Spectroscopic study of quark dynamics in baryons at J-PARC

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- Third White Paper -

Taskforce on the extension of the Hadron Experimental Facility,

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Origin & Evolution of Matter

Matter Evolution

- flavor symmetry breaking
- hadron interaction
- formation of a nucleus

Birth of Matter

- CP symmetry violation
- weak interaction

Matter in Extreme Conditions

- hyperon puzzle in neutron stars

Matter in Extreme Conditions

- fundamental structure of matter

HIHR/K1.1

- Hypernuclei spectroscopy
- YN scattering

$\pi 20/K10$

- Hadron spectroscopy
- Meson in nuclei

KL2

- Kaon decays
Current Hadron Experimental Facility

30 GeV Proton Beam

J-PARC
Linac
RCS
MLF
East
West

Pacific Ocean

Hadron Exp. Facility

COMET

High-p

Main Ring
Extended Hadron Experimental Facility
Charm Baryon Spectroscopy at High-p (π20)

Diquark [qq]: an effective degree of freedom to describe hadrons
- [qq] would be singled out by Introducing a Heavy Quark
- Characteristic level structure, production rate, and decay branching ratio

π20 Beam Line:
- $1.0 \times 10^7$ pions/sec @ 20GeV/c
- $\Delta p/p \sim 0.1\%$

![Diagram of Charm Baryon Spectrometer]
Xi/Omega Baryon Spectroscopy at K10

- Intense Kaon Beam: \( K^- \) 7.9M/spill@8 GeV/c (50-kW p on T2 [Au 66mm])
- RF-separated Kaon Beam: \( K^-/\pi^- \sim 1:2.1@8 \text{ GeV/c} \) (1:2.5@10 GeV/c)

※K10-dedicated Design

※Design to share upstream w/ HIRH is in progress
Issue: How does QCD build baryons?

High $E$
perturbative

\[ \alpha_s = \infty \]
at $\Lambda_{\text{QCD}}$

• Non-trivial gluon field
  $\Rightarrow \langle \bar{q}q \rangle$, $U_A(1)$ anomaly
• Confinement

Low $E$
non-perturbative

Meson Cloud
(~1 fm)

“Quark Core”
(<0.5 fm)

(A typical figure)

Yet to be clarified

Eff. DoF emerge:
“massive” quarks
NG bosons (pion, ...)

Instanton
(LQCD demo.
by D. Leinweber)
Dynamics of Effective DoF

- Non-trivial gluon field
- Confinement

\[ H = K + V_{\text{Conf}} + V_{\text{Coul}} + V_{SS} + V_{LS} + \ldots \]

“short-range” int.

Diquark correlation
- short-range spin-spin correlation
- source of \( \langle qq \rangle \) in highly dense matter

Systematics of SS/LS forces
- Origin? : OGE vs III, else

Quark motions in “quark core”
- Size of “cloud”/“core”

Issue: How does QCD build baryons?
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.

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

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

\[
[qq] \quad [\overline{qq}]
\]
Spectroscopy of strange and charmed baryons

Disentangle motions of a quark pair by introducing different flavors

P-wave ($L=1$)

Flavor dependence to be studied

G.S.

ud diquark corr.

qs diquark corr.

Flavor symmetric

No diquark corr.? No pion cloud?

Systematic behaviors in Excited Baryons

- \( \Delta M' \)'s btw 8tet and 10plet baryons are well explained by the SS int.
  - \( \Delta M' \)'s btw PS and V mesons as well
  - CMI by OGE seems successful.
  - OGE cannot explain the small LS splitting in N* and finite one in Heavy Baryons

• A cancellation scenario in LS
  - Instanton Induced Int. (III) [KMT int.]
  - Same structure as OGE
  - Effective for only light quarks
  - \( U_A(1) \) anomaly in III introduces \( \Delta M(\eta' - \eta) \)

- OGE + Instanton Induced Int. (III) in SS
  - No affect in SS splitting both in Baryons and Mesons
  - OGE – III in LS

※Origin of LS forces:
Vanished in Light System
Observed in Heavy System

\[
V^{SS} = \sum_{i<j} \alpha_s^{SS} \frac{16\pi}{9m_im_j} \delta(r_{ij}) \vec{s}_i \cdot \vec{s}_j
\]
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Systematic behaviors in Excited Baryons

※Universality of “Roper Like” states:
By chance or Mechanism behind them?
(3) The Roper like states

Another method to look at the internal quark motion

Decay of Roper like states

NR expansion of ME

$\langle \text{Roper} | \Omega | \text{G.S.} \rangle \sim \langle \overline{\sigma} \cdot \overline{q} \rangle (c_0 + a_2 \overline{p}_i^2 + \ldots)$

Leading order (LO) suppressed

Unique for radial excitations

Next to leading order (NLO)

$\langle p_i^2 \rangle \sim \frac{1}{\langle r^2 \rangle} \sim \text{Size}$

Arifi et al., PRD 103 (2021) 9, 094003

- Previous calculations (LO): too small
- Inclusion of NLO: 50 - 100 MeV for $\Omega^*(3/2^+)$

A. Jafar Arifi’s Talk in Parallel Session 1-B
What we will explore at $\pi20$ and K10

- $\Lambda_c^*(cud) @ \pi20$
  - $1P_\lambda, 2P_{\lambda\lambda}$: Establish “$ud$” diquark corr.
  - $1P_\rho(1/2^-)$: $U_A(1)$ anomalous mass term

- $\Xi^*(qss)$ Baryons @ $\pi20/K10$
  - $1P_\rho$: LS splitting $\rightarrow$ “$us/ds$” diquark corr.

