$</td>
<td>9390.7 ± 2.9</td>
<td>?</td>
<td>0−−</td>
<td>$\Upsilon(2S) \to \gamma + (\ldots)$</td>
<td>BABar [59] (10), CLEO [50] (4.0)</td>
<td>2008</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>$\Upsilon(2S) \to \gamma + (\ldots)$</td>
<td>BABar [61] (3.0)</td>
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<tr>
<td>$\Upsilon(1S)D_2$</td>
<td>10163.8 ± 1.4</td>
<td>?</td>
<td>2−</td>
<td>$\Upsilon(3S) \to \gamma\gamma\Upsilon(1S)$</td>
<td>CLEO [62] (10.2)</td>
<td>2004</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td>$\Upsilon(3S) \to \gamma\gamma(\pi^+\pi^-\Upsilon(1S))$</td>
<td>BABar [63] (5.8)</td>
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<tr>
<td>$\psi(10888)$</td>
<td>10888.4±3.0</td>
<td>30.7±0.9</td>
<td>1−−</td>
<td>$e^+e^- \to (\pi^+\pi^-\psi(3S))$</td>
<td>Belle [37, 117] (3.2)</td>
<td>2010</td>
</tr>
</tbody>
</table>
Current Status

- All states below open flavor threshold well understood & conform to quark model $qq\bar{q}$ interpretation
- Region above open $cc$ flavor more complicated

- Little exploration of the region above $Y(4S)$
  - Recent Belle evidence for $Z_{b}^{+}$ states (structures in $Y(nS)\pi$ and $h_{b}(1P,2P)\pi$ from $Y(5S)$)
  - No analogues to the $X,Y$ states found yet

- Much higher statistics needed:
  - Spin-parity information from charmonium decays to exclusive final states
  - Information in the bottomonium sector in the region above the $Y(4S)$