CHARM SPECTROSCOPY
AT BABAR

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On behalf of the BaBar collaboration
CHARM SPECTROSCOPY AT BABAR

- c$\bar{s}$ mesons
  - $D_{s1}(2536)$: precise measurements
  - $D_{s0}^*(2317)$ and $D_{s1}(2460)$: the first surprises
  - $D_{sJ}^*(2860)$: one more surprise
  - $X(2690)$ and $D_{sJ}(2700)$: last surprises?

- Charmed baryons
  - Observation of $\Omega_c^0$ and discovery of $\Omega_c^{*0}$
  - Discovery of $\Lambda_c(2940)$
  - Observation of $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$
  - Discovery of $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$

- Not mentioned in this talk
  - D, D* mesons

- Charmonium spectroscopy in BaBar is covered by Arafat Mokhtar
  - Talk given on Monday at 14h00, in the session “Quarkonia states”
BABAR: B AND c-FACTORIES

The BaBar Detector
1.5 T solenoid (superconducting)

Calorimeter
6580 CsI(Tl) crystals

Cherenkov Detector
144 quartz bars
11,000 PMTs

e⁻ (9 GeV)

Silicon Vertex Tracker
5 double-sided layers

Drift Chamber
40 layers

Ionized Flux Return
18–19 layers

e⁺ (3.1 GeV)

Peak luminosity: $12.1 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

477 fb$^{-1}$
c$\bar{s}$ MESONS

WHAT IS NEW FOR $D_{sJ}$ STATES?
CURRENT SITUATION

- **Ds0\(^+(2317)\)**, Apr. 2003: unexpected observation of a narrow resonance in BaBar
- **Ds1\(^+(2460)\)**, May 2003: CLEO, BaBar observed a new narrow resonance
- **DsJ\(^*(2860)\)**, Jul. 2006: new state discovered by BaBar
- **DsJ\(^+(2700)\)**, Jul. 2006: new state discovered by Belle
- **X(2690)**, Jul. 2006: broad enhancement seen in BaBar

Let's go step by step!

- **Ds\(^*\)**, **Ds1\(^+(2536)\)**, **Ds2\(^+(2573)\)**: well known, but **J^P** only inferred (not measured!)
- **Ds0\(^*(2317)\)**, Apr. 2003: unexpected observation of a narrow resonance in BaBar
- **Ds1\(^+(2460)\)**, May 2003: CLEO, BaBar observed a new narrow resonance
- **DsJ\(^*(2860)\)**, Jul. 2006: new state discovered by BaBar
- **X(2690)**, Jul. 2006: broad enhancement seen in BaBar
- **DsJ\(^+(2700)\)**, Jul. 2006: new state discovered by Belle (≡ X(2690)?)
**D_{s1}(2536): NEW RESULTS**

- High precision measurement of \( D_{s1} \rightarrow D^*K^0_s \) in continuum

- **Mass**
  - \( M = 2534.85 \pm 0.02 \pm 0.40 \text{ MeV} \)

- **First measurement of the width**
  - \( \Gamma = 1.03 \pm 0.05 \pm 0.12 \text{ MeV} \)

- **First observation of \( D_{s1} \) in B decays**
  - \( B \rightarrow D^{(*)}D_{s1} \) (8 modes), \( D_{s1} \rightarrow D^*K \)
  - \( N = 182 \pm 19 \) events, \( 12\sigma \)

- **Mass**
  - \( M = 2534.78 \pm 0.31 \pm 0.40 \text{ MeV} \)

- **\( J^P \) quantum number**
  - Statistics **too low** to conclude yet
Ds0*(2317) AND Ds1(2460) UPDATE

- Discovered 4 years ago in e^+e^- \rightarrow c\bar{c} events; subsequently observed in B decays

- Ds0*(2317) and Ds1(2460) very well established and known experimentally
  - Masses and tight upper limits on widths
  - J^P: 0^+ for Ds0*(2317) and 1^+ for Ds1(2460)
  - Decay modes and branching fractions

- Interpretation of these new states still unclear!
  - One possibility: identify these 2 states as the 0^+ and 1^+ c\bar{s} states
    - However strong difficulties within the potential model
  - Other possibilities
    - 4 quark states? DK molecule? Dπ atom? Chiral symmetry?

- Are there some more surprises? Yes!

