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Hadron Physics at J-PARC

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The Japan Proton Accelerator Research Complex, J-PARC, is a high-intensity proton accelerator complex in Japan. The Hadron Experimental Facility is one of the experimental facilities at J-PARC and it utilizes slowly extracted proton beams from the 30-GeV Main Ring synchrotron. The beam intensity at the Hadron Experimental Facility has been improved greatly since its first beam in 2009, and now real Kaon-induced experiments are made possible. Physics cases at the Hadron Experimental Facility include structure of hadrons, baryon interaction, and properties of high-density hadronic matter and hadrons in matter. Recently remarkable results on these topics have been announced, and more experiments are being carried out. Extension of the Hadron Experimental Facility is also planned.

KEYWORDS: Hadronic physics, nuclear physics, strangeness nuclear physics, high-intensity kaon and pion beams, high-intensity proton facility.

1. J-PARC and the Hadron Experimental Facility

The Japan Proton Accelerator Research Complex, J-PARC, is a world-class accelerator facility located at Tokai, Ibaraki, Japan. The complex consists of three accelerators such as the Linac, the 3-GeV Rapid Cycling Synchrotron, and the Main Ring (MR), and the experimental facilities such as the Materials and Life science Facility (MLF), the Neutrino Facility and the Hadron Experimental Facility. J-PARC aims at providing the proton beams with the world's highest intensity, namely 1 MW at the MLF, 750 kW or more at the Neutrino Facility, and 100 kW or more at the Hadron Experimental Facility.

The Hadron Experimental Facility utilizes the 30-GeV proton beams which are slowly extracted from the MR for 2 seconds. As shown in the Fig. 1, the proton beams are then transported to the Hadron Hall through the so-called switchyard and incident to the production target, T1. Secondary particles produced at the T1 target, such as pions and kaons, are transported to the secondary beam lines, K1.8, K1.8BR, and KL. The K1.8 beam line is designed to provide good purity kaons up to 2 GeV/c with two-stage electrostatic separators, as well as pions. The typical momentum of the K1.8 beam line, 1.8 GeV/c was chosen as the production cross section of the Xi hyperon is the largest around that. The K1.8BR is a branch line of the K1.8 beam line, where the maximum momentum is 1.1 GeV/c with a single-stage electrostatic separator. The KL line is dedicated to the kaon rare decay experiment, KOTO. Table I lists the typical characteristics of these secondary beam lines.

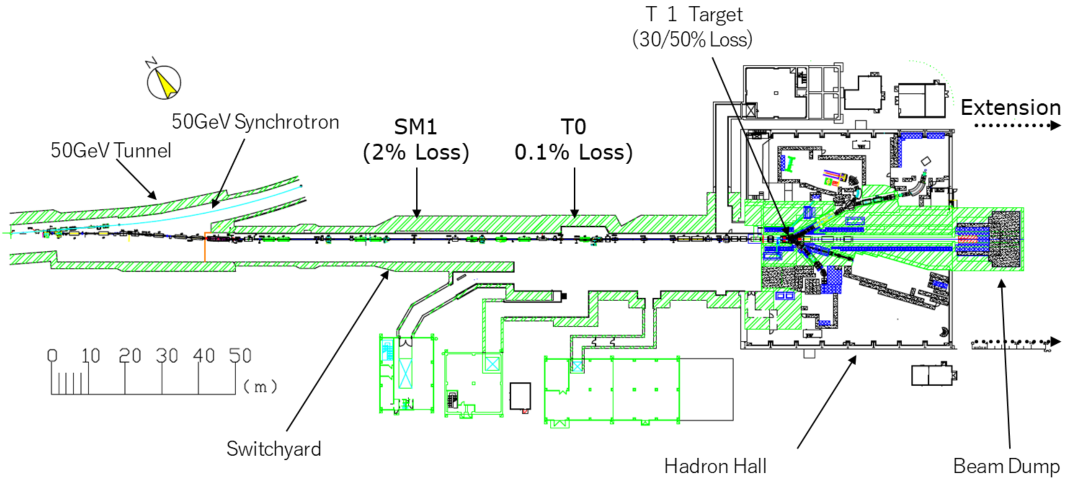

Fig. 1. Layout of the Hadron Experimental Facility. In the figure, the Main Ring accelerator is located at the left. The proton beams are extracted from the MR and traveling through the switchyard, and then they hit the production target named “T1 Target”. There are secondary beam lines from the T1. Almost 50 % of the primary protons are used to produce secondary particles at the T1, and the rest goes to the beam dump to be absorbed safely. Extension of the Hadron Hall to the right is planned.

