PROCEEDINGS OF SCIENCE

J-PARC Hadron Experimental Facility, present and future

Hitoshi Takahashi*

Institute of Particle and Nuclear Studies, KEK,
1-1 Oho, Tsukuba, Japan
The Graduate University for Advanced Studies (SOKENDAI),
1-1 Oho, Tsukuba, Japan

E-mail: hitoshi.takahashi@kek.jp

The Hadron Experimental Facility (HEF) at J-PARC utilizes a slowly extracted 30-GeV proton beam and provides a variety of secondary particle beams such as pions, kaons, and antiprotons for particle and nuclear physics experiments. In addition, a part of the primary protons are split to the B-Line and delivered directly to hadron physics experiments. So far, the primary beam power of 84 kW has been achieved, and R&D is underway for a new production target capable of 150 kW. Recently, the extension project of the HEF (HEF-ex) was discussed. This project will double the size of the Hadron Experimental Hall and construct a second target station and new secondary beam lines. These include the HIHR, which uses a dispersion match technique for a high-precision (π, K) spectroscopy; the K1.1 and K1.1BR, which provide low-momentum separated charged kaons for $S = -1$ physics; the KL2, which is for a next-generation neutral kaon rare decay experiment; and the K10, which provides high-momentum (up to 10 GeV/c) separated charged beams for hadron physics experiments. Moreover, the B-Line will be upgraded to a high-momentum (up to 20 GeV/c) unseparated charged secondary beam line for charmed baryon spectroscopy and other hadron physics experiments.

This paper briefly summarizes the current status of the HEF and presents the future plan, including the HEF-ex project.

The 21st International Conference on Hadron Spectroscopy and Structure (HADRON2025)
27 - 31 March, 2025
Osaka University, Japan

*Speaker

https://pos.sissa.it/

PoS(HADRON2025)186

1. Introduction

The Hadron Experimental Facility (HEF) is one of the two facilities in the J-PARC Main Ring (MR). The HEF uses a slowly extracted primary proton beam with an energy of 30 GeV, producing neutral and charged secondary beams with a momentum of up to 2 GeV/c for various particle and nuclear physics experiments. Beam operation at the facility began in 2009. Since then, the beam power has gradually increased to 84 kW.

This paper presents the current status and future plans of the HEF. The next section briefly summarizes the existing primary and secondary beam lines, as well as highlights of their experimental outputs. The production target is the most important piece of equipment for increasing beam intensity. The development of a new target is described in section 3. Section 4 introduces the extension project of the HEF and presents its current situation.

2. Current beam lines

A schematic drawing of the HEF is shown in Fig. 1. Primary protons are accelerated to an energy of 30 GeV, then slowly extracted from the MR. They are transported to the Hadron Experimental Hall through a beam-line tunnel called the Switch Yard (SY) and injected into the production target T1. Various secondary particles are generated at the T1 and provided to physics experiments. This primary beam line is called the A-Line. A small portion (about 1/10,000) of the primary protons splits from the A-Line to the B-Line in the middle of the SY and is used directly by user experiments. The current experiment on the B-Line aims to study the spontaneous breaking of the chiral symmetry by measuring the mass modification of vector mesons in a nuclear medium[1], which was first observed in the KEK-PS E325 experiment. The B-Line branches again in the hall into the C-Line, which delivers 8-GeV primary protons to the Hadron South Building. The COMET experiment[3], which searches for the μ-e conversion, is currently preparing for its Phase-1 program in the building, and the first beam commissioning was carried out in 2023.

Three secondary beam lines are operated at the T1 target station. The K1.8 and K1.8BR beam lines deliver well-separated charged secondary beams with momenta of up to 2 and 1.1 GeV/c, respectively. These beam lines are primarily used for strangeness nuclear physics experiments. The KL beam line provides a neutral kaon beam for the kaon decay physics experiment. The KOTO experiment searches for the decay of $K_L^0 \to \pi^0 \nu \bar{\nu}$ with the world's best sensitivity[2].

