J-PARC HADRON PHYSICS PROGRAM

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Shin’ya Sawada
澤田 真也
KEK (High Energy Accelerator Research Organization)
Contents

• J-PARC and Hadron Experimental Facility (Hadron Hall)
• Physics overview and fruits so far obtained
• High-momentum beam line
• Extension
• Summary
Bird's eye photo in January of 2016

- **PARC Facility**
  - KEK/JAEA

- **Experimental Areas**
  - Neutrino Beams (to Kamioka)

- **Facilities**
  - JFY2009 Beams
  - Hadron Exp. Facility
  - Materials and Life Experimental Facility

- **Accelerators**
  - 3 GeV Synchrotron
  - Linac
  - 50 GeV Synchrotron
<table>
<thead>
<tr>
<th>Beam Lines</th>
<th>Experiment</th>
<th>Secondary particles</th>
<th>Max. Mom.</th>
<th>Max. Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1.8</td>
<td>Hypernuclei, Hadron Physics with S</td>
<td>$\pi$, K, p (2 separators)</td>
<td>&lt; 2.0 GeV/c</td>
<td>$\sim 10^5$ Hz for K$^+$</td>
</tr>
<tr>
<td>K1.8BR</td>
<td>Hadron Physics with S</td>
<td>$\pi$, K, p (1 separator)</td>
<td>&lt; 1.0 GeV/c</td>
<td>$\sim 10^4$ Hz for K$^+$</td>
</tr>
<tr>
<td>K1.1BR</td>
<td>Lepton Flavor violation</td>
<td>$\pi$, K, p (1 separator)</td>
<td>&lt; 1.1 GeV/c</td>
<td>$\sim 10^4$ Hz for K$^+$</td>
</tr>
<tr>
<td>KL</td>
<td>Neutral K rare decay</td>
<td>Neural Kaon</td>
<td>~ 2 GeV/c</td>
<td>$\sim 10^6$ Hz</td>
</tr>
</tbody>
</table>

The Hadron Experimental Facility (HEF) is shown with various beam lines and experiments, including K1.8, K1.8BR, K1.1BR, and KL. The diagram highlights secondary particles such as $\pi$, K, and p, and their maximum momenta and intensities.
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Origin and evolution of (quark) matter in Universe (Phase diagram)

Cooling by

Nucleosynthesis

Hadron Physics (J-PARC)

Neutron starts

Quark stars*

Compression by gravity

Strangeness Physics (J-PARC)

s quark

Supernova

High-density matter

Normal nuclei

Stars

Quark stars

Gas → Fluid

Big Bang

Phase transition

QGP

Cooling by

Compressing by gravity

Superconductivity
Nuclear/Hadron Physics at HEF

- Modern picture of **nuclear force** based on QCD
  - Hypernuclear spectroscopy → YN/YY int. → lattice-QCD
    - $\gamma$-ray spectroscopy (E13), double-strangeness system (E03/E05/E07/E42)
  - YN scattering (E40)

- **Hadrons in vacuum and medium**
  - Exotic hadrons (E19)
  - In-medium property of hadrons → Chiral Symmetry Breaking (CSB)
    - meson-mass spectroscopy (E16)
  - $\Lambda NN$ three-body force

- Phase diagram and Equation Of State (EOS) of quark (hadron) matter
  - low-$T$ high-$\rho$ region - Strangeness physics
    - n-rich $\Lambda$-nuclei (E10), multi-strangeness, $K^{\text{bar}}N$ interaction (E15/E17/E27/E31)
  - Hadronization phase - Hadron physics
    - exotic hadrons (E19), charmed baryon spectroscopy (E50)
Results (1)

- E19: Search for \( \Theta^+ \) by \( \pi^-+p\rightarrow K^-X \)
  - No peak was observed
  - U.L. of cross section: 0.28\( \mu \)b/sr
  - U.L. of \( \Theta^+ \) width: 0.36 \((1.9)\) MeV for \( \frac{1}{2}^+ \left(\frac{1}{2}^-\right)\)

