Charmed baryon decays at Belle
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- $\Xi_c^* \rightarrow \Lambda D$
- Doubly Cabibbo Suppressed decay $\Lambda_c^+ \rightarrow pK^+\pi^-$
- Hidden Strange pentaquark via $\Lambda_c^+ \rightarrow \pi^0 \phi p$ decay
Charmed baryon production at Belle

- Charmed baryons are produced mainly via $e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$

- Total integrated luminosity $\sim 1.0$ ab$^{-1}$. $\rightarrow \sim 1.0 \times 10^9 e^+e^- \rightarrow c\bar{c}$.

- Many charmed baryons are discovered by Belle and BaBar so far. ($\Lambda_c(2940), \Sigma_c(2800), \Xi_c(2980), \Xi_c(3055), \Xi_c(3080), \Omega_c(2770)$)
Charmed strange baryons ($\Xi_c$)

- $u/d$-$s$ diquark system!

- $u$-$s$ di-quark, which can not be achieved in the $\Lambda$ state.

- The states below $\Xi_c(2815)$ are well described by the quark model.

- Higher excited states contain rich dynamical information!

$\Xi_c(3123)$?

- $\Xi_c(3080)$
- $\Xi_c(3055)$
- $\Xi_c(2980)$

- $\Xi_c(2815)(3/2^-)$
- $\Xi_c(2790)(1/2^-)$

- $\Xi_c(2645)(3/2^+)$

- $\Xi_c'(1/2^+)$
- $\Xi_c(1/2^+)$
Both Belle and BaBar observed \( \Xi_c(2980)^+ \), \( \Xi_c(3055)^+ \), and \( \Xi_c(3080)^+ \) in \( \Sigma_c^{++}K^- \) final state. \( \Xi_c(3080)^+ \) in \( \Sigma_c^{*++}K^- \) final state (only BaBar observed \( \Xi_c(3123)^+ \)).

Decays where charm quark in contained in meson will give more insight \( \rightarrow \Lambda D! \)
First observation of the “decay” of $\Xi_c(3055/3080)$ into $\Lambda D^+$. 

$N(\Xi_c(3055)^+)>N(\Xi_c(3080)^+)$: Opposite to $\Sigma_c^{++}\Lambda^-$. 

First observation of $\Xi_c(3055)^0$ (8.6σ)
Relative branching fractions

\[ \Xi_c(3055)^+ \]
\[ \text{Br}(\Lambda D^+)/\text{Br}(\Sigma_c^{++}K^-) = 5.09 \pm 1.01 \pm 0.76 \]

\[ \Xi_c(3080)^+ \]
\[ \text{Br}(\Lambda D^+)/\text{Br}(\Sigma_c^{++}K^-) = 1.29 \pm 0.30 \pm 0.15 \]
\[ \text{Br}(\Sigma_c^{*++}K^-)/\text{Br}(\Sigma_c^{++}K^-) = 1.07 \pm 0.27 \pm 0.01 \]

First ever measurement of relative branching fraction of (heavy-baryon + light-meson) and (light-baryon + heavy-meson).

Partial width of \( \Xi_c(3055) \) by chiral quark model (MeV)

| \[ |\Xi_c^2 D_{\lambda\lambda} (3/2^+)\] | \[ |\Xi_c^2 D_{\rho\rho} (3/2^+)\] | \[ \Sigma_c \bar{K} \] | \[ \Xi_c^* (2645) \pi \] | \[ \Xi_c' \pi \] | \[ \Sigma_c^* \bar{K} \] | \[ D \Lambda \] | \[ \text{total} \] |
|---|---|---|---|---|---|---|---|
| 2.3 | 0.5 | 1.0 | 0.1 | 0.1 | 4.0 |
| 5.6 | 0.8 | 3.3 | 0.3 | - | 10.0 |

Inconsistent with our measurement!
Doubly Cabibbo Suppressed decay: $\Lambda_c^+ \to pK^+\pi^-$

- In the baryon sector, Doubly Cabibbo Suppressed (DCS) decay had never been observed. $\Lambda_c^+ \to pK^+\pi^-$ is expected to be sensitive.

- Naively, ratio to CF decay, $pK^-\pi^+$ is expected to be

$$ \frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} \approx \tan^4 \theta_c $$

- $W$-exchange diagram can contribute only in CF decay.

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DCS decays

CF decays
Results

- Branching fraction ratio = \((2.35 \pm 0.27\text{(Stat)} \pm 0.21\text{(Sys)}) \times 10^{-3}\)
  = \((0.82 \pm 0.12) \times \tan^4\Theta_c\)

- After subtracting contribution of \(\Lambda(1520)\) or \(\Delta\) intermediate, which contribute only on the CF decay, the ratio is
  \((1.10 \pm 0.17) \times \tan^4\Theta\)

- Contribution from W exchange diagram is not large.

