Charm Baryon Results from BaBar

Veronique Ziegler
SLAC National Accelerator Laboratory
Representing the BaBar Collaboration

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Outline

• Introduction: BaBar as a charm factory

• Spectroscopy

• Production studies

• Studies of excited Cascade states produced in charm baryon decays

• Future possibilities
BaBar as a Charm Baryon Factory

Present data sample contains:

- $> 450 \text{ M } \Upsilon(4S) \rightarrow \bar{B}B$ 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 D⁰p
  - previously observed Λ_c(2880)⁺ (in Λ_c π⁺ π⁻) [Q ~ 317 MeV/c²]
  - BaBar measurements from D⁰p [Q ~ 79 MeV/c² → much greater precision]:
    \[ M = 2881.9 ± 0.1 \text{(stat)} ± 0.5 \text{(syst)} \text{ MeV/c}^2 \]
    \[ \Gamma = 5.8 ± 1.5 \text{(stat)} ± 1.1 \text{(syst)} \text{ MeV} \] [First measurement]
  - new state:
    \[ M = 2939.8 ± 1.3 \text{(stat)} ± 1.0 \text{(syst)} \text{ MeV/c}^2 \]
    \[ \Gamma = 17.5 ± 5.2 \text{(stat)} ± 5.9 \text{(syst)} \text{ MeV} \]

- 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 Λ_c states, not Σ_c states

---

\[ \Lambda_c^+ \] u d c

\[ \Lambda_c^- \] u d c

\[ \Lambda_c^0 \] u d c

\[ \Sigma_c^+ \] u d c

\[ \Sigma_c^- \] u d c

\[ \Sigma_c^0 \] u d c

\[ \Xi_c^- \] u d c d

\[ \Xi_c^0 \] u d c d

\[ \Omega_c^- \] u d c d d

\[ \Omega_c^0 \] u d c d d

\[ \Omega_c^{+} \] u d c d d
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 $\Xi_c(3123)^+$
  → 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
  → 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 $\Lambda_c^+ K \pi$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Lambda_c^+ \rightarrow pK^- \pi^+$</th>
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<tbody>
<tr>
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<td>$\Lambda_c^+ \rightarrow pK^0_s$</td>
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<tr>
<td></td>
<td>$\Lambda_c^+ \rightarrow pK^0_s\pi^+\pi^-$</td>
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<tr>
<td></td>
<td>$\Lambda_c^+ \rightarrow \Lambda\pi^+$</td>
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<td></td>
<td>$\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^-\pi^+$</td>
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</tbody>
</table>

- 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/c²)</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>\ldots</td>
</tr>
<tr>
<td>Significance</td>
<td>&gt;9.0σ</td>
<td>1.7σ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$\Xi_c(3077)^+$</th>
<th>$\Xi_c(3077)^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c²)</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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<tr>
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<th>$\Xi_c(3055)^+$</th>
<th>$\Xi_c(3123)^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c²)</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 $(\Lambda_c^+ K^- \pi^+ \pi^+)$
The Search for the \( \Omega^*_c (J^P=3/2^+) \)

PRL 97, 232001 (2006)

- 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

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

- Splitting $M(\Omega_c^*) - M(\Omega_c^0)$
  
  $= 70.8 \pm 1.0 (\text{stat}) \pm 1.1 (\text{syst}) \text{ MeV/c}^2$

- Consistent with pQCD predictions

- $M(\Omega_c^*) = 2768.3 \pm 3.0 \text{ MeV/c}^2$

- Ratio of the inclusive production cross sections

  $R = \frac{\sigma(e^+ e^- \rightarrow \Omega_c^* X, x_p (\Omega_c^* > 0.5))}{\sigma(e^+ e^- \rightarrow \Omega_c^0 X, x_p (\Omega_c^0 > 0.5))}$

  $= 1.01 \pm 0.23 (\text{stat}) \pm 0.11 (\text{syst})$
The Search for the $\Xi_{cc}^{+}(\Xi_{cc}^{++})$ Baryons in the $\Lambda_{c}^{+}K^{-}\pi^{+}(\pi^{+})$ and $\Xi_{c}^{0}\pi^{+}(\pi^{+})$ Final States

