A review of the experimental results on charmed baryons with an accent on recent results.
Why Study Charmed Baryons?

The charmed baryon sector offers the richest spectroscopy of quark combinations.

- Compared with mesons there are more states as there are more possibilities for orbital excitations.
- Compared with mesons, the extra mass associated with orbital excitations is less, leading to less phase space for decays and narrower states.
- Because the charm quark has a large mass, the states can be described as a combination of a heavy quark and a light di-quark - this picture does not work well for strange baryons.
- Compared with the $B$ sector, charmed baryons are much easier to study experimentally. Once charmed baryons are understood, extrapolation to $B$ baryons is easy.
- There are four weakly decaying charmed baryons - good laboratory for studying weak decays.
How To Study Charmed Baryons

Two main techniques:

Fixed Target Experiments, e.g. FOCUS, SELEX, E-791.
  • Advantage: Long pathlength can be used measure the lifetimes, and as a tag of charm.
  • Disadvantage: Charm particles are a small minority of events.

Experiments at $e^+e^-$ Machines, e.g. CLEO, BELLE.
  • Advantage: $\approx 40\%$ of continuum events are charm.
  • Disadvantage: Short pathlength, difficult to separate vertices.

Running at $\Lambda_c^+\Lambda_c^-$ threshold would be exciting. Maybe CLEO_c in 2006?
Naming Charmed Baryons

We always consider a charmed baryon as being the combination of a charmed quark and a light diquark with its own $J^P_{LIGHT}$ to give a state of a particular $J^P$.

If the two light quarks are $u$ and/or $d$, then the particle is $\Lambda_c$ or a $\Sigma_c$.

If the wave-function is antisymmetric under interchange of the two light quarks, then the particle is a $\Lambda_c$ and is $I=0$. If it is symmetric, then it is a $\Sigma_c$ and it is $I=1$.

The lowest lying state is therefore the $\Lambda_c^+ \uparrow \downarrow \uparrow \downarrow_{cud}$ with $J^P = \frac{1}{2}^+, J^P_{LIGHT} = 0^+$.

Next lowest is the isotriplet of $\Sigma_c$'s $\uparrow \downarrow \downarrow \downarrow_{cqq}$ with $J^P = \frac{1}{2}^+, J^P_{LIGHT} = 1^+$.

Then is the isotriplet of $\Sigma_c^*$'s $\uparrow \uparrow \uparrow \downarrow_{cqq}$ with $J^P = \frac{3}{2}^+, J^P_{LIGHT} = 1^+$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Mode 2</th>
<th>$B_1/B_2$</th>
<th>Previous</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda K^+$</td>
<td>265 ± 35</td>
<td>$\Lambda \pi^+$</td>
<td>0.074 ± 0.010 ± 0.012</td>
<td></td>
</tr>
<tr>
<td>$\Sigma K^+$</td>
<td>75 ± 18</td>
<td>$\Sigma^0 \pi^+$</td>
<td>0.056 ± 0.014 ± 0.008</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+ K^+ \pi^-$</td>
<td>105 ± 24</td>
<td>$\Sigma^+ \pi^+ \pi^-$</td>
<td>0.047 ± 0.011 ± 0.008</td>
<td>0.24$^{+0.24}_{-0.16}$</td>
</tr>
<tr>
<td>$\Sigma^+ K^+ K^-$</td>
<td>246 ± 20</td>
<td>$\Sigma^+ \pi^+ \pi^-$</td>
<td>0.076 ± 0.007 ± 0.009</td>
<td>0.094 ± 0.017 ± 0.019</td>
</tr>
<tr>
<td>$\Sigma^+ \phi$</td>
<td>129 ± 17</td>
<td>$\Sigma^+ \pi^+ \pi^-$</td>
<td>0.085 ± 0.012 ± 0.012</td>
<td>0.094 ± 0.033 ± 0.025</td>
</tr>
<tr>
<td>$\Xi (\Sigma^+ K^-) K^+$</td>
<td>75 ± 16</td>
<td>$\Sigma^+ \pi^+ \pi^-$</td>
<td>0.023 ± 0.005 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>$\Xi (\Lambda \bar{K}^0) K^+$</td>
<td>75 ± 16</td>
<td>$\Lambda \bar{K}^0 K^+$</td>
<td>0.26 ± 0.08 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>$p K^+ K^-$</td>
<td>676 ± 89</td>
<td>$p K^- \pi^+$</td>
<td>0.014 ± 0.002 ± 0.002</td>
<td>0.039 ± 0.009 ± 0.007</td>
</tr>
<tr>
<td>$p \phi$</td>
<td>345 ± 43</td>
<td>$p K^- \pi^+$</td>
<td>0.015 ± 0.002 ± 0.002</td>
<td>0.024 ± 0.006 ± 0.003</td>
</tr>
</tbody>
</table>

Some of these decays can proceed only by W-exchange diagrams:
New measurements from:

**SELEX** $\tau(\Lambda_c^+) = 198.1 \pm 7.0 \pm 5.6$ fs.
PRL 86 5243 (2001).

**FOCUS** $\tau(\Lambda_c^+) = 204.6 \pm 3.4 \pm 2.4$ fs.
PRL 88 161801 (2002)

(c.f. PDG 2001 value of $188 \pm 7$ fs from 6 experiments.)

