20th International Conference on Hadron Spectroscopy and Structure (Hadron 2023) 5 - 9 June, 2023

#### Physics at J-PARC

Hiroyuki NOUMI\*,# \*Research Center for Nuclear Physics, Osaka University #Institute of Particle and Nuclear Studies, KEK 20th International Conference on Hadron Spectroscopy and Structure (Hadron 2023) 5 - 9 June, 2023

## Hadron Physics at J-PARC

Hiroyuki NOUMI\*,# \*Research Center for Nuclear Physics, Osaka University #Institute of Particle and Nuclear Studies, KEK

### Current Hadron Experimental Facility at J-PARC



### Matter Evolution in the Universe

- Hadrons: complex system of quarks (and gluons)
- How are hadrons formed from quarks?
  - yet unanswered question
  - behavior of the Strong Interaction (QCD)

 proton
 proton
 proton
 proton

 Quark (Gluon)
 hadron
 Nucleus
 Neutron Star
 Quark Matter?

 10<sup>-15</sup> m
 10<sup>-14</sup> m
 10<sup>+4</sup> m
 Quark Matter?

 2x10<sup>+8</sup> t/cc
 ~20x10<sup>+8</sup> t/cc 4

**Hyperon Matter?** 



#### Spectroscopy of Hadrons



How do they change properties in medium?

- How does QCD form hadrons?
  - Mechanism of dynamical mass generation
  - Dynamics of effective DoF in Hadrons

# Recent Hadron Physics Programs at J-PARC

http://j-parc.jp/researcher/Hadron/en/Proposal\_e.html

- Meson in Nuclear Medium
  - Spectral changes of vector mesons in nuclei (E16)
  - $-\phi \rightarrow K^+K^-$  in A (E88),  $J/\psi$  prod. off A (Intrinsic charm) (P91)
- Exotic systems and Hadron Interactions
  - Lambda(1405) (E31) and Kaonic nuclei (E15/E80/E89)
  - H Dibaryon (E42), Lambda(1665) (E72), Missing N\*/ $\Delta$ \*/Y\* (E45)
- Spectroscopy of Baryons
  - Charm Baryons (E50)
  - Multi-strange Baryons (E97/P85)
  - $D_{30}$  dibaryon (E79) and  $\pi^- p \rightarrow \phi n$  (P95)
  - Exclusive Drell-Yan (LoI)
- Strangeness Nuclear Physics ⇒ to be covered by the Next Speaker

#### Meson in Nuclear Medium Spectral changes of vector mesons in nuclei • $pA \rightarrow \rho X, \omega X, \phi X \rightarrow e^+ e^- X$ (J-PARC E16)





#### Meson in Nuclear Medium -- Related Programs

•  $pA \rightarrow \phi X$  $\rightarrow K^+ K^- X$ (J-PARC E88) - High Statistics

- $pA \rightarrow J/\psi X$ (J-PARC P91) – Intrinsic Charm (IC) in a Nucleon
  - |uud<mark>c</mark>c̄⟩



Exotic systems and Hadron Interactions Lambda(1405) and Kaonic Nuclei

# $\Lambda(1405): 1405.1^{+1.3}_{-0.9}$ MeV (PDG in 2022)

 $J^{P} = \frac{1}{2}$ , I = 0,  $M_{\Lambda(1405)}$   $M_{K^{bar}N}$ , lightest in neg. parity baryons



 $\Lambda(1116), 1/2^+$ 

 $\Sigma(1192), 1/2^+$ 





Mass spectrum of Lambda(1405) seems dynamical (reaction-dependent).  $\Rightarrow \overline{K}N$  scattering data below the  $\overline{K}N$  mass threshold are vital.

 $\overline{K}N$  molecule?

#### $\overline{K}N$ scattering below the $\overline{K}N$ mass threshold (J-PARC E31)

K-





$$\frac{d\sigma}{dM_{\pi\Sigma}} \left| \theta_n = 3^\circ \sim \left| \left\langle n\pi\Sigma \right| T_2^{I'}(\overline{K}N_2 \to \pi\Sigma) G_0 T_1^{I}(K^-N_1 \to \overline{K}n) \left| K^-\Phi_d \right\rangle \right|^2$$

$$\sim \left|T_2^{I'}(\overline{K}N \to \pi\Sigma)\right|^2 F_{\mathrm{res}}(M_{\pi\Sigma})$$

$$T_2^{I'}(\overline{K}N \to \overline{K}N) = \frac{A}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$$

$$T_2^{I'}(\overline{K}N \to \pi\Sigma) = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA - \frac{1}{2}|A|^2 ImRk_2^2}}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$$



K1.8BR

# Best fit $\overline{K}N(I' = 0)$ scattering amplitude



A pole at  $(1417.7_{-7.4-1.0}^{+6.0+1.1}) + (-26.1_{-7.9-2.0}^{+6.0+1.7})i$  MeV/ $c^2$   $\left|T_2^{I'=0}(\overline{K}N \to \overline{K}N)\right|^2 / \left|T_2^{I'=0}(\overline{K}N \to \pi\Sigma)\right|^2 = 2.2_{-0.6-0.3}^{+1.0+0.3}$   $A^{I'=0} = (-1.12 \pm 0.11_{-0.07}^{+0.10}) + i(0.84 \pm 0.12_{-0.07}^{+0.08})$  fm  $R^{I'=0} = (-0.18 \pm 0.31_{-0.06}^{+0.08}) + i(0.41 \pm 0.13_{-0.09}^{+0.09})$  fm \*best fit value  $\pm$  fitting error  $\pm$  systematic error

systematic errors assuming the K<sup>-</sup>p/K<sup>0</sup>n mass threshold

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Exotic systems and Hadron Interactions Lambda(1405) and Kaonic Nuclei •  $K^{-3}\text{He} \rightarrow n^{"}K^{-}pp^{"} \rightarrow n\Lambda p$  (J-PARC E15)