- SELEX [using Fermilab 600 GeV/c charged hyperon beam] reported evidence for $cc$ baryons with mass 3518.7 MeV/c$^2$ decaying to $\Lambda_{c}^{+}K^{-}\pi^{+}$ and $pD^{+}K^{-}$ and with mass 3460 MeV/c$^2$ decaying to $\Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+}$. PRL 89, 112001(2002), Phys.Lett. B 628, 18(2005)
- The mass difference $\Xi_{cc}^{+} - \Xi_{cc}^{++} \sim 60$ MeV/c$^2$ measured by SELEX inconsistent with the $J=1/2$ isodoublet interpretation
- The photoproduction experiment FOCUS observed $\sim 12 \times$ more $\Lambda_{c}^{+}$s than SELEX and yet did not observe $\Xi_{cc}$ states. Nucl.Phys. B, Proc.Suppl. 115, 33 (2003)
- Predicted cross section values for doubly charm production in e$^+e^-$ collisions at c.m. energy near 10.58 GeV range from 1 to 250 fb corresponding to rates $\Theta(10^{-4} - 10^{-2})$
- BaBar searched for $\Xi_{cc}$ states in 232 fb$^{-1}$ of data and found no evidence of doubly charm baryons. PRD 74, 011103(R) (2006)
Charm Baryon Production at the Y(4S) Resonance

Production from B decays $e^+e^-$ Continuum Production
Charm Baryon Production at the Y(4S) Resonance

Typical c.m. momentum ($p^*$) distribution

Production from B decays (+some continuum)

Continuum production

Diagram showing the cross section in fb / 0.5 GeV/c versus $\Lambda_c \rightarrow pK_S^0$ and $p^*$ GeV/c.
Measurements of $\text{BR}(\bar{B}^0 \rightarrow \Lambda_c^+ p)$ and $\text{BR}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-)$ and Studies of $\Lambda_c^+ \pi^-\text{ Resonances}$

\[
\frac{\mathcal{B}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-)}{\mathcal{B}(B^0 \rightarrow \Lambda_c^+ \bar{p})} = 15.4 \pm 1.8 \pm 0.3
\]

\[
\frac{\mathcal{B}(B^- \rightarrow \Sigma_c(2455)^0 \bar{p})}{\mathcal{B}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-)} = (12.3 \pm 1.2 \pm 0.8) \times 10^{-2}
\]

\[
\frac{\mathcal{B}(B^- \rightarrow \Sigma_c(2800)^0 \bar{p})}{\mathcal{B}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-)} = (11.7 \pm 2.3 \pm 2.4) \times 10^{-2}
\]

\[
\frac{\mathcal{B}(B^- \rightarrow \Sigma_c(2520)^0 \bar{p})}{\mathcal{B}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-)} < 0.9 \times 10^{-2} \ (90\% \ C.L.)
\]

- Predicted favored B to baryon—anti-baryon decay rate for baryon and anti-baryon close in phase space (i.e. 3-body final state)


- Study of baryon production in B decays by comparison of $(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p})$ and $(B^- \rightarrow \Lambda_c^+ p \pi^-)$ decay rates

- Use of 3-body decay to study $\Lambda_c^+ \pi^-$ resonant structures
  - mass, width of $\Sigma_c(2455)$
  - spin of $\Sigma_c(2455)$

<table>
<thead>
<tr>
<th>Fit Parameter</th>
<th>Value</th>
<th>PDG Value [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{\text{sig}}$</td>
<td>$1522 \pm 149$</td>
<td></td>
</tr>
<tr>
<td>$m_R$ (GeV/c²)</td>
<td>$2.4540 \pm 0.0002$</td>
<td>$2.4538 \pm 0.0002$</td>
</tr>
<tr>
<td>$\Gamma_R$ (MeV)</td>
<td>$2.6 \pm 0.5$</td>
<td>$2.2 \pm 0.4$</td>
</tr>
</tbody>
</table>
Spin Measurement of the $\Sigma_c (2455)^0$ Resonance

angential analysis of the decay $B^- \rightarrow \Sigma_c (2455)^0 \bar{p}$

$\Lambda_c^+ \pi^-$

$\Sigma_c (2455)$ produced with helicity $\pm 1/2$

assume $J(\Lambda_c^+) = 1/2$

\[
J(\Sigma_c^0) = \frac{1}{2} : \frac{dN}{d \cos \theta_h} \propto 1
\]

\[
J(\Sigma_c^0) = \frac{3}{2} : \frac{dN}{d \cos \theta_h} \propto 1 + 3 \cos^2 \theta_h
\]
**$\Xi'_c$ Production**

