J-PARC hadron experimental facility extension project *

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Abstract. The J-PARC Hadron Experimental Facility was constructed with an aim to explore the origin and evolution of matter in the universe through experiments with intense particle beams. In the past decade, many results from particle and nuclear physics experiments have been obtained at the present facility. To expand the physics programs to as yet unexplored regions, the extension project of the Hadron Experimental Facility has been extensively discussed. This contribution presents the physics of the extension of the Hadron Experimental Facility to resolve issues related to strangeness nuclear physics, hadron physics, and flavor physics.

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1 Introduction

The Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose accelerator facility located in Tokai village, Japan. The aim of J-PARC is to promote a variety of scientific research programs ranging from the basic science of particle, nuclear, atomic, and condensed-matter physics and life science to industrial application and future nuclear transmutation using various types of intense particle beams.

The Hadron Experimental Facility focuses on particle and nuclear physics to explore the origin and evolution of matter in the universe, using the primary 30 GeV proton beam and secondary beams of pions, kaons, and muons. With the intense hadron beams, three core lines of research – strangeness nuclear physics, hadron physics, and flavor physics – have been conducted to approach the open questions in the universe.

2 Present status of J-PARC hadron experimental facility

A low-momentum charged-kaon beam line (K1.8/K1.8BR), a neutral-kaon beam line (KL), and a primary proton beam line (high-p) are being operated at the present Hadron Experimental Facility. A new primary beam line for a muon-to-electron conversion experiment (COMET) will also be ready for operation in 2023.

Primary protons are slowly extracted from the main ring accelerator (MR) and transported to the experimental hall (MR-SX operation) [2]. Kaons produced at the primary target (T1) are extracted to each secondary kaon beam line. The primary protons are also delivered to the high-p and COMET beam lines by branching off the protons in the switchyard upstream of the T1 target. As of June 2021, a beam power of 64.5 kW was achieved with a 2.0 s beam duration in a 5.2 repetition cycle, which corresponds to 7.0×10^{13} protons per pulse.

Since the first delivery of the proton beam to the Hadron Experimental Facility in January 2009, many experiments have been conducted and fruitful results have been obtained. The nuclear physics programs at the Hadron Experimental Facility are summarized in Ref [3].

3 Extension project at J-PARC hadron experimental facility

To expand programs for particle and nuclear physics to as yet unexplored regions, more beam lines are necessary. In the present Hadron Experimental Facility, however, a single production target is in place and is shared with a limited number of secondary beam lines due to the limited space of the present hall. The extension of the facility by the addition of more production targets and the installation of new secondary beam lines will substantially expand research opportunities.

In the extension project, the construction of the following new beam lines will expand the potential for particle and nuclear physics programs at J-PARC.

- **HIHR beam line**: High-intensity, high-resolution (HIHR) charged π meson beam line for high-precision spectroscopy of Λ-hypernuclei. The beam line will adopt state-of-the-art technology using dispersion-matching, and will enable operation at more than 10^8 pions / spill up to 2 GeV/c with a beam momentum resolution of $\delta p/p \sim 10^{-4}$. A $(\pi^{\pm}, K^{+})$ missing-mass resolution of a few 100 keV (FWHM) will be achieved, corresponding to Λ-hypernuclei mass determination with several tens keV accuracy, which has never been realized to date.

- **K10 beam line**: High-momentum (2–10 GeV/c) charged K meson and anti-proton beam line for investigations of $S = -2$ and $S = -3$ strangeness physics and charm physics. The beam line will provide separated secondary beams with higher momentum than any existing beam lines. High-momentum particle separation will be realized by two-stage RF separators.
- **K1.1 beam line**: Low-momentum (<1.2 GeV/c) charged K meson beam line optimized for investigations of $S = -1$ strangeness physics. High-purity, high-intensity secondary particles will be available by the use of two-stage electrostatic separators. A branched beam line (K1.1BR) focusing on experiments using stopped kaons will also be prepared.
- **KL2 beam line**: High-intensity neutral K_L meson beam line dedicated to measuring the branching ratio of the rare decay $K_L \rightarrow \pi^0 \nu\bar{\nu}$. An extraction angle of 5 degrees will be adopted, instead of the value of 16 degrees used in the existing beam line to increase the K_L yield while maintaining the ratio of kaons and neutrons which could become a source of background events.

