Doubly charmed baryon results from SELEX

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Introduction

Charm about 15 years ago:
- The “Traditional” Charm Experiments: E791, FOCUS, SELEX, (WA89, WA92), CLEO, H1/ZEUS
- “Traditional” Topics: Production, Lifetime, rare decays, resonances in decay, $D^0 - \bar{D}^0$ mixing
- Small number of theory and phenomenology papers

In the last 10 years or so:
- New players: BaBar and Belle, CDF, D0 (beauty), LHCb, Atlas
- New charm states: double charm baryons, hidden double charm ($J/\psi c\bar{c}$), $D_s^*$, $X (Y, Z)$
- Penta-quark Euphoria
- Large number of “theory” papers: spectroscopy, production
- Shift of used words in papers: di-quark
Outline

1. Update on Double Charm Baryons
   - The Discovery of Double Charm Baryons
   - Features, Problems, and Solutions
   - Observation of $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$
   - Observation of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+, \Xi_c^+ \pi^- \pi^+ \pi^+$

2. My Personal List of Mysteries in Charm and Beauty

3. Summary
Doubly Charmed Baryons

BARYONS WITH LOWEST SPIN (J = \(1/2\))

- \(\Xi_{cc}^+\)
- \(\Xi_{cc}^{++}\)
- \(\Omega_{cc}^+\)
- \(\Sigma_c^0, \Sigma_c^+\)
- \(\Delta^0, \Delta^+\)

SELEX candidates

TWO CHARMI QUARKS

- \(dsc\)
- \(ucc\)

NO CHARM QUAKE

- \(udd\)

BARYONS WITH HIGHEST SPIN (J = \(3/2\))

- \(\Omega_{cc}^{++}\)
- \(\Xi_{cc}^+\)
- \(\Xi_{cc}^{0}\)
- \(\Sigma_c^0, \Sigma_c^+\)
- \(\Delta^0, \Delta^+\)

SELEX candidate

THREE CHARM QUARKS

- \(ccc\)

TWO CHARMI QUARKS

- \(udd\)

ONE CHARMI QUARK

- \(uds\)

NO CHARM QUAKE

- \(uss\)
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Model Predictions for DCB Masses

- Several Authors (Bjorken 1986, Fleck & Richard 1989, Roncaglia 1995, Ellis 2002)

- Different models (Phenomenology, Bag, Quarkonium, Lattice)


Overall Features

- ground states near 3.6 GeV/$c^2$

- ground states Isospin=1/2 multiplets degenerate

- Hyperfine splitting around 60 – 120 MeV/$c^2$

- Most predict electromagnetic hyperfine transition (but some pionic)

- Model dependent predictions for orbital and radial excitations
The SELEX Collaboration

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- Forward ($x_F > 0.1$) charm production
- $\Sigma^-, \pi^\pm, p$ beam at 600 GeV/c
- RICH PID above $\sim 22$ GeV/c
- 20 plane Si-Vertex.
- Data taken 1996/7
Hyperon Beam

- 800 GeV/c protons from Tevatron
- \( \sim 40 \text{ cm long Be-Target (} \sim 1 \text{ Interaction Length)} \)
- \( \sim 7.3 \text{ m, } B = 3.5 \text{ T Magnet with Tungsten filling} \)
- curved slit with \( \sim 1.5 \text{ mm opening at thinnest point} \)
- 650 GeV/c nominal, 610 GeV/c mean
- Beam composition: neg 50/50 \( \Sigma^-/\pi^- \), pos 92/8 \( p/\pi^+ \)
- Tagging with a TRD
- Rates: \( 10^{12} \) Protons per 20 sec spill, \( 5 \cdot 10^5/\text{sec} \) at charm target
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Vertex Spectrometer Performance

- transverse vtx resolution 8-15 $\mu$m
- 20 highly-efficient vertex planes over-determine tracks, reduce tracking confusion in high-multiplicity events
- target foils 0.8-2.2 mm thick with 1.5 cm spacing to localize primary interaction
- Lifetime resolution 20 – 40 fs depending on particle/mode