- Confirmation of CLEO [0.5fb$^{-1}$] observation of $\Xi'_c$

  \[ \Xi'_c^+ \rightarrow \Xi_c^+\gamma \]
  \[ \quad \rightarrow \Xi^-\pi^+\pi^+ \]
  \[ \quad \rightarrow \Lambda\pi^- \]

  \[ \Xi'_c^0 \rightarrow \Xi_c^0\gamma \]
  \[ \quad \rightarrow \Xi^-\pi^+ \]

- Charm baryons produced in $e^+e^-$ continuum ($p^* \gtrsim 2$ GeV/c) and in $B$ decays ($p^* \lesssim 2$ GeV/c)

![Graphs showing production of $\Xi'_c$ particles in different channels with data points and histograms.](image)
\( \Xi'_c \) Momentum Spectra

- **Substantial B meson decay to** \( \Xi'_c^{\pm,0} \)
  - first observation of these decays
  - stat. significance > 12 \( \sigma \)

- **Product branching fractions**
  \[
  BF(B \rightarrow \Xi'_c X) \times BF(\Xi'_c \rightarrow \Xi^- \pi^+ \pi^+) = [1.69 \pm 0.17\text{(exp)} \pm 0.10\text{(model)}] \times 10^{-4}
  
  BF(B \rightarrow \Xi'_c^0 X) \times BF(\Xi'_c^0 \rightarrow \Xi^- \pi^+) = [0.67 \pm 0.07\text{(exp)} \pm 0.03\text{(model)}] \times 10^{-4}
  \]

- **Cross sections at** \( \sqrt{s}=10.58 \) GeV
  \[
  \sigma(e^+ e^- \rightarrow \Xi'_c^+ X) \times BF(\Xi'_c \rightarrow \Xi^- \pi^+ \pi^+) = [141 \pm 24\text{(exp)} \pm 19\text{(model)}] \text{ fb}
  
  \sigma(e^+ e^- \rightarrow \Xi'_c^0 X) \times BF(\Xi'_c^0 \rightarrow \Xi^- \pi^+) = [70 \pm 11\text{(exp)} \pm 6\text{(model)}] \text{ fb}
  \]
Light Quark Spectroscopy

Excited Cascades produced in charm baryon decays
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 Ξ(1530) Spin Information

Efficiency-corrected $P_2$ Moment Dist.

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

Spin 3/2 Test

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

- Spin 3/2 clearly established
- 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 $\Lambda_c^+ \rightarrow (\Lambda K_S) K^+$ Decay

$m(\Lambda K_S) \leftrightarrow \Lambda_c^+$ mass-signal region

$m(\Lambda K_S) \leftrightarrow \Lambda_c^+$ mass-sideband region

$m(\Lambda K_S) \leftrightarrow (\Lambda_c^+)$ mass-sideband-subtracted

$N \sim 2900$ events

HWHM $\sim (3.1 \pm 0.5)$ MeV/c

$\Lambda_c^+$ Low-mass sideband limit

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

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

$\Xi(1690)^0 \rightarrow$

\[ w_j = (7/\sqrt{2}) P_4(\cos\theta) \]

from $\Lambda_c^+$ signal region

Efficiency-corrected $P_4$ Moment Dist.

Spin 5/2 Test

$\omega_j = \sqrt{10} P_2(\cos\theta)$

from $\Lambda_c^+$ signal region

Efficiency-corrected $P_2$ Moment Dist.

Spin 3/2 Test

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

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

Accumulation of events in $K_S K^+$ near threshold $\Rightarrow$ evidence of $a_0(980)^+$

$m = 1682.9 \pm 0.9\,(stat) \pm 0.8\,(syst)\ \text{MeV}/c^2$

$\Gamma = 9.3^{+2.0}_{-1.7}\,(stat) \pm 0.4\,(syst)\ \text{MeV}$

$J = 1/2$ 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 $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$

$\Xi(1690)$ seen in inclusive environment in hyperon beam expt.