DCS mode: pK^+\pi^-

- 3587 \pm 380 events
- Significance: 9\sigma

CF mode: pK^-\pi^+

\((1.452 \pm 0.015) \times 10^6\) events

Phys. Rev. Lett. 117, 011801
Search for pentaquark via $\Lambda_c^+ \rightarrow \pi^0 \phi p$

- LHCb observed hidden charm pentaquark state in the $\Lambda_b^0 \rightarrow K^- P_c^+ \rightarrow K^- (J/\psi \, p)$

- Natural extension is analogue search for hidden-strange pentaquark by switching $b \rightarrow c$ ($\Lambda_b^0 \rightarrow \Lambda_c^+$), $c \rightarrow s$ ($J/\psi \rightarrow \phi$) $: \Lambda_c^+ \rightarrow \pi^0 P_s^+ \rightarrow \pi^0 (\phi \, p)$

- $\Lambda_c^+ \rightarrow \pi^0 \phi p$ decay itself is not observed so far.
Results

Perform 2D fit on $M(K^+K^-p\pi^0)$ and $M(K^+K^-)$ plane. No significant $\Lambda_c^+$ signals is observed.

New upper limits:
- $\text{Br}(\Lambda_c^+\rightarrow\phi p \pi^0) < 15.3 \times 10^{-5}$
- $\text{Br}(\Lambda_c^+\rightarrow K^+K^-p\pi^0)_{NR} < 6.3 \times 10^{-5}$

Also perform 2D fit in each $M(\phi p)$ bin. No significant $P_s^+$ signal observed.
- $\text{Br}(\Lambda_c^+\rightarrow P_s^+\pi^0)\times\text{Br}(P_s^+\rightarrow\phi p) < 8.3 \times 10^{-5}$
• First observation of the decay $\Xi_c(3055)$ and $\Xi_c(3080) \to \Lambda D$
  - $Br(\Lambda D)/Br(\Sigma_{c}^{++}K^-)$ are different for two states.
  - First observation of $\Xi_c(3055)^0$

• First observation of Doubly Cabibbo Suppressed decay: $\Lambda_c^+ \to pK^+\pi^-$
  - The ratio to CF decay can be explained by CKM suppression.
  - Contribution from $W$-exchange diagram is small.

• Search for hidden strange pentaquark $P_s^+$ in $\Lambda_c^+ \to \pi^0 (\phi p)$
  - No signal for $P_s^+$ as well as the decay $\Lambda_c^+ \to \pi^0 (\phi p)$

• Stay tune for more results on charmed baryon from Belle!
Backup
Physics of single charmed baryons

- Charm quark is heavy: \((1500 \, \text{MeV/c}^2) > u,d,s\) quarks \((300-500 \, \text{MeV/c}^2)\)
- Spin-spin interaction \(\propto 1/m_1 m_2\)
- Di-quark correlation in light quarks (more simple!).

Nucleon

Every pair can not be distinguished.

Charmed baryon

Light di-quark and charm quark.
### Observed charmed baryons

<table>
<thead>
<tr>
<th>Charmed Baryon</th>
<th>Spin</th>
<th>Parity</th>
<th>Quark Content</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c$</td>
<td>(1/2$^+$)</td>
<td>1/2$^-$</td>
<td>C d u</td>
<td>CLEO 8(7) (1995~2001)</td>
</tr>
<tr>
<td>$\Lambda_c(2595)^+$</td>
<td>1/2$^-$</td>
<td></td>
<td>C d u</td>
<td>BELLE 3 (2006~)</td>
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<tr>
<td>$\Lambda_c(2625)^+$</td>
<td>(3/2$^-$)</td>
<td></td>
<td>C d u</td>
<td>BABAR 5(2) (2007~)</td>
</tr>
<tr>
<td>$\Lambda_c(2765)^+$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c(2880)^+$</td>
<td>5/2$^+$</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c(2940)^+$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Sigma_c(2455)$</td>
<td>(1/2$^+$)</td>
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<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Sigma_c(2520)$</td>
<td>(3/2$^+$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Sigma_c(2800)$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c$</td>
<td>(1/2$^+$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(2645)$</td>
<td>(3/2$^+$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(2790)$</td>
<td>(1/2$^-$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(2815)$</td>
<td>(3/2$^-$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(2930)$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(2980)$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(3055)$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(3080)$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Xi_c(3123)$</td>
<td>?</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c$</td>
<td>(1/2$^+$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
<tr>
<td>$\Omega_c(2770)$</td>
<td>(3/2$^+$)</td>
<td></td>
<td>C d u</td>
<td></td>
</tr>
</tbody>
</table>

- 16/21 (12/17) charmed baryons are observed in $e^+e^-$ collider experiment.
- All the ground states predicted by quark model are discovered.

