Spectroscopy of charmed baryon at the J-PARC high-momentum beam line

K. Shirotori
for the J-PARC E50 collaboration

Research Center for Nuclear Physics (RCNP)
Osaka University

International workshop on J-PARC hadron physics in 2016
3 Mar 2016
Contents

• Physics motivation
  – Essential degree of freedom of hadrons
  – Diquark correlation

• Experiment at J-PARC
  – High-momentum beam line
  – Spectrometer system
  – Expected spectrum
  – Systematic study

• Summary
Physics motivation
What is an essential degree of freedom?

Constituent Quark

- Hadrons
  - Baryon: qqq
  - Meson: q\bar{q}

⇒ Constituent Quark model
  - c.f. Mass and Magnetic moment of Ground States

However, we cannot understand...

- Missing states
- Exotic hadrons
What is an essential degree of freedom?

Constituent Quark

Exotic hadron

- Hadron molecular & Multi-quark states
  - $\Lambda(1405): \bar{K} + \text{Nucleon}$
  - $X, Y, Z, Z_b$ particle
  - $\Theta^+, P_c$: Pentaquark
Bridge from quark to hadron

- **Quark**
  - Bare quark

- **Constituent**
  - Constituent quark
  ⇒ Need constituent pictures for understanding

- **Hadron**
  - Observables
Bridge from quark to hadron

- **Quark**
  - Bare quark

- **Constituent**
  - Constituent quark, *diquark correlation*, *hadron molecule*
  \[ \Rightarrow \text{Need constituent pictures for understanding} \]

- **Hadron**
  - Observables
  \[ \Rightarrow \textit{Exotic hadrons} \]
Charmed baryon spectrum: “Excitation Mode”

Heavy Quark: Weak color-magnetic interaction

⇒”q-q” isolated and developed: “q-q + Q”
Production by hadron beam

Hadronic production: $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$

Production cross section

$\Rightarrow$ Overlap of wave function

*charm and $q$-$q$ (spectator)

$$R \sim \left\langle \varphi_f \left| \sqrt{2} \sigma_+ \exp(iq_{\text{eff}} \cdot \vec{r}) \right| \varphi_i \right\rangle$$

1. Spin/Parity of $Y_c^*$

2. Momentum transfer ($q_{\text{eff}}$)

$$I_L \sim \left( q_{\text{eff}}/A \right)^L \exp(-q_{\text{eff}}^2/2A^2)$$

$A$: (baryon size parameter)$^{-1}$

$D^*$ exchange at a forward angle

S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori
Production by hadron beam

Hadronic production: \( \pi^- + p \rightarrow Y_c^{*+} + D^{*-} \)

Similar mechanism to \( \pi^+ + {}^\Lambda Z \rightarrow {}^\Lambda \Lambda Z + K^+ \) reaction

\[ {}^{90}_\Lambda Zr \] (simulation)
Production by hadron beam

*Production rates ⇔ Excitation mode

- Forward angles: $\lambda$ mode
- Angular distribution: $\lambda/\rho$ modes
- Spin/parity of $Y_c^*$

⇒ Study from “Production”

$L = 0$  \hspace{1cm} L = 1 \hspace{1cm} L = 2$

$I_L / I_{g.s.} \sim (q_{eff}/A)^L$

$q_{eff}$: Momentum transfer
$A$: (baryon size parameter)$^{-1}$

Simulation
Production by hadron beam

* Production rates ⇔ Excitation mode
  - Forward angles: \( \lambda \) mode
  - Angular distribution: \( \lambda/\rho \) modes
  - Spin/parity of \( Y_c^* \)

⇒ Unique approach to investigate “q-q + Q” system

![Graph showing counts vs. missing mass for different L values](image)

- \( L = 0 \): \( \Lambda_c \) and \( \Sigma_c \) peaks
- \( L = 1 \): \( \Delta_c \) and \( \Sigma_c \) peaks
- \( L = 2 \): All \( \Lambda_c \) peaks

Hypernuclear production \( {}^A_Z(\pi^+, K^+) Z \)

- \( {}^{90}_{\Lambda} Zr \) (simulation)

Simulation
• Decay property

\[\Gamma_{\pi\Sigma_c} > \Gamma_{ND}\]

\[\Gamma_{\pi\Sigma_c} < \Gamma_{ND}\]

- Decay measurement: \(\Gamma_{\pi\Sigma_c} \leftrightarrow \Gamma_{ND}\)
  - \(\pi^- + \Sigma_c^{++}, \pi^+ + \Sigma_c^0\)
  - \(p + D^0\)