Belle: Belle-Conf-0461 (2006)
DsJ*(2860): ANOTHER NEW STATE

- Looking in the c\bar{c} continuum: e^+e^- \rightarrow D^0(K^-\pi^+,K^-\pi^+\pi^0)K^+X and e^+e^- \rightarrow D^+(K^-\pi^+\pi^+)K_0^sX

- New state at 2860 MeV/c^2! (fit with a Breit-Wigner)
- Bump at 2690 MeV/c^2? (better fit with a Gaussian than a Breit-Wigner)
**D_{sJ}^*(2860) AND... X(2690)?**

- **Combining the 3 modes**
  - $M = (2856.6 \pm 1.5 \pm 5.0)$ MeV/c$^2$
  - $\Gamma = (47 \pm 7 \pm 10)$ MeV
  - $J^P = 0^+, 1^-, 2^+, \ldots$
    - Final state is DK, i.e. two pseudoscalars

- **Interpretation of D_{sJ}^*(2860)?**
  - Radial excitation of D_{s0}^*(2317)?
  - $c\bar{s}$ with $J^P = 3^-$?
  - $c\bar{s}$ with $J^P = 0^+$?

- **Another structure at 2690 MeV/c$^2$?**
  - $M = (2688 \pm 4 \pm 3)$ MeV/c$^2$
  - $\Gamma = (112 \pm 7 \pm 36)$ MeV

- **Need confirmation** by other experiments or in other channels…

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**Sum of 3 modes**

- $X(2690)$
  - $240$ fb$^{-1}$
  - bkg subtracted
- $D_{sJ}^*(2860)$

- $m(DK)$ GeV/c$^2$
EVEN MORE STATES: $D_{sJ}(2700)$

- New resonance decaying to $D^0K^+$ discovered by Belle in $B^+ \rightarrow \bar{D}^0(D^0K^+)$
  - $D_{sJ}(2700)$
- Same resonance as seen by BaBar in continuum, $X(2690)$?
  - Mass and width consistent, same decay mode
- Study of $B \rightarrow \bar{D}^*(D^*)K$ decays in BaBar
  - Looking at 8 $DK + 8 D^*K$ invariant masses

- Enhancement observed around 2700 MeV/c$^2$ in $DK$ and $D^*K$
- Full Dalitz plot analysis ongoing
CHARMED BARYONS
CURRENT STATE

- All 9 ground states with $J^P=1/2^+$ observed
- 5 out of 6 ground states with $J^P=3/2^+$ observed
  - only $\Omega_c^{*0}$ was missing
STUDY OF $\Omega_c^0$

- $\Omega_c^0$: css charm baryon ground state
- Observed in 4 modes
- First observation of $B \to \Omega_c^0 X$

$B(B \to \Omega_c^0 X) \times B(\Omega_c^0 \to \Omega^- \pi^+) = (5.2 \pm 0.9 \pm 0.5) \times 10^{-6}$

DISCOVERY OF $\Omega_c^{*0}$

- $\Omega_c^{*0} \rightarrow \Omega_c^0 \gamma$, in $\text{e}^+\text{e}^- \rightarrow \Omega_c^{*0} X$
  - css baryon, $J^P = 3/2^+$
- Combining 4 decay modes of $\Omega_c^0$ gives
  - 105 $\pm$ 21 $\pm$ 6 events
  - 5.2$\sigma$ significance
- Difference of mass $\Delta m = m(\Omega_c^{*0}) - m(\Omega_c^0)$
  - Measured: 70.8 $\pm$ 1.0 $\pm$ 1.1 MeV/c$^2$
  - Predicted range: 50 – 94 MeV/c$^2$
- Branching fraction ratio:
  $$\frac{\sigma(e^+e^- \rightarrow \Omega_c^{0}X, x_p(\Omega_c^{*0}) > 0.5)}{\sigma(e^+e^- \rightarrow \Omega_c^{0}X, x_p(\Omega_c^0) > 0.5)} = 1.01 \pm 0.23 \pm 0.11$$

$\Omega_c^0 \rightarrow \Omega^- \pi^+, \Omega^- \rightarrow \Lambda K^-$
- $\Omega_c^0 \rightarrow \Omega^- \pi^+\pi^0, \Omega^- \rightarrow \Lambda K^-$
- $\Omega_c^0 \rightarrow \Omega^- \pi^+\pi^-\pi^+, \Omega^- \rightarrow \Lambda K^-$
- $\Omega_c^0 \rightarrow \Xi^- K^-\pi^+\pi^+, \Xi^- \rightarrow \Lambda \pi^-$
DISCOVERY OF $\Lambda_c(2940)$

- New baryon: $\Lambda_c(2940) \rightarrow D^0p$
  - First observation of charmed baryons decaying to $D$ meson and light baryon
  - Simplest explanation: $udc$ baryon
- Measurements of $M$ and $\Gamma$ are consistent