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
Concluding 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
Concluding Remarks

• Future experiments expected to provide large charm baryon samples to further our understanding of heavy flavor baryons
  - LHCb
  - Super-B
  - GlueX [associated production; e.g. $\gamma p \rightarrow \Lambda_c^+ D^0$]
BACKUP SLIDES
BaBar-GlueX Comparisons

- Large acceptance, multi-pupose detector
  - Acceptance: \(-0.92 < \cos \theta^* < 0.85\) (\(\theta^*\) : c.m.s. polar angle w.r.t. collision axis)
- Excellent charged particle tracking (SVT & Drift Chamber) and P.I.D. (& DIRC)
- Excellent \(\gamma\) measurement (i.e. \(\pi^0 \rightarrow \gamma \gamma\), \(\eta \rightarrow \gamma \gamma\), etc.) in EMC

\(*) Would also like to reconstruct \(\Xi^0\).

[Note: 1st \(\Omega^-\) event in BC was \(\Omega^- \rightarrow \Xi^0 \pi^-\)]
Excellent Vertex Reconstruction Capability (1)

233 fb$^{-1}$ $e^+$ $e^-$ data

SVT support tube
DCH inner wall

SVT

B1 Dipole

DOCA < 3 mm
$K_S^0$ FL > 2 mm

Fe
Be
Ta

DOCA < 3 mm
$K_S^0$ FL > 2 mm
Excellent Vertex Reconstruction Capability (2)
Excellent Vertex Reconstruction Capability (3)

Radial Distribution for Be–water Region

Radial Vertex Resolution \( \sim 90 \, \mu m \)

○ measured
+ fit
Chew-Low Plot Acceptance

$K^{-} p \rightarrow X \Lambda$ (11 GeV/c)

$X = \pi^{+}\pi^{-}$

$\gamma p \rightarrow X p$ (9 GeV/c)

$X = \pi^{+}\pi^{-}$

($\sim 34$ k events)

SLAC-R-421

Baryon exchange

Meson exchange
Possible Ξ Studies with GlueX

1. Survey Processes to Provide an Overview of Ξ(*) Photoproduction
   • Inclusive Ξ⁻ (Ξ⁰ ?) Production
     – Feynman $x$ and $p_T^2$ distributions
     – Chew-Low plot(s)
     – Polarization measurements
     – Etc…

   • Similar Studies for Cascade Resonance Production (e.g. Ξ(1530)$\rightarrow$Ξ⁻π⁺) and Associated Spectra
     – Note: In the LASS search for $\Omega^-$ states, the inclusive mass distribution for (Ξ⁻π⁺K⁻) showed nothing; however when the (Ξ⁻π⁺) was selected to correspond to the Ξ(1530)⁰, a signal for the $\Omega(2250)^-$ was observed.
2. 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 $\Xi$ Studies with GlueX (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

  States analyzed in $\Lambda_c^+$ decay

  **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
Fit Results: \((K^+ K_S) & (\Lambda K_S)\) Mass Projections

\[ m(\Lambda K_S) \text{ mass cut-off } \]
\[ [1.62 < m(\Lambda K_S) < 1.765 \text{ GeV/c}^2] \]
introduces a kink because of restricted range of \((\Lambda K^+)\) helicity cosine

\[ m^2(\Lambda K^+) \text{ (GeV/c}^2)^2 \]
\[ m^2(\Lambda K_S) \text{ (GeV/c}^2)^2 \]
Comparison of Max. Likelihood Fit Result to the Signal Projections

Under the assumption of spin 3/2 for the $\Xi(1690)$:

$$I = p q C \left[ p_0^2 I_1 \left( \frac{3 \cos^2 \theta_\Lambda + 1}{4} \right) + \frac{g_{KK}^2 I_2}{2} \right]$$

$$+ \frac{k}{\sqrt{2}} \left( \cos \theta_\Lambda \right) p_0 g_{KK} I_1 I_2 \left[ (M_1 M_2 + G_1 G_2) \cos \delta + (G_1 M_2 - G_2 M_1) \sin \delta \right]$$

$\chi^2/NDF = 234.3/192$

C. L. = 1.9 %

Interference term very small
$\Rightarrow$ Equiv. to incoherent superposition of amplitudes

Lineshape skewing not reproduced!
Comparison of Max. Likelihood Fit Result to the Signal Projections

