Review of Recent Results in Charm Physics

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Introduction

Open Charm in the previous ~ 5 years:

- 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 year or so:

- New players: BaBar and Belle, CDF
- New charm states: double charm baryons, hidden double charm ($J/\Psi c\bar{c}$), $D_s^*$, $X(3872)$
- New particles: $Z^+$ ($\Theta^+$), triggered $\Theta^0_c$ predictions
- Large number of “theory” papers: spectroscopy, production
- Shift of used words in papers: di-quark
Outline

- $D^0 - \overline{D^0}$ Mixing
- Decays of $D^0$, $D^+$, $D_s^+$ Mesons
- New $D_s$ states
- Charmed Baryons: New Modes in $\Lambda_c^+$, $\Xi_c^+$, $\Xi_c^0$, $\Omega_c^0$
- Charmed Baryons: Mass of $\Sigma_c$, $\Omega_c^0$
- Doubly Charmed Baryons: Update on SELEX Observations

More talks about charm:
- Chunhui Chen: Heavy Flavour Production at the Tevatron (today 11:30)
- J.C. Wang: Review of New $D_s$ States (today 2pm)
- Karim Trabelsi: Charm Physics at Belle (today 2:45pm)
- Robert Harr: Recent Heavy Flavor Results from CDF (yesterday 9:30) (Belle $X(3872)$)
- David Asner: CLEO$_c$
**$D^0 - \bar{D}^0$ Mixing**

usually measured: Lifetime difference between $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow K^- \pi^+$

$$y_{CP} = \frac{\tau(K^- \pi^+)}{\tau(K^- K^+)} - 1$$

Standard Model: $y_{CP} \sim 10^{-3}$

**Recent Results:**

- **Belle:**
  $$y_{CP} = (+1.15 \pm 0.69 \pm 0.38)\%$$  (hep-ex/0308034)

- **BaBar:**
  $$y_{CP} = (-0.8 \pm 0.4 \pm^{0.5}_{-0.4})\%$$  (hep-ex/0306003)  also includes $D^0 \rightarrow \pi^+ \pi^-$

- **CLEO:**
  $$y_{CP} = (-1.2 \pm 2.5 \pm 1.4)\%$$  (PRD65, 2002)  also includes $D^0 \rightarrow \pi^+ \pi^-$

- **FOCUS:**
  $$y_{CP} = (3.42 \pm 1.39 \pm 0.74)\%$$  (PLB485, 2000)

- **E791:**
  $$y_{CP} = (0.8 \pm 2.9 \pm 1.0)\%$$  (PRL83, 1999)  Measured $\Delta \Gamma = (0.04 \pm 0.14 \pm 0.05) \text{ ps}^{-1}$

**Also:** Analyze “wrong sign” Double Cabibbo Suppressed $D^0 \rightarrow K^+ \pi^-$

- **BaBar:**
  $$-0.056 < y' < 0.039 \text{ (95\% C.L.)}$$  (hep-ex/0304007)

- **CLEO:**
  $$-0.058 < y' < 0.01 \text{ (95\% C.L.)}$$  (PRL84, 2000)
Rare Decays of $D$ Mesons: $D^0$

**FOCUS:** $D^0 \rightarrow K^-K^-K^+\pi^+$

\[
\frac{\Gamma(D^0 \rightarrow K^-K^-K^+\pi^+)}{\Gamma(D^0 \rightarrow K^-\pi^-\pi^+\pi^+)} = 0.00257 \pm 0.00034 \pm 0.00024
\]

Resonant substructures with $\Phi$ and $K^*(892)^0$ dominant.