In the K1.8 experimental area, the KURAMA spectrometer magnet, which was used in hypernuclear experiments such as hybrid-emulsion[4–6] and hyperon-proton scattering[7–9] experiments, was recently replaced with the new spectrometer S-2S. Figure 2 shows a photograph of the S-2S spectrometer, which has a QQD configuration. The S-2S was designed for the Ξ-hypernuclear spectroscopy, offering a large acceptance of 55 msr and a high energy resolution of 2 MeV in FWHM[10]. The first physics run of the spectroscopy started in February 2025.

The observation of kaonic nuclei ($\bar{K}NN$ bound state)[11] is one of the most important physics results from the K1.8BR beam line. To study kaonic nuclei more systematically, the spectrometer system and the beam line are being upgraded[12]. The solenoid spectrometer was removed in March 2025, and a new, larger superconducting solenoid spectrometer will be installed next year. Thanks to this spectrometer upgrade, the detector acceptance will increase by a factor of 1.6, and

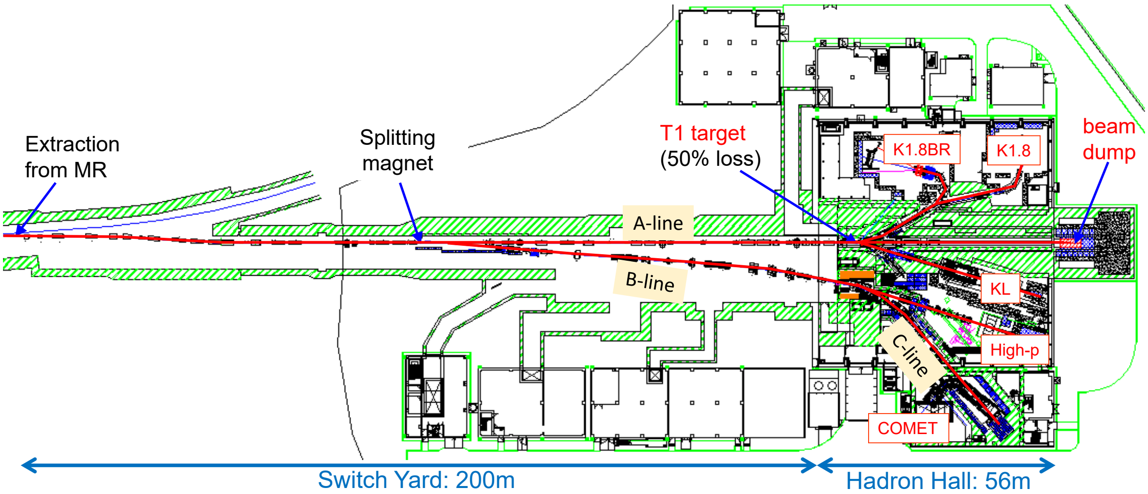

Figure 1: Schematic drawing of the current HEF.

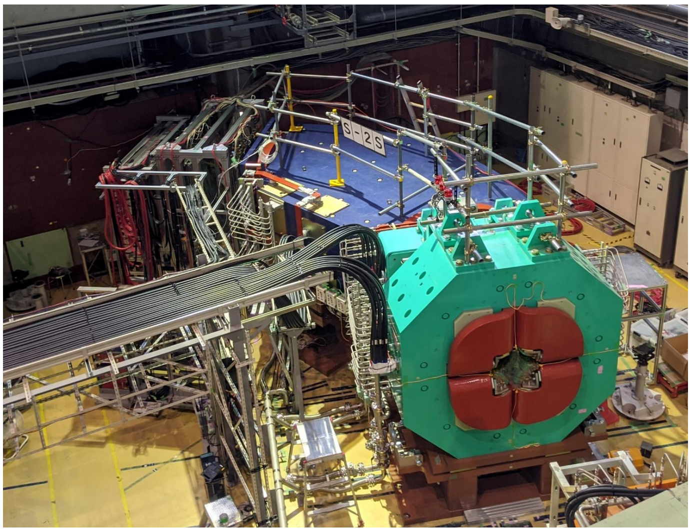

Figure 2: Photograph of the S-2S spectrometer installed in the K1.8 experimental area.