• B.E.(" $K^-pp$ ") = 42 ± 3(stat.)<sup>+3</sup><sub>-4</sub>(syst.) MeV •  $\Gamma("K^-pp") = 100 \pm 7(stat.)^{+19}_{-9}(syst.)$  MeV

T. Yamaga et al., Phys. Rev. C100, 044002(2020)

#### Exotic systems and Hadron Interactions Lambda(1405) and Kaonic Nuclei

 $m_{\bar{K}} + 3m_N$ 

- $K^{-4}\text{He} \rightarrow n''K^{-}ppn'' \rightarrow n\Lambda d/n\Lambda pn$  (J-PARC E80)
- $K^{-3}\text{He} \rightarrow n''K^{-}pp'' \rightarrow n\overline{\Lambda p}$  (J-PARC E89 for  $J^{P}$ )



#### Exotic systems and Hadron Interactions H Dibaryon, Lambda(1665), Missing $N^*/\Delta^*/Y^*$



•  $K^-C \rightarrow K^+HX \rightarrow K^+\Lambda\Lambda X$ (J-PARC E42)

•  $K^- p \rightarrow \Lambda^* \rightarrow \Lambda \eta$  (E72)

•  $\pi^{\pm}p \rightarrow \pi\pi N$ , KY (E45)

### Exotic systems and Hadron Interactions H Dibaryon, Lambda(1665), Missing $N^*/\Delta^*/Y^*$



•  $K^-C \rightarrow K^+HX \rightarrow K^+\Lambda\Lambda X$ (J-PARC E42)

Analysis in progress

• 
$$K^- p \rightarrow \Lambda^* \rightarrow \Lambda \eta$$
 (E72)

- Determine its Spin/Parity
- Ready for data-taking in 2024
- $\pi^{\pm}p \rightarrow \pi\pi N$ , KY (E45)
  - Search for Missing  $N^* / \Delta^* / Y^*$
  - Exp. in preparation
    - → P. Cole, 14:00- 8/Jun@Room 5H 17

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### Spectroscopy of Baryons to reveal dynamics of Constituent Quarks

"short-range" int.

 $H = K + V^{Conf} + V^{Coul} + V^{SS} + V^{LS} + \cdots$ 

- Diquarks (DQs)
  - Color Magnetic Interaction (OGE)
    - Origin of the SS and LS forces is an open question

*i.e.* Instanton Induced Interaction (III, KMT int.)

- may form "BE condensate" in high-density matter
- Hadronic Molecule
  - Behavior of QCD in a long-range region



#### Spectroscopy of Baryons at p20/K10 Charm and Multi-strange Baryons

XDisentangle motions of a quark pair (diquark) by introducing different flavors



T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Phys. Rev. D92 (2015) 114029

#### Production and Decay of Charmed Baryons (E50)



#### Production and Decay of Multi-strange Baryons (E97/P85)



### Charm Baryon Spectroscopy at High-p ( $\pi 20$ )

Diquark [qq]: an effective degree of freedom to describe hadrons

• [qq] would be singled out by Introducing a Heavy Quark

Drift Chamer

(DC)

cintillating Fiber Tracker (FT)

Active are

• Characteristic level structure, production rate, and decay branching ratio

**Resistive Plate** 

Chamber (RPC)

20 GeV



 $D^{*-}$   $D^0$ 

*Y*<sup>\*+</sup>

 $p(\pi)$ 

 $D^{\theta}(Y_{c})$ 

1.0 x 10<sup>7</sup> pions/sec @ 20GeV/c

 $\pi^{-}$ 

Target)

RI

•  $\pi$ 20 Beam Line :

Charm Baryon

Spectrometer

H, TG

K+

Dipole Magnet

∆p/p~0.1%

#### Spectroscopy of Baryons at $\pi 20$ $D_{30}$ Dibaryon and $P_c$ -analog $N^*$ state

•  $pp \to \pi^{-}\pi^{-}D_{30}^{++++}$  $\to \pi^{-}\pi^{-}\pi^{+}\pi^{+2}$ He (E79)



•  $\pi^- p \rightarrow \phi n \rightarrow K^+ K^- n$  (P95)

-  $N^*(2050)$  coupled to  $\phi n$ ?



 $P_C$ 

LHCb collab.

PRL 122 , 222001(2019)



#### π\_nucleon resonances p n

#### Sang-Ho Kim, private comm.

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#### Spectroscopy of Baryons at $\pi 20$ Baryon Structure in an Exclusive Drell-Yan Process





(arXiv:2110.04462)

Extension

Extension Project of the J-PARC Hadron Experimental Facility

November 2022

Taskforce on the extension of the Hadron Experimental Facility

#### Main Ring

**J-PARC** 

Extension Project of the J-PARC Hadron Exp. Facility



West

→F. Sakuma's talk, 8/Jun 15:20PM @Room0B

Linac

MLF

H SER

RCS



# Summary

- J-PARC Hadron Exp. Facility provides unique opportunities to attack yet-unanswered questions how matter is created and evolved in the universe.
- Spectroscopic studies of hadrons are challenging to unveil behavior of QCD at low energy through investigating the dynamics of constituents to form hadrons and hadronic systems.