Hadronic Physics Program
at J-PARC

APCTP Focus Program in Nuclear Physics 2021 Part II
Science Opportunities with EIC
July 20, 2021
Shinya Sawada (KEK/J-PARC)
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• J-PARC and its Hadron Experimental Facility
• Hadronic physics opportunities at the Hadron Experimental Facility
• Hadronic physics achievements
• Hadronic physics possibilities in the future
• Summary
J-PARC Facility
(KEK/JAEA)

South to North

Experimental Areas

3 GeV Synchrotron

Materials and Life Experimental Facility

50 GeV Synchrotron

Hadron Exp. Facility

Bird's eye photo in January of 2016
Goals at J-PARC

Proton
3 GeV, 30 GeV

Target Nucleus

Neutron (n)
Proton (p)

Pion (π)

Muon (μ)
Neutrino (ν)

Kaon (K)

Anti Proton (p̅)

Materials & Life Sciences at 3 GeV
Nuclear & Particle Physics at 30 GeV
R&D toward Transmutation at 0.6 GeV
<table>
<thead>
<tr>
<th>Beam Lines</th>
<th>Secondary particles</th>
<th>Max. Mom.</th>
<th>Max. Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1.8</td>
<td>$\pi$, K, p (2 separators)</td>
<td>&lt; 2.0 GeV/c</td>
<td>$\sim 10^6$ /spill for K⁻</td>
</tr>
<tr>
<td>K1.8BR</td>
<td>$\pi$, K, p (1 separator)</td>
<td>&lt; 1.1 GeV/c</td>
<td>$\sim 10^5$ /spill for K⁻</td>
</tr>
<tr>
<td>KL</td>
<td>Neutral Kaon</td>
<td>~ 2.1 GeV/c</td>
<td>$\sim 10^7$ /spill</td>
</tr>
<tr>
<td>High-p</td>
<td>Proton</td>
<td>30 GeV</td>
<td>$\sim 10^{10}$ /spill</td>
</tr>
</tbody>
</table>
Development of Beam Intensity

Accumulated beam time and intensity for HD (as of 19th Jun, 2021)

<table>
<thead>
<tr>
<th>Period</th>
<th>Spills</th>
<th>Accumulated Power (kW*days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before accident (Feb, 2009 – May, 2013)</td>
<td>1.28x10^6</td>
<td>568 kW*days</td>
</tr>
<tr>
<td>JFY2015 run (Apr, 2015 – Dec, 2015)</td>
<td>1.07x10^6</td>
<td>2365 kW*days</td>
</tr>
<tr>
<td>JFY2016 run (May, 2016 – Jun, 2016)</td>
<td>0.34x10^6</td>
<td>893 kW*days</td>
</tr>
<tr>
<td>JFY2017 run (Apr, 2017 – Feb, 2018)</td>
<td>0.81x10^6</td>
<td>2039 kW*days</td>
</tr>
<tr>
<td>JFY2018 run (Jun, 2018 – Mar, 2019)</td>
<td>0.76x10^6</td>
<td>2321 kW*days</td>
</tr>
<tr>
<td>JFY2019 run (Apr, 2019)</td>
<td>0.25x10^6</td>
<td>765 kW*days</td>
</tr>
<tr>
<td>JFY2020 run (May, 2020 – Apr, 2021)</td>
<td>0.65x10^6</td>
<td>1844 kW*days</td>
</tr>
<tr>
<td>JFY2021 run (May, 2021 – Jun, 2021)</td>
<td>0.54x10^6</td>
<td>2045 kW*days</td>
</tr>
</tbody>
</table>

※spill: # of beam shots to HD
※8-GeV operation was not included.
# K beam intensity

KEK-PS: K purity was for example ~25%.