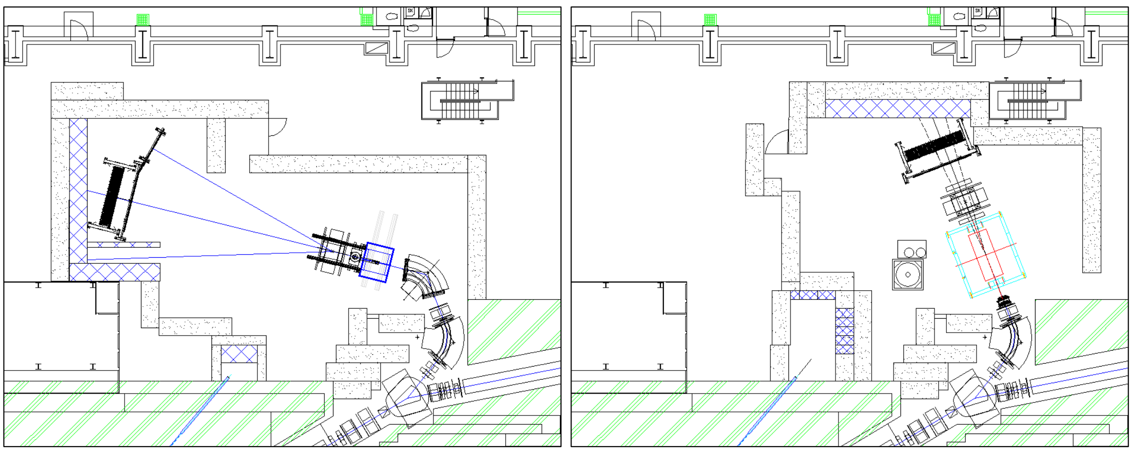

Figure 3: Schematic drawings of the K1.8BR experimental area before (left) and after (right) the upgrade.

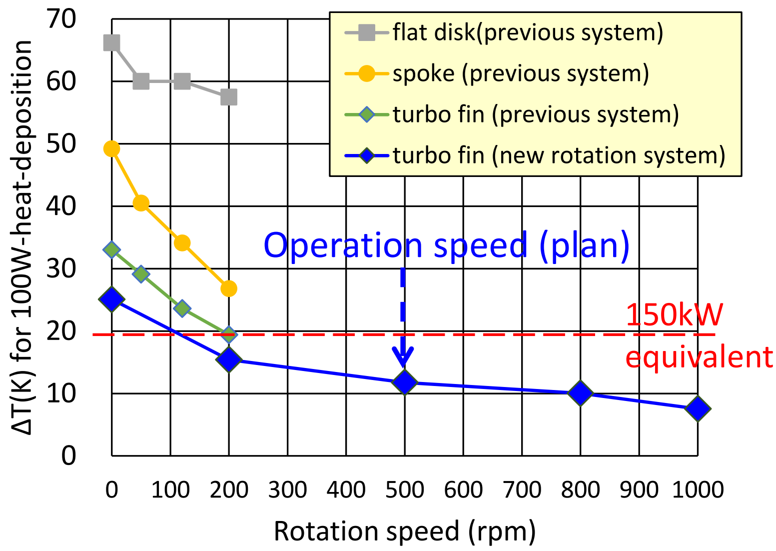

Figure 4: Results of the measurements of the cooling efficiency of gas-cooled rotating disks.

the neutron detection efficiency will improve sevenfold. Shortening the beam line will increase the K^- beam intensity by a factor of 1.6 at a momentum of 1.0 GeV/c by removing the last dipole magnet from the beam line. Figure 3 shows the schematic drawings of the K1.8BR before and after the upgrade.

3. Target development

The current production target is a 66-mm-long gold bar bonded to a copper base that is cooled by water[14]. The target is placed in an airtight chamber, and helium gas is circulated to monitor its soundness. The target was designed to be capable of the beam power of up to 95 kW for a 5.2-s spill cycle, and 115 kW for a 4.24-s spill cycle. As of March 2025, a beam power of 84 kW was achieved for continuous user beam operation, approaching the design value of the current target.

In order to increase the beam power to over 100 kW, we are developing a new production target[15]. The target is a rotating disk that is directly cooled by helium gas. There are two options for the target material; a disk made of nickel or copper with a gold, platinum, or tungsten edge, or a disk made entirely of tungsten.

The helium gas is used not only as a coolant but also for rotation drive. With this design, a driving motor and a long shaft are unnecessary, so the system can be small in a very high radiation environment, and the airtightness of the target chamber can be easily achieved.

