Charmed Baryons

A Review of Doubly Charmed Baryons &
New Results

Peter S. Cooper

Fermi National Accelerator Laboratory

Batavia, IL
Double Charm Baryons: SU(4)

- QCD: isodoublet of (ccq) baryons
- Models agree: ground state ~3.5-3.6 GeV/c²
- Lattice concurs: Flynn, et al., hep-lat/030710
Hunting for QQq Baryons

• Expect Cabibbo-favored ccq decay to lead to charm baryon + strange meson or charm-strange baryon + pion

• For Selex the $\Lambda_c^+$ dominates charm baryons; some $\Xi_c^+$ too, so it’s natural to look for states like $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$, $pD^+ K^-$, $\Xi_c^+ \pi^+ \pi^-$ for ccd, $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$, $\Xi_c^+ \pi^+ \pi^+ \pi^-$ for ccu.

• Use standard single-charm cuts to select $\Lambda_c^+$ - no optimization

• Reconstruct additional vertex between primary and charm vertices. No PID on $K^-$ or $\pi^-

• Expect combinatoric background when $L_1 \sim \sigma$
Features of First Selex $\Xi_{cc}^+$ Observation

- First candidate for new baryon comes from baryon beam experiment:
  - $\Xi_{cc}^+(ccd) \rightarrow \Lambda_c^+ K^- \pi^+$ Cabibbo-favored spectator mode
  - State seen from $\Sigma^-$, p but not $\pi^-$

- Lifetime is very short – <35 fs at 90% confidence. Disagrees with prediction from HQ single charm lifetime hierarchy.

- Cross section is large! Involves 40% of Selex $\Lambda_c^+$ production. Fragmentation predictions are much, much, smaller.

- Anomalously large charmed baryon yield in a hyperon beam (WA62) is why we did Selex in the first place.
Improved Selex Background Analysis

• Short lifetime for $\Xi_{cc}^+$: dominant background is combinatoric but low – hard to pin down exact shape from data sample. Absolutely normalized combinatoric background by event mixing.

• Select $\Lambda_c^+$ reconstructions from events having no $\Xi_{cc}^+$ candidates
  • Take opposite-sign track pairs ($K^- \pi^+$) from different events
  • Build statistics by re-using each $\Lambda_c^+$ 25 times and renormalizing output mass plot to reflect this.

• This method can be applied to any final state dominated by combinatoric background and always has absolute normalization – no adjustments.
Application: New $\Xi_{cc}^+ \rightarrow pD^+K^-$ Decay Mode

- $\Xi_{cc}^+ \rightarrow pD^+K^-$ is quark rearrangement from $\Lambda_c^+K^-\pi^+$
- Q-value of decay is smaller than that for $\Lambda_c^+K^-\pi^+ \Rightarrow$ lower rate
- Check physics background with wrong sign $pD^+K^+ -$ no peaks
- Event-mixed background (green) matches background fit to data (solid line) – confirms signal.
- Mass matches within 1 MeV of $\Lambda_c^+K^-\pi^+$ value

Combined $\Xi_{cc}^+$ Distributions

- Fit Gaussian with width fixed from MC to $pD^+K^-$ data to fix mass: $3518 \pm 3$ MeV/c².

- Mass was $3519 \pm 2$ MeV/c² from $\Lambda_c^+K^-\pi^+$ mode:

- Combined mass:
  \[ M(\Xi_{cc}^+) = 3518.7 \pm 1.8 \text{ MeV/c}^2 \]
  \[ \frac{\Gamma(pD^+K^-)}{\Gamma(\Lambda_c^+K^-\pi^+)} = 0.20 \pm 0.12 \]
Doubly Charged Double Charm: $\Xi_{cc}^{++}(3780)$

- $Q=2$ candidates in $\Lambda_c^+ K^- \pi^+ \pi^+$ final state from $\Sigma^-$ beam. No new cuts.

- (We actually found this one first)

- See broad structure at 3780 MeV/c$^2$ – wider than resolution.

- Combinatoric background from event mixing (green) describes background well in shape and normalization.