Under the assumption of spin 5/2 for the $\Xi(1690)$:

$$I = pq C \left[ p_0^2 I_1 3 \left( \frac{5\cos^4 \theta_\Lambda - 2\cos^2 \theta_\Lambda + 1}{8} \right) + \frac{g_{KK}^2 I_2}{2} \right]$$

$$+ \frac{\sqrt{3}k}{4} (3\cos^2 \theta_\Lambda - 1) p_0 g_{KK} I_1 I_2 [(M_1 M_2 + G_1 G_2) \cos \delta + (G_1 M_2 - G_2 M_1) \sin \delta]$$

$\chi^2$/NDF = 210.3/192

C. L. = 17.4 %

Net interference term very small

⇒ Equiv. to incoherent superposition of amplitudes

Lineshape skewing not reproduced!
### Summary of Results & Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimated Systematic Uncertainty</th>
</tr>
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<tbody>
<tr>
<td>Background Normalization and Parametrisation</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
<tr>
<td>Resolution Function Lineshape</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
<tr>
<td>Efficiency Parametrisation</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
<tr>
<td>Orbital Ang. Momentum Variation</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
<tr>
<td>$a_0(980)^+$ Parameter Values</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
<tr>
<td>Detector Effects</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>Ξ(1690)$^0$ Mass [MeV/c$^2$]</td>
</tr>
<tr>
<td></td>
<td>Ξ(1690)$^0$ Width [MeV]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>1682.9 ± 0.9</td>
<td>9.3 ± 1.9</td>
<td>0.4 ± 0.2</td>
<td>0.3 ± 0.5</td>
<td>188.4/192</td>
<td>56.4</td>
</tr>
<tr>
<td>3/2</td>
<td>1684.9 ± 0.8</td>
<td>8.8 ± 2.1</td>
<td>0.2 ± 0.2</td>
<td>−2.7 ± 1.1</td>
<td>234.3/192</td>
<td>1.9</td>
</tr>
<tr>
<td>5/2</td>
<td>1684.9 ± 0.8</td>
<td>9.0 ± 2.0</td>
<td>0.9 ± 0.2</td>
<td>2.4 ± 0.2</td>
<td>210.3/192</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Spin 1/2 favored

Fail to reproduce skewed lineshape; fit mass value moves higher in attempt to compensate

Poor C.L. Accept. C.L.
# MIGRAD FIT PARAMETER VALUES

<table>
<thead>
<tr>
<th>Fit Parameter</th>
<th>Value</th>
<th>Neg. Error</th>
<th>Pos. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi(1690)$ Ampl. Rel. Strength [MeV] ($p_0$)</td>
<td>24 ± 8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\Xi(1690)$ Mass [MeV/c²]</td>
<td>1682.9 ± 0.9</td>
<td>-0.9</td>
<td>+0.9</td>
</tr>
<tr>
<td>$\Xi(1690)$ Width [MeV]</td>
<td>9.3 ± 1.9</td>
<td>-1.7</td>
<td>+2.0</td>
</tr>
<tr>
<td>Effective Phase $\delta$ [rad.]</td>
<td>0.3 ± 0.5</td>
<td>-0.4</td>
<td>+0.6</td>
</tr>
<tr>
<td>Effective Scale $k$</td>
<td>0.4 ± 0.2</td>
<td>-0.2</td>
<td>+0.3</td>
</tr>
<tr>
<td>Overall Normalization Factor</td>
<td>1205 ± 726</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$g_{KK}$ [MeV]</td>
<td>349 ± 136</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Coupling Ratio Squared ($r^2$)</td>
<td>0.5 ± 0.4</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

$\chi^2$/NDF = 188.4/192

Prob. = 56.4%

SLAC-R-868
Very uniform $\Lambda_c^+ \rightarrow \Lambda \bar{K}^0 K^+$ Dalitz Plot Acceptance Efficiency Parametrization as a Function of $m(\Lambda K_S)$

$E_0 = \text{Average Efficiency}$

Smooth efficiency as a fcn of $(m, \cos \theta)$

- $E_i = \text{fcn(mass)} = 2^{\text{nd}} \text{ order polynomial}$

Weak dependence on $\cos \theta_{\Lambda}$
Isobar Model Description of the $\Lambda_c^+ \rightarrow \Lambda \bar{K}^0 K^+$ Dalitz Plot

\[ A(\Xi[1690]) = \frac{p^L \cdot q^l}{(m_0^2 - m^2) - i m_0 \Gamma(m)} \]

\[ \Gamma(m) = \Gamma(m_0) \frac{q^l m_0}{m q_0^{2l+1}} \]

