Recent Results on Doubly Charmed Baryons

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Outline

➢ Brief theory and model review
➢ Search methods and Previous results
➢ Where are the isospin partners?
➢ New States - A pair of Isodoublets?
➢ What are these? Properties and production
➢ Conclusions
First Observation of the Doubly Charmed Baryon $\Xi_{cc}^{+}$


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We observe a signal for the doubly charmed baryon $\Xi_{cc}^{+}$ in the charged-baryon mode $\Xi_{cc}^{+} \rightarrow \Xi_{cc}^{0} K^{+}$ in this from SELEX, the charm-hadron physics experiment at Fermilab. We observe an excess of 15.9 events over an expected background of 6.1 ± 0.5 events, a statistical significance of 13.9σ. The observed mass of this state is 3048 ± 1 MeV/c², consistent with resolution; its lifetime is less than 35 fs at 90% confidence.

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5/5
Some Nomenclature

In this talk we replace PDG names with suggestive labels. While SU$_4$ is badly broken by the charm mass it still classifies all the states. There are many model predictions in the 3.5-3.8 GeV range.

\[ \Xi_{cc}^{++}(J=1/2) = ccu^{++} \]
\[ ccu^{++} \rightarrow \Lambda_c^+ K \pi^+ \pi^+ \]

\[ \Xi_{cc}^{+(J=1/2)} = ccu^+ \]
\[ ccd^+ \rightarrow \Lambda_c^+ K^{-}\pi^+ \]

\[ \Xi_{cc}^{++}(J=3/2) = ccu^{*++} \]
\[ ccu^{*++} \rightarrow \Lambda_c^+ K^{-}\pi^+ \pi^+ \]
Many Doubly Charmed Baryon Models

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Model</th>
<th>$\Xi_{cc}(J=3/2)$</th>
<th>$\Xi_{cc}(J=1/2)$</th>
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<tr>
<td>Bjorken</td>
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<td>Phenom</td>
<td>3.70 GeV</td>
<td>3.64 GeV</td>
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<td>Fleck &amp; Richard</td>
<td>1989</td>
<td>Bag</td>
<td>3.636</td>
<td>3.516</td>
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<tr>
<td>Fleck &amp; Richard</td>
<td>1989</td>
<td>Quarkonium</td>
<td>3.741</td>
<td>3.613</td>
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<tr>
<td>Roncaglia</td>
<td>1995</td>
<td>Feynman/Hellamn</td>
<td>3.81</td>
<td>3.66</td>
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<tr>
<td>Ellis</td>
<td>2002</td>
<td>Phenom</td>
<td>3.711</td>
<td>3.651</td>
</tr>
</tbody>
</table>

**Sampling of Models**

**Overall Features**

- ground states near 3.6 GeV
- ground states I=1/2 multiplets degenerate
- Hyperfine splitting around 60-120 MeV
- Most models predict on electromagnetic hyperfine transitions
- Some models predict pionic transitions for J=3/2 - J=1/2
- Model dependent predictions for orbital and radial excitations
SELEX Experiment at Fermilab
Data taken 1996-7 in P-Center @ FNAL

SELEX Experiment
- Forward charm production $x_F > 0.1$
- $\pi^- p$ and $\Sigma^-$ beams @ 600 GeV
- Typical boost ~100
- RICH PID above 22 GeV
- 20 plane - 4 view svx - $\sigma > 4 \mu m$
Experimental Evidence from 2002

**SELEX** reported 3 significant high mass peaks

- $\Lambda_c^+ K^- \pi^+$
- $\Lambda_c^+ K^- \pi^+ \pi^+$
- $\Lambda_c^+ K^- \pi^+ \pi^+ \pi^+$

We argued that these states are doubly-charmed baryons
Search strategy and results

- **ccq** weak decays into **csq**. Look for charm, strange and baryon in the final state, starting with Selex’s $\Lambda_c^+$ sample: $\Lambda_c^+ K^- \pi^+$, $\Lambda_c^+ K^- \pi^+ \pi^+$

- Look for new secondary vertex between primary and $\Lambda_c^+$

- No RICH PID on new $K^- \pi^+$ tracks (5-20 GeV/c - too soft)

- All cuts set (and fixed!) from previous searches (e.g. $L/\sigma > 1$)

**ccd^+(3520) results**

- Fix $\Lambda_c^+$ mass to 2284.9 MeV/c^2 (PDG)

- Right sign has a mass peak at 3520 consistent with resolution. Wrong sign ($\Lambda_c^+ K^+ \pi^-$) has no structure.