\(\rho\)-mode decay: \(qqQ + q\bar{q}\)

\(\lambda\)-mode decay: \(qqq + Qq\bar{q}\)
Charmed baryon spectroscopy

J-PARC E50 experiment

• Investigate charmed baryons by Missing Mass spectroscopy
  • Systematic measurement
    – Excited states search
    – Excitation energy
    – Production cross section
    – Decay property

⇒ Diquark correlation
  – Excitation mode

Observed charmed baryons in PDG
Experiment
High-momentum beam line

Construction by 2018
High-momentum beam line for 2ndary beam

- **High-intensity beam**: $> 1.0 \times 10^7 \text{ Hz } \pi (< 20 \text{ GeV/c})$
  - Unseparated beam
- **High-resolution beam**: $\Delta p/p \sim 0.1\% (\text{rms})$
  - Momentum dispersive optics method
High-momentum beam line for 2ndary beam

- **High-intensity beam**: \( > 1.0 \times 10^7 \) Hz \( \pi \) (< 20 GeV/c)
  - Unseparated beam
- **High-resolution beam**: \( \Delta p/p \approx 0.1\% \text{(rms)} \)
  - Momentum dispersive optics method

Sanford-Wang

Prod. Angle = 0 degrees
15 kW Loss on Pt, Acceptance : 2 msr%, 132 m

Counts/sec

\[ \pi^+, \pi^-, K^+, K^- \]
\[ p_\text{bar} \]

/spill \( \Rightarrow \times 6 \)
\[ \pi^- + p \rightarrow Y_c^{**} + D^{*-} \text{ reaction @ 20 GeV/c} \]

1) Missing mass spectroscopy
   - \( D^{*-} \rightarrow \bar{D}^0 \pi_s^- \rightarrow K^+ \pi^- \pi_s^- \): \( D^{*-} \rightarrow \bar{D}^0 \pi_s^- \) (67.7%), \( \bar{D}^0 \rightarrow K^+ \pi^- \) (3.88%)

2) Decay measurement
   - Decay particles (\( \pi^\pm \) & proton) from \( Y_c^* \)
Expected production cross section

High energy 2-body reaction based on the Regge theory

Normalized to strangeness production \[ \Rightarrow \text{Charm production: } \sim 10^{-4} \]

No old data @ 10-20 GeV/c

\* Assumed production cross section: \( \sigma \sim 1 \text{ nb} \)
- \( \pi^- + p \rightarrow \Lambda_c^+ + D^{*-} \) reaction @ 13 GeV/c: \( \sigma < 7 \text{ nb} \) (BNL data)

- High-rate beam & Multi-purpose spectrometer system
  - Beam intensity: \( 6 \times 10^7 / 2.0 \) sec spill
  - Large acceptance spectrometer
Spectrometer design

- Scattered partials: Forward direction
  - $D^*$ detection by forward detectors
  - $Y_c^*$ decay particle detection with wide angular range
    ○ Internal detectors in magnet gap
Charmed baryon spectrometer
Charmed baryon spectrometer
Charmed baryon spectrometer

[Diagram of a charmed baryon spectrometer with labeled components: LH₂-target, Beam π⁻, Fiber tracker, T₀, TOF wall, DC, PID counter, Ring Image Cherenkov Counter, K⁺, π⁻, πₛ⁻, 2m]
Charmed baryon spectrometer

- LH$_2$-target
- Beam $\pi^-$
- $\pi^-$
- $\pi^+$
- $\pi_s^-$
- $K^+$
- PID counter
- Ring Image Cherenkov Counter
- TOF wall
- Fiber tracker
- Internal DC
- 2m
Charmed baryon spectrometer
Charmed baryon spectrometer

Large Acceptance Multi-Purpose Spectrometer
Charmed baryon spectrometer

- **Acceptance**
  - Momentum: 0.2–20 GeV/c
  - Angle: < 40°
  - \( D^* : 50–60\% \)
  - Decay particle: \(~80\%\)
  - Wide angular coverage

- **Resolution**
  - \( \Delta p/p = 0.2\% \) @ 5 GeV/c
  - \( \Delta M_{\Lambda c^*} = 10 \text{ MeV} \) @ 2.8 GeV/c²

> Decay angle: \( \Lambda_c(2940)^+ \rightarrow \Sigma_c(2455)^0 + \pi^+ \)

To be “Multi-purpose”

⇒ High-speed DAQ system
  - Trigger less system

* On-line event reconstruction by using PC clusters
  - Momentum & PID analysis
**DAQ: Scheme**

