High Mass States in SELEX
Have Doubly-charmed Baryons Been Discovered?

Fermilab Wine and Cheese
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Outline

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\item (very!) Brief Theory Review
\item Results from Previous Experiments
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\item Selex Single-Charm Baryon Review
\item Observation of High Mass States
\item Are These States Double-Charm Baryons?
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High Mass States in SELEX

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Flavor-Independent QCD Demands Double-Charm Baryons

- Broken SU(4) provides accurate classification of baryon states.

- All predicted states with $N_{ch} \leq 1$ have been observed.

- Double- and Triple-Charm Baryons must exist.

- Characteristics $\sim$ charm meson spectra
  - ccq potential for cc in $\{3\}$ state is $1/2\,\bar{c}q$ potential
  - cc system in HQET approximation provides static color source to bind $q$, analogous to D-meson system.
  - finite $m_c$ leads to 3-body effects in binding

SU(4) Baryon Multiplets
Many Models, Many Predictions

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<th>author</th>
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<th>model</th>
<th>$\Xi_c(J = 3/2)$</th>
<th>$\Xi_c(J = 1/2)$</th>
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<td>Roncaglia et al.</td>
<td>1995</td>
<td>Feynmann/Hellman</td>
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</table>

Sampling of ccq mass predictions

Overall features of models:
- ground state near 3.6 GeV/$c^2$
- hyperfine splitting around 60-120 MeV/$c^2$

- some models predict pionic transitions for $3/2 \rightarrow 1/2$
- most potential model calculations based on non-charmed decuplet-octet splits predict only electromagnetic transitions.
- Model-dependent predictions for orbital, radial excitations
Some Nomenclature

In this talk we replace PDG names by suggestive labels.

- $\Xi_{cc}^{++}(J=1/2) \equiv \text{ccu}^{++}$
  
  decay: $\text{ccu}^{++} \rightarrow K^-\pi^+\pi^+\Lambda_c^+$

- $\Xi_{cc}^+(J=1/2) \equiv \text{ccd}^+$
  
  decay: $\text{ccd}^+ \rightarrow K^-\pi^+\Lambda_c^+$

- $\Xi_{cc}^{++}(J=3/2) \equiv \text{ccu}^{+++}$
  
  decays:
  
  $\text{ccu}^{+++} \rightarrow K^-\pi^+\pi^+\Lambda_c^+$
  and $\text{ccu}^{+++} \rightarrow \text{ccd}^+\pi^+$
Previous Experimental Evidence
Experimental Evidence Today - a Preview

Selex reports 3 significant high-mass peaks

\[ \Lambda_c^+ K^- \pi^+ \]

Mean 3520 MeV/c^2

\[ \frac{\text{signal}}{\sqrt{\text{back}}} = 6.4\sigma \]

\[ \Lambda_c^+ K^+ \pi^+ \]

Mean 3460 MeV/c^2

\[ \text{Sigma 3.5 MeV/c}^2 \]

\[ \frac{\text{signal}}{\sqrt{\text{back}}} = 5.6\sigma \]

\[ \Lambda_c^+ K^- \pi^+ \pi^+ \]

Mean 3780 MeV/c^2

\[ \text{Sigma 24 MeV/c}^2 \]

\[ \frac{\text{signal}}{\sqrt{\text{back}}} = 4.5\sigma \]

We will argue that these states are doubly-charmed baryons.
SELEX Apparatus Features

- Forward production
- $\pi$, $\Sigma^-$, $p$ beams
- Typical Lorentz Boost $\sim 100$
- RICH identification above 25 GeV/c
Vertex Spectrometer Performance

- transverse vtx resolution 8-15 μm
- 20 highly-efficient vertex planes overdetermine tracks, reduce tracking confusion in high-multiplicity events
- target foils 0.8-2.2 mm thick with 1.5 cm period to localize primary int
SELEX Single Charm Analysis

- Decay vertex separation significance $L/\sigma$
- Charm vector momentum points back to primary: cut on $(b/\sigma_b)^2$ (point-back cut)
- Decay vertex lies outside target material (space cut)

$\Lambda_c^+ \rightarrow pK^-\pi^+$ sample used to search for double charm
SELEX Charm Selection Criteria

Charm Selection Cuts for single charm studies:

- secondary vertex significance:
  - $L/\sigma \geq 1$ for short-lived states $(\Xi_c^0, \Omega_c^0)$
  - $L/\sigma \geq 8$ for long-lived states $(\Lambda_c^+, \ldots)$

- Pointback $\leq 4$ ($2 \sigma_b$)

- second largest miss significance among decay trks $\geq 4$.