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DCB
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Ring Imaging Cherenkov Counter Performance (1)
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Ring Imaging Cherenkov Counter Performance (2)

Proton efficiency

Proton momentum [GeV/c]

$N / 1 \text{MeV/c}^2$

Efficiency

$P(K)$, [GeV/c]

$M(K^+K^-)$, [GeV/c$^2$]

$4346 \pm 225 \phi$

$4206 \pm 126 \phi$

$3896 \pm 96 \phi$
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SELEX Single Charm Analysis

Charm Analysis Cuts

- 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
- Proton and Kaon identified in RICH detector
SELEX Charm Selection Criteria

Charm Selection Cuts for single charm studies:

- secondary vertex significance:
  - $L/\sigma \geq 1$
  - short-lived states ($\Xi^0_c, \Omega^0_c$)
  - $L/\sigma \geq 8$
  - long-lived states ($\Lambda^+_c, D^+$)

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

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

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ccq decays to csqu$d$. Look for charm, strange and baryon in final state. SELEX started with $\Lambda_c^+ K^- \pi^+ (\pi^+)$. Look for new secondary vertex between primary and $\Lambda_c^+$

- no RICH PID on new $K^- \pi^+$ tracks (too soft)
- All other cuts fixed from previous searches
SELEX: Experimental Evidence from 2002

SELEX reported 3 significant high mass peaks

SELEX argued that these states are doubly-charmed baryons

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First Observation of the Doubly Charmed Baryon $\Xi_{cc}^{+}$


(SELEX Collaboration)
An exited state and a pair of isodoublets?

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

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

3780 MeV (1/2–)

260 MeV

337 MeV

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

3520 MeV (1/2–)

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

3541 MeV

78 MeV

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

3460 MeV (L=0)

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

3443 MeV (1/2–)

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3520 MeV (1/2–)

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

3443 MeV (1/2–)
Features and Problems in Original Analysis. . .

- All Signals have very low statistics
- There is nearly no background (→ difficult to determine)
- Entries in histograms only from baryon \((\Sigma^-\text{, proton})\) beams
- Other experiments do not see the states
  (but: nobody else has baryon beams. . .)
- Lifetime is short \((< 33 \text{ fs})\)
All Signals have very low statistics
There is nearly no background (→ difficult to determine)
Entries in histograms only from baryon ($\Sigma^-$, proton) beams
Other experiments do not see the states
(but: nobody else has baryon beams...)
Lifetime is short (< 33 fs)
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- Lifetime is short ($< 33$ fs)
... and Possible Solutions

- Look for other decay modes to confirm DCB hypothesis
- Develop new method for background determination
- Include single-charm in vertex fit of double-charm vertex
- Redo full analysis chain to increase statistics
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...and Possible Solutions

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- Include single-charm in vertex fit of double-charm vertex
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Other Decay Modes of Double Charm Baryons

**Cabibbo allowed decay of $\Xi_{cc}^+$:**

\[
\begin{array}{c}
\Xi_{cc}^+ \\
\uparrow u \\
W^+ \\
\downarrow \bar{d} \\
\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \\
\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \pi^- \\
\Xi_{cc}^+ \rightarrow pD^+ K^- \\
\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+ \\
\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^+ \pi^- \\
\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+ \pi^- \\
\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+ \pi^+ \\
\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+ \pi^- \\
\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+ \pi^+ \pi^- \\
\end{array}
\]

*In Final State:*

- Baryon
- Quarks $csd\bar{d}$
- Plus pairs from sea
- Cascaded decay chain
Other Decay Modes of Double Charm Baryons

Cabibbo allowed decay of $\Xi^{+}_{cc}$:

In Final State:

