Studies of $\Lambda_c(2765)^+$ quantum numbers & other charmed baryons at Belle

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Introduction – Charmed baryons

• Heavy quark in Baryon
  – Bare quark $\approx$ constituent quark
  – Makes a “static core”, light quarks play around $\Rightarrow$ Diquark correlation enhanced?
  – New symmetry – heavy quark symmetry $\Rightarrow$ Hyperfine doublet for heavy quark spin.

Nucleon

Charmed baryon

Indistinguishable pairs

Light di-quark with inert charm?

HQS: spin Approximately conserved
Known charmed baryons

• A few dozens of states are known
• $I(J^P)$ are experimentally determined for very few states
• Quark model predictions are quite good up to $E_x \sim 400$ MeV – assignment of $I(J^P)$
Many States have yet to be observed. Quark model prediction (L.A. Copley et al, PRD20 (1979) 768) and Observed (PDG, 2012 online) both show missing and unknown states.
Known charmed baryons

• A few dozens of states are known
• \( I(J^P) \) are experimentally determined for very few states
• Quark model predictions are quite good up to \( E_x \sim 400 \text{ MeV} \) – assignment of \( I(J^P) \)
• There are many predicted states above that
  – Identification needs (at least) experimental determination of \( I(J^P) \)
This talk

• Introduces recent activities from the Belle experiment

1. Determination of quantum numbers of $\Lambda_c/\Sigma_c(2765)$
   — Especially isospin

2. Confirmation of $\Xi_c(2930)$ in B decays
Belle experiment

- √s~10.6 GeV
- Integrated Luminosity ~ 1 ab⁻¹

Almost 4π, good momentum resolution (∆p/p ~ 0.1%), EM calorimeter, PID & Si Vertex detector
1. $\Lambda_c / \Sigma_c (2765)$
First observation by CLEO

\( \Lambda_c(2765)^+ \)
or \( \Sigma_c(2765) \)

CLEO[PRL86 (2001) 4479]

- B decay → \( \Lambda_c^* \) → \( \Lambda_c \pi \pi \) (\( \Sigma_c \pi, \Sigma_c^* \pi \) included)
- Width \( \sim \) 50 MeV (no uncertainty given)
**Known things**

- **Experimentally – very poor**
  - $I(J^P)$ not determined yet
  - No uncertainty on mass from CLEO

- **Theoretically – so many**
  - Quark models: six states in this mass region
    - $I(J^P)= 0(1/2^+), 0(1/2^-), 1(1/2^-), 1(1/2^-), 1(3/2^-), 1(3/2^-)$
  - Including other models, any combination of $I=0$ or $1$, $J=1/2$ or $3/2$, and $P=\pm$ seems possible

- **Experimental determination of $I(J^P)$ is necessary to identify the nature of $\Lambda_c/\Sigma_c(2765)$**
How to determine $I(J^P)$?

• Spin (J): angular distribution of the decay $\Lambda_c/\Sigma_c(2765) \rightarrow \Sigma_c(*)\pi$ & angular correlation of two pions in $\Lambda_c/\Sigma_c(2765) \rightarrow \Sigma_c^*\pi_1 \rightarrow \Lambda_c\pi_1\pi_2$

• Parity (P): Use branching ratio (used for $\Lambda_c(2880)$)

$$R = \frac{\Gamma(\Lambda_c^* \rightarrow \Sigma_c^*\pi)}{\Gamma(\Lambda_c^* \rightarrow \Sigma_c\pi)}$$

• Isospin (I): Search for possible isospin partners $(\Sigma_c(2765)^{++/0})$ by $\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0 \rightarrow \Lambda_c(2765)^+\pi^\pm\pi^0$
How to determine $I(J^P)$?

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- Parity ($P$): Use branching ratio (used for $\Lambda_c(2880)$)
  \[ R = \frac{\Gamma(\Lambda_c^* \rightarrow \Sigma_c^*\pi)}{\Gamma(\Lambda_c^* \rightarrow \Sigma_c\pi)} \]

- Isospin ($I$): Search for possible isospin partners ($\Sigma_c(2765)^{++/0}$) by
  $\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0 \rightarrow \Lambda_c(2765)^+\pi^\pm\pi^0$
Reference mode: $\Lambda_c/\Sigma_c(2765)^+ \rightarrow \Sigma_c\pi$

(a) Inclusive $\Lambda_c\pi^+\pi^-$  
(b) With $\Sigma_c$ selection

- Analyzed with full data of Belle (980 fb$^{-1}$)
- Clear peaks are observed
- Fit with Breit-Wigner functions to extract yield.
\[ \Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0 \]

[Expected for \( I=1 \)]

- No peak seen \( \Rightarrow \) **Isospin is not 1, but 0.**
- The name is indeed \( \Lambda_c(2765) \)

[Belle-Conf-1905, Submitted to ArXiv]
2. $\Xi_c(2930)$
Observed $\Xi_c$ states

- Most are observed in continuum production:
  - $\Xi_c$, $\Xi'_c$, $\Xi_c^*(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2970)$, $\Xi_c(3055)$, $\Xi_c(3080)$, ...

- $\Xi_c(2930)$: First reported by Babar [PRD77 031101 (2008)], in B decays, but not reported in other modes.
\( \Xi_c(2930)^0 \) and \( \Xi_c(2930)^+ \)

Now confirmed by Belle using \((772 \pm 11) \times 10^6 \, B\bar{B} \) pairs

\[ \Xi_c(2930)^0 \rightarrow K^- \Lambda_c^+ \text{ in } B^- \rightarrow K^- \Lambda_c^+ \bar{\Lambda}_c^- \]

\[ \Xi_c(2930)^+ \rightarrow K_s^0 \Lambda_c^+ \text{ in } B^0 \rightarrow K_s^0 \Lambda_c^+ \bar{\Lambda}_c^- \]

- \( \Xi_c(2930)^0 \): 5.1σ significance, \( M = 2928.9 \pm 3.0^{+0.9}_{-12.0} \) MeV
- \( \Xi_c(2930)^+ \): > 3.5σ significance, \( M = 2942.3 \pm 4.4 \) MeV
Can it be seen in other modes?

• Not in inclusive $\Lambda_c K$ [Babar: PRD77,012002]

• There is a hint in $\Xi_c \pi \pi$ mode [Belle: PRD94,052011], but not conclusive. Anyway much fewer than $\Xi_c(2970)$.

• May have a different structure from others
Spin-parity?

• Spin could be determined from angular distribution, i.e., line density in the Dalitz plot, if we have enough statistics...

• We have to wait for Belle II

• Parity needs even more (polarization, ...)
Summary & Prospect

• Charmed baryons are actively studied in Belle

• $\Lambda_c(2765)$: Study on $I(J^P)$ quantum numbers are ongoing
  – Isospin ($I$) is determined to be 0.
  – Spin-parity ($J^P$) will be coming soon
  → We can discuss the nature of the state

• $\Xi_c(2930)$:
  – The existence is confirmed.
  – Need Belle II statistics to determine Spin-parity

• More results are coming in the future.