Figure 1 shows the layout of the extended Hadron Experimental Facility together with the present facility. The size of the experimental area will be twice as large and a new production target (T2) will be implemented. The new beam lines will be connected from the T2 target station. Construction of a test beam line is planned in the experimental area that has been used for the KL experiment. In the extended experimental hall, five beam lines (plus the test beam line) will be operated simultaneously. For further details, please refer to Ref [1].

Construction of the extended hadron hall will take 6 years in total, including a period of 2.5 years of suspending beam delivery to the existing beam lines. The project was selected as top priority, to be budgeted in the mid-term plan (FY2022-26) of of The High Energy Accelerator Research Organization (KEK) in KEK-PIP2022 (Project Implementation Plan) [4]. Funding of the extension project will start in FY2024 at the earliest, and then the expansion programs with new beam lines will start from around the end of 2029.

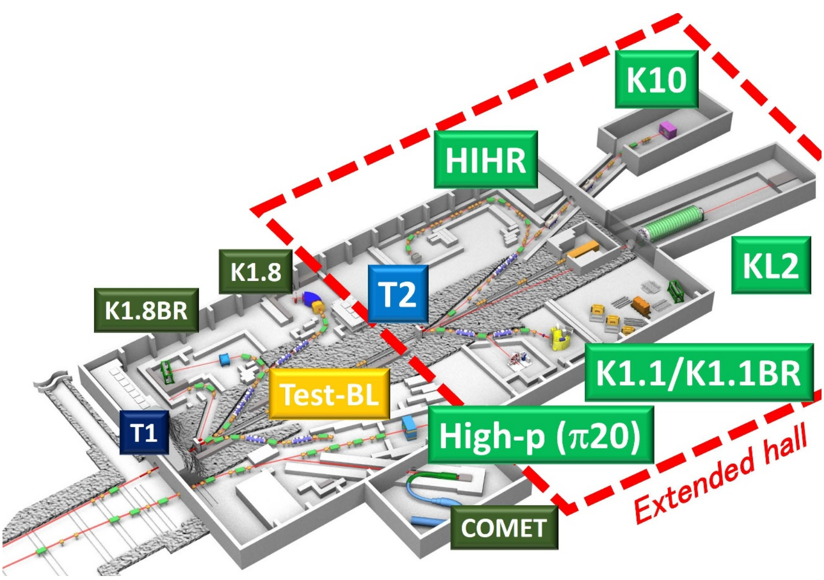

Figure 1. Layout of the extended Hadron Experimental Facility. The T2 production target and the HIHR, K1.1/K1.1BR, KL2, and K10 beam lines will be newly constructed. In addition, the π20 beam line and the test beam line are expected to be realized in the early stage of the project.

4 Scientific goals for extension project

The scientific goals and expected achievements for the extension project are summarized for each subject in this section together with the present situation: what is the problem to be solved, what has been achieved at the present facility to date, and how to approach the goal in the new project.

4.1 Strangeness nuclear physics - microscopic elucidation of neutron star matter through solving the hyperon puzzle

The so-called "hyperon puzzle" refers to the difficulty in reconciling astronomical observations of two-solar-mass neutron stars [5, 6] with the presence of hyperons in their interiors as predicted by nuclear physics; the presence of hyperons makes the equation of state (EOS) softer, so that the maximum mass of neutron stars is incompatible with observations. The solution to this problem requires a mechanism that provides an additional repulsion between baryons to make the EOS stiffer. Such additional repulsion could be described by two-body baryon-baryon interactions and three-body baryon-baryon-baryon interactions including hyperons, which produce a strong effect in dense nuclear matter. Much more comprehensive information on hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions both in free space and in the nuclear medium are required. To determine the strength of hyperonic three-body repulsive forces, it is vital to precisely measure the Λ binding energy (B_Λ) for Λ-hypernuclei in a wide mass-number region. Information on the density-dependent ΛN interaction can be obtained from this binding energy.

Experiments on hypernuclei have been proposed and performed at the Hadron Experimental Facility to determine the strength of baryon-baryon interactions extended to the strangeness sector. The $\Lambda\Lambda$ and ΞN interactions have been and will be continued to be investigated using the world's most accurate measurements of $\Xi/\Lambda\Lambda$ hypernuclei at the existing **K1.8** beam line based on the (K^-, K^+) reaction. ΛN interactions in free space will be precisely determined by Λp scattering experiments planned at the new **K1.1** and **high-p** beam lines. The strength of ΛN-ΣN coupling will also be precisely obtained by spectroscopic studies of light neutron-rich hypernuclei and precision measurements of charge symmetry-breaking in Λ hypernuclei. γ-ray spectroscopy of Λ hypernuclei is a powerful tool to precisely determine low-lying level structure of hypernuclei. Differential cross-section measurements of $\Sigma^- p \to \Lambda n$ and $\Lambda p \to \Sigma^0 p$ scattering are essential for determining the ΛN-ΣN coupling in free space because this coupling could be different in the nuclear medium. These experiments have been and will be performed at K1.8 and K1.1.

