Evidence for Doubly Charmed Baryons at SELEX

Quarkonium 2003   September 21, 2003
Peter S. Cooper
Fermi National Accelerator Laboratory

Outline

➢ Brief theory and model review
➢ Search methods and Previous results
➢ Where are the isospin partners?
➢ New States  - A pair of Isodoublets?
➢ Excited State of Double Charm
➢ Conclusions
First Observation of the Doubly Charmed Baryon \( \Xi_{cc}^{+} \)


(SELEX Collaboration)

We observe a signal for the doubly charmed baryon \( \Xi_{cc}^{+} \) in the charged decay mode \( \Xi_{cc}^{+} \to \Lambda \bar{K} K^+ \) at \( \sqrt{s} = 191 GeV \) in this \( \Xi_{cc} \) measurement. We observe an excess of \( 15 \pm 7 (8) \) events over the expected background of \( 6.8 \pm 1.9 \) events, with a significance of \( 5.4 \sigma \). The observed mass of this state is \( 3900 \pm 100 \) MeV/c\(^2\), consistent with resonance; its lifetime is less than 3.3 fs at 90% confidence.

DOI: 10.1103/PhysRevLett.89.112001

PACS numbers: 14.65.Ha, 13.20.Fc

We observe a signal for the doubly charmed baryon \( \Xi_{cc}^{+} \) in the charged decay mode \( \Xi_{cc}^{+} \to \Lambda \bar{K} K^+ \) at \( \sqrt{s} = 191 GeV \) in this \( \Xi_{cc} \) measurement. We observe an excess of \( 15 \pm 7 (8) \) events over the expected background of \( 6.8 \pm 1.9 \) events, with a significance of \( 5.4 \sigma \). The observed mass of this state is \( 3900 \pm 100 \) MeV/c\(^2\), consistent with resonance; its lifetime is less than 3.3 fs at 90% confidence.

DOI: 10.1103/PhysRevLett.89.112001

PACS numbers: 14.65.Ha, 13.20.Fc

We observe a signal for the doubly charmed baryon \( \Xi_{cc}^{+} \) in the charged decay mode \( \Xi_{cc}^{+} \to \Lambda \bar{K} K^+ \) at \( \sqrt{s} = 191 GeV \) in this \( \Xi_{cc} \) measurement. We observe an excess of \( 15 \pm 7 (8) \) events over the expected background of \( 6.8 \pm 1.9 \) events, with a significance of \( 5.4 \sigma \). The observed mass of this state is \( 3900 \pm 100 \) MeV/c\(^2\), consistent with resonance; its lifetime is less than 3.3 fs at 90% confidence.

DOI: 10.1103/PhysRevLett.89.112001

PACS numbers: 14.65.Ha, 13.20.Fc

We observe a signal for the doubly charmed baryon \( \Xi_{cc}^{+} \) in the charged decay mode \( \Xi_{cc}^{+} \to \Lambda \bar{K} K^+ \) at \( \sqrt{s} = 191 GeV \) in this \( \Xi_{cc} \) measurement. We observe an excess of \( 15 \pm 7 (8) \) events over the expected background of \( 6.8 \pm 1.9 \) events, with a significance of \( 5.4 \sigma \). The observed mass of this state is \( 3900 \pm 100 \) MeV/c\(^2\), consistent with resonance; its lifetime is less than 3.3 fs at 90% confidence.

DOI: 10.1103/PhysRevLett.89.112001

PACS numbers: 14.65.Ha, 13.20.Fc
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>Ξcc(J=3/2)</th>
<th>Ξcc(J=1/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bjorken</td>
<td>1986</td>
<td>Phenom</td>
<td>3.70 GeV</td>
<td>3.64 GeV</td>
</tr>
<tr>
<td>Fleck &amp; Richard</td>
<td>1989</td>
<td>Bag</td>
<td>3.636</td>
<td>3.516</td>
</tr>
<tr>
<td>Fleck &amp; Richard</td>
<td>1989</td>
<td>Quarkonium</td>
<td>3.741</td>
<td>3.613</td>
</tr>
<tr>
<td>Roncaglia</td>
<td>1995</td>
<td>Feynman/Hellamn</td>
<td>3.81</td>
<td>3.66</td>
</tr>
<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

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⁺ ~3.5σ 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 $S_{\text{MC}}/\sqrt{B_{\text{tot}}}$, $(\cos \theta^*_K > -0.6)$
- 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, 7.5σ, 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 $\text{ccd}^+(3520)$ decay is flat
- What happens if we apply $\cos \theta_K > -0.6$ cut here?
- $\text{ccd}^+(3520)$ strongly attenuated: $16/6 \to 5/1$
- $\text{ccd}^+(3520)$ clearly not like phase space $\to L>0$
- Not Isodoublet with 3460 – different angular dist