<table>
<thead>
<tr>
<th>KEK-PS Beamline</th>
<th>K / spill (4s)</th>
<th>Protons / spill (4s)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2</td>
<td>2x10^4 K^-</td>
<td>2x10^{12}</td>
<td>1.67GeV/c, E522</td>
</tr>
<tr>
<td></td>
<td>1x10^4 K^-</td>
<td>3x10^{12}</td>
<td>1.0GeV/c, E549</td>
</tr>
<tr>
<td>K5</td>
<td>1.9x10^5 K^+</td>
<td>2.2x10^{12}</td>
<td>0.66GeV/c, E470</td>
</tr>
<tr>
<td></td>
<td>6x10^3 K^-</td>
<td>1.5x10^{12}</td>
<td>stopped, E549</td>
</tr>
<tr>
<td>K6</td>
<td>1.3x10^4 K^+</td>
<td>0.87x10^{12}</td>
<td>1.2GeV/c, E559</td>
</tr>
</tbody>
</table>

### J-PARC K1.8 Beamline

<table>
<thead>
<tr>
<th>Beamline</th>
<th>K / spill (5.2s)</th>
<th>Protons / spill (5.2s)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1.8</td>
<td>3.3x10^5 K^-</td>
<td>5.4x10^{13}</td>
<td>1.8GeV/c, E07 purity=82.5%</td>
</tr>
<tr>
<td></td>
<td>7.3x10^5 K^-</td>
<td>7x10^{13}</td>
<td>1.8GeV/c, purity=48%</td>
</tr>
</tbody>
</table>
Hadronic physics opportunities at the Hadron Experimental Facility

- Experiments with pions/kaons
  - Hadron interactions structures are eagerly investigated.
  - Strangeness degree of freedom is one of the keys.
  - Understanding of the hadron interaction in a microscopic way leads also to understanding of very dense nuclear matter such as neutron star.

- Experiments with primary protons
  - Mass modification of a vector meson inside nuclei

- Kaon rare decay experiment
Hadron interactions with strangeness

- Nucleon-nucleon interaction, especially at medium and long ranges, has been rather well studied, since Yukawa’s prediction of the pi meson.
- Especially, the origin of the repulsive core and the spin-orbit force has not been understood.
- We explore the hadron interaction not only with up and down quarks but also with strange quarks.
Importance of understanding hadron interaction

- We need to understand the bound system by the strong interaction in completely different scales from hadrons to a giant nucleus, a neutron star, in a microscopic way.

- Recent observation of 2-solar-mass neutron stars suggests
  - Our understanding of hadron interaction and the equation of state (EoS) based on it cannot well describe the neutron star EoS.
  - Baryon interaction in nuclear matter is important.

- Gravitational waves from neutron star merger provide an information on a kind of the stiffness of the EoS.

Hyperons should appear inside a neutron star

Strangeness is a key!
Toward microscopic understanding of the strong interaction and nuclear matter

Data
- Nuclear data: binding energy of hyperons through spectroscopy
- NN scattering data (rich)
- YN scattering data (sparse)

Theoretical tools
- Baryon-Baryon interaction by Lattice QCD
- Chiral Effective Field Theory
- Baryon-Baryon interaction by meson exchange models

Realistic strong interaction which can reproduces hypernuclei and neutron stars

Understanding of the repulsive core?
Hyper-nuclear spectroscopy ($S=-1$)

**Editors' Suggestion**

Observation of Spin-Dependent Charge Symmetry Breaking in $\Lambda N$ Interaction: Gamma-Ray Spectroscopy of $^4_\Lambda$He

The energy spacing of the spin-doublet states in the $^4_\Lambda$He hypernucleus indicate a large spin dependent charge symmetry breaking in the $\Lambda N$ interaction.

T. O. Yamamoto et al. (J-PARC E13 Collaboration)

Hyper-nuclear spectroscopy (\(S=-2\))

- Double strangeness nuclei are produced through \((K^-, K^+)\) reactions.
- Nuclear emulsions were used with relatively lower intensity \(K^-\) beam. "Counter" experiments to come.

### MINO event

\[ ^{16}\text{O} + \Xi^- \rightarrow (^{10}\text{Be}, ^{11}\text{Be}, ^{12}\text{Be}) + ^4\text{He} + (t, d, p), \]
\[ \rightarrow \Xi^- + ^3\text{He} + (p, d, t) + p + xn, \]
\[ \rightarrow ^4\text{He} + p + \pi^-. \]

Updated Kinematic fitting \(\chi^2\) (DOF=3)