Fit for $m_0$ & $\Gamma(m_0)$ with $L=0$, $l=0$

\[ A(a_0[980]) = \frac{g_{KK}}{m_a^2 - m_{\bar{KK}}^2 - i g_{KK}^2 \left( \rho_{KK} + \frac{1}{r^2} \rho_{\eta\pi} \right)} \]

$g_{\eta\pi} = 324 \pm 15 \text{ MeV}$ [Crystal Barrel Exp.]

$g_{KK} = 473 \pm 49 \text{ MeV}$ [BaBar Exp.]

$g_{KK} = 473 \pm 49 \text{ MeV}$ [BaBar Exp.]

Isobar Model Description of the $\Lambda_c^+ \rightarrow \Lambda \bar{K}^0 K^+$ Dalitz Plot

\[
|A|^2 = C \left( p_0^2 I_1 + g_{KK}^2 I_2 \right)
\]

Under the assumption of spin 1/2 for the $\Xi(1690)$:

\[
\text{Weak decay yields 4 terms with same structure but different amplitude and phase}
\]

Hence define:

\[
\Lambda a_0(980)^+ - \Xi(1690)^0 K^+ \text{ Interference}
\]

\[
2 p_0 g_{KK} I_1 I_2 k \left( (M_1 M_2 + G_1 G_2) \cos \delta + (G_1 M_2 - G_2 M_1) \sin \delta \right)
\]

\[
M_2 = (m_a^2 - m_{KK}^2)
\]

\[
G_2 = \rho_{\eta\pi} g_{\eta\pi}^2 + \rho_{KK} g_{KK}^2
\]

\[
M_1 = (m_0^2 - m^2)
\]

\[
G_1 = m_0 \Gamma(m)
\]

\[
I_1 = \frac{1}{M_1^2 + G_1^2}
\]

\[
I_2 = \frac{1}{M_2^2 + G_2^2}
\]

\[
m_{KK} = \sqrt{m_{\bar{K}}^2 + m_K^2 + 2 (E_{\bar{K}} E_K - q p' \cos \theta_{\Lambda})}
\]

where $p'$ = momentum of $K^+$ in $(\Lambda K\bar{\eta})$ rest-frame.

Individual Breit-Wigner Intensity Contributions
Partial wave amplitude description of the \((\Xi^- \pi^+)\) system produced in the decay \(\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+\)

Amplitudes of the \((\Xi^- \pi^+)\) system: \(A^{3/2}_{\lambda_f} (\Xi(1530)) \& \ A^{1/2}_{\lambda_f} \) (non-resonant)

Angular distribution of the \(\Xi^-\) produced in the decay of the \((\Xi^- \pi^+)\) system:

\[ I = \sum_{\lambda_i = \pm 1/2, \ \lambda_f = \pm 1/2} \rho_{\lambda_i} \left| D^{1/2*}_{\lambda_i \lambda_f} (\phi, \theta, 0) A^{1/2}_{\lambda_f} + D^{3/2*}_{\lambda_i \lambda_f} (\phi, \theta, 0) A^{3/2}_{\lambda_f} \right|^2 \]

\(\rho_{\lambda_i} \) (i = \pm 1/2) \rightarrow density matrix elements describing the spin population of the \(\Lambda_c^+\)

where, \(\lambda_i = helicity \ of \ (\Xi^- \pi^+) \) system = \(\lambda_i (\Lambda_c^+)\)