<table>
<thead>
<tr>
<th></th>
<th>$M$, MeV/$c^2$</th>
<th>$\Gamma$, MeV</th>
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</thead>
<tbody>
<tr>
<td>BaBar $\Lambda_c(2940)^+$</td>
<td>$2939.8 \pm 1.3 \pm 1.0$</td>
<td>$17.5 \pm 5.2 \pm 5.9$</td>
</tr>
<tr>
<td>Belle $\Lambda_c(2940)^+$</td>
<td>$2938.0 \pm 1.3^{+2.0}_{-4.0}$</td>
<td>$13^{+8+27}_{-5-7}$</td>
</tr>
<tr>
<td>CLEO $\Lambda_c(2880)^+$</td>
<td>$2882 \pm 1 \pm 2$</td>
<td>$4 \pm 2 \pm 2$</td>
</tr>
<tr>
<td>BaBar $\Lambda_c(2880)^+$</td>
<td>$2881.9 \pm 0.1 \pm 0.5$</td>
<td>$5.8 \pm 1.5 \pm 1.1$</td>
</tr>
<tr>
<td>Belle $\Lambda_c(2880)^+$</td>
<td>$2881.2 \pm 0.2 \pm 0.4$</td>
<td>$5.8 \pm 0.7 \pm 1.1$</td>
</tr>
</tbody>
</table>

- No signals in $D^+p$ for both baryons
  - Isospin = 0
  - Both states are isoscalars ($\Lambda_c$ not $\Sigma_c$)

Confirmed later by Belle in $\Lambda_c^{*+}\pi^+\pi^-$
OBSERVATION OF \( \Xi_c(2980)^+ \) AND \( \Xi_c(3077)^+ \)

- \( \Xi_c(2980)^+ \), \( \Xi_c(3077)^+ \) and \( \Xi_c(3077)^0 \) first observed by Belle
  - Excited \textbf{charm-strange} baryons
- Confirmed by BaBar in
  \( \Lambda_c^+ K^- \pi^+ \), with
  \( \Lambda_c^+ \rightarrow p K^- \pi^+ \)
- BaBar confirmed also \( \Xi_c(3077)^0 \)
- Comparison of \( M \) and \( \Gamma \) measurements

<table>
<thead>
<tr>
<th></th>
<th>( M ), MeV/c^2</th>
<th>( \Gamma ), MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle ( \Xi_c(2980)^+ )</td>
<td>2978.5 ± 2.1 ± 2.0</td>
<td>43.5 ± 7.5 ± 7.0</td>
</tr>
<tr>
<td>BaBar ( \Xi_c(2980)^+ )</td>
<td>2967.1 ± 1.9 ± 1.0</td>
<td>23.6 ± 2.8 ± 1.3</td>
</tr>
<tr>
<td>Belle ( \Xi_c(3080)^+ )</td>
<td>3076.7 ± 0.9 ± 0.5</td>
<td>6.2 ± 1.2 ± 0.8</td>
</tr>
<tr>
<td>BaBar ( \Xi_c(3080)^+ )</td>
<td>3076.4 ± 0.7 ± 0.3</td>
<td>6.2 ± 1.6 ± 0.5</td>
</tr>
<tr>
<td>Belle ( \Xi_c(3080)^0 )</td>
<td>3082.8 ± 1.8 ± 1.5</td>
<td>5.2 ± 3.1 ± 1.8</td>
</tr>
<tr>
<td>BaBar ( \Xi_c(3080)^0 )</td>
<td>3079.3 ± 1.1 ± 0.2</td>
<td>5.9 ± 2.3 ± 1.5</td>
</tr>
</tbody>
</table>

Different: BaBar incorporates phase space effects near threshold and decay to \( \Sigma_c^{++} K^- \)

Good agreement

BaBar: hep-ex/0607042
DISCOVERY OF $\Xi_c(3055)^+$ AND $\Xi_c(3123)^+$

- Updated analysis with more statistics
DISCOVERY OF $\Xi_c(3055)^+$ AND $\Xi_c(3123)^+$

- Updated analysis with more statistics
- New state (looking in the $\Sigma_c(2455)^{++}$ band):

<table>
<thead>
<tr>
<th>$\Xi_c(3055)^+$</th>
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<tbody>
<tr>
<td>Mass (MeV/c²)</td>
</tr>
<tr>
<td>Width (MeV)</td>
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<tr>
<td>Yield</td>
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<tr>
<td>Significance</td>
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</table>

$\Sigma_c(2455)^{++}K^+\rightarrow\Lambda_c^+K^+\pi^+\rightarrow\Xi_c^+(3055)^+$

$\Sigma_c(2455)^{++}K^+\rightarrow\Lambda_c^+K^+\pi^+$

$\Xi_c(2980)^+$

$\Xi_c(3055)^+$

$\Xi_c(3077)^+$

384 fb⁻¹
DISCOVERY OF $\Xi_c(3055)^+$ AND $\Xi_c(3123)^+$

- Updated analysis with more statistics
- New state (looking in the $\Sigma_c(2455)^{++}$ band):
  