<table>
<thead>
<tr>
<th>Possible interpretation</th>
<th>(B_{\Xi^-}) [MeV]</th>
<th>(\chi^2) (DOF=3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most likely</td>
<td>(15.05 \pm 0.11)</td>
<td>11.5</td>
</tr>
<tr>
<td>(\Xi^- + ^{16}\text{O} \rightarrow ^{10}\text{Be} + ^4\text{He} + t)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Xi^- + ^{16}\text{O} \rightarrow ^{12}\text{Be}^* + ^4\text{He} + p)</td>
<td>(13.68 + 0.11 + E_{xx})</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Where, \(B_{\Xi^-} = 0.23\) MeV (3D state)
Multi-Strangeness world revealed with S-2S

J-PARC K1.8
(K⁻,K⁺) spectroscopy
ΔE<2 MeV
ΔΩ=55msr

Establish the Ξ bound states
Hints in Emulsion
(KISO, IBUKI, ...)

B-B Interactions
EOS@ High-density

Lattice QCD
Binary NS Merger
YN interaction

Ultra-fast (x100) Tracking detector Using MPPC

Λ–Σ coherent coupling

Sattered proton detector

See Miwa-san’s talk on Friday, July 23.
Mass modification of vector mesons

- Invariant mass spectra of $e^+e^-$ pairs in pA collisions
  - Vector meson mass modification due to nuclear matter effects
  - High statistics/Good resolution
- Similar as KEK-PS E325, but with x100 stat.
- The beam line construction was completed and the engineering run was conducted until June, 2021. The physics run will start in 2022.
K⁻-pp bound states

• The E15 collaboration has announced findings of a bound state of K⁻ + p + p.

• This should be a door to investigation of high density matter.

\[ B_{K-pp} = 47+3(\text{stat.})+3-6(\text{sys.}) \text{ MeV} \]

\[ \Gamma_{K-pp} = 115+7(\text{stat.})+10-9(\text{sys.}) \text{ MeV} \]
H-Dibaryon Search

- E42 experiment headed by Prof. Jung Keun Ahn (Korea).
- The H-dibaryon is the lightest S=-2 system which can be decomposed into a symmetric six-quark object made from uuddss and two baryon states involving ΛΛ, ΞN, and ΣΣ components.
- The experiment measured the event topology with the (K⁻, K⁺) reactions.
- The beam time was successfully carried out from May through June, this year.

E42 Detector for the H-Dibaryon Search

\[ {^{12}C}(K^-, K^+) \text{ Reaction Event} \]

- (K⁻, K⁺) reaction events are tagged by the K1.8 beam line and the KURAMA spectrometers.
- Decays of the S = -2 system are reconstructed using the Superconducting Hyperon Spectrometer.

Reconstructed \( K^- \) beam and outgoing \( K^+ \) tracks share the vertex at the diamond target position.
Two Vs are seen in the HypTPC and four decay particles hit the HTOF.
Kaon rare decay experiment

Results from 2016-2018 data.

The number of the events in the signal region is consistent with the expected background.

The number of the events in the signal region is consistent with the expected background.

KOTO is collecting more data with improved detectors against the background.
Future of the Hadron Experimental Facility
Origin & Evolution of Matter

Matter Evolution
- fundamental structure of matter

Birth of Matter
- matter dominated universe

Matter in Extreme Conditions
- hyperon puzzle in neutron stars

Hadron interaction
- formation of a nucleus

Chiral symmetry breaking
- quark interaction

CP symmetry violation
- weak interaction

Hypernuclei spectroscopy
- YN scattering

Hadron spectroscopy
- Meson in nuclei

KEK50 年 KEK 2021
Elucidation of Neutron Star Matter from Nuclear Physics

A tiny fraction of 3 Baryon Force effect is essential

We need:
- Realistic YN interaction model
- Precise Λ binding energy for wide-mass range for density dependence of ΛN interaction → ΛNN interaction

More accurate YN scattering data

Realistic BB interaction model

SU(3) Chiral EFT, Nijmegen models

Potential from LQCD

Theoretical calculation of Λ single-particle energies

ΛNN, ΛN-ΣN

EOS, Neutron star matter

Femtoscopy at HIC

HIHR@HEF-ex

Much higher-resolution Λ spectroscopy

ΛPb (KEK-PS)

PRC53(1996)210

arXiv:2104.04427

Ξ-hyp @ S-2S
ΛN @ High-p

Total CS

EPJA56(2020)91

208ΛPb (KEK-PS)