Along with these secondary beam lines, we are preparing two new beam lines; one is the high-momentum beam line which will provide primary proton beams of the 10^9 protons/sec level of the intensity and be ready in a year. The other is the COMET beam line which branches from the high-momentum beam line for 8-GeV high intensity protons.

The Hadron Experimental Facility started its operation with low-intensity beams around 3 kW in 2009, and has improved the intensity a lot, as shown in Fig. 2. The proton beam intensity has reached to about 51 kW recently, which is the highest intensity approved with the current T1 target. The T1 target will be replaced in 2019 to a new one, whose maximum beam intensity will be around 90 kW. The proton beams of more than 51 kW are expected in the coming years.

With the improvement of the proton beam intensity, the intensity and quality of the secondary beams have also been improved to a new stage. As shown in Table II, the K1.8 beam line can provide $2\text{x}10^5$ K^- /5.2sec with a very high purity of 82.5% while we had $2\text{x}10^4$ K^- /4sec with the purity of about 25% at the KEK-PS, the predecessor of J-PARC.

Currently three secondary beam lines are available; the K1.8 beam line can provide secondary beams such as kaons and pions up to about 2 GeV/c, with a double-stage electro-static separator system for an excellent separation for pions and kaons, the K1.8BR beam line is a branch from the K1.8, for pions and kaons up to about 1 GeV/c with a single-stage electro-static separator, and the KL beam line is the neutral kaon beams line dedicated to the kaon rare decay experiment, KOTO.

Table I. The secondary beam lines at the Hadron Experimental Facility.

Beam lines	Secondary particles	Momentum	Max. intensity
K1.8	π, K, p^{bar} (2 separators)		~10^6 /spill (K^-)
K1.8BR	π, K, p^{bar} (1 separator)	< 1.1 GeV/c	~10^5 /spill (K^-)
KL	neutral K	< 2.0 GeV/c	~10^7 /spill

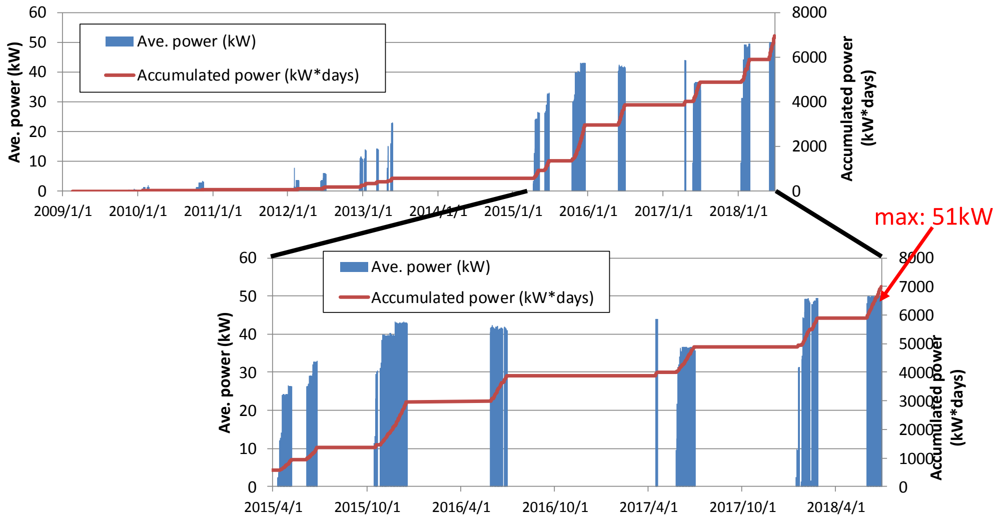

Fig. 2. Development of the beam intensity at the Hadron Experimental Facility.

2. Recent Hadron Physics Topics and Coming Experiments

2.1 Goals of Hadron Physics at the Hadron Experimental Facility

In the history of the universe, matter has been created just after the Big Bang, where the elements of the matter, quarks, were freely moving. While the universe was cooled down, nucleons and hadrons were created with so-called hadronization. A nucleus was produced as a result of nucleosynthesis, and then, high density hadronic matter was created at a neutron star.