\(\lambda_f = \lambda_{\Xi^-} - \lambda_{\pi^+} = \lambda_{\Xi^-}\)
\[
I = \sum_{\lambda_i=\pm 1/2, \lambda_f=\pm 1/2} \rho_{\lambda_i} |d_{\lambda_i}^{1/2} (\theta) A_{\lambda_f}^{1/2} + d_{\lambda_i}^{3/2} (\theta) A_{\lambda_f}^{3/2}|^2
\]

\[
= \rho_{1/2} \left[ |d_{1/2}^{1/2} (\theta) A_{1/2}^{1/2} + d_{1/2}^{3/2} (\theta) A_{1/2}^{3/2}|^2 + |d_{1/2}^{1/2} -1/2 (\theta) A_{-1/2}^{1/2} + d_{1/2}^{3/2} -1/2 (\theta) A_{-1/2}^{3/2}|^2 \right]
+ \rho_{-1/2} \left[ |d_{-1/2}^{1/2} (\theta) A_{1/2}^{1/2} + d_{-1/2}^{3/2} (\theta) A_{1/2}^{3/2}|^2 + |d_{-1/2}^{1/2} -1/2 (\theta) A_{-1/2}^{1/2} + d_{-1/2}^{3/2} -1/2 (\theta) A_{-1/2}^{3/2}|^2 \right]
\]

\[|JM_1, \lambda_1 \lambda_2\rangle = \sum_{L,S} \beta_{LS} |JM_1, LS\rangle; \quad \beta_{LS} = \langle JM_1, LS | JM_1, \lambda_1 \lambda_2\rangle, \quad \text{where} \quad \lambda_1 = \lambda(\Xi) \quad \text{and} \quad \lambda_2 = \lambda(\pi) = 0, \]

\[= \sqrt{\frac{2L+1}{2J+1}} \langle L,0; s, \lambda_1 - \lambda_2 | J, \lambda_1 - \lambda_2 \rangle |s_1, \lambda_1; s_2, -\lambda_2 | S, \lambda_1 - \lambda_2 \rangle.
\]

\[\Rightarrow A_{1/2}^{1/2} = |1/2 1/2, 1/2 0\rangle = \frac{1}{\sqrt{2}} [S_{1/2}^1 - P_{1/2}]
\]

\[\Rightarrow A_{1/2}^{3/2} = |1/2 -1/2, -1/2 0\rangle = \frac{1}{\sqrt{2}} [S_{1/2}^1 + P_{1/2}]
\]

\[\Rightarrow A_{1/2}^{3/2} = |3/2 1/2, 1/2 0\rangle = \frac{1}{\sqrt{2}} [P_{3/2}^3 - D_{3/2}]
\]

\[\Rightarrow A_{1/2}^{3/2} = |3/2 1/2, 1/2 0\rangle = \frac{1}{\sqrt{2}} [P_{3/2}^3 + D_{3/2}]
\]

\[
\frac{dN}{d \cos \theta} = \begin{cases}
\frac{1}{2} |S_{1/2}^1|^2 + |P_{3/2}^3|^2 \left( \frac{1 + 3 \cos^2 \theta}{4} \right) + \sqrt{2} \Re(S_{1/2}^1 P_{3/2}^3^*) \cos \theta & \text{S-P interf.} \\
\frac{1}{2} |P_{1/2}^1|^2 + |D_{3/2}^3|^2 \left( \frac{1 + 3 \cos^2 \theta}{4} \right) + \sqrt{2} \Re(P_{1/2}^1 D_{3/2}^3^*) \cos \theta & \text{P-D interf.}
\end{cases}
\]

\( \text{Cannot distinguish between } (S_{1/2}^1 + P_{3/2}^3) \quad \text{nor between } (P_{3/2}^3 + D_{3/2}^3) \) \quad \text{~however strong } P_{3/2}^3 \text{ wave suggests term containing } S_{1/2}^1, P_{3/2}^3 \text{ amplitudes dominates}
Amplitude Analysis Assuming S and P Waves

\[ \frac{dN}{d \cos \theta} = \left( \left| S^{1/2} \right|^2 + \left| P^{1/2} \right|^2 + \left| P^{3/2} \right|^2 \right)^{1/2} P_0(\cos \theta) + \sqrt{\frac{1}{10}} \left| P^{3/2} \right|^2 P_2(\cos \theta) \]

\[ + \frac{2}{\sqrt{3}} |S^{1/2}||P^{3/2}| \cos(\varphi_S - \varphi_P) P_1(\cos \theta) \]

\[ \sqrt{2} P_0(\cos \theta) \text{ moment} \]

\[ \sqrt{10} P_2(\cos \theta) \text{ moment projects too much signal!!} \]

\[ \Rightarrow \text{need more than S and P waves} \]
Implication of Fits to the $\Xi(1530)^0$ Lineshape