**Still many things to do!**
- Spin-parity almost from quark model prediction ().
- Some states has only poor evidence (states in []).
- Many states are observed in only 1 decay mode.
- Accuracy of mass/width is not good enough.
- No $\lambda$ and $\rho$ mode excitation states identified.

Today’s topic
Belle experiment

- Asymmetric energy $e^+e^-$ collider.
- $\sqrt{s}=10.58$ GeV = $\Upsilon(4S)$ mass (and other energies)
- Peak luminosity = $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  = World highest luminosity!
- General purpose feature of the Belle detector make it possible to study hadron spectroscopy.
Comparison with quark model prediction

- In the quark model, they should be N=2 shell and these states are identified as:
  $\Xi_c(3055) = \left|^2D_{\lambda\lambda}(3/2^+)\right|$ or $\left|^2D_{\rho\rho}(3/2^+)\right|$.

  (Phys. Rev. D 86, 034024)

| $|\Xi_c^2D_{\lambda\lambda}(3/2^+)\rangle$ | $\Sigma_c\bar{K}$ | $\Xi_c^*(2645)\pi$ | $\Xi^*_c\pi$ | $\Sigma_c^*\bar{K}$ | $D\Lambda$ | total |
|---|---|---|---|---|---|---|
| 2.3 | 0.5 | 1.0 | 0.1 | 0.1 | 4.0 |
| 5.6 | 0.8 | 3.3 | 0.3 | - | 10.0 |

- They predicted
  - $\Lambda D$ decay is suppressed for both $\Xi_c(3055)^+$

- Inconsistent with this measurement.

- Challenge for theorists!
### Comparison of $\Lambda_c^+$ and $\Xi_c$ or $\Sigma_c$ and $\Xi_c'$

<table>
<thead>
<tr>
<th>$J^p$</th>
<th>$\Lambda_c^+$</th>
<th>$\Xi_c$</th>
<th>$\Delta M$(Mev/c$^2$)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2$^+$</td>
<td>$\Lambda_c(2286)^+$</td>
<td>$\Xi_c(2470)$</td>
<td>181</td>
<td>ground state</td>
</tr>
<tr>
<td>1/2$^-$</td>
<td>$\Lambda_c(2595)^+$</td>
<td>$\Xi_c(2790)$</td>
<td>194</td>
<td>$\Lambda$(1405) like</td>
</tr>
<tr>
<td>3/2$^-$</td>
<td>$\Lambda_c(2625)^+$</td>
<td>$\Xi_c(2815)$</td>
<td>188</td>
<td>$\Lambda$(1520) like</td>
</tr>
<tr>
<td>??</td>
<td>$\Lambda_c(2765)^?^+$</td>
<td>$\Xi_c(2980)^?$</td>
<td>205</td>
<td>Isospin not determined</td>
</tr>
<tr>
<td>5/2$^+$</td>
<td>$\Lambda_c(2880)^+$</td>
<td>$\Xi_c(3080)^?$</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$J^p$</th>
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<th>$\Xi_c'$</th>
<th>$\Delta M$(Mev/c$^2$)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2$^+$</td>
<td>$\Sigma_c(2455)$</td>
<td>$\Xi_c(2575)$</td>
<td>120</td>
<td>ground state</td>
</tr>
<tr>
<td>3/2$^+$</td>
<td>$\Sigma_c(2520)$</td>
<td>$\Xi_c(2645)$</td>
<td>125</td>
<td>$\Sigma$(1385) like</td>
</tr>
<tr>
<td>??</td>
<td>$\Sigma_c(2800)$</td>
<td>??</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The mass difference of $\Lambda_c$ and $\Xi_c$ is $\sim 200$ MeV/c$^2$, $\Sigma_c$ and $\Xi_c'$ is $\sim 120$ MeV

$\Xi_c(3055)$ has no corresponding state in $\Lambda_c/\Sigma_c$
DCS decay of the $\Lambda_c^+$

- In the baryon sector, Doubly Cabbibo Suppressed (DCS) decay has NEVER been observed. $\Lambda_c^+ \rightarrow pK^+\pi^-$ is expected to be sensitive.

- Naively, ratio to CF decay, $pK^-\pi^+$ is expected to be
  
  \[
  \frac{B(\Lambda_c^+ \rightarrow pK^+\pi^-)}{B(\Lambda_c^+ \rightarrow pK^-\pi^+)} \approx \tan^4 \theta_c
  \]

- In the CF decay, the W exchange diagram may contribute.

DCS decay

CF decay with W exchange
Dalitz plot for $\Lambda_c^+ \rightarrow pK^-\pi^+$

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Weak decay of charmed baryon is unique light baryon laboratory