- 15.8 signal, 6.2 background, $15.8/\sqrt{6.2} = 6.3\sigma$

- Possion Prob=1x10^-6; anywhere, 1.1x10^-4
ccd\(^+\)(3520) Iso-partner?

- Same cuts as ccd\(^+\) \(\sim 3.5\sigma\) hint in \(\Lambda_c^+ K^- \pi^+ \pi^+\)
- Nothing in wrong sign: \(\Lambda_c^+ K^+ \pi^- \pi^+\)
- \(\cos \theta_K^*\) for mass sidebands (soft vtx tracks). Set cut with \(S_{MC}/\sqrt{B_{tot}}\), \((\cos \theta_K^* > -0.6)\)
- MC signal is flat, expect: \(s \rightarrow 0.8s, b \rightarrow b/3\)

ccu\(^++\) results

- Right sign has a mass peak at 3460 consistent with resolution, \(L=0\). Wrong sign \((\Lambda_c^+ K^+ \pi^- \pi^-)\) - no structure.
- 7.1 signal, 0.9 background, 7.5\(\sigma\), Possion Prob \(< 10^{-5}\)
- 60 MeV is too big for an isospin splitting.

Doubly charmed baryons: \(\Xi_{cc}^{++}(3460), \Xi_{cc}^+(3520)\)
Hard to understand these as an Isodoublet
Where are the Iso-partners?

- MC signal for phase space ccd\(^+(3520)\) decay is flat
- What happens if we apply cos \(\theta_k^* > -0.6\) cut here?
- ccd\(^+(3520)\) strongly attenuated: \(16/6 \rightarrow 5/1\)
- ccd\(^+(3520)\) clearly not like phase space \(\rightarrow L>0\)
- Not Isodoublet with 3460 – different angular dist

**New ccd\(^+(3443)\) candidate now very significant**

- Before cut we ignored bump at 3443 – only 4\(\sigma\)
- Background departs - bump at 3443 remains
- 7.4 signal, 1.6 background, 5.8\(\sigma\), Prob<3.8x10\(^{-5}\)
- Consistent with \(L=0\) : \(11/7 \rightarrow 7.4/1.6\)
- A partner for the ccd\(^{++}(3460)\) \(\Delta M=17\) MeV
ccd\(^+(3520)\) Iso-partner?

- \(\text{ccd}\(^+(3520)\) mostly has \(\cos \theta^*_{K} < -0.6\)

- \(\Lambda_c^+\) and \(K^-\) back-to-back: \(\cos \theta^*_{K} \cos \theta^*_{\Lambda_c} < -0.25\) keeps 90% of the \(\text{ccd}\(^+(3520)\) signal

- Apply to the ccu\(^++\) sample to search for an Iso-partner for the \(\text{ccd}\(^+(3520)\)

- No signal / little background with \(L/\sigma > 1\).
  Try reducing cut to \(L/\sigma > 0.25\)

**New ccu\(^++(3443)\) candidate now very significant**

- Bump at 3443 remains – background departs
- 7.4 signal, 1.6 background, 5.8\(\sigma\), Prob<3.8x10\(^{-5}\)
- Consistent with \(L > 0\)
- A partner for the \(\text{ccd}\(^+(3520)\) \(\Deltam=21\) MeV
Recap - A Pair of Isodoublets?
Lifetimes

