Heavy-quark Baryons

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I. Baryon Structure with Heavy Quarks
II. Charmed Baryon Spectroscopy
III. New Platform of Hadron Physics at J-PARC
Hierarchy of Matter in the Universe

Matter Evolution from Quark to Hadron, Nucleus, and Neutron Star

How QCD works in Hadron?
- Effective DoF (building blocks) to describe hadrons
- Change of Hadron Properties in High-T and High-\(\rho\) Matter

How are nuclei formed?
- Extended Nuclear Force: Baryon-Baryon Int.
- Stability of Heavy Neutron Stars (EoS)

Dense Nucl. Matter

Hypron Matter?

Mystery of Neutron Star

Atom \rightarrow Molecule \rightarrow Material, Human, Star, Galaxy

Effective DoF

Quark

Hadron

Nucleus

Hypernuclei

We attack here.
Non-trivial QCD vacuum in Baryon Structure

- Non-trivial gluon field $\langle \bar{q}q \rangle$
  "massive" constituent $q$, NG boson ($U_A(1)$ anomaly)
- Dynamics of Effective DoF
  - OGE (as a residual int.)/Instanton Induced Int.
    - Too large $\alpha_S$ in Spin-Spin Int.
    - Meson Cloud

Short-range $qq$ spin correlation $\Rightarrow$ Origin of Spin Dependent force

*$\star$ Derek Leinweber, 2003, 2004

*$\star$ WS on Physics of Omega Baryons at J-PARC K10: https://indico.rcnp.osaka-u.ac.jp/event/1689/
Roles of Heavy Flavors

- Motion of “qq” is singled out by a heavy Q
- **Diquark correlation**
- Level structure, Production rate, Decay properties
- sensitive to the internal quark(diquark) WFs.
- Properties are expected to depend on a Q mass.

\[ V_{\text{CMI}} \sim \frac{\alpha_s}{(m_i m_j)}(\lambda_i, \lambda_j)(\sigma_i, \sigma_j) \]
\[ \to 0 \text{ if } m_{i,j} \to \infty \]

\[ V_{\text{CMI}}(1S_0, 3_c) = \frac{1}{2} V_{\text{CMI}}(1S_0, 1_c) \]

\[ [qq] \quad [\bar{q}q] \]
Disentangle motions of a light-quark pair w/ a heavy quark (HQ)

※ Identifying l/r modes -> provide internal quark motions and correlation

\[ J^P = s_Q + J_{BM} \]

\[ J_{BM} : \text{total spin w/o } Q \]

Isotope Shift

\[ L=2 \]

HQ Doublet (Spin Doublet)

\[ L=1 \]

HQ Doublet (Spin Doublet)

\[ L=0 \]

Ground State

\[ \text{Light Baryon} \]

\[ \text{Charmed Baryon} \]

\[ \rho \text{ mode} \]

\[ \lambda \text{ mode} \]
Effect of the Isotope Shift

Quark Model Calculation (curves) for Excitation Energy Spectra as a function of Heavy quark mass ($M_Q$)

※Mass/spin/parity of $\Lambda, \Lambda_c, \Lambda_b$ observed so far are shown below: Their excitation modes (internal structure) to be clarified

※Further understanding of baryon structure though systematic change of the excitation modes in different flavors

- Light baryon: $M_Q = m_q \sim m_u \sim m_d$
- Charmed Baryon: $M_Q = m_c \gg m_q$

Production and Decay of Charmed Baryons

Reactions Diagram

$\pi^-$ $\bar{u}$ $d$ $D^{*-}$ $\bar{c}$ $\pi^-$ $D^0$ $K^+$ $\pi^-$

$D^0$ $Y_{c^{*+}}$ $p$

Replacing $u$-quark in a proton into $c$-quark

Remarks

- Introducing a finite orbital angular momentum $L \Rightarrow$ favor $\lambda$-mode excitations
- Production ratio of the HQ doublet to be $L:L+1 \Rightarrow$ Spin, Parity
- Production and Decay measurement $\Rightarrow$ Branching Ratio (partial width)
Production of Charmed Baryons: Theoretical Study

Reggeon Exchange Model in 2-body reaction
S.H. Kim, A. Hosaka, H.C. Kim, and H. Noumi
PRD92 (2015) 094021

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

\[ I_L \sim \left( \frac{q_{\text{eff}}}{\alpha} \right)^L \exp\left(-\frac{q_{\text{eff}}^2}{\alpha^2} \right) \]

Mom. Trans.: \( q_{\text{eff}} \sim 1.4 \text{ GeV/c} \)
\( \alpha \sim 0.4 \text{ GeV} \) ([Baryon size]^{-1})

※favor \( \lambda \)-mode
excited state with finite \( L \) is
populated by factor \( (q_{\text{eff}}/\alpha)^L \)

※no data available is in the charm sector.

S.I. Shim, A. Hosaka, H.C. Kim,
PTEP 2020, (2020) 5, 053D01

※excite \( \rho \)-mode, giving how much the two-quark process contributes.

Pπ=20 GeV/c

\[ \sigma = \frac{\text{[Total E]}}{\text{[threshold E]}} = \frac{s}{s_0} \]

\( (P\pi)^{-1} \)

\[ \sigma \text{ [nb]} \]

1nb

Data in the strange sector

Estimation in the charm sector

10nb

K*0Λ

K0Λ

P=20 GeV/c

[(Total E)/(threshold E)]^2 = s/s_0

※no data available is in the charm sector.
Expected Mass Spectrum (Simulation)

Simulation

$\lambda$-mode excitation?