However, to obtain information on the hyperonic three-body repulsive force, innovative measurements of Λ hypernuclei with unprecedented precision in a wide mass-number region are required. Such three-body effects affect the Λ binding energy, particularly in heavy Λ hypernuclei. The effect is expected to be from a few hundred keV to a few MeV, depending on the two-body ΛN interaction. In heavy Λ hypernuclei, Λ couples to core nuclei with various one-hole excited states with a small energy difference between each other, which results in several hypernuclear states with narrow energy spacings of typically a few hundred keV. A past experiment at KEK could not separate these states due to the limited energy resolution of ~2 MeV (FWHM). Therefore, a new spectroscopic method should be introduced to determine the Λ binding energies by separating each state and to provide accurate information including the ΛNN three-body effect. New experiments proposed at the newly constructed **HIHR** beam line will resolve this problem. The binding energy will be determined with a resolution of a few hundred keV (FWHM) for light ($^4_\Lambda$He) to heavy ($^{209}_\Lambda$Pb) hypernuclei, using (π, K^+) missing-mass spectroscopy with high-intensity pion beams and thin nuclear targets.

Systematic high-precision spectroscopy of light to heavy Λ hypernuclei provides essential data for determining the repulsive hyperonic three-body force effect through theoretical studies based on realistic ΛN interactions determined from Λp scattering experiments at K1.1. γ-ray spectroscopy provides additional information for determining the level structure of Λ hypernuclei, particularly for the heavy Λ hypernuclei where the level spacing could be narrower than the HIHR resolution. The γ-ray information will also be used to interpret the binding energy spectrum obtained by HIHR measurements. Density-dependent ΛN interaction effects also appear in the mass-number dependence of the level spacing between the s_Λ and p_Λ states because the average nuclear density in each orbital is expected to be different for different mass numbers. The level spacing between s_Λ and p_Λ will be determined with an accuracy of a few keV from γ-ray spectroscopy using germanium detectors.

Only after combining realistic YN and YY interactions with the hyperonic three-body force strength obtained from comprehensive studies in hypernuclear physics, a realistic EOS can be established to solve the hyperon puzzle.

4.2 Hadron physics - revelation of baryon structure built by quarks and gluons through spectroscopic studies of strange and charmed baryons

Quantum chromodynamics (QCD) has been successful at describing the interactions between quarks and gluons, and hadron properties. However, low-energy phenomena such as the formation of hadrons have not yet been clearly explained, because perturbative calculations do not work in the low-energy regime.

At the present Hadron Experimental Facility, experimental approaches to investigate the in-medium properties of mesons are proceeding. These approaches are expected to provide crucial information on the spontaneous breaking of chiral symmetry associated with the mass generation of hadrons, which is the most important feature of QCD at low energy. Various investigations of in-medium meson properties have been and will be performed, such as precise measurements of the spectral functions of vector mesons in media at **High-p** and systematic measurements of light kaonic nuclei at **K1.8BR**.

Baryon spectroscopy is another important approach for investigating how QCD works at low energy, and will be explored at J-PARC. In particular, the fundamental question "how quarks build hadrons" has not yet been answered clearly. It is vital to understand the dynamics of the effective degrees of freedom, which are constituent quarks and Nambu-Goldstone bosons, brought by the non-trivial gluon field at low energy. The spectroscopy of baryons with heavy flavors provides a good opportunity to investigate interactions and correlations of the effective degrees of freedom in hadrons. In excited baryons containing a heavy quark, the correlation between a quark pair inside the baryon is expected to be enhanced, and this is referred to as diquark correlation. There are longstanding arguments about whether diquark correlations play a role in the baryon structure and are related to diquark condensation in highly dense quark matter.