So far, QCD motivated models describe nucleons and hadrons, and a nucleus can be understood by meson-exchange-based nuclear force models. One of the goals of hadron physics is to understand the matter evolution in the universe through the understanding of properties of various forms of matter. At J-PARC, we would like to investigate three research topics: structure of hadrons, baryon interaction, and properties of high-density hadronic matter and properties of hadrons in matter.

Table II. Comparison of K beam intensities at KEK-PS and J-PARC. Note that the purity of K mesons was for example around 25 % at KEK-PS.

KEK-PS

Beam lines	K / spill (4 s)	Protons / spill (4 s)	Note
K2	$2\text{x}10^4$ K^-	$2\text{x}10^{12}$	1.67GeV/c, E522
	$1\text{x}10^4$ K^-	$3\text{x}10^{12}$	1.0GeV/c, E549
K5	$1.9\text{X}10^5$ K^+	$2.2\text{x}10^{12}$	0.66GeV/c, E470
	$6\text{x}10^3$ K^-	$1.5\text{x}10^{12}$	stopped, E549
K6	$1.3\text{x}10^4$ K^+	$0.87\text{x}10^{12}$	1.2GeV/c, E559

J-PARC K1.8 beam line

Beam lines	K / spill (5.2 s)	Protons / spill (5.2 s)	Note
K1.8	$3.3\text{x}10^5$ K^-	$5.4\text{x}10^{13}$	1.8GeV/c, purity = 82.5 %
	$7.0\text{x}10^5$ K^-	$5.4\text{x}10^{13}$	1.8 GeV/c, purity = 44 %

2.2 Recent Topics

The baryon interaction, not only of protons and neutrons but also of baryons with strangeness degrees of freedom, is a key to understand the universe [1]. The hadrons with strange quarks play an important role inside high density matter, such as neutron stars.

One of the strong tools to study baryonic interactions is gamma-ray spectroscopy. A group, which consists of Tohoku University, KEK, JAEA, J-PARC, and other universities and institutions, announced that the charge symmetry breaking in ΛN interaction was observed with the measurement of gamma rays from $^{4}_{\Lambda}$He hypernuclei [2]. As the charge symmetry breaking is sensitive to the Σ mixing in the ΛN interaction, the ΛN-ΣN coupling force in the existing baryon-baryon interaction should be modified. They also published a new result on the first observation of gamma rays from an sd-shell hypernuclei, $^{19}_{\Lambda}$F, [3], a step toward understanding of ΛN interactions in heavier nuclei.

The K1.8 beam lines of the Hadron Experimental Facility was designed to produce K^- meson around 1.8 GeV/c, which is the momentum most suitable to produce Ξ particles with (K^-, K^+) reactions. A Ξ particle contains two strange quarks, while Λ and Σ have one, and its “strangeness” (S) is –2. The experimental data on the baryon interaction in the S=–2 sector are very limited. Thanks to the high intensity K^- beam at the Hadron Experimental Facility, full-scale research on the S=–2 sector has been made possible. A group of Gifu University, Kyoto University, KEK, J-PARC and other institutions conducted an experiment with a hybrid method of nuclear emulsions and a magnetic spectrometer. They irradiated 118 emulsion sheets and are analyzing the data. Though only 30% of the total emulsion sheets have been scanned, they have found almost twice as many events with stopped Ξ^- as the previous experiment carried out at the KEK 12-GeV proton synchrotron [4]. They announced an observation of a double-Lambda hypernucleus, $_{\Lambda\Lambda}$Be [5]. There are three possibilities of the bound system, such as $^{10}_{\Lambda\Lambda}$Be, $^{11}_{\Lambda\Lambda}$Be, and $^{12}_{\Lambda\Lambda}$Be*, and the binding energies of two Λ hyperons ($B_{\Lambda\Lambda}$) of these double-Λ hypernuclei were obtained. More and more information on the interactions of S=–2 systems is expected to come from this experiment.

A possibility of a bound system of a K^- meson and two protons, K^- + p + p, has been discussed for a long time. A group of RIKEN, Osaka University, JAEA, Instituto Nazionale di Fisica Nucleare, Stefan Meyer Institute, and other institutions, announced an observation of a K^-pp bound system with the ^{3}He(K^-, p)n reaction, and also reported the binding energy B_{Kpp} = 47 ±3 (stat.) +3–7 (sys.) MeV with the width of 115 ±7 (stat.) +10–20 (sys.) MeV [6]. This result implies that a meson can form a quantum state within the nuclear medium constituted of baryons, and will lead to wider discussions including meson properties in high-density nuclear medium, etc.