- Have $ccu$ excited state like $\Lambda_c^{*+}$. 

```
\begin{figure}
\hspace{1cm}
\includegraphics[width=0.5\textwidth]{chart.png}
\end{figure}
```
More About the $\Xi_{cc}^{++}(3780)$

• If it’s an excited state, is there a chain decay? Look for $\Xi_{cc}^{++*} \rightarrow \Xi_{cc}^+ \pi^+$

**PRELIMINARY EVIDENCE:** All the $\Xi_{cc}^{++}$ signal events can be accounted for by chain decays.

• Much more work needs to be done to understand this state, but double charm system seems to follow baryon excitation dynamics with pion chain decays.
Search for $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+$ Decay Mode

- Selex first observed Cabibbo-suppressed decay $\Xi_c^+ \rightarrow pK^- \pi^+$

- This $\Xi_c^+$ mode has excellent momentum resolution – good to use in vertexing.

- Just like in $\Lambda_c^+$ case, proton and kaons are RICH-identified

- Cabibbo-suppressed mode: more background.

Preliminary

Ibrahim Torres
UA San Luis Potosi (Mexico)
The $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+$ Signal

- Make reconstruction. No new cuts on tracks. Vertex significance > 0
- Another narrow peak $\sim 3520$ MeV/c$^2$ Width agrees with MC calculation.
- Event-mixed background (green) describes sidebands well.
- Cabibbo-suppressed mode: more background.
Recent Analysis Developments

• Double charm analysis is ‘statistics-challenged’ – few events

• Recent tracking and other improvements raise single charm yields by 50% [e.g. $N(\Lambda_c^+) 1630 \rightarrow 2450$]

• We understand double charm background well (event mixing)

• Possible New Analysis Choice - relax cuts to accept more background but increase signal

• Also improve fit on $\Xi_{cc}^+$ vertex for lifetime studies
$\Xi_{cc}^+$ Lifetime Study

- Experimental Problem: $c\tau \sim \sigma$ ... events go away by $4\sigma$
- Decay curve measured in 10 fs bins!
- Plot proper time for events in same mass band from signal and sideband
- Uncorrected lifetime always too long because of selection cuts
- Use MC to get true lifetime
- Detection efficiency goes down with $\tau$.
- Corrected Lifetime $15^{+10}_{-??}$ fs.
- Still can’t exclude $\tau=0$. 

![Graphs showing data and plots]
Selex Doubly Charmed Baryons ~2003

An excited state and a pair of isodoublets?
(an internal Selex plot)
Working Without a Net

- Selex has seen and known about these states for 5+ years
- No one else sees them.
  - Babar & Belle enthusiastically report their non-observations
  - Nothing seen in Focus (photo-production) or E791 ($\pi^{-}$ beam)
  - CDF & D0 are awash in combinatorics ($\tau[B] \sim 1400$ fs)
  - No new opportunities until LHCb
- Selex has chosen to proceed very slowly, with extreme caution. Confirm, confirm, confirm (e.g. 3 modes)
- The damned things won’t go away! They keep reappearing.
- An now for something completely (nearly) the same :) .
Where is the $\Xi_{cc}^{++}(ccu)$ ground state?

- $\Xi_{cc}^{++}(ccu)$ [3780] isn’t it (too wide too high)
- Look in $\Xi_{cc}^{++}(ccu) \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+, \Xi_c^+ \pi^+ \pi^+ \pi^-$
- Apply all the same techniques to 3 prong vertices
  - daughter charmed baryon mass within 20 MeV/c$^2$
  - $L/\sigma_{(ccu)} > \{1, 1.25\}, \{7, 10\} < L/\sigma_{(cu\{d,s\})} < 20$
  - $P_t(ccu) > 0.2$ GeV/c
  - Suppress events with more than one $ccu$ track combo
- Lifetime guess from $L/\sigma$ looks “larger” than $\Xi_{cc}^+$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Lambda_c^+ K^- \pi^+ \pi^+$</th>
<th>$\Xi_c^+ \pi^+ \pi^+ \pi^-$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ [MeV/c$^2$]</td>
<td>3452(3.4)</td>
<td>3451(3.8)</td>
<td>3542(2.5)</td>
</tr>
<tr>
<td>Sig / Bkg</td>
<td>14 / 9</td>
<td>10.2 / 3.8</td>
<td>26 / 14</td>
</tr>
<tr>
<td>Gaussian Sig.</td>
<td>4.2$\sigma$ (4.6)</td>
<td>3.8$\sigma$ (4.2)</td>
<td>6.1$\sigma$</td>
</tr>
<tr>
<td>Poisson excess</td>
<td>$&lt;6.5 \times 10^{-5}$</td>
<td>$&lt;3.6 \times 10^{-4}$</td>
<td>$&lt;1.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
$\Xi_{cc}^{++}(ccu)$ ground state II

- We see the state we saw in 2003 again without any “additional cuts”. 2 mode with a consistent mass
- Combined Poisson excess prob is $1.1 \times 10^{-8}$
- All different events, analysis done twice.

