Baryon spectroscopy with secondary hadronic beams at J-PARC

K. Shirotori
for the E50/E31 collaboration

Research Center for Nuclear Physics (RCNP)
Osaka University

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  • Study of excited states: Effective degree of freedoms of hadron
  • Spectroscopy of charmed baryon and hyperon at J-PARC

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• Study of hadron molecule state: Λ(1405)
  • J-PARC E31 experiment

• Summary
Motivations

Investigations of excited states
Charmed baryon and hyperon spectroscopy
How hadrons are originated by quark and gluon?

• Understand hadrons by new effective degree of freedom ⇒ Semi-Hierarchies between Hadron and Quark • Gluon (A02)

* J-PARC & LEPS2 projects

- Constituent quark
- Diquark
- Hadron molecule
Excited states: Observation of exotic hadrons

Constituent quark

Meson

Baryon

Hadron molecule

Multi-quark

Exotic hadrons

* Excited states: Rich properties
⇒ Mass, width, decay branching ratio, spin and parity
from new effective degree of freedoms extended to ordinary constituent quark model
Excited states: Observation of exotic hadrons

Constituent quark

Meson

Baryon

Hadron molecule

Multi quark

Diquark correlation

Exotic hadrons

Diquark correlation & Hadron molecule
Excited states and effective degree of freedoms

- Properties of excited states? (Mass, Γ, J^P)
- Role of effective degree of freedoms? (Systematics)
- How (where) configurations emerge? (Threshold region …)
- Understand whole hadron properties universally?
Excited states and effective degree of freedoms

- Properties of excited states ? (Mass, $\Gamma$, $J^P$)
- Role of effective degree of freedoms ? (Systematics)
- How (where) configurations emerge ? (Threshold region …)
- Understand whole hadron properties universally ?
Excited states with heavy quark: Diquark

“Excited mode”: $\lambda$ and $\rho$ modes in heavy baryon excited states ($q$-$q$ + $Q$ system)

$\Rightarrow$ Diquark correlation: $q$-$q$ isolated and developed
Charmed baryon spectroscopy experiment: J-PARC E50

\[ \pi^- + p \rightarrow Y_c^{*+} + D^{*-} \text{ reaction} \ @ \ 20 \text{ GeV/c} \]

- High-intensity \( \pi^- \) beam: \( 6.0 \times 10^7 \) /spill
- Production rates & Decay branching ratios

Excited states with heavy quark: Diquark

"Excited mode": \( l \) and \( r \) modes in charmed baryon excited states (\( q^-q^+ \) system)

\( \Rightarrow \) Diquark correlation from Production rate and Decay branching ratio

\( c \) \( q^-q^+ \)

Corrective motion btw \( q^-q^+ \) and \( Q \)

Excited states by spin-spin interaction

\( \Rightarrow \) Observables

Light quark baryon

See diagram for detailed visual representation.
Production rates by hadronic reaction

- \( \pi^- + p \rightarrow Y_c^{*+} + D^{*-} \) reaction: Missing mass method
- Production rates \( \Leftrightarrow \) Internal structure of excited states
  \( \Rightarrow \) Selective production of corrective motion: \( \lambda \) mode

\[ R \sim \left\langle \varphi_f \left| \sqrt{2} \sigma_- \exp(iq_{\text{eff}} \mathbf{r}) \right| \varphi_i \right\rangle \]

\* Production cross section
  \( \Rightarrow \) Overlap of wave function
  \* charm and \( q-q \) (spectator)

\* Angular momentum transfer between diquark \( (q-q) \) and charm quark

S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori
Decay property

\[ \rho\text{-mode decay: } qqQ + q\bar{q} \]

\[ \lambda\text{-mode decay: } qqq + Qq\bar{q} \]

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

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

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

\[ \Rightarrow \text{Absolute value of branching ratio by missing mass method} \]
- Compliment study with high-energy experiments
Spectroscopy with heavy quark

- **Clear distinction** by separating effects from one quark
  - Systematic study

- Charmed baryon spectroscopy: **To understand role of diquark correlation**
  - Dynamical information: Production rates & Decay branching ratios

![Diagram showing production and decay processes involving quarks and mesons.](image_url)
Excitation spectrum: $q$-$q + Q$ system

**Strange baryons**

- $\Lambda(1/2^-, 3/2^-, 5/2^-)$
- $\Lambda(1/2^-, 3/2^-)$
- $\Sigma^*(3/2^+)$
- $\Sigma(1/2^+)$
- $\Lambda(1/2^+)$

**P-wave states**

- $\rho$ (red)
- $\lambda$ (blue)

**Charmed baryons**

- $\Lambda_c(1/2^-, 3/2^-, 5/2^-)$
- $\Lambda_c(1/2^-, 3/2^-)$
- $\Sigma_c^*(3/2^+)$
- $\Sigma_c(1/2^+)$
- $\Lambda_c(1/2^+)$

* Diquark correlation: $\lambda$ & $\rho$
* Heavy quark sector (charm) → Light quark sectors (u, d, s)