2.3 Coming Experiments

In a few years, several important experiments are planned to be carried out.

The E40 experiment, which measures Σ^-p and Σ^+p scatterings, is taking beams at the Hadron Experimental Facility [7]. The Σ^-p channel is important to test the present theoretical framework of the baryon interactions based on the meson exchange picture, and the Σ^+p channel is expected to have a strong repulsive core due to the Pauli effect. This experiment aims at confirming the Pauli effect between quarks for the first time. Thanks to the high-intensity pion beams and the newly-developed sophisticated detector system, the E40 experiment will take 100 times more statistics than the previous experiments which used imaging detectors.

The E42 experiment, which aims at searching a doubly-strange dibaryon of a uuddss quark configuration, H, with (K^-, K^+) reactions, will be carried out [8]. They will measure the invariant mass of the ΛΛ final states and search for a peak near the ΛΛ threshold. Note that according to some of the recent Lattice QCD calculations, the baryon-baryon interaction in the H-dibaryon channel be attractive and the H dibaryon may be formed near the ΛΛ threshold. The high-intensity K meson beam at the Hadron Experimental Facility is essential for the experiment, and the superconducting spectrometer system dedicated to this experiment is under preparation.

A new beam line, named the high-momentum beam line, is under construction. A small fraction of the 30-GeV main proton beams, whose intensity is typically in the order of 10^{13} protons per second, is separated to the high-momentum beam line at the middle of the primary beam line to the hadron experimental hall. The proton beam intensity of the high-momentum beam line is 10^9 to 10^{10} protons per second. At this beam line, the E16 experiment is being prepared [9]. The goal of the E16 experiment is to measure the mass of the ϕ meson produced by a proton hitting the target by identifying electron and positron pairs from a decay of the ϕ meson, and to see if the ϕ meson mass inside nuclear medium is changed. They are constructing a new electron-positron spectrometer and the experiment is expected to start in the spring of 2020.

There are proposals to use high-momentum pions of ~20 GeV/c and an experiment, E50, has been “stage-1” approved in the two-stage approval process. If we install a production target at the branching point of the high-momentum beam line, an intense high-momentum pion beam of $\sim 10^7$ pions/sec. can be expected. The E50 experiment aims at charmed baryon spectroscopy with these high-momentum pion beams [10].

3. Extension of the Hadron Experimental Facility

The extension of the Hadron Experimental Facility is planned. Currently one production target is installed at the 56-m long experimental hall. In the extension plan, the hall will be extended for 105 m and two more production targets will be installed. From these two production targets, four secondary beam lines will be constructed, such as the High-Intensity High-Resolution beam line (HIHR), the K10 beam line, the K1.1 beam line, and the new KL beam line (Fig. 3).

The specifications of these beam lines are summarized also in Fig. 3. The HIHR beam line will deliver high-intensity pion beams of the order of 10^8 pions/pulse and the momentum resolution of the pion beams will be $\Delta p/p \sim 1/10000$, which is an order of magnitude better than the existing beam lines, thanks to the dispersion matching technique. The primary purpose of the HIHR beam line is to conduct high precision (π, K) spectroscopy with $\Delta E = 0.1$ MeV. With this reaction, the binding energies of the Λ hyperon in the wide mass range of the nuclei will be determined, and the effect of the three-body force, which would be necessary to account for the repulsion in the short range. The information is essential to understand the equation of state of the high-density nuclear medium such as neutron stars.