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Meson properties in nuclei

- Investigation of meson properties has been proceeded at present HEF, using high-intensity kaon beam
  - $K^\text{bar}N - \pi\Sigma - \Lambda(1405)$
  - Kaonic atoms/nuclei
  - ($\phi$ meson in nuclei, now launched)

**Key Issue**

**Baryon structure**

- Still no clear answer to “How quarks build baryons?”
- Dynamics of non-trivial QCD vacuum in baryon structure is a key
- comprehensive and systematic studies of “detailed” baryon spectroscopy

**Expand physics to baryon**

- exotic hadron searches in s-sector
  - $\Theta^+$ penta-quark baryon
  - $H$-dibaryon

**Explore low-E (non-pert.) QCD**

- Confinement of Hadron
- Chiral Symmetry Breaking

- @ present HEF

- $\pi20/K10@HEF$-ex

- KEK50 年

- KEK 2021
Toward New Physics: Flavor Physics

- So far, no clear evidence of new physics beyond the SM from direct searches
- Flavor physics in intensity frontier plays an important role more and more

**Key Issue**

**KOTO:**
- Will reach the sensitivity of $O(10^{-11})$ around FY2025

**KOTO Step2:** KL2@HEF-ex
- Will explore the region beyond the SM
“Extended” Hadron Experimental Facility is Essential

1 new production target (T2) +
4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10) +
2 modified beamlines (High-p ($\pi$20), Test-BL)
## Timeline with the current programs

<table>
<thead>
<tr>
<th></th>
<th>FY2021</th>
<th>FY2022</th>
<th>FY2023</th>
<th>FY2024</th>
<th>FY2025</th>
<th>FY2026</th>
<th>FY2027</th>
<th>FY2028</th>
<th>FY2029</th>
<th>FY2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR</td>
<td></td>
<td>Upgrade of Magnet PS</td>
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<td></td>
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<tr>
<td>HD</td>
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<tr>
<td>COMET</td>
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<td>Construction</td>
<td></td>
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</tbody>
</table>

- **The Extension Project of the HEF (6 years)**
  - **Construction parallel to beam operation in the first 3 years, beam-suspension in the next 2.5 years**

- **Current Programs with SX Power towards 100kW**
- **Hall Extension**
- **Expanded Programs with more BLs**
- **COMET1 Construction**
- **COMET2 Construction**

- **We would like to start the project from FY2023**
  - 4 years operation before beam suspension (except for COMET)
  - 3 years operation for COMET (Beamline completion in FY2022)
Progress in the approval process of the HEF extension

- "Master Plan 2020" by the Science Council of Japan: Selected as one of the 31 important large scale projects.
- "Roadmap 2020" by MEXT: Selected as one of the 15 important large scale projects.
- "KEK Roadmap 2021" and "KEK Project Implementation Plan (KEK-PIP) 2022": KEK-PIP 2022 defines the priority of the funding request from KEK to MEXT during the JFY2022-2027 period. We are working hard to get a good position, including workshops and reviews.

<table>
<thead>
<tr>
<th>SX schedule</th>
<th>2021</th>
<th>2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31th PAC</td>
<td>SAC(3/19-20)</td>
<td>32th PAC</td>
</tr>
<tr>
<td></td>
<td>speaker決定</td>
<td>1st WS(7/5-9で3日)</td>
</tr>
<tr>
<td></td>
<td>1st review(8月頭)</td>
<td>2nd review(11月-12月頭)</td>
</tr>
<tr>
<td>HIHR/K1.1</td>
<td>第1回：5/23(domestic)、第2回：6/17-19(international)</td>
<td></td>
</tr>
<tr>
<td>K10</td>
<td>第1回：5/13-14(domestic)、第2回：6/7-9(international)</td>
<td></td>
</tr>
<tr>
<td>KL</td>
<td>適時勉強会</td>
<td></td>
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</tbody>
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 KEK50 年

 KEK 2021
Summary

• J-PARC provides opportunities of hadronic physics with hadron beams, such as pions, kaons, and protons.

• Toward understanding of the strong interaction, “strangeness” is a key. Research on hyper-nuclear spectroscopy and hyperon-nucleon scatterings is being conducted.

• Also, a rare kaon decay experiment is intensively taking data.

• In order to go forward, the extension project has been planned, and extensively discussed for approval.