(hep-ex/0308054)

**Belle:** $D^0 \rightarrow \phi \pi^0$, $\phi \eta$, $\phi \gamma$

**CLEO:** $D^0 \rightarrow \pi^-\pi^+\pi^0$

**CLEO:** $D^0 \rightarrow K_s\eta\pi^0$

Review of Recent Results in Charm Physics
Rare Decays of $D$ Mesons: $D^+$, $D_s^+$

: CLEO: $D^+ \rightarrow \pi^+ \pi^0, K^+ K^0, K^+ \pi^0$

\[
\mathcal{B}(D^+ \rightarrow \pi^+ \pi^0) = (1.31 \pm 0.17 \pm 0.09 \pm 0.09) \cdot 10^{-3} \\
\mathcal{B}(D^+ \rightarrow K^+ K^0) = (5.24 \pm 0.43 \pm 0.20 \pm 0.34) \cdot 10^{-3} \\
\mathcal{B}(D^+ \rightarrow K^+ \pi^0) < 4.2 \cdot 10^{-4} \ (90\% \ C.L.)
\]

FOCUS: Limits on Rare and SM-Forbidden Di-Muon Decays for $D^+$ and $D_s^+$

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>FOCUS Limit</th>
<th>Previous Best</th>
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</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^+ \mu^- \mu^+$</td>
<td>$9.2 \cdot 10^{-6}$</td>
<td>$44 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^- \mu^+ \mu^+$</td>
<td>$13 \cdot 10^{-6}$</td>
<td>$120 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+ \mu^- \mu^+$</td>
<td>$8.8 \cdot 10^{-6}$</td>
<td>$15 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^- \mu^+ \mu^+$</td>
<td>$4.8 \cdot 10^{-6}$</td>
<td>$17 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+ \mu^- \mu^+$</td>
<td>$36 \cdot 10^{-6}$</td>
<td>$140 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^- \mu^+ \mu^+$</td>
<td>$13 \cdot 10^{-6}$</td>
<td>$180 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+ \mu^- \mu^+$</td>
<td>$26 \cdot 10^{-6}$</td>
<td>$140 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^- \mu^+ \mu^+$</td>
<td>$29 \cdot 10^{-6}$</td>
<td>$82 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

(hep-ex/0306049)

CDF: $D^0 \rightarrow \mu^+ \mu^- < 2.5 \cdot 10^{-6}$ (hep-ex/0308059)
E791: Scalar Resonances in $D^+$ and $D_s^+$ Decays

Need to include two Scalar Resonance:

$K\pi$ with mass $(797 \pm 19 \pm 43)$ MeV/$c^2$, width $(410 \pm 43 \pm 87)$ MeV/$c^2$

$\pi\pi$ with mass $(478^{+24}_{-23} \pm 17)$ MeV/$c^2$, width $(324^{+42}_{-40} \pm 21)$ MeV/$c^2$

(PRL89, 2002; hep-ex/0307008; PRL86, 2001)

Review of Recent Results in Charm Physics
April 12, 2003: BaBar announced Observation of a Narrow Resonance, decaying to $D_s \pi^0$, at 2.32 GeV/c$^2$

BaBar:  
(hep-ex/0304021; PRL90, 2003)

CLEO:  
(PRD68, 2003; hep-ph/0308166)

BELLE:  
(hep-ex/0308019; hep-ex/0307052)
Charmed Baryons: $\Lambda_c^+, \Sigma_c^{0,++}$

CLEO: $\Lambda_c^+ \rightarrow \Lambda \pi^+ \pi^+ \pi^- \pi^0$

$$B = (1.79 \pm 0.47 \pm 0.43)\%$$

Most of resonant into $\Lambda_c^+ \rightarrow \Lambda \omega \pi^+$

(PRD67, 2003)