Short lifetime of the $\Lambda_c^+$ presumably due to W-exchange decays.
RECENT $\Sigma_c^{++}$ AND $\Sigma_c^0$ RESULTS

All 3 masses well measured. Measurement of widths from CLEO and FOCUS

CLEO

$$\Gamma(\Sigma_c^{++}) = 2.3 \pm 0.2 \pm 0.3 \text{ MeV},$$
$$\Gamma(\Sigma_c^0) = 2.5 \pm 0.2 \pm 0.3 \text{ MeV}.$$  

FOCUS

$$\Gamma(\Sigma_c^{++}) = 2.05^{+0.41}_{-0.38} \pm 0.38 \text{ MeV},$$
$$\Gamma(\Sigma_c^0) = 1.55^{+0.41}_{-0.37} \pm 0.38 \text{ MeV}.$$
CLEO finds a signal of $327^{+78}_{-73}$ Events.
\[\Delta M(\Sigma_c^+) = 231.1 \pm 1.1 \pm 2.0 \text{ MeV}.\]
**SUMMARY**

<table>
<thead>
<tr>
<th></th>
<th>In MeV</th>
<th>0</th>
<th>+</th>
<th>++</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta M(\Sigma_c)$</td>
<td>CLEO</td>
<td>167.2 ± 0.1 ± 0.2</td>
<td>166.4 ± 0.2 ± 0.3</td>
<td>167.4 ± 0.1 ± 0.2</td>
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<tr>
<td></td>
<td>FOCUS</td>
<td>167.35 ± 0.19 ± 0.20</td>
<td></td>
<td>167.38 ± 0.19 ± 0.12</td>
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<td></td>
<td>PDG 2001</td>
<td>167.30 ± 0.20</td>
<td>168.7 ± 0.6</td>
<td>167.87 ± 0.19</td>
</tr>
<tr>
<td>$\Gamma(\Sigma_c)$</td>
<td>CLEO</td>
<td>2.5 ± 0.2 ± 0.3</td>
<td>&lt; 4.6</td>
<td>2.3 ± 0.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>FOCUS</td>
<td>$1.55^{+0.41}_{-0.37}$ ± 0.38</td>
<td></td>
<td>$2.05^{+0.41}_{-0.38}$ ± 0.38</td>
</tr>
<tr>
<td>$\Delta M(\Sigma_c^*)$</td>
<td>CLEO</td>
<td>232.6 ± 1.0 ± 0.8</td>
<td>231.1 ± 1.1 ± 2.0</td>
<td>234.5 ± 1.1 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>FOCUS</td>
<td>$(232.7 ± 1.2)$</td>
<td></td>
<td>$(234.2 ± 1.5)$</td>
</tr>
<tr>
<td>$\Gamma(\Sigma_c^*)$</td>
<td>CLEO</td>
<td>$13.0^{+3.7}_{-3.0}$ ± 1.0</td>
<td>&lt; 17</td>
<td>$17.9^{+3.8}_{-3.2}$ ± 4.0</td>
</tr>
<tr>
<td></td>
<td>FOCUS</td>
<td>$(9.4 ± 3.7)$</td>
<td></td>
<td>$(23.6 ± 4.5)$</td>
</tr>
</tbody>
</table>

- Note small isosping splitting (but singly charged state lowest mass?)
- Note $\Gamma(\Sigma_c^*) \approx 7 \times \Gamma(\Sigma_c)$.
SEARCH FOR HIGHER STATES

$\Lambda_c J^p = 1/2^-$  
$\Lambda_c J^p = 3/2^-$  
$\Lambda_{c1} J^p = 3/2^-$  
$\Lambda_{c1} J^p = 1/2^-$  
$\Lambda_{c0} J^p = 1/2^-$  

L = 1 Between q and q

$\Sigma_{c1} J^p = 3/2^-$  
$\Sigma_{c1} J^p = 1/2^-$  

$\Sigma_{c2} J^p = 5/2^-$  
$\Sigma_{c2} J^p = 3/2^-$  
$\Sigma_{c1} J^p = 3/2^-$  
$\Sigma_{c1} J^p = 1/2^-$  
$\Sigma_{c0} J^p = 1/2^-$  

L = 1 Between c and qq

$\Sigma_c^* J^p = 3/2^+$  
$\Sigma_c J^p = 1/2^+$

L = 0

$\Lambda_c J^p = 1/2^+$

++ + 0 + ++
Lower resonance:
Yield=$997^{+141}_{-129}$, $\Delta M_{\pi\pi} = 480.1 \pm 2.4$ MeV, $\sigma = 20.9 \pm 2.6$ MeV.