- E10: Neutron-rich \( ^6\_\Lambda H \) via the \( ^6\text{Li}(\pi^-,K^+) \)
  - No peak was observed
  - U.L. of cross section: 1.2\( \text{nb/sr} \)
  - Observation of 3 candidates by FINUDA (PRL 108, 04251(2012))

\[ \text{Counts / (MeV/c^2)} \]

\[ \text{Missing Mass [GeV/c^2]} \]
Results (2)

- Analysis of inclusive spectrum was also published. PTEP 2014, 101D03(2014)


<table>
<thead>
<tr>
<th>Binding Energy</th>
<th>95</th>
<th>(stat.)</th>
<th>(syst.) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>162</td>
<td>(stat.)</td>
<td>(syst.) MeV</td>
</tr>
</tbody>
</table>

- $L(1405)+p K^-$

- Experimental Method
  - $E27$: Search for $K^-pp$ bound states by the $d(p+,K^+)$ at $P_p=1.7\text{GeV/c}$
  - A positive signature of $K^-pp$ bound state was obtained. Comparison with other experiments and theoretical studies are necessary and important to establish $K^-pp$ bound state.
Results (3)

- E15: Search for K-pp bound states by the $^3\text{He}(K^-,n)X^\Lambda_p$ 1st-stage RUN with 1% of the proposal May 2013

- "semi-inclusive ~10 MeV/c^2 resolution

Contribution of $S \rightarrow np$ (No other contribution in a bound-region due to kinematical limitations)

Significant enhancements were observed in a bound-region

arXiv:1408.5637 [nucl-ex]
Hadron Beam Operation in 2015

2015

Renovation

Test operation

User operation
Restart of Hadron Beam Operation

- The first beam extraction to the Hadron hall (3kW)
- The first beam injection to the target
- 12kW test operation started.
- Facility inspection for the license as a radiation facility
- 24kW test operation started.
- The certificate was issued.

- The whole system, including newly installed equipment, was checked during the test operation period.
- In each step of the beam power improvements, new target system, monitoring system, etc. were confirmed to work properly.
Restart of Hadron Beam Operation

User operation restarted with the proton beam power of 24kW!
(Almost 2 years after the accident)
Accumulated beam time and intensity for HD

Before accident (Feb, 2009 – May, 2013): $1.26 \times 10^6$ spills, 560 kW*days

After accident (Apr, 2015 – Dec, 2015): $1.05 \times 10^6$ spills, 2338 kW*days

spill: # of beam shots to HD
Beam time used by experiments in 2015

- E15: search for deeply-bound kaonic nuclear states, 708 hours
- E14: KL->π^0νν Experiment, 1509 hours
- E13: γ-ray spectroscopy of light hypernuclei, 435 hours
- E05: Spectroscopic Study of Ξ-Hypernucleus, 319 hours
- E07: Systematic Study of Double Strangeness System with an Emulsion-Counter Hybrid Method, 42 hours
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)
Production Target

50 kW target
• April, 2015 -
• Indirect cooling
• Currently working

80 kW target
• Fall, 2017 or 2018 -
• Indirect cooling
• Ready to manufacture

>100 kW target
• Around 2020/2021 -
• Direct cooling
• Under R&D
Temperature of each gold piece was measured with thermocouples every 100ms using 0.5mm sheath thermocouples.

Measured temperature was in good agreement with calculation.

Copper pipes were used with a diameter of 66mm.

The temperature rise at 41.6 kW on spill (2sec) was max 297°C (ΔT=267K) offspill (3.52sec).

Beam-power dependence was observed with a linear relationship between beam power and max temp rise (K).

Data points are shown along with calculated values.
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Next Indirect Cooling Target

- Gold target on Cu holder
- Indirect water cooling as the current target
- Relatively straightforward to develop.
- ~80 kW proton beam can be accepted.
- Will be installed as a replacement of the current target.