- Baryon
- Quarks $c s d u \bar{d}$
- Plus pairs from sea
- Cascaded decay chain

Easily accessible in SELEX:

$$\Xi^{+}_{cc} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+}$$
$$\Xi^{+}_{cc} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+} \pi^{+} \pi^{-}$$
$$\Xi^{+}_{cc} \rightarrow pD^{+} K^{-}$$
$$\Xi^{+}_{cc} \rightarrow \Xi^{+}_{c} \pi^{-} \pi^{+}$$

$$\Xi^{++}_{cc} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+} \pi^{+} \pi^{+}$$
$$\Xi^{++}_{cc} \rightarrow pD^{+} K^{-} \pi^{+} (?)$$
$$\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} \pi^{+}$$
$$\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} \pi^{+} \pi^{+} \pi^{-}$$

$$\Omega^{+}_{cc} \rightarrow \Xi^{+}_{c} K^{-} \pi^{+}$$
$$\Omega^{+}_{cc} \rightarrow \Xi^{+}_{c} K^{-} \pi^{+} \pi^{+} \pi^{-}$$
Other Decay Modes of Double Charm Baryons

Cabibbo allowed decay of $\Xi^{+}_{cc}$:

\[
\begin{align*}
\Xi^{+}_{cc} & \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \\
\Xi^{+}_{cc} & \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \pi^{+} \pi^{-} \\
\Xi^{+}_{cc} & \rightarrow pD^{+} K^{-} \\
\Xi^{+}_{cc} & \rightarrow \Xi^{+} \pi^{-} \pi^{+}
\end{align*}
\]

Easily accessible in SELEX:

\[
\begin{align*}
\Xi^{+}_{cc} & \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \\
\Xi^{+}_{cc} & \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \pi^{+} \pi^{-} \\
\Xi^{+}_{cc} & \rightarrow pD^{+} K^{-} \pi^{+} (?) \\
\Xi^{+}_{cc} & \rightarrow \Xi^{+} \pi^{+} \\
\Xi^{+}_{cc} & \rightarrow \Xi^{+} \pi^{+} \pi^{+} \pi^{-} \\
\Omega^{+}_{cc} & \rightarrow \Xi^{+} K^{-} \pi^{+} \\
\Omega^{+}_{cc} & \rightarrow \Xi^{+} K^{-} \pi^{+} \pi^{+} \pi^{-}
\end{align*}
\]

In Final State:

- Baryon
- Quarks $csdud$ plus pairs from sea
- Cascaded decay chain
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$\Xi_{cc}^{+} \rightarrow pD^{+}K^{-}$ (PLB628 (2005) 18)
Background Determination: Event Mixing

- First decay vertex close to primary vertex: assume all bkgd is combinatoric
- Make combinatoric bkgd by taking first decay vertex from one event, second from other
- Use each single-charm event 25 times to increase statistics

Resulting combinatoric bkgd is absolutely normalized \( \Rightarrow \) Bkgd shape known

- \( \Xi_{cc}^+ \) Decay Schematic

* Peak mass: 3516 MeV
* 4-bin Poisson Prob < 6.4 \( \times 10^{-3} \)
* \( L/\sigma > 1.0 \)

PLB628 (2005) 18
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\( \Xi_{cc}^{+} \rightarrow \Lambda_{c}^{+}K^{-}\pi^{+} \) – New Analysis

Re-analysis of full data set ⇒ More \( \Lambda_{c} \) cands (1630 → 2450)

- Refit \( \Xi_{cc}^{+} \) vertex using \( \vec{p}_{\Lambda_{c}^{+}} \) together with \( K^{-}\pi^{+} \) tracks ⇒ Better \( L_{1} \) resolution
- Use event mixing for background
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$\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$, $\Lambda_c^+ \rightarrow pK^- \pi^+ \pi^+ \pi^+$ – New Analysis

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DCB
33/51
Features of new Analysis

- **Re-Analysis and Relaxing Cuts on Single Charm:**
  - some more background, but shape is well understood from combinatoric analysis
  - more signal