**E50: Streaming DAQ system**

**Frontend modules**
- **Signal digitalization**
  - Self or periodic trigger
  - Pipelined system
    - ~30,000 ch

**Buffer PCs (~50 GB/spill)**
- **Event accumulation**
  - Several 10 GB memories
  - > 10 spill data

**High-speed data link**
Gigabit transceivers, Ethernet

**Filter PCs (~50 GB/spill)**
- **Event reconstruction**
  - Several 10 GB memories
  - 100–200 CPUs

**Storage (< 0.5 GB/spill)**
- Local storage
- Transferred to KEKCC/RNCP

**Data rate:** 4 g/cm² target and 30 MHz beam conditions
Data taking channels: For example

- **Charmed baryons**
  - $\pi^- + p \rightarrow Y_c^+ + D^{*-}$

- **$\Xi_c$ baryons**
  - $\pi^- + p \rightarrow \Xi_c^0 + D^{*+} + K^+$

- **$Y$ baryons: Yield = $Y_c \times 10^4$**
  - $\pi^- + p \rightarrow Y^0 + K_S^0$
  - $\pi^- + p \rightarrow Y^0 + K^{*0}$
  - $\pi^- + p \rightarrow Y^- + K^{*+}$
  - $\pi^- + p \rightarrow \Theta^+ + K^{*-}$

- **$\Xi$ baryons: Yield = $Y_c \times 10^3$**
  - $K^- + p \rightarrow \Xi^0 + K^{*0}$
  - $K^- + p \rightarrow \Xi^- + K^{*+} : (K_S^0 + \pi^+)$
  - $\pi^- + p \rightarrow \Xi^- + K_S^0 + K^+$
  - $\pi^- + p \rightarrow \Xi^- + K^{*0} + K^+$

- **$\Omega$ baryons: Yield = $Y_c \times 10^2$**
  - $K^- + p \rightarrow \Omega^- + K_S^0 + K^+$
  - $K^- + p \rightarrow \Omega^- + K^{*0} + K^+$

*Hyperon beams as well*

- **Drell-Yan channels**
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$ (Same as $P_c^0$)
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$
Data taking channels: For example

- **Charmed baryons**
  - $\pi^- + p \rightarrow Y_c^+ + D^-\bar{\pi}$

- **Ξ_c baryons**
  - $\pi^- + p \rightarrow \Xi_c^0 + D^{*-} + K^+$

- **Y baryons: Yield = $Y_c \times 10^4$**
  - $\pi^- + p \rightarrow Y^0 + K_S^0$
  - $\pi^- + p \rightarrow Y^0 + K^{*0}$
  - $\pi^- + p \rightarrow Y^- + K^{*+}$
  - $\pi^- + p \rightarrow \Theta^+ + K^{*-}$

- **Ξ baryons: Yield = $Y_c \times 10^3$**
  - $K^- + p \rightarrow \Xi^0 + K^{*0}$
  - $K^- + p \rightarrow \Xi^- + K^{*+} + (K_S^0 + \pi^+)$
  - $\pi^- + p \rightarrow \Xi^- + K_S^0 + K^+$
  - $\pi^- + p \rightarrow \Xi^- + K^{*0} + K^+$

- **Ω baryons: Yield = $Y_c \times 10^2$**
  - $K^- + p \rightarrow \Omega^- + K_S^0 + K^+$
  - $K^- + p \rightarrow \Omega^- + K^{*0} + K^+$

*Hyperon beams as well*

- **Drell-Yan channels**
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$ (Same as $P_c^0$)
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$

Main channel
Data rate: < 0.1 kHz
Data taking channels: For example

- **Charmed baryons**
  \[ \pi^- + p \rightarrow Y_c^+ + D^{*-} \]

- **Ξ_c baryons**
  \[ \pi^- + p \rightarrow \Xi_c^0 + D^{*-} + K^+ \]

- **Y baryons:** \( \text{Yield} = Y_c \times 10^4 \)
  \[ \pi^- + p \rightarrow Y^0 + K_S^0 \]
  \[ \pi^- + p \rightarrow Y^0 + K^{*0} \]
  \[ \pi^- + p \rightarrow Y^- + K^{*+} \]
  \[ \pi^- + p \rightarrow \Theta^+ + K^{*-} \]