CLEO: Masses and Widths of $\Sigma_c^{++}$ and $\Sigma_c^0$

$$M(\Sigma_c^{++}) - M(\Lambda_c^+) = (167.4 \pm 0.1 \pm 0.2) \text{ MeV}/c^2$$

$$M(\Sigma_c^0) - M(\Lambda_c^+) = (167.2 \pm 0.1 \pm 0.2) \text{ MeV}/c^2$$

$$\Gamma(\Sigma_c^{++}) = (2.3 \pm 0.2 \pm 0.3) \text{ MeV}/c^2$$

$$\Gamma(\Sigma_c^0) = (2.5 \pm 0.2 \pm 0.3) \text{ MeV}/c^2$$

(PRD65, 2002)
Charmed Baryons: FOCUS: $\Xi^+_c$ Branching Ratios

--- | --- | --- | ---
$\Gamma(\Xi^+_c \rightarrow \Sigma^+ K^- \pi^+)$ | $0.91 \pm 0.11 \pm 0.04$ | $1.18 \pm 0.26 \pm 0.17$ | $0.92 \pm 0.20 \pm 0.07$
$\Gamma(\Xi^+_c \rightarrow \Xi^- \pi^+ \pi^\pm)$ | $0.16 \pm 0.06 \pm 0.01$ | $0.28 \pm 0.06 \pm 0.06$ | $0.58 \pm 0.16 \pm 0.07$
$\Gamma(\Xi^+_c \rightarrow \Sigma^+ K^+ K^-)$ | $0.07 \pm 0.03 \pm 0.03$ | $0.07 \pm 0.03 \pm 0.03$ | $0.07 \pm 0.03 \pm 0.03$
$\Gamma(\Xi^+_c \rightarrow \Sigma^+ (1385)^+ K^0)$ | $1.00 \pm 0.49 \pm 0.24$ | $1.00 \pm 0.49 \pm 0.24$ | $1.00 \pm 0.49 \pm 0.24$

Also have upper limits for other resonance modes.
Charmed Baryons: CLEO: $\Xi_{c}^{+}$ Lifetime, $\mathcal{B}(\Xi_{c}^{0} \rightarrow pK^{-}K^{-}\pi^{+})$

\[ \tau(\Xi_{c}^{+}) = (503 \pm 47 \pm 18) \text{ fs} \]

(PRD65, 2002)

\[ \frac{\mathcal{B}(\Xi_{c}^{0} \rightarrow pK^{-}K^{-}\pi^{+})}{\mathcal{B}(\Xi_{c}^{0} \rightarrow \Xi^{-}\pi^{+})} = 0.35 \pm 0.08 \pm 0.05 \]

Also see evidence for resonant $K^*(892)^0$ substructure.

(hep-ex/0309020)
Charmed Baryons: Mass and semileptonic decays of $\Omega^0_c$

Mass measurements:
Belle: $(2693.9 \pm 1.1 \pm 1.4)$ MeV/$c^2$ (LP2003)
CLEO: $(2694.6 \pm 2.6 \pm 1.9)$ MeV/$c^2$ (PRL86, 2001)
PDG2000: $(2704 \pm 4)$ MeV/$c^2$

Semileptonic decays:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Omega^0_c \rightarrow \Omega^- \mu^+ \nu$</th>
<th>$\Omega^0_c \rightarrow \Omega^- e^+ \nu$</th>
<th>$\frac{B(\Omega^0_c \rightarrow \Omega^- \pi^+)}{B(\Omega^0_c \rightarrow \Omega^- l^+ \nu)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle (LP2003)</td>
<td>$33.1 \pm 8.2$</td>
<td>$31.9 \pm 7.1$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
</tr>
<tr>
<td>CLEO (PRL89, 2002)</td>
<td>$11.4 \pm 3.8$</td>
<td>$0.41 \pm 0.19 \pm 0.04$</td>
<td></td>
</tr>
</tbody>
</table>
We observe a signal for the doubly charmed baryon in data from SELEX, the charm hadro production experiment at Fermilab. We observe an excess of 15.9 events over an expected background of 2.4 events, a statistical significance of 6.5σ. The observed mass of this state is \( m = 5553.0 \pm 1.2 \) MeV. The Gaussian mass width of this state is \( \Gamma = 4.7 \pm 0.3 \) MeV, consistent with resolution; its lifetime is less than 33 fs at 90% confidence.

DOI: 10.1103/PhysRevLett.89.112001
PACS numbers: 14.20.Lq, 13.30.Eg

The addition of the charmed quark to the \((|\bar{c}\bar{c}\bar{s}|, |\bar{c}\bar{c}\bar{d}|)\) triplet extends the flavor symmetry of the baryon octet and decuplet from SU(3) to SU(4). Even though the large breaking of flavor symmetry, SU(4) still provides a good classification scheme for baryons composed of \( |\bar{c}\bar{c}\bar{s}|\) and \( |\bar{d}\bar{d}\bar{d}|\). There is strong experimental evidence for all the predicted baryon states which contain zero or one valence charmed quark [1]. In this Letter, we present the first experimental evidence for one of the six predicted baryon states which contain two valence charmed quarks—the doubly charmed baryons. There have been many predictions of the masses and other properties of these states [2–5]. The properties of these states are consistent with the predictions of SU(4) flavor symmetry.
Model Predictions for Doubly Charmed Baryon Masses