$\Lambda_c^+$ event

- primary vertex tagged by beam track
- secondary vertex must lie outside material
SELEX Double Charm Baryon Search Strategy

2 vertices to consider, L/σ cuts

- ccq baryons can decay to cqq baryon; look for \( \Lambda_c^+ \) plus extra vertex
- Cabibbo-allowed modes: \( c \rightarrow s + W^+ \) ⇒ require \( K^- \) (not \( K^+ \)) at second vertex
- No RICH PID on tracks from second vertex.

- Made independent data sets to search for ccu++ state and ccu++ state
- Used SELEX \( \Lambda_c^+ \rightarrow pK^-\pi^+ \) sample with RICH identification required on p, K-
- search for \( K^-\pi^+\pi^+\Lambda_c^+ \) vertex between primary vertex and \( \Lambda_c^+ \) decay point
PRELIMINARY Results from $ccd^+$ Search

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

- Use a baryon to find a baryon: require $\Lambda_c^+$ daughter
- look for extra vertex between primary and $\Lambda_c^+$
- If it’s double charm, $ccq$ decay has to make a $K^-$

All requirements are met by the peak at 3520 MeV/$c^2$

This looks like a $ccd^+$ Decay!
SELEX $ccu^{++}$ Baryon Data

Is there a $ccu^{++}$ partner to the $ccd^+$ Candidate?

$ccu^{++}$ candidate channel $K \pi^+\pi^+\Lambda_c^+$

$ccu^{++}$ wrong-sign backgnd channel $K^+\pi^-\pi^+\Lambda_c^+$

- NO RICH PID except on $\Lambda_c^+$ tracks
- cuts on data from single-charm analysis
- large mass peak at 3.78 GeV/$c^2$

- in wrong-sign ($K^+$) combination, no equivalent large peak
- ⇒ right-sign $ccu$ candidate is not random combinatoric vertex from only primary tracks
**Do These Data Match Double Charm?**

**Data:** Fit with Gaussian + Linear Background

- Signal Poisson significance is 5.6 $\sigma$.
- The peak is broad.
- Peak mass is at high end of expected range.

**Monte Carlo:** Simulate weakly-decaying ccu(3780)

- Resolution is $1/3$ the width of the data

Is the 3.78 GeV/c$^2$ object a ccu excited state?
Remove Slow $\pi^+$ from $ccu^{++}$ Sample and ... Voila!

Choosing only slow pion costs some signal but minimizes background

$cc^+$ Mass Spectrum from $ccu^{++}$ Sample

Rediscover $cc^+(3520)$ in independent sample

- Poisson significance of signal peak is $6.3\,\sigma$.
- position, width are same as in $cc^+$ sample

Check fakes: Increase $L/\sigma$ cut from 1.25 to 2

- Now have $5.0\,\sigma$ peak
- sideband background falls faster than signal as $L/\sigma$ is increased.

This state does NOT originate from accidental overlap of primary tracks.
How Did the $ccd^+$ State Appear in the $ccu^{++}$ Reconstruction?

- slow pions have sizeable track errors
- track is allowed to be consistent with two vertices
- primary pion can overlap with true $K^-\pi^+\Lambda_c^+$ vertex to simulate $ccu^{++}$ state

Event contributes to both $ccu^{++}$ peak at 3.78 and $ccd^+$ peak at 3.52 when slow pion is removed

Candidate for $ccu^{++}(3780) \rightarrow \pi^+ + ccd^+(3520)$
Are the $ccd^+$ and $ccu^{++}$ States Related?

The $ccu^{++}$ Decay is Complicated.

- The solid line is the fit from the previous page.
- The background extrapolation is in blue.
- The $ccu^{++}(3780)$ has some decays via $\pi^+$ emission to $ccd^+$. The area shown in magenta represents events like this.
- The area shown in red represents direct decays to $K^-\pi^+\pi^+\Lambda_c^+$

There appear to be two independent decay modes of the $ccu^{++}(3780)$ (??)
Any Other Explanation for These Data?

Look at the Wrong-Sign Plots

\[
\begin{align*}
K^-\pi^-\pi^+\Lambda_c^+ \\
\pi^-\pi^-\pi^+\Lambda_c^+ \\
K^+\pi^-\Lambda_c^+
\end{align*}
\]

- No peaks seen in \(K^-\pi^-\pi^+\Lambda_c^+\).
- No peaks seen in \(\pi^-\pi^-\pi^+\Lambda_c^+\).
- Previously showed no peaks in \(K^+\pi^-\pi^+\Lambda_c^+\).