Efficiency-corrected $P_2(\cos\theta)$ moment

$$\langle P_2 \rangle = \sqrt{10} \left( |P_3^{3/2}|^2 + |D_3^{3/2}|^2 + \frac{8}{7} |D_5^{3/2}|^2 + \sqrt{20} \Re \left( S_1^{1/2} D_5^{5/2*} \right) \right)$$

$$\langle P_4 \rangle = \frac{\sqrt{2}}{7} |D_5^{5/2}|^2$$

Efficiency-corrected $P_0(\cos\theta)$ moment

Effect should disappear in $P_0(\cos\theta)$ moment distribution

Expected improvement in fit quality not realized

Structure in $\Xi^- K^+$ i.e. another isobar? Or $(K^+\pi^+)$ $I=3/2$ amplitude contribution?

Poor fit $\Rightarrow$ due to interference with other waves?

Data - Fit

Residuals
Spin measurement of $\Omega^-$ from $\Xi_c^0 \rightarrow \Omega^- K^+$, $\Omega^- \rightarrow \Lambda K^-$ Decays

$\bar{K}^+$
\[ \lambda(K) = 0 \]
$\Xi_c^0 = 0$
$\bar{\Omega}^-$
\[ \Omega^- = 0 \]

$\bar{K}^-$
\[ \lambda(K) = 0 \]

$\Omega$ spin projection ± 1/2 only
$\Rightarrow$ decay angular distr. different
for each assumed spin, $J$

$$\bar{\Xi}_c^0 \rightarrow \Omega^- K^+, \Omega^- \rightarrow \Lambda K^-$$

$\Xi_c^0 \rightarrow 0$

$\Omega^- \rightarrow 0$

$\bar{\Omega}^-$

$\bar{K}^-$

$\lambda(K) = 0$

$\bar{\Lambda}$

$\lambda(\Lambda) = \pm 1/2$

Quantization axis

Babar
PRL 97, 112001(2006)

Data

~ 115 fb$^{-1}$

Background-Subtracted
Efficiency-Corrected

$J_\Omega = 1/2 \Rightarrow I \propto 1$

$J_\Omega = 3/2 \Rightarrow I \propto (1 + 3 \cos^2 \theta)$

$J_\Omega = 5/2 \Rightarrow I \propto (1 - 2 \cos^2 \theta + 5 \cos^4 \theta)$

$\rightarrow$ Fit Prob = $10^{-17}$
$\rightarrow$ Fit Prob = 0.64
$\rightarrow$ Fit Prob = $10^{-17}$

$J_\Omega \geq 7/2$ also excluded: angular distribution increases more steeply near $\cos \theta \sim \pm 1$ and has $(2 J_\Omega - 2)$ turning points.
Measurements of BF(\(B^0 \to \Xi_c \Lambda_c^-\)) and BF(\(B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- \bar{K}\))

- Predictions for B decays to final states with 2 charm baryons \(\Theta(10^{-3})\)
- Belle measurement for BF(\(B \to \Xi_c \bar{\Lambda}_c\)) of \(~1\%\) comparable with predictions

- B decays to final states with only singly-charm final states \(~\Theta(10^{-5})\)

- Rate difference due to final state interactions or intermediate charmonium resonances?
- Use of 3-body decay to study \(\Lambda_c^+ \bar{\Lambda}_c^- \bar{K}\) to investigate resonant structures
  - BF measurement consistent with predictions
  - 2-body mass projections indicative of \(\Xi_c^0\) resonant decay contribution
A Precision Measurement of the $\Lambda_c^+$ Mass

*Using low Q-value decay modes*


First Observation

\[ \Lambda_c^+ \rightarrow \Sigma^0 K_S^0 K^+ \]
264 ± 20 evts
Q ≈ 102 MeV/c^2

Combined measurement

\[ m(\Lambda_c^+) = 2286.46 \pm 0.14 \text{ MeV/c}^2 \]

PDG 2004: $2284.9 \pm 0.6$ MeV/c^2

Baryon (decaying to a $\Lambda_c^+$) masses estimated as mass differences w.r.t. the $\Lambda_c^+$ with PDG $\Lambda_c^+$ mass added $\Rightarrow$ more precise $\Lambda_c^+$ mass measurement affects these baryon mass measurements