  $\Xi_c(3055)^+$
  Mass ( MeV/$c^2$ ) 3054.2 ± 1.2 ± 0.5
  Width ( MeV ) 17 ± 6 ± 11
  Yield 218 ± 53 ± 79
  Significance 6.4$\sigma$

- Evidence for (looking in the $\Sigma_c(2520)^{++}$ band):
  
  $\Xi_c(3123)^+$
  Mass ( MeV/$c^2$ ) 3122.9 ± 1.3 ± 0.3
  Width ( MeV ) 4.4 ± 3.4 ± 1.7
  Yield 101 ± 34 ± 9
  Significance 3.6$\sigma$
CONCLUSIONS

- Tens of new charmed states have been discovered since 1999, beginning of BaBar!

- $c\bar{s}$ summary:
  - $D_{s0}^*(2317)$, $D_{s1}(2460)$: well determined experimentally, not understood theoretically
  - $D_{sJ}^*(2860)$, $D_{sJ}(2700)$: still unclear experimentally and theoretically

- Charmed baryons
  - Many states studied by BaBar: $\Omega_c^0$, $\Xi_c(2980)^+$ and $\Xi_c(3077)^+$
  - Many new states discovered: $\Omega_c^{*0}$, $\Lambda_c(2940)$, $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$

Experimental status:
- Lots of on-going analyses with the current dataset
  - More decay modes investigated to understand these resonances
- BaBar is taking data till Sept. 2008
- Lots of new data to analyse!
  - We can bet that more surprises will arise!
ADDITIONAL SLIDES
\( D_{s0}^*(2317) \) IN INCLUSIVE DATA

- Study of \( e^+e^- \rightarrow c\bar{c} \) events
  - Resonance in \( D_s^+\pi^0 \)
- Complex kinematics with competing contributions and mutual cross-feed

- Properties
  - \( M = (2319.6 \pm 0.2 \pm 1.4) \text{ MeV}/c^2 \)
  - \( \Gamma < 3.8 \text{ MeV} \) at 95% CL

- No decay to \( D_s^+\pi^0 \) or \( D_s^+\pi^- \)
  - No indication of isospin partners
  - 4 quark model disfavored

\( D_s^+\pi^0 \) final states

\( D_{s0}^*(2317) \) Contribution from \( D_s^*(2112) \)

\( D_{s1}(2460)^+ \rightarrow D_s^+\pi^0 \) No indication

$D_s(2460)$ IN INCLUSIVE DATA

- $D_s(2460)$ observed in 3 decay final states

$D_s^+ \gamma$ final states

$D_s^+ \pi^0 \gamma$ final states

$D_s^+ \pi^+ \pi^-$ final states

- Properties
  - $M = (2460.1 \pm 0.2 \pm 0.8)$ MeV/$c^2$
  - $\Gamma < 3.5$ MeV at 95% CL

No $D_{s0}^{*}(2317)^+ \rightarrow D_s^+ \gamma$

No search for $D_s^+ \pi^+/\pi^- \pi^0$ isospin partners as yet

EVEN MORE STATES: $D_{sJ}(2700)$

- Study of $B^+ \rightarrow \bar{D}^0D^0K^+$
  - Looking at the Dalitz plot and the $D^0K^+$ projection
- New resonance decaying to $D^0K^+$
  - $B^+ \rightarrow \bar{D}^0D_{sJ}, D_{sJ} \rightarrow D^0K^+$
  - $M = (2715 \pm 11^{+11}_{-14})$ MeV/$c^2$
  - $\Gamma = (115 \pm 20^{+36}_{-32})$ MeV
  - $J^P = 1^-$ favored

- Same resonance as seen by BaBar in continuum, $X(2690)$?
  - Mass and width consistent, same decay mode

Interpretation?
  - c$s$ state $2^3S_1$?
    - expected mass at 2720 MeV/$c^2$
  - Chiral symmetry: $1^+ - 1^-$ doublet paired with $D_{s1}(2536)$?

STUDY OF $\Xi(1530)^0$ AND $\Xi(1690)^0$

$\Xi(1530)^0$ from $\Lambda_c^+ \rightarrow (\Xi^- \pi^+) K^+$
- Use of Legendre polynomial moments to determine the spin
  - Spin $3/2$ clearly established
  - Using previous results: P-wave $3/2^+$
- Showed the presence of an S-wave $\Xi^- \pi^+$ amplitude, with some indication of a $\Xi(1690)$ S-wave contribution

$\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda K^0) K^+$
- Legendre polynomial moments
  - Spin $1/2$ preferred
- Fitting now the whole Dalitz Plot
  - to get more precise $(M, \Gamma)$ measurements
  - to show the existence of $\Lambda_c^+ \rightarrow \Lambda a^0(980)^+$

Both results to be updated soon!