- Non-rel. QM: $H = H_0 + V_{\text{conf}} + V_{SS} + V_{LS} + V_T$
- $\lambda$-$\rho$ mixing
(called by T. Yoshida et al., Phys. Rev. D92, 114029(2015))
Excitation spectrum: $q-q + Q$ system

Strange baryons

- $\Lambda(1830, 5/2^-)$
- $\Lambda(1690, ?)$
- $\Lambda(1670, 1/2^-)$
- $\Lambda(1520, 3/2^-)$
- $\Lambda(1405, 1/2^-)$
- $\Sigma^*(1385, 3/2^+)$
- $\Sigma(1190, 1/2^+)$
- $\Lambda(1116, 1/2^+)$

$P$-wave states

Charmed baryons

- $\Lambda_c(2940, ?)$
- $\Lambda_c(2880, 5/2^+)$
- $\Lambda_c(2765, ?)$
- $\Lambda_c(2625, 3/2^-)$
- $\Lambda_c(2595, 1/2^-)$
- $\Sigma_c^*(2520, 3/2^+)$
- $\Sigma_c(2455, 1/2^+)$
- $\Lambda_c(2286, 1/2^+)$

- Non-rel. QM: $H = H_0 + V_{\text{conf}} + V_{SS} + V_{LS} + V_T$
- $\lambda$-$\rho$ mixing

* Diquark correlation: $\lambda$ & $\rho$
* Heavy quark sector (charm)
  $\Rightarrow$ Light quark sectors (u, d, s)
Strange baryon systems

- $\Lambda^*/\Sigma^*$: $q-q + Q$ system
  - Systematics with charmed baryon
    - Production rate: $\lambda$ and $\rho$ selection
    - Decay branching ratio

- $\Xi^*$: $q + QQ$ system
  - Excitation with two heavy quarks
    - Interchange of $\lambda$ and $\rho$ modes

- $\Omega^*$: $QQQ$ system
  - Same weight of three heavy quarks

Spectroscopy by high-momentum $K^-$ beam

- Several GeV/c beam
- Poor data of $\Xi$ and $\Omega$ states
- Exotic states

⇒ Systematic measurement is necessary.
High-momentum beam line for 2\textsuperscript{nd}ary beam

- **High-intensity beam**: $> 10^7$ Hz $\pi$ ($> 10^5$ Hz $K/p_{\text{bar}}$) up to 20 GeV/c
  - Unseparated beam: $\pi/K/p_{\text{bar}}$

- **High-resolution beam**: $\Delta p/p \sim 0.1\% (\text{rms})$
  - Momentum dispersive optics method
Charmed baryon spectrometer

\[ \Lambda_{c}^{*} \rightarrow \Sigma_{c}^{*} \rightarrow D \rightarrow \pi^{+} + p \]

Beam \( \pi^{-} \)

LH\(_{2}\)-target

Fiber tracker

T0

Pole face detector

Internal DC

Internal TOF

Fiber wall

PID counter

DC

TOF wall

Ring Image Cherenkov Counter

\( K^{+} \)

\( \pi^{-} \)

\( \Lambda_{c}^{*+} \)
Large Acceptance **Multi-Purpose** Spectrometer

+ **Trigger–less DAQ system**

Charmed baryon spectrometer

⇒ New platform for Hadron experiment
Hadron molecular state

Study of $\Lambda(1405)$
J-PARC E31 experiment at K1.8BR
**Λ(1405): Lightest in negative parity baryons**

* J$^P = 1/2^-$, I = 0, $M_{\Lambda(1405)} < M_{K^\bar bN}$

- $\Lambda(1520), 3/2^-$
- $\Lambda(1405), 1/2^-$
- $\Sigma(1385), 3/2^+$
- $\Delta(1192), 1/2^+$
- $\Lambda(1116), 1/2^+$
- $\Sigma^*(1385), 3/2^+$
- $\overline{K^N(1432)}$

| (state|E)$|^2 |
|---|
| $\overline{K^N}$ |

-27 MeV

<table>
<thead>
<tr>
<th>$m_\pi$ (MeV)</th>
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<tbody>
<tr>
<td>156</td>
</tr>
<tr>
<td>296</td>
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* Chiral Unitary Model
  - $K_{\bar bN}$ & $\pi\Sigma$
  - $\Sigma(1405)$
  - $K_{\bar bN}$
  - $\pi\Sigma$

⇒ **Double pole structure**

**LQCD: $K_{\bar bN}$ molecule**

PRL114, 132002 (2015)


ChU model, T. Hyodo
K\textsubscript{bar}N scattering below the K\textsubscript{bar}N threshold

- S-wave K\textsubscript{bar}N→πΣ scattering below the K\textsubscript{bar}N threshold
  - d(K\textsuperscript−,n)πΣ at a forward angle of n: 1 GeV/c K\textsuperscript− beam