- $\Omega^*(sss)$ Baryons @ K10
  - $1P$: LS origin of $V_{\text{conf}}$ $\rightarrow$ no OGE/III contributed
  - $2S$: width $\rightarrow \langle p^2 \rangle \sim 1/\langle r^2 \rangle$ (size of “Quark Core”)

$\text{16}$
Production and Decay of Charmed Baryons

References for estimations on production cross sections:

Measure D*- and Identify $Y_c^{*+}$ in the Missing mass spectrum
Measure Decay particles, too
Production and Decay of Charmed Baryons

- Introducing a finite orbital angular momentum $L \Rightarrow$ favor $\lambda$-mode excitations
  - Establish “$ud$” diquark motion in baryon
- Production ratio of the HQ doublet to be $L:L+1 \Rightarrow$ Spin, Parity
  - The ratio would be a measure of how “$ud$” is correlated.
- Production and Decay measurement $\Rightarrow$ Branching Ratio (partial width)
  - Decay rates would be a measure of how “$ud$” is firmly correlated.

Simulation (100 days)

- $L = 0$
  - $\Lambda_c(2625)^+$
- $L = 1$
  - $\Lambda_c(2595)^+$
- $L = 2$
  - $\Lambda_c(2800)^+$

Ground state

- 1/2+
- 2/1-
- 3/2-
- 3/2+
- 5/2+

Mass spectrum of Charmed Baryons [GeV/c^2]
Diquark in Heavy Baryons

Chiral partner 
(qq: 0^+) $\leftrightarrow$ (qq: 0^-)

$U_A(1)$ anomalous singlet current 
in Chiral diquark effective theory

Scalar diquark

$$S_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a - d_{L,i}^a)$$
$$\rightarrow M(0^+) = \sqrt{m_0^2 - m_1^2 - m_2^2},$$

Pseudo-scalar diquark

$$P_i^a = \frac{1}{\sqrt{2}}(d_{R,i}^a + d_{L,i}^a)$$
$$\rightarrow M(0^-) = \sqrt{m_0^2 + m_1^2 + m_2^2},$$

Kim et al, Phys.Rev.D 102 (2020) 014004
Expected Spectra in $K^- p \rightarrow K^{*0} \Xi^{*0}$ at 8 GeV/c

※simulation: known states are included w/ BG estimated by JAM. Many of their $J^P$ have yet to be determined.
Closed-up the low-lying $\Xi$ states

- Interest of $\rho$-mode excited states
  - $\Xi(1820)3/2^-$ to be confirmed
  - LS partner (1/2-) to be found
  - Reveal $us$-diquark correlation

※$\Xi(1800)1/2^-$ assumed for demo.
Expected Spectra in $K^- p \rightarrow K^*0 K^+ \Omega^{*-}$ at 8 GeV/c

Physics Highlight

- 1P excited states
  - $\Omega(2012) J^P$ to be measured
    - $3/2$-?
  - $LS$ partner (1/2-) to be found
    - No $LS$ splitting by CQM due to flavor symmetry
  - If a Finite $LS$ splitting, Relativistic effect in confinement force?
- Is $\Omega(2012) : \Xi^* \overline{K}$ Molecular?
  - PRD101, 094016(2020)
**Ω*(2012): a Molecular State?**

Energy of the Ξ*K state will be lower in coupled channel → Ω*(2012)?

If so, how is it different from its LS partner (1/2⁻)?

**Mass [MeV/c²]**

- **Ξ(1530)**, 3/2⁺
- **ΞK(1811)**
- **ΞK(2024)**
- **Ξ*(2220)**
- **Ωη(2220)**
- **Ω(2012)**, 1P state?
- **Ω(2250)**
- **Ω(2380)**, Ω(2470)

**PRD101, 094016(2020)**

1P state?
Expected Spectra in $K^- p \rightarrow K^{*0} K^+ \Omega^{*-}$ at 8 GeV/c

Roper (2S state)?

Physics Highlight

- 2S excited states
  - Radial excitation
  - So-called Roper-like state, yet to be found
    - $\Omega(2160), \Gamma \sim 100$ MeV assumed in the Sim.
  - The width
    - $\propto \langle p^2 \rangle$ : “Quark core” size
    - no pion cloud
  - The excitation energy
    - Universality?
Summary

- Spectroscopy of Baryon: good place to investigate dynamics of effective DoF, through which nature of low-E QCD, behavior of non-trivial QCD vacuum, is to be revealed.
- J-PARC provides unique opportunities.

Effective theory

- Quarks
  - SSB of $\chi$ symm.
  - Confinement
  - Various correlators
- Instantons
- Ground states
- Excited states
- Hadrons@$\pi20$/K10

Lattice QCD

High-T Matter
- Extension to various strongly interacting systems
- BB Int.
- High-$p$ Matter

※D. Leinweber, 2003, 2004