The most important factor in realizing a gas-cooled target is cooling efficiency. We began measuring the cooling efficiency using a simple flat disk in order to compare the results with those estimated using an empirical formula. Since the results were consistent with the estimation, we concluded that the cooling efficiency was measured properly. After testing a few spoke structures for the disk, we achieved sufficient cooling efficiency for a 150-kW beam at a rotation speed of 200 rpm by adopting a turbo-fin shape. Figure 4 shows the temperature rise measured for a heat

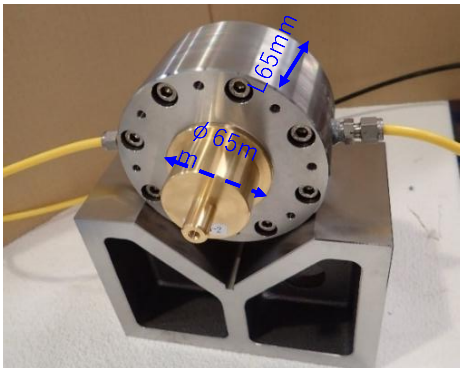

Figure 5: Photograph of the trial production of a gas bearing.

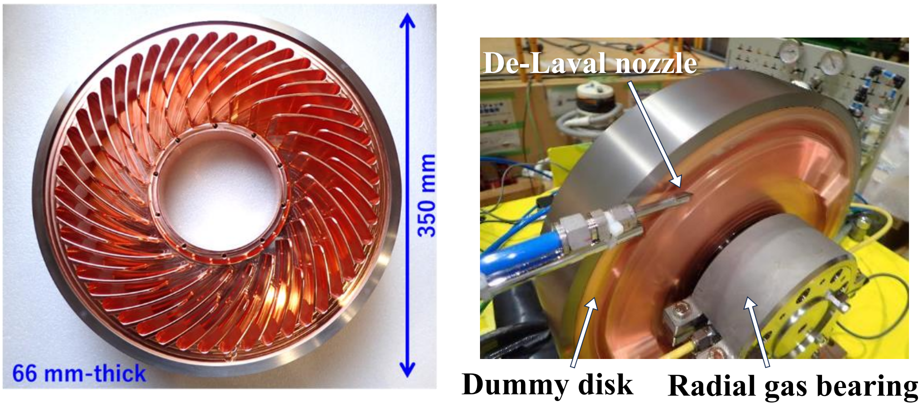

Figure 6: Photographs of the dummy disk (left) and the rotation test using the sonic nozzle (right).

deposition of 100 W on various shapes of the target disk. The dashed line indicates the temperature rise equivalent to a 150-kW beam loss.

The key component of the rotating target is the bearing because the target's lifetime is determined by the bearing's lifetime. We are developing a gas bearing for our rotating target. It has essentially no lifetime, even in a high-radiation environment, and it can withstand a higher rotation speed than a rad-hard ball bearing (330 rpm maximum). The photograph of the first trial production of the gas bearing is shown in Fig. 5.

To test the rotation drive by helium gas, we prepared a dummy disk made of tungsten alloy and copper that has the same size and weight as a real disk. As shown in Fig. 6, we tested the rotation system with the dummy disk and the gas bearings. By selecting the appropriate diameter for the sonic nozzle, we succeeded to drive the target disk at a speed exceeding 500 rpm.

4. Extension project

One of the major features of the HEF is that it allows for the research of various layers of matter, from quarks to hadrons, nuclei, and neutron stars, all within a single facility. Currently, however, only three experiments can be performed simultaneously at most. To strengthen this unique feature of the HEF, we plan to construct additional beam lines with new characteristics to