Though the secondary beam lines of the current Hadron Experimental Facility are for relatively low-momentum secondary particles, high-momentum secondary beams with quite high intensity and good purity are also important. The K10 beam line will

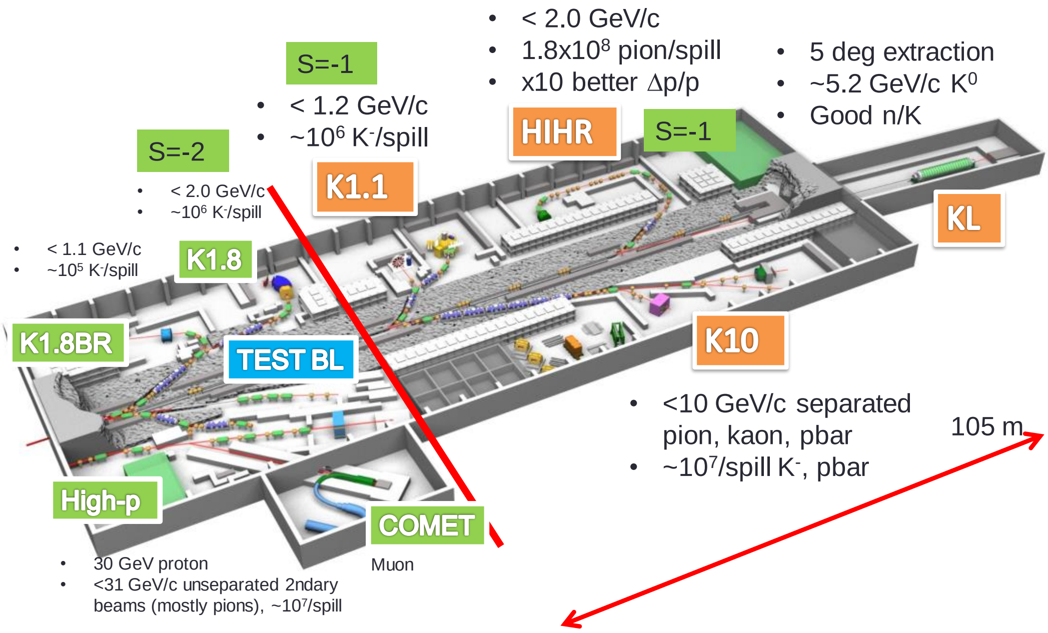

Fig. 3. Plan view of the extended Hadron Experimental Facility. The left part of the bold red line is the existing Hadron Hall. Characteristics of the beam lines are summarized.

realize separated kaon and antiproton beams up to ~6 GeV/c, and its maximum momenta would be about 10 GeV/c. One of the goals of the beam line is to conduct spectroscopy of baryons with heavy flavors such as strangeness and charm, to reveal the effective degrees of freedom which plays a crucial role to determine the structure of these heavy baryons.

On the contrary, there are much needs also for the low-momentum separated kaon beams, which are used for spectroscopy of mainly Λ hypernuclei. The K1.1 beam line has good characteristics to deliver intense and good-purity kaon beams up to 1.1 GeV/c.

The new KL beam line will be dedicated to the K^0 to $\pi^0+\nu+\nu^{bar}$ rare decay experiment and the collaboration of the current experiment, KOTO, is extensively designing the beam line.

In order to be successful in funding of the extension, we need to pass several steps. One of the first stages is to get high recognition from the Science Council of Japan (SCJ). The SCJ compiles “important large-scale scientific projects” in its “Master Plan” in every three years. The extension project of the Hadron Experimental Facility was selected as one of the important project in the Master Plan 2017. The next step is for the extension project to be selected as on of the projects in the “roadmap” of the ministry of education, culture, sports, science and technology (MEXT) for fundamental research. The last step is to be approved for funding from the ministry of finance. Unfortunately, the extension project was not selected at the last roadmap, and we need to continue efforts to get understanding from the funding agencies.

For the extension, the Hadron Hall Users’ Association (HUA) [11] has worked extensively. The HUA hosted several workshops to discuss physics and the facility design of the extension and issued a report [12]. The Japanese scientific communities of nuclear physics and high-energy physics have supported the extension project.

4. Summary

Almost 10 years have passed since the Hadron Experimental Facility of J-PARC started its beam operation. The beam intensity has been improved much, and around 2016, it reached ~40 kW when many experiments which require intense K meson beams were made possible. We can say that the real "Kaon era" then started. With the improvement of the beam intensity, remarkable results with strangeness nuclear physics have been published, such as observation of charge symmetry breaking in ΛN interaction, observation of new kinds of S=–2 hypernuclei, and observation of a K^-pp bound system. New experiments are being carried out, including the ΣN scattering experiment, the experiment on the ΛΛ system, and the measurement of the ϕ mass in nuclear medium. In addition, extension of the Hadron Experimental Facility is planned, to make physics cases much broader and deeper.

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