- **Ξ baryons:** \( \text{Yield} = Y_c \times 10^3 \)
  \[ K^- + p \rightarrow \Xi^0 + K^{*0} \]
  \[ K^- + p \rightarrow \Xi^- + K^{*+} : (K_S^0 + \pi^+) \]
  \[ \pi^- + p \rightarrow \Xi^- + K_S^0 + K^+ \]
  \[ \pi^- + p \rightarrow \Xi^- + K^{*0} + K^+ \]

- **Ω baryons:** \( \text{Yield} = Y_c \times 10^2 \)
  \[ K^- + p \rightarrow \Omega^- + K_S^0 + K^+ \]
  \[ K^- + p \rightarrow \Omega^- + K^{*0} + K^+ \]

- **Hyperon beams as well**

- **Drell-Yan channels**
  \[ \pi^- + p \rightarrow n + \mu^+ + \mu^- \] (Same as \( P_c^0 \))
  \[ K^- + p \rightarrow Y^0 + \mu^+ + \mu^- \]

---

**Byproducts**

*Event selection as you like!*

- Single scattered channels
  c.f. \( \pi^- + p \rightarrow Y + K^+/K^0 \)
  - \( K^+/K^0 \) rate: \(~200\) kHz

- Kaon beam rate \(~1/100\)
  c.f. \( K^- + p \rightarrow \Xi^- + K^+ \)
Expected spectra

~2000 counts @ $N_{\text{pot}} = 8.64 \times 10^{13}$ (100 days, $\varepsilon_{\text{total}} = 0.5$)

- $\Lambda_c$(g.s.): 1 nb production cross section
  - Production ratio for excited states
- Background level and reductions were precisely studied.

* Achievable sensitivity of 0.1–0.2 nb: (3$\sigma$ level, $\Gamma < 100$ MeV)
**Expected spectra**

- **λ-mode excitation doublets:** Production enhanced
  ⇒ Internal structure of charmed baryon
  - Decay measurement also performed: $\Gamma_{\pi \Sigma_c} \leftrightarrow \Gamma_{pD}$

*Diquark correlation: Excitation mode*
Systematics of strangeness baryons

* Yield: $10^4$–$10^5$/day @ 1 µb
  - 4 g/cm², $6 \times 10^7$/spill ($\sim 10^6$/spill for K beam)
  - 50% acceptance, 50% efficiency (DAQ, PID, Analysis)

• **Y**: q-q + Q system @ Strangeness sector
  c.f. $\pi^- + p \rightarrow Y^* + K^{*0}$ reaction
  - Production ratio
    - Reflect q-q excitation mode
  - Decay branching ratio
    - $\Gamma(NK_{\bar{b}ar})/\Gamma(\pi\Sigma)$

• **Ξ**: q + QQ system
  c.f. $K^- + p \rightarrow \Xi^* + K/K^*$ and $\pi^- + p \rightarrow \Xi^* + K/K^* + K$ reactions
  - Heavier diquark (q-s, s-s) system?

• **Ω**: QQQ system
  c.f. $K^- + p \rightarrow \Omega^* + K/K^* + K$ reaction
  - Much simpler system: Diquark less system?
Summary

• Charmed baryon spectroscopy
  – Essential way to understand hadron structure
  – Diquark correlation: $\lambda$ and $\rho$ mode excitation

• Experiment at the J-PARC high-$p$ beam line
  – Inclusive measurements by missing mass spectroscopy with multi-purpose spectrometer system
    ○ Unique information from the production measurement
  – Multi-purpose spectrometer system
    ○ Data taking of many reaction channels by high-speed DAQ

• Systematic study of baryons at J-PARC
  – Excitation energy, production, decay with strangeness sector: $q$-$q + Q$, $q + QQ$, $QQQ$
    ○ Pilot studies for the K10 beam line
  – Systematics to understand hadron structure
J-PARC E50 collaboration

- RCNP
- KEK
  - K. Aoki, Y. Morino, K. Ozawa
- RIKEN
  - Y. Ma, F. Sakuma
- Tohoku ELPH
  - T. Ishikawa
- Yamagata U
  - Y. Miyachi
- JAEA
  - K. Tanida, Y. Ichikawa
- Kyoto U
  - M. Naruki
- Tohoku U
  - K. Miwa
- Academia Sinica
  - T. Sawada, C.W. Chang
- Korea U
  - J.K. Ahn
- Osaka U
  - R. Honda
- JLab
  - J.T. Goetz

Next Generation Hadron Experiment at the J-PARC High-p beam line

Let’s do it together!

High-p

Thank you for your attention
Joint collaboration at High-p

- Primary beam: E16
- Secondary beam: E50
- Heavy Ion beam: High-p