- Selex uses reduced proper lifetime technique
  \[ c\tau = \frac{m}{p_z}[L - L_{\text{min}}], L_{\text{min}} = \sigma \]
- Make simulation templates for different lifetimes
- Lifetimes of all states near our resolution limits
  \(< 30 \text{ fsec} ; \ 0 \text{ not ruled out} \)

Model Predictions

- Guberina, et.al. HQET + 1/M_Q
  - \( \tau[\Xi_{cc}^+] \sim 200 \text{ fsec} \)
  - \( \tau[\Xi_{cc}^{++}] \sim 1000 \text{ fsec} \)
- Observed states don’t seem to follow predictions
- How can the decay rate for ccq states be so large?
# Production

**Beam Hadrons**

<table>
<thead>
<tr>
<th>Luminosity fraction</th>
<th>$\Sigma^-$</th>
<th>proton</th>
<th>$\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ccu++(3443) signal/ sidebands</td>
<td>6 /10</td>
<td>2 / 2</td>
<td>0 / 1</td>
</tr>
<tr>
<td>ccu++(3460) signal/ sidebands</td>
<td>8 / 9</td>
<td>3 / 0</td>
<td>0 / 0</td>
</tr>
<tr>
<td>ccd+ (3520) signal /sidebands</td>
<td>18/18</td>
<td>4 / 1</td>
<td>0 / 1</td>
</tr>
<tr>
<td>ccd+ (3541) signal /sidebands</td>
<td>7/10</td>
<td>4 / 1</td>
<td>0 / 1</td>
</tr>
</tbody>
</table>

| Total | 86 | 17 | 3 (11?) |

Dominantly produced by baryon beams

for ccd+  $<x_F> \sim 0.35$ (200GeV), $<p_t> \sim 1$ GeV/c  - like single charm SELEX

> **Focus (E831) has looked in 250 GeV/c photo-production**

   NO signals with 20K $\Lambda_c^+$, many other modes searched - no signals anywhere

> **E791 has looked in 250 GeV/c $\pi^-$ production** - no signals
Conclusions

- Selex reports 4 high mass baryon states in an apparent pair of Isodoublets.
  - Lower mass doublet is consistent with $L = 0$ decay
  - Upper mass doublet is inconsistent with $L = 0$ decay
- All 4 states decay like doubly charmed baryons with very short lifetimes (<30fs)
- The splitting (~19 MeV) is large for an isodoublet.
- Radiative decays (e.g. $3520 \rightarrow 3443 \gamma$) suppressed below weak decay rate?

Where do these states fit into our theoretical framework?

- Bardeen, Eichten and Hill and suggest these might be the spectroscopy of the cc “nucleus” of a ccq baryon:
  \[ J^\pi = 1/2^+ \left[ c \uparrow c \uparrow L = 0, J^\pi = 1^+ \right] q \downarrow \quad J^\pi = 1/2^- \left[ c \uparrow c \downarrow L = 1, J^\pi = 1^- \right] q \downarrow \]
- Predicted splitting consistent with observed 78 MeV
- First EM transition is $M2$. Decay rate ~ 1/1.5 [fsec]
Conclusions (2)

Other Interpretations

- Narrow very high mass singly charmed baryon states?
  - Like Babar’s $D_s^*(2317)$ and Cleo’s $D_s^*(2460)$?
  - Quark content of $\Lambda_c^+ K^- \pi^+ \pi^+$ is a pentaquark $[c s u \bar{d} u]$ not a baryon
  - Why should there be ultra narrow baryon states with $Q \sim 500$ MeV?

Open questions

- Production
  - $1/2$ of Selex’s $\Lambda_c^+$ of come though these states
  - Only seen in forward production by baryons, no $\pi$ or $\gamma$ production
- Radiative decay rate – can EM really be slower than weak?
- Who else could confirm? CDF / D0, Belle/Babar, BTeV / LHCb, Compass Selex ($pD^+K^-$)
Selex observes two Pair of Doubly Charmed Baryons: Two Isodoublets?