**New $\text{ccd}^+(3443)$ 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<$3.8\times10^{-5}$
- Consistent with $L = 0$ : $11/7 \to 7.4/1.6$
- A partner for the $\text{ccu}^{++}(3460)$ $\Delta M=17$ MeV

Quarkonium-2003

Peter S. Cooper - Fermilab
**ccd⁺(3520) Iso-partner?**

- **ccd⁺(3520)** mostly has $\cos \theta_K^* < -0.6$
- $\Lambda_c^+ \text{ and } K^-$ back-to-back: $\cos \theta_K^* \cos \theta_{\Lambda_c}^* < -0.25$ keeps 90% of the **ccd⁺(3520)** signal
- Apply to the ccu++ sample to search for an Iso-partner for the **ccd⁺(3520)**
- No signal / little background with $L/\sigma > 1$. Try reducing cut to $L/\sigma > 0.25$

**New ccu++(3541) candidate now very significant**

- Bump at 3541 remains – background departs
- 7.4 signal, 1.6 background, $5.8\sigma$, $\text{Prob}<3.8 \times 10^{-5}$
- Consistent with $L > 0$
- A partner for the **ccd⁺(3520)** $\Delta M = 21 \text{ MeV}$
Recap - A Pair of Isodoublets?

Mass 3520 MeV/c²
Sigma 3 MeV/c²
\( \Lambda_c^+ K^- \pi^+ \)

Mass 3443 MeV/c²
Data \( \cos \theta_{K^-} = -0.6 \)
\( L/\sigma > 1 \)
\( \text{sig/bkg} \ 7.4/1.6 \)
\( \text{Poisson Prob} < 3.8 \times 10^{-3} \)

\( \Lambda_c^+ K^- \pi^+ \)
\( \text{ccu}^+ \)

3520 MeV
21 MeV
3443 MeV
17 MeV
3460 MeV
78 MeV
3541 MeV

Mass 3460 MeV/c²
\( \Lambda_c^+ K^- \pi^+ \pi^0 \)

\( \Lambda_c^+ K^- \pi^+ \pi^0 \)

\( \Lambda_c^+ K^- \pi^+ \pi^- \)

\( \text{L} > 0 \)
\( \text{L} = 0 \)

\( \cos(\theta_{K^-}) > -0.6 \)

\( 7.1/\nu(9) = 7.5 \sigma \)

Poisson Prob
< 10^{-3}
Excited State of Double Charm

• SELEX has a broad $Q=2$ excitation 320 MeV above the $ccu(3460)$

• Similar to the p-wave $\Lambda_c^+$ doublet at 325 MeV above the ground state
Pionic Transition to ccd(3520)

- Remove slow pion from $\Lambda_c^+ K^- \pi^+ \pi^+$
  - Peak at 3520 MeV/c\(^2\)
  - Sig/bkg 9.6/3.4
  - Prob. $< 5.3 \times 10^{-6}$

- Plot Q=1 mass spectrum

Ellicity distribution of slow pion in ccd(3780) rest frame suggests p-wave decay

- Consistent with HQET picture and double charm interpretation
Conclusions

- Selex reports 4 high mass baryon states in a pair of Isodoublets.
  - Lower mass doublet is consistent with \( L = 0 \) decay
  - Upper mass doublet is inconsistent with \( L = 0 \) decay
  - 5th state with strong decay seen (ccu++(3780) \( \rightarrow \) ccd+(3520) \( \pi^+ \)).

- 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 (cont)

Other Interpretations

- Narrow very high mass singly charmed baryon states?
  - Like $D_s^*(2317)$ and $D_s^*(2460)$?
  - Quark content of $\Lambda_c^+K^-\pi^+\pi^+$ is a pentaquark $[csu\bar{d}u]$ not a baryon
  - Why should there be ultra narrow baryon states with $Q\sim500$ 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 ($pD^*K^-$)
A possible picture

Quarkonium-2003

Peter S. Cooper - Fermilab
Additional Slides
Lifetimes

- Selex uses reduced proper lifetime technique
  \[ c\tau = \frac{m}{p_z} \left[ L - L_{\text{min}} \right], L_{\text{min}} = \sigma \]
- 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></th>
<th>$\Sigma^-$</th>
<th>proton</th>
<th>$\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity fraction</td>
<td>0.77</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<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