- **Improved sec. vertex resolution:**
  - Cleaner Signals, access to other modes
  - Possibility (but challenging) to measure lifetime (is around 1 $\sigma$)
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$\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^- - $ First Observation

FIRST OBSERVATION: $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-, \Xi_c^+ \rightarrow pK^- \pi^+$
Observation of \( \Xi^{+} \rightarrow \Xi^{+}_{c} \pi^{+} \pi^{−} \)
Observation of \( \Xi^{++} \rightarrow \Lambda^{+}_{c} K^{−} \pi^{+} \pi^{+}, \Xi^{+}_{c} \pi^{−} \pi^{+} \pi^{+} \)
Comparing the Mass of the Three Decay Modes

\[ \Lambda^{+}_{c} K^{+} \pi^{+} L_{1}/\sigma > 1.8 \]
\[ Mass \ 3521.8 \pm 1.7 \text{ MeV}/c^2 \]
\[ \Xi^{+}_{c} K^{−} \pi^{+} L_{1}/\sigma > 0. \]
\[ p D^{+} K^{−} L_{1}/\sigma > 1. \]
Observation of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

- If we have a ccd state ($\Xi_{cc}^+$), there has to be a ccu state as well ($\Xi_{cc}^{++}$)
- Look in $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$
- Use same cuts as before
  - Use same code
  - Just ask for one more $\pi^+$

Green: Absolutely-normalized background
Gaussian with fixed width (MC)

New $\Xi_{cc}^{++}$ at 3452 MeV/c²!
Observation of $\Xi_{cc}^{++} \rightarrow \Xi_{c}^{+} \pi^{-} \pi^{+} \pi^{+}$

- Now look in $\Xi_{c}^{+} \pi^{-} \pi^{+} \pi^{+}$
- Same as before, ask for additional $\pi^{+}$
- Only use $\Xi_{c}^{+} \rightarrow pK^{-}\pi^{+}$

- Add data from both modes
- Significance $6.5 \sigma$
- Mixed event background describes sidebands
\[ \Xi_{cc}(3780)^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \]

- Re-Analyzed Data
- Restrict to \( \Sigma^- \)–Beam
- Peak wider than Resolution
- Half decay to \( \Xi_{cc}(3520) \)
- Still working on Details
Why weakly decaying Doublet?

- If Excitation is Chromomagnetic:
  - Expect dominant M1 Dipole Transition (like in $D^* \rightarrow D\gamma$)
  - Weak decay of Chromomagnetic Excited State Suppressed by $\sim 6$ orders of magnitude

- Bardeen, Eichten and Hill: spectroscopy of $cc$ compared to $c\bar{s}$ (PRD68 054024, hep-ph/0305049)

Ground State: $J^P = \frac{1^+}{2} \left[ c \uparrow c \uparrow L = 0, J^P = 1^+ \right] q \downarrow$

Excited State: $J^P = \frac{1^-}{2} \left[ c \uparrow c \downarrow L = 1, J^P = 1^- \right] q \downarrow$

- First excited state is $L = 1$ of heavy ($cc$) di-quark
- In at least one version of the model splitting is consistent with observed 78 MeV/$c^2$
- First EM transition is M2.
Doubly Charmed Baryons Production

- SELEX: Dominantly produced by baryon beam.
- E791 has looked in 250 GeV/c \(\pi^-\) production
  no signal
- FOCUS looked in 250 GeV/c photo-production
  no signal
- BaBar looked:
  no signal
- Waiting for LHCb upgrade... or After?
- Hadro-Production Theory/Phenomenology:
  Most just assume independent production
  But: Are intrinsic components important?
My Personal List of Mysteries in Charm and Beauty

Mysteries: Observations which have no commonly accepted explanation within the usually accepted theory.
Charm Mysteries (1) – Discovery of the $\Xi_c^+$