The \(ccu^{++}(3780)\) is not a reconstruction artifact.

- The Wrong-Sign plot for the \(ccd^+\) shows no peaks.
- The \(ccd^+(3520)\) is not a reconstruction artifact.
Where Are We?

We have shown two new high-mass peaks with high statistical significance.

Decays are consistent with coming from doubly-charmed baryons.

\[
ccd^+(3520) \text{ seen two ways}
\]

- 6.4\(\sigma\) peak in direct search for \(ccd^+\) states
- 6.3\(\sigma\) peak in restricted search from sample of \(ccu^{++}\) candidates
- \(\approx 60\%\) overlap of samples

\[
\text{broad } ccu^{++} \text{ seen in direct search}
\]

- decay analysis suggests that this state may have more than one decay
- statistics are too low to do much more investigation
only $\text{ccd}^+(3520)$ decaying to $K^-\pi^+\Lambda_c^+$

chain decay of $\text{ccu}^{++}(3780)$ to $\text{ccd}^+\pi^+$

- $\text{ccu}^{++}$ reconstruction forces random extrapolation to be included along with tracks from $\text{ccd}^+(3520)$
- see clean $\text{ccd}^+(3520)$ peak after removing slow $\pi^+$. (left plot)
- $\text{ccu}^{++}$ mass distribution (right plot) rises sharply above 3.64 GeV/$c^2$

- Simulate $\text{ccu}^{++}$ with width $\Gamma = 30$ MeV/$c^2$
- see background step and broad $\text{ccu}^{++}(3780)$ peak. (right plot)
- Drop slower $\pi^+$; see narrow $\text{ccd}$ peak. (left)

data and simulation agree on peaks, other features
Is There a Narrow $ccu^{++}$ State in SELEX Data?

Look in vicinity of $ccd^+(3520)$ for narrow $ccu^{++}$ state decaying to $K \pi^+\pi^+\Lambda_c^+$

Data show $5.6 \sigma$ peak at $3460$ MeV/$c^2$.

- State on edge of acceptance ⇒ only 2 evts below $3.4$ GeV/$c^2$
- acceptance changes much faster for 4-prong $ccu^{++}$ vs. 3-prong $ccd^+$
- simulation: $\epsilon(ccu^{++}(3460))/\epsilon(ccd^+(3520)) \sim 1/2$

Have a third high-mass peak with double-charm decay characteristics
ccd$^+(3520)$ Lifetime

Plot reduced proper length
\[ c_t = \frac{m}{pz^*}(l-l_{\text{min}}) \]

\[ l_{\text{min}} = 1.25\sigma \] for this sample.

- mean $l/\sigma$ is 1.94
- Average $l$ is 1.8 mm
- average boost is 62

For each event $\sigma(c_t) \sim c_t$

- blue curve (normalized to 26 events) shows simulation results for 25 fs lifetime - about right!

- $\text{ccd}^+(3520)$ looks like weakly-decaying state with $\tau_{\text{ccd}} \sim 0.5 \times \tau_{\Omega_c}$ (60 fs)
**$\Lambda_c^+$ Economics**

**How many $\Lambda_c^+$s are associated with double-charm states?**

**The short answer - about half**

How did we get this?

- simulation: 10% $ccd^+(3520)$ detection efficiency if $\Lambda_c^+$ is reconstructed
- $ccu^{++}(3460)$ detection efficiency $\sim$5%.

16 $ccd^+$ and 7 $ccu^{++}$ $\Rightarrow$ 30 efficiency-corrected events $\Rightarrow$ 300 $\Lambda_c^+$s out of 1650

- BR into $\bar{K}^0\pi^0$ is 1/2 that into $\bar{K}^-\pi^+ \Rightarrow 15 \Lambda_c^+$/observed event

- Handwave over modes with more pions: overall estimate 25 $\Lambda_c^+$/observed event

$ccq$’s take $\sim$40% of the SELEX $\Lambda_c^+$’s

- non-chain $ccu^{*++}(3780)$ decays raise $\Lambda_c^+$ consumption to about half

- The observed signals don’t violate $\Lambda_c^+$ conservation

This sounds enormous, but consider BELLE: double charm there is half single charm.
Charm Lifetimes, $D^0 - \bar{D}^0$ Mixing and Double $c\bar{c}$ Production

P. Pakhlov
(ITEP, BELLE Collaboration)
Charm physics is not abandoned: all experiments show their interest in this field.