Result of Thermal Analysis (80kW, 5.52s cycle)

- Maximum temperature: 325°C
- Bonded interface: 229°C
- Von Mises stress: 51MPa
- Vertical expansion: max 0.10mm
- Bonding strength: 128MPa (@229°C)
- Design margin: 2.5

Ready to manufacture
Production Target

50 kW target
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80 kW target
- Fall, 2017 or 2018 - 
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>100 kW target
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- Direct cooling 
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Rotating “EURO Coin” Target

- Beam
- Ni
- Au or Pt
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New Primary Proton Beam Line

- New primary Proton Beam Line
  = High-momentum BL + COMET BL
  has been funded and the construction
  started.

**High-momentum Beam Line**
- Primary protons ($\sim 10^{10} - 10^{12}$ pps)
  - E16 (phi meson) is considered to be
    the first experiment.
  - Unseparated secondary particles (pi, ...)
    - High-resolution secondary beam by
      adding several quadrupole and
      sextupole magnets.

**COMET**
- Search for $\mu$ to $e$ conversion
- 8 GeV, 50 kW protons
- Branch from the high-momentum BL
- Annex building is being built at the
  south side.
Secondary beams

Thin production target!
Unseparated Secondary Beam

Prod. Angle = 0 deg. (Neg.)

Counts/sec

$\pi^-$

$K^-$

$\bar{p}$

0 5 10 15 20

[GeV/c]

Prod. Angle = 3.1 deg (Pos.)

Counts/sec

$\pi^+$

$K^+$

0 5 10 15 20

[GeV/c]

* Sanford-Wang: 15 kW Loss on Pt, Acceptance: 1.5 msr%, 133.2 m
“GPD” and “Transition GPD”

- $\pi^- p \rightarrow \gamma^* n$
- $\pi^- p \rightarrow \gamma^* \Delta^0$
- $\pi^- n \rightarrow \gamma^* \Delta^-$
- $\pi^+ n \rightarrow \gamma^* p$
- $\pi^+ p \rightarrow \gamma^* \Delta^{++}$
- $\pi^+ n \rightarrow \gamma^* \Delta^+$

- $K^- p \rightarrow \gamma^* \Lambda$
- $K^- p \rightarrow \gamma^* \Lambda(1405)$
- $K^- p \rightarrow \gamma^* \Lambda(1520)$
- $K^- n \rightarrow \gamma^* \Sigma^-$
Acceptance: \( \sim 60\% \) for \( D^* \), \( \sim 80\% \) for decay \( \pi^+ \)
Resolution: \( \Delta p/p \sim 0.2\% \) at \( \sim 5 \text{ GeV/c} \) \( (\text{Rigidity} : \sim 2.1 \text{ Tm}) \)
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Hadron Hall Extension

- Extend the Hadron Hall for ~105m.
- Construct 2 production targets with beam lines.

- Single strangeness experiments to explore generalized baryon-baryon interaction
- Spectroscopy of multi-strangeness and charm systems
- From discovery to measurement of K0 rare decay
Hadron Hall Extension

• Hadron Hall extension has been proposed to the Science Council of Japan for their recommendation as a next big project, and selected as one of the 27 important big projects.

• A review committee at MEXT selected the J-PARC future project including the Hadron Hall extension as one of the 11 major projects on its roadmap.

• The Institute of Particle and Nuclear Studies, KEK has made the discussion for future projects (ILC, neutrino, and Hadron extension) at the research program committee, and they have concluded that the Hadron extension should be promoted, as well as other projects.
Summary

- The beam operation at the Hadron Facility restarted from April, 2015.
- The beam power at the restart was 24kW, and then improved gradually to 42kW in December.
- The high-momentum beam line is under construction, and will be available in a few years.
- The extension of the Hadron Hall has been proposed, and got a good message from initial reviews.