- Beam: 135 GeV/$c$ $\Sigma^-$
- 3 weeks of running
- no silicon detectors
- 83 events $\Xi_c^+ \rightarrow \Lambda K^- \pi^+ \pi^+$
- measured $\Xi_c^+$ lifetime correctly
Beauty Mysteries – $\Lambda_b$ at ISR

**CERN-ISR R422 (Split Field Magnet), 1988/1991**

\[ \Lambda_b^0 \rightarrow pD^0\pi^- \]

\[ \Lambda_b^0 \rightarrow \Lambda_c^+\pi^+\pi^-\pi^- \]

*Il Nuovo Cimento* 104, 1787
(Double)-Charm Mysteries (2) – $J/\psi \eta_c$ Production

- Belle observed high double charm production in
  \[ e^+ e^- \rightarrow J/\psi \ c\bar{c}, \]
  \[ e^+ e^- \rightarrow J/\psi \ \eta_c \]
  (PRL 89 (2002) 142001)

- At publication, ×40 higher cross section than theory

- BaBar confirms a few years later

- Today still x10 higher

- From Vato: In LHCb double-$J/\psi$ also not understood
Charm Mysteries (3) – Narrow $D_s$ Resonances

BaBar, CLEO, Belle (2003)

$D_{sJ}^*(2315) \rightarrow D_s \pi^0$,
$D_{sJ}(2463) \rightarrow D_s \gamma \pi^0$

PRL90 (hep-ex/0304021);
PRD68;
PRL91 (hep-ex/0308019)

SELEX 2004

$D_{sJ}^*(2632) \rightarrow D_s^+ \eta$ and $D^0 K^+$

PRL 93, 242001 (hep-ex/0406045)
Charmonium-like states
Are they Charmonium? Are they Tetra-quark states?
Do the charged states (observed by Belle) really exist?
Baryon Mysteries – “Missing” Resonances

- Experiments at Jefferson Lab (and other places) search for Baryon Resonances
- About half the states predicted by $SU(6)_{SF} \times SO(3)$ are missing
- $SU(6)_{SF} \times SO(3)$ is non-relativistic, spin and angular momentum are separate.
- Other schemes predicting the correct number of resonances exist (e.g. $SU(3)_F \times SO(3, 1)$, $SO(3, 1)$ is Lorentz-Group)
Conclusions – Double Charm Baryons

- SELEX is still the only experiment observing Double Charm Baryons (until LHCb trigger upgrade?)

- Published results on $\Xi^{+}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+}, \Xi^{+}_{cc} \rightarrow pD^{+} K^{-}$

- SELEX is re-analyzing the data, with improved efficiency

- Presented $\Xi^{+}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+}, \Xi^{+}_{cc} \rightarrow \Xi^{+}_{c} \pi^{-} \pi^{+}$
- Presented $\Xi^{++}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \pi^{+}, \Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} \pi^{-} \pi^{+} \pi^{+}$

- Working on determination of the $\Xi_{cc}$ Lifetime
- Searching for $\Omega^{+}_{cc}$
Conclusions

Ongoing Analyses in SELEX:

- Working on Double Charm Baryons
- Study of Charm Hadro-Production
- Preliminary result on semi-leptonic decay of $\Lambda_c^+$
- Study Cabibbo Suppressed Decays of charm baryons
  - First Observation of $\Xi_c^+ \rightarrow \Sigma^+ \pi^- \pi^+, \Xi_c^+ \rightarrow \Sigma^- \pi^+ \pi^+$
  - More modes to come...
My Personal Wishlist for Theorists and Phenomenologists

- What is the correct potential (model) for heavy-light systems?
- What is the correct potential in charmonium?
- How to transfer this to double-heavy baryons? ($c\bar{c} \rightarrow cc$)
- Make a good pre(post)diction of the mass of the $\Xi_{cc}$
- What is the mass difference between $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$ (including sign!)?
- What are the quantum numbers of the lowest exited state of the $\Xi_{cc}$?
- I do not care how you calculate it (HQET, Lattice, . . . ), JUST DO IT
- In this field, Experiments are Ahead!