⇒ Decomposition of all I = 0 and 1 amplitudes

<table>
<thead>
<tr>
<th>π±Σ±</th>
<th>I=0, 1</th>
<th>Δ(1405) (I=0, S wave), non-resonant[I=0/1] (Σ(1385) (I=1, P wave) to be suppressed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁻Σ⁰</td>
<td>I=1</td>
<td>Non-resonant (Σ(1385) to be suppressed)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d(K\textsuperscript−, p)πΣ⁰ [π⁻Λ]</td>
</tr>
<tr>
<td>π⁰Σ⁰</td>
<td>I=0</td>
<td>Δ(1405) (I=0, S wave), non-resonant</td>
</tr>
</tbody>
</table>
Experimental results: Cross section of $\pi \Sigma$ modes

Cross sections of each $\pi \Sigma$ mode

$\pi^+ \Sigma^- / \pi^- \Sigma^+ (I = 0, 1)$  
$\pi^- \Sigma^0 (I = 1)$

$\frac{d\sigma}{d\Omega}(\pi^+ \Sigma^- / \pi^- \Sigma^+) \propto \frac{1}{3} |f_{I=0}|^2$  
$\frac{d\sigma}{d\Omega}(\pi^- \Sigma^0) \propto \frac{1}{3} |f_{I=1}|^2$  
$\frac{d\sigma}{d\Omega}(\pi^0 \Sigma^0) \propto |f_{I=0}|^2$

*I = 0 amplitude seems dominant.*
To deduce scattering amplitude and extract pole position

- 2-step process

\[
\frac{d\sigma}{dM_{\pi\Sigma}} \bigg|_{\theta_n=0} \sim |\langle n\pi\Sigma | T_2^I(\bar{K}N_2 \rightarrow \pi\Sigma) G_0 T_1(K^-N_1 \rightarrow \bar{K}n) | K^-\Phi_d \rangle|^2 \\
\sim |T_2^I(\bar{K}N \rightarrow \pi\Sigma)|^2 F_{\text{res}}(M_{\pi\Sigma})
\]

**Factorization Approximation**

\[
F_{\text{res}}(M_{\pi\Sigma}) \sim \int_0^{\infty} dq_{N_2}^3 T_1 \frac{1}{E_{\bar{K}} - E_{\pi}(q_{\pi\Sigma}) + i\epsilon} \Phi_d(q_{N_2}) \bigg|_{\theta_n=0}^2, q_{\bar{K}} + q_{N_2} = q_{\pi\Sigma}
\]

\[
\frac{d\sigma}{dM_{\pi\Sigma}} \bigg|_{\theta_n=0} \sim |T_2^I(\bar{K}N \rightarrow \pi\Sigma)|^2 F_{\text{res}}(M_{\pi\Sigma})
\]

**Pole at** \((1417^{+6}_{-7} - i27^{+5}_{-9})\) MeV/c\(^2\)

*Seems consistent with higher pole by the Chiral Unitary Model based calculations*
Related subjects and experiments

• High-p beam line: Beam delivered from 2020 February!
  • Measurement of mass modification of $\phi$ meson: J-PARC E16
  $\Rightarrow$ 2ndary beam line and heavy baryon spectroscopy (charm, $\Xi$&$\Omega$)

• Studies of $\Lambda(1405)$
  • $K^-$ beam @ J-PARC: Production angle dependence
  • High-p beam @ J-PARC: Quark counting rule
  • $\gamma$ beam @ LEPS2: Polarized beam

• $K$–pp state
  • Deeply bound state due to help by strong attraction of $K_{\text{bar}} N(\Lambda(1405))$
  • Production by $K^-$ and $\gamma$ beam: Experiments are planned at J-PARC & LEPS2.

• H-Dibaryon search: J-PARC E42
  • By ($K^-$, $K^+$) reaction on nuclear target

• $\pi$ N $\rightarrow$ $\pi$ $\pi$ N experiment: J-PARC E45
  • Basics data for N*/$\Delta^*$ resonances

*Hadron spectroscopy
By Hadronic beams @ J-PARC
and Photon beam @ LEPS, ELPH
Summary

• Motivations
  • Study of excited states: Effective degree of freedoms of hadron
    • Diquark correlation and hadron molecular
  • Spectroscopy of charmed baryon and hyperon at J-PARC
    • To understand role of diquark correlation
      by dynamical information: Production rates & Decay branching ratios
  • Systematic measurement: Charm, strangeness = −1, −2, −3

• High-p beam line and multi-purpose spectrometer
  • Beam line from Feb. 2020 ⇒ 2ndary beam for hadron spectroscopy
  • Spectrometer system for many physics reactions: Trigger-less DAQ

• Study of hadron molecule state: Λ(1405)
  • Cross section of all πΣ modes
    ⇒ $K_{\text{bar}}N$ scattering amplitude to extract pole ⇒ $(1417^{+6}_{-7} - i27^{+5}_{-9})$ MeV/c²

• Related studies for hadron physics
  * Hadronic and photon beams @ J-PARC, LEPS, ELPH