At present:

- BaBar measured $y_{CP} = (1.4 \pm 1.0^{+0.6}_{-0.7})\%$ with $D^{*+}$ tag.
- Belle updated $D^0 \rightarrow K^+\pi^-$: $R_{WS} = (0.38 \pm 0.03)\%$.
- FOCUS: new measurement of $D^0$ and $D^+$ lifetimes:
  \begin{align*}
  \tau_{D^0} &= (409.6 \pm 1.1 \pm 1.5) \, \text{fs} \quad \text{and} \\
  \tau_{D^+} &= (1039.4 \pm 4.3 \pm 7.0) \, \text{fs}.
  \end{align*}
- Belle observed $e^+e^- \rightarrow 2(c\bar{c})$:
  \begin{align*}
  \sigma(e^+e^- \rightarrow J/\psi \eta_c(\gamma)) \times \mathcal{B}(\eta_c \rightarrow \geq 4\text{ charged}) &= (0.033^{+0.007}_{-0.006} \pm 0.009) \, \text{pb} \\
  \sigma(e^+e^- \rightarrow J/\psi c\bar{c}) &= 0.89^{+0.21}_{-0.19} \pm 0.21 \quad \text{and} \\
  \sigma(e^+e^- \rightarrow J/\psi c\bar{c})/\sigma(e^+e^- \rightarrow J/\psi X) &= 0.61^{+0.15}_{-0.13} \pm 0.12.
  \end{align*}
- Many new results are coming, and come soon.
What About Production?

Which beam hadrons(\(\Sigma\), \(\pi\), p) make these states?

<table>
<thead>
<tr>
<th>state</th>
<th>(\Sigma^-)</th>
<th>proton</th>
<th>(\pi^-)</th>
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<tr>
<td>luminosity fraction</td>
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<td>ccu(3460) signal</td>
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<tr>
<td>ccu(3460) sideband</td>
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<tr>
<td>ccd(3520) sideband</td>
<td>18</td>
<td>1</td>
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</tbody>
</table>

The high-mass states dominantly produced by baryon beams.
Why Does SELEX See These States?

They’re produced in a corner of phase space:

Take ccd$^+$ (3520) for example.

- mean $x_F \sim 0.35$ (200 GeV/c)
- mean $p_T \sim 1$ GeV/c
- they make leading $\Lambda_c^+$’s, which have to be reconstructed fully

Other particle production puzzles in this corner of phase space

- Why does the Hyperon beam work? Leading strange baryon production at Fermilab
- The discovery experiment for the $\Xi_c^+$ (135 GeV $\Sigma$ beam: WA62)

Cross section calculations for small $p_T$, large $x_F$ processes are very unreliable. Experiment must lead, and there are surprises.

There are other hints that double-charm may not be so rare

- Large 4-charm/2-charm production ratios seen in Hybrid Emulsion experiments
- BELLE: huge $[J/\psi \Xi]/[J/\psi]$ ratio in continuum $e^+e^-$ collisions.
  We don’t understand the production mechanism, but we see the states
Summary-1

Selex has a high-mass ccd$^+$ candidate at 3520 MeV/c$^2$

- This state decays like a doubly-charmed baryon
- Its mass falls nicely within range of doubly-charmed baryon predictions
- Its lifetime appears to be in the 30 fs range
- The ccd$^+(3520)$ candidate fits all expectations for double charm.

Based on this state, it’s time to remove the question mark.
SELEX has discovered a doubly-charmed baryon.
Summary-2

Selex has a high-mass ccu$^{++}$ candidate at 3460 MeV/c$^2$

- The ccu$^{++}$(3460) candidate decays like a doubly-charmed baryon.
- Its mass is low end of the range expected.
- It lies far from the ccd$^+$(3520) state to be an isospin partner (60 MeV).
Summary-3

Selex has a broad high-mass ccu*++ candidate at 3780 MeV/c^2

- The ccu*++(3780) decay scheme is confusing
- The mass splitting from the lower-lying narrow states is large.

The ccu*++(3780) state doesn’t fit neatly into the basic scheme.

but it’s there.
The Final Word for Today

Selex has observed 3 significant high-mass peaks

• SELEX has preliminary but strong evidence for a family of high-mass states
• These states decay like doubly-charmed baryons
• The spectroscopy is not easy to understand
• The production rate is astoundingly high, but the double-charm world has seen a partner surprise from $e^+e^-$ collisions.

It’s difficult to avoid calling these states doubly-charmed baryons.