- Several Authors (Bjorken 1986, Fleck&Richard 1989, Roncaglia 1995, Ellis 2002)
- Different models (Phenomenology, Bag, Quarkonium)

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 Experiment at Fermilab

SELEX experiment

- Forward \((x_F > 0.1)\) charm production
- \(\Sigma^-, \pi, p\) beam at 600 GeV/c
- RICH PID above
  \(~ 22\) GeV/c
- 20 plane Si-Vertex.
- Data taken 1996/7
SELEX: Experimental Evidence from 2002

SELEX reported 3 significant high mass peaks

SELEX argued that these states are doubly-charmed baryons
SELEX Search Strategy for Doubly-Charmed Baryons

- $ccq$ decays to $csq\bar{u}d$. 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

(PRL89, 2002)  
- $L/\sigma > 1$.  
- Right sign has peak at 3520.  
  15.8 signal, 6.2 background. 6.3 $\sigma$  
- Wrong sign has no structure
**SELEX: Search for $ccd^+(3520)$ Isopartner: $ccu^{++}$**

- same cuts as before: $3.5 \sigma$ hint in $\Lambda_c^+ K^- \pi^+ \pi^+$.
- No peak in wrong sign ($\Lambda_c^+ K^+ \pi^- \pi^+$).
- Try additional cut: $\cos \Theta_K^* > 0.6$ to remove soft vertex tracks

- Mass peak at 3460.
  7.1 signal, 0.9 background. $7.5 \sigma$
- Loss of signal consistent with phase space ($L = 0$)

- $\Xi_{cc}^{++}(3460), \Xi_{cc}^{+}(3520)$ Isodoublet??
SELEX: Where is the Isopartner to $\Xi_{cc}^{++}(3460)$?

- apply $\cos \Theta_K^* > 0.6$ also to $\Lambda_c^+ K^- \pi^+$
- $ccd^+(3520)$ strongly attenuated:
  $\Rightarrow$ not phase space
- $\Rightarrow$ NOT isopartner to $ccu^{++}(3460)$

New $ccd^+(3443)$ now very significant
- there was a “bump” before – was ignored
- Now: 7.4 signal, 1.6 background. 5.8 $\sigma$
- Consistent with $L = 0$

- $ccd^+(3443)$ is partner to $ccd^{++}(3460)$
SELEX: Where is the Isopartner to $\Xi_{cc}^{+}(3520)$?

- $ccd^{+}(3520)$ not phase space ($\cos \Theta_K^* < 0.6$)
- $\Lambda_c^+$ and $K^-$ are back-to-back:
  $\cos \Theta_K^* \cos \Theta_{\Lambda_c} < -0.25$ keeps most of signal
- Apply also to $\Lambda_c^+ K^- \pi^+ \pi^+$ sample: Nothing
- Reduce cut to $L/\sigma > 0.25$

New $ccu^{++}(3541)$ now very significant
- 7.4 signal, 1.6 background. 5.8 $\sigma$
- Consistent with $L > 0$

- $ccu^{++}(3541)$ is partner to $ccd^{+}(3520)$
An exited state and a pair of isodoublets?
Doubly Charmed Baryons

Lifetimes

- SELEX tried to measure lifetime
  All lifetimes near resolution limit $< 30$ fs
- Model predictions: several hundreds of fs.
- Bardeen, Eichten and Hill: spectroscopy of $cc$

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

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

- Predicted splitting consistent with observed $78$ MeV$/c^2$
- First EM transition is M2.

Production

- SELEX: Dominantly produced by baryon beam.
- E791 has looked in $250$ GeV$/c\ \pi^- \ production$
  no signal
- FOCUS looked in $250$ GeV$/c\ \pi^- \ production$
  no signal
FOCUS $\Xi_{cc}$
search results

Review of Recent Results in Charm Physics

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Conclusions

- Charm Physics is more exciting than ever
- New Results on Mixing, (rare) decays, and masses of Mesons and Baryons
- New States in the $D_s$ system
- Doubly Charmed Baryons