At the energy of J-PARC, excited baryons with a charm quark or multi-strange quarks are appropriate targets for study. An experiment to investigate diquark correlation in charmed baryons (denoted as Y_c^*) is planned at the $\boldsymbol{\pi}$**20** beam line with secondary high-momentum pions. Spectroscopy of Ξ baryons is planned at the new **K10** beam line with intense, separated kaons to investigate diquark correlation in the strangeness sector, and to explore the unknown field of excited Ξ baryons (denoted as Ξ^*). The relative motion of two quarks in a diquark and the collective motion of a diquark to the other quark are kinematically separated by the introduction of quarks with different flavors and with different masses in a baryon. The $\pi^- p \to D^{*-} Y_c^{*+}$ and $K^- p \to \Xi^* K^{(*)}$ reactions will be employed because the production cross sections reflect such diquark motions [7, 8]. It is noted that Y_c^{*+} and Ξ^* can be systematically populated from the ground states up to highly excited states because they are identified in the missing mass spectra. The branching ratio (decay partial width), which carries information on the internal structure of the excited baryon, can be easily determined by measuring decay particles in coincidence with a populated state. This is an advantage of fixed-target experiments.

Further investigations of quark correlations can be performed at the K10 beam line, via the simplest sss systems - Ω baryons. The Ω baryons are unique because the pion coupling is rather weak compared to other hadrons, including $u/\bar{u}$ and $d/\bar{d}$ quarks, and the quark-gluon dynamics will thereby be directly reflected to the exited state Ω^*. However, the production cross sections for Ω^{*-} are expected to be small in the case of the $K^- p \rightarrow K^+ K^{(*)0} \Omega^{*-}$ reaction; therefore, investigations can only be performed using the intense, separated kaon beams available at K10.

4.3 Flavor physics - investigation of new physics beyond the Standard Model through rare kaon decays

The Standard Model (SM) in particle physics successfully describes how elementary particles interact with each other. The last missing particle in the SM, the Higgs particle, was discovered in 2012 by the ATLAS and CMS experiments at the LHC [9, 10]. However, many questions that cannot be answered using the SM still remain, such as the matter-dominant universe and the low mass of the Higgs boson, and therefore the search for new physics beyond the SM has been pursued intensively. The direct production of new particles would not be discovered so easily in the LHC; therefore, the role of flavor physics experiments, which investigate new physics at a high energy scale through rare phenomena using intensity frontier machines, has become more important.

At the **KL** beam line in the present hall, the KOTO experiment searches for the rare kaon decay $K_L \rightarrow \pi^0 \nu\bar{\nu}$. This decay directly violates CP symmetry. The branching ratio is highly suppressed and is predicted to be 3.0×10^{-11} with a small theoretical uncertainty of 2% [11]. This decay is thus one of the most sensitive probes to search for new physics. The KOTO experiment set the most stringent upper limit on the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ branching ratio to be 3.0×10^{-9} at a 90% confidence level with the data-set taken in 2015 [12]. A sensitivity of 7.2×10^{-10} was achieved with the data-set taken in 2016-2018. Three events were observed in the signal region, which was consistent with the number of expected background events, 1.22 ± 0.26 [13]. With newly installed counters to reduce background events, the KOTO experiment continues to take physics data and will achieve a sensitivity of better than 10^{-10} in 3-4 years. However, the achievable sensitivity will eventually become saturated. It is thus desirable to design a new experiment that can observe a sufficient number of SM-predicted events for measurement of the $K_L \rightarrow \pi^0 \nu\bar{\nu}$ decay.

In the extended facility, the KOTO step-2 experiment plans to build a new neutral kaon beam line (**KL2**) with a smaller extraction angle than that for the KOTO experiment to increase the K_L flux, and prepare a longer detector to extend the signal region and improve the signal acceptance. The KOTO step-2 experiment aims to measure the branching ratio for $K_L \rightarrow \pi^0 \nu\bar{\nu}$ decay with a beam intensity of 100 kW for three snow-mass-years and an accuracy of 27% by observing 35 SM events with a signal-to-background ratio of 0.63.

The breaking of time-reversal (T) symmetry, which is connected to CP violation through the CPT theorem, is an important key to solve the matter-antimatter asymmetry in the universe. T violation will be investigated at the **K1.1BR** beam line by measuring the transverse polarization of muons from the $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay.

Charged lepton flavor violation is a definite sign for new physics beyond the SM. The **COMET** experiment, which aims to search for coherent neutrino-less conversion of a muon to an electron ($\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)$) in muonic atoms ($\mu - e$ conversion), provides a window on new physics with the world's highest sensitivity.

The observables associated with kaon rare decays and $\mu - e$ conversion, together with measurements in B factories such as the Belle II experiment, play an important role in the investigation of the flavor structure in new physics.

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