<table>
<thead>
<tr>
<th>$L$</th>
<th>Ground state</th>
<th>HQ doublet</th>
<th>HQ doublet</th>
<th>To be settled</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/2+</td>
<td>$\Lambda_c(2625)$</td>
<td>1/2-</td>
<td>3/2-</td>
<td>5/2+</td>
</tr>
<tr>
<td>1</td>
<td>$\Lambda_c(2880)$</td>
<td>$\Lambda_c(2940)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Entr/0.005GeV/c^2

Missing Mass of Charmed Baryon [GeV/c^2]

$\times$ Prediction of low mass states

Simulate with known states assuming

- $\lambda/\rho$ and Spin-Parity
- Cross sections estimated by theoretical model
- Background due to particle mis-identification

Decay pattern of $\lambda$ mode

$Y_c^{*+} \rightarrow D^0 p$

Decay pattern of $\rho$-mode

$Y_c^{*+} \rightarrow \pi$

$\times$ Prod. Rates and Decay Pattern

- Specify a pair of the HQ doublet
- Unexpected pair may be identified.
- Spin-parity is to be determined

Identify $\lambda/\rho$ mode

- Internal structure (wave func.) (q motion and qq correlation)
Unsettled Problem: Expected “LS” Pattern

OGE: One Gluon Exchange, III: Instanton Induced Interaction
A, B = finite numbers (flavor dependent)

<table>
<thead>
<tr>
<th></th>
<th>$\Omega^-$</th>
<th>$N^*$</th>
<th>$\Lambda_c^*$</th>
<th>$\Lambda_b^*$</th>
<th>$\Delta$</th>
<th>$\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-state</td>
<td>D-state</td>
<td>P</td>
<td>D</td>
<td>P</td>
<td>D</td>
</tr>
<tr>
<td>OGE</td>
<td>–</td>
<td>+A</td>
<td>+A</td>
<td>+A</td>
<td>+A</td>
<td>+A</td>
</tr>
<tr>
<td>III</td>
<td>–</td>
<td>–</td>
<td>-B</td>
<td>-B</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sum</td>
<td>0</td>
<td>A</td>
<td>~ 0</td>
<td>~ 0</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Exp (MeV)</td>
<td>?</td>
<td>?</td>
<td>~ 0</td>
<td>~ 0</td>
<td>36</td>
<td>?</td>
</tr>
</tbody>
</table>

Yet to be measured (in J-PARC K10 Proj.)

Vanished

Observed

to be studied (in J-PARC High-p)

Unclear
Charmed Baryon Spectroscopy at J-PARC

High-p Beam Line
- 20 GeV/c π-
- Intensity >10⁷ /s
- Δp/p~ 1/1000

※At present, E16 (ϕ → e⁺e⁻ in nuclei) is in operation with a 30GeV (primary) proton beam
Spectrometer System:

Acceptance: ~ 60% for $D^*$, ~ 80% for decay $\pi^+$
Resolution: $\Delta p/p \sim 0.2\%$ at $\sim 5$ GeV/c (Rigidity: $\sim 2.1$ Tm)

J-PARC High-$p$ Beam Line
Spectrometer System:

Acceptance: ~ 60% for $D^*$, ~ 80% for decay $\pi^+$
Resolution: $\Delta p/p \sim 0.2\%$ at ~5 GeV/c (Rigidity: ~2.1 Tm)

J-PARC High-$p$ Beam Line

Fiber Tracker

Drift Chamber (DC)

Resistive Plate Chamber (RPC)

Ring Image Cherenkov Counter (RICH)

H$_2$ Target

Dipole Magnet

Time Zero (T0)

20 GeV/c $\pi^-$ Beam
Development of prototype RICH in progress

Precise Measurement of a Cherenkov radiation angle → Particle velocity

Particle Identification in wide momentum range of 2~16GeV/c

Designed RICH

Photon Sensor

Mirror

Aerogel

Particle

Photon Sensor (MPPC)

Mirror (奥行 5.4m)

Aerogel (n=1.021)

C₄F₁₀ Gas

Ring Image

Performance test w/ an electron beam

Spherical Mirror φ60cm

Angular res. ~ 1.7mrad
Hadron Physics at High-p BL

- **Baryon Spectroscopy**
  - $p(\pi^-, D^*) Y_c^* (E50)$
  - $p(K^-, K^*) \Xi^*, p(K^-, K^+K^*) \Omega^* (\text{LoI: KEK/J-PARC-PAC 2014-4})$
  - Search for $D_{30}$ Dibaryon State in $pp \rightarrow \pi^- \pi^- D_{30} (E79)$
  - $p(\pi^-, K^*) \Lambda(1405)$ at large $s, t$ (to be proposed)

- **Hadron Tomography**
  - Exclusive DY, $\pi^- p \rightarrow \mu^- \mu^+ n (\text{LoI: KEK/J-PARC-PAC 2019-7})$

- **For Strangeness Nuclear Physics**
  - $\Lambda p$ Scattering for the study of high-dense nuclear matter (LoI: KEK/J-PARC-PAC 2020-08)

- **For Neutrino Physics**
  - Hadron Production for neutrino beams
Summary

• A heavy quark plays an inert particle in a hadron and is quite helpful to investigate internal motions and/or correlations of quarks.
  – Excitation Energy, Production Rate, and Decay Branching Ratio

• We conduct charmed baryon spectroscopy by means of missing mass technique at the J-PARC high-momentum beam line, where the intense pion beams up to 20 GeV/c will be delivered.
  – New platform of hadron physics will be covered owing to the general purpose spectrometer