Upper resonance:
Yield=$350^{+57}_{-55}$, $\Delta M_{\pi\pi} = 595.8 \pm 0.8$ MeV, $\sigma = 4.2 \pm 0.7$ MeV.
**Higher Level States Conclusion**

CLEO explanation:

Lower resonance is two of the first orbital excitations of the $\Sigma_c$. These are $\Lambda_c^{(u,d)} \bar{c}$, where the $J^{P_{LIGHT}} = 1^-$ diquark combines with the charm quark to give a $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ pair.

Upper resonance could be the first orbital excitation where the excitation is between the two light quarks. $\Lambda_c^{(u,d)} \bar{c}$, where the $J^{P_{LIGHT}} = 0^-$ diquark combines with the charm quark to give a $J^P = \frac{1}{2}^-$ $\Lambda_c^0$ particle.
$\Xi_c$ States - Predicted

$\Lambda_c/\Sigma_c$ and $\Xi_c$ Spectroscopy

$\Lambda_c J^p=3/2^-$
$\Lambda_c J^p=1/2^-$
$\Sigma_c J^p=3/2^+$
$\Sigma_c J^p=1/2^+$
$\Xi_c J^p=1/2^+$

0 cdd cud 0 csu
++ cuu ++

$\rho$-wave $\pi$ transition
$\gamma$ transition
$s$-wave $\pi$ transition

Mass (GeV)
States - DISCOVERED

Discovery of $\Xi_c$ States

$\Xi_{c1} J^P = 3/2^-$

$\Xi_{c1} J^P = 1/2^-$

CLEO PRL 83, 3390 (1999)
CLEO PRL 86 4243 (2001)

$\Xi_c J^P = 3/2^+$

$\Xi_c J^P = 1/2^+$

CLEO PRL 75 4234 (1995)
CLEO PRL 77 810 (1996)

$\Xi_c' J^P = 1/2^+$

CLEO PRL 82 3390 (1999)

$\Xi_c J^P = 1/2^-$

WA62 PL 122B 455 (1983)

csd 0
csu +

Mass (GeV)
PDG has $330^{+60}_{-40}$ fs
CLEO $503 \pm 47 \pm 18$ fs
FOCUS $439 \pm 22 \pm 9$ fs
THE $\Omega_c$

$\Omega_c$ is css combination. Many sightings over the years, in particular E-687 in $\Sigma^+ K^- K^-\pi^+$. CLEO (2001) finds a signal in the sum of 5 modes:

$$(\Omega^-\pi^+, \Omega^-\pi^+\pi^-\pi^+, \Omega^-\pi^+\pi^0, \Xi^0 K^-\pi^+, \Xi^- K^-\pi^+\pi^+).$$

BELL has the best signal yet, using $\Omega^-\pi^+$.

CLEO measures: $M=2694.6 \pm 2.6 \pm 1.9$ MeV/$c^2$

BELL measures: $M=2693.7 \pm 1.3 ^{+1.1}_{-1.0}$ MeV/$c^2$
To look for semi-leptonic decays of the $\Omega_c$, CLEO first looks for inclusive $\Omega^-$ production and finds a yield of $760 \pm 32$ events. 

Look for $\Omega^-$'s with a) “right” sign lepton, and b) “wrong” sign lepton. 

After subtracting measured backgrounds, excess of: $11.4 \pm 3.8$ events due to $\Omega_c \rightarrow \Omega^- e^+ \nu$.

Find $\frac{\Omega_c \rightarrow \Omega^- \pi^+}{\Omega_c \rightarrow \Omega^- e^+ \nu} = 0.41 \pm 0.19 \pm 0.04$

Note: $\frac{\Xi_c^0 \rightarrow \Xi^- \pi^+}{\Xi_c^0 \rightarrow \Xi^- e^+ \nu} = 0.44 \pm 0.09$ and $\frac{\Lambda_c \rightarrow \Lambda \pi^+}{\Lambda_c^+ \rightarrow \Lambda e^+ \nu} = 0.3 \pm 0.1$
LOOKING FOR THE $\Xi_{cc}^{++}$

SELEX VERY preliminary....looking in $\Lambda_c^+K^-\pi^+\pi^+$
CONCLUSIONS
AND HOPES FOR THE FUTURE

- There are 22 charmed baryons found. Many of them need confirmation, but they give a spectroscopic picture that is complex, but orderly and understandable.
- Still work to be done on spectroscopy. I anticipate more discoveries such as $\Omega^*_c \rightarrow \Omega \gamma$, $\Omega_{c1} \rightarrow \Xi_c K$, $\Xi_{c1} \rightarrow \Xi_c \pi \pi$, more $\Sigma_{c1}$ states, $\Lambda_{c1} \rightarrow pD$.
- Much work being done details - $\Omega_c$ lifetimes, production mechanisms, precise masses, widths, absolute branching fractions, more semi-leptonic decays etc. etc.
- BELLE and BaBar are in a good position to contribute to this research. If CESR$_c$ runs at $\Lambda_c^+$ threshold, so can CLEO$_c$.