Physics

- Isospin splitting is $67 \pm 3$ MeV ??? Must be 2 isodoublets

=> $\Xi_{cc}^{+}(3519)$ is not a ground state

- Why do we see it as a weak decay?

=> photon emission highly suppressed ($2\gamma$) [remember $2S \rightarrow 1S$ Hydrogen?]

- There must be 2 more states to find.

- This spectroscopy is interesting!
Selex  \( \Lambda_c^+ \to \Lambda^0(1520) e^+ \nu \)

- Old Cleo 1.x limit [PLB 323,219(1994)] gives
  \[ Br[\Lambda_c^+ \to e^+X\nu] < 3.4 \pm 0.4\% , \]
  \[ Br[\Lambda_c^+ \to \Lambda^0e^+\nu] = 2.1 \pm 0.6\% \]
  What about the rest?

- Search for \( \Lambda_c^+ \to \Lambda^0(1520)e^+\nu, \Lambda^0(1520) \to pK^- \)

- Technique
  - Matched \( pK^-\pi^+ \) & \( pK^-e^+ \) samples
  - \( K^- + pe^+ \) event mixing for combinatoric backgrounds
  - \( e^+ \) PID with TRDs (E715 \( \Sigma^- \beta \) decay TRDs)
  - Remove \( \phi^0 \to K^+K^- \) & \( \Xi^0(1690) \to \Sigma^+K^- \) reflections
  - Yield before eTRD is 193 \( \pm 43 \) pK\(^-\)e\(^+\) events &
    1461\( \pm 83 \) \( \Lambda_c^+ \to pK^-\pi^+ \) events.
Selex $\Lambda_c^+ \rightarrow \Lambda^0(1520) e^+ \nu$

- Weight signal and background events by measured energy dependent eTRD efficiency
- Background subtracted weighted yield is $143 \pm 12$ events.
- Relative mode efficiency is $1.213 \pm 0.012$
- After correcting for efficiency and $Br[\Lambda^0(1520) \rightarrow pK^-] = 24.34\%$ we get:
  $Br[\Lambda_c^+ \rightarrow \Lambda^0(1520)e^+\nu] = 3.04 \pm 0.62 \pm 0.79\%$
  $1.44 \pm 0.34$ times $Br[\Lambda_c^+ \rightarrow \Lambda^0e^+\nu]$
- More than just combinatoric backgrounds. Other excited states?
- $\Lambda_c^+ \rightarrow \Lambda^0(1520)\mu^+\nu$ and other excited states are still under study
Summary 1

• Double charm is here to stay

• Selex has seen 3 double charmed baryon states in 3, 1 and 2 decay modes.

• $\Xi_{cc}^{++}(3520)$ seen decaying into three different single charm states.

• $\Xi_{cc}^{++}(3780)$ excited state shows chain decay via pion emission.

• $\Xi_{cc}^{++}(3452)$ ground state observed in two different decay modes. Splitting is too large (67 MeV) for this state to sensibly be the isospin partner of the $\Xi_{cc}^{++}(3519)$. Radiative decays are suppressed?

• This logic requires at least two more weakly decaying states, the isospin partners of the $\Xi_{cc}^{++}(3452)$ ground state and the partner of the EM decay suppressed $\Xi_{cc}^{++}(3519)$.

• Selex has some hints of these but makes no claims now.

• No report yet on the third double charm baryon, the $\Omega_{cc}^{+}(ccs)$
Summary II

- Double charm production comes only from baryon-baryon interactions with VERY large cross section – totally inconsistent with fragmentation production.

- Double charm baryons NOT seen in fragmentation processes at Belle, BaBar, $\gamma$ or $\pi^-$ production – consistent with Selex baryon-only production.

- If this is correct LHCb should make these states copiously. If they trigger on them they should see them.

- $\Lambda_c^+$ Semi-leptonic decay to excited state seen and measured
  
  143 ± 12 events seen
  
  $\text{Br}[\Lambda_c^+ \rightarrow \Lambda^0(1520)e^+\nu] = 3.04 \pm 0.62 \pm 0.79\%$

- Both charmed baryon physics and Selex are far from being finished or becoming uninteresting
Ok Galik - let’s see if I can dodge the fruit

Selex group meeting @ UASLP  June 2006