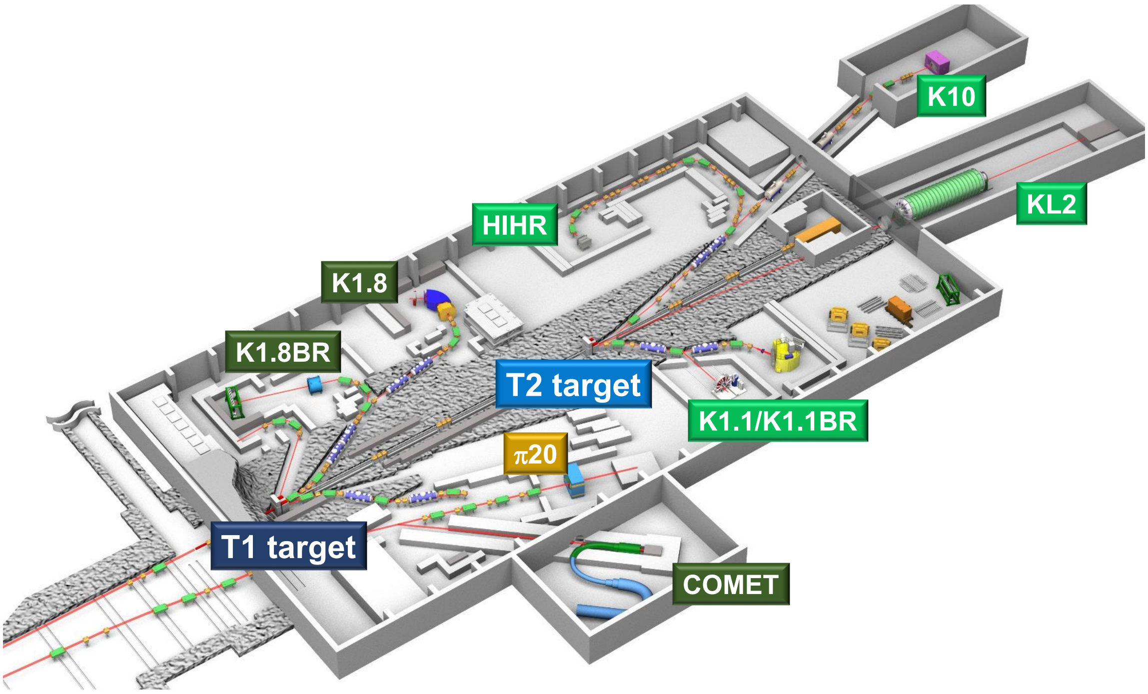

Figure 7: Planned drawing of the extended HEF.

enable a wider variety of experiments to be conducted simultaneously. This is the HEF Extension Project (HEF-ex)[13].

Figure 7 illustrates the planned view of the HEF-ex. The area of the Hadron Experimental Hall will double, and the A-Line will extend downstream. The second production target, T2, will be placed in the expanded area, and following new secondary beam lines will be constructed at the T2 target station.

The HIHR beam line is designed for high-precision spectroscopy of the $S = -1$ hypernuclei using high-intensity pion beams. An energy resolution of 10^{-4} is expected by using a dispersion matching technique. Three-body forces are considered key to solving a so-called "hyperon puzzle" of neutron stars. Precise measurements of Λ binding energies of Λ-hypernuclei across a wide mass number range will provide essential information on these forces.

The K1.1 and K1.1BR beam lines will deliver low-momentum (up to about 1 GeV/c) separated charged secondary beams. Various strangeness nuclear physics experiments have been proposed, including a hyperon-nucleon scattering experiment and gamma-ray spectroscopy of hypernuclei.

The K10 beam line will provide high-momentum charged secondary beams. RF separators will allow for the provision of well-separated kaons and antiprotons with a maximum momentum of 10 GeV/c. Spectroscopy of hadrons with multiple strange quarks is planned to investigate dynamics of the effective degrees of freedom in hadrons.

The KL2 is a neutral secondary beam line for a kaon rare decay experiment. The extraction angle from the production target is set at 5 degrees, smaller than the current KL beam line's angle of 16 degrees. This increases the K_L yield by a factor of 5 and the K_L momentum to 5.2 GeV/c, whereas the momentum in the current KL beam line is 2.1 GeV/c. The KOTO II experiment was proposed to measure the branching ratio of the decay mode of $K_L^0 \to \pi^0 \nu \bar{\nu}$. It aims to achieve a single event sensitivity of below 10^{-12}, which is much smaller than the Standard Model prediction of a branching ratio of 3×10^{-11}.

In addition, the B-Line will be upgraded to the high-momentum charged secondary beam line (π20) by replacing the splitting magnets with a production target. The beam optics are designed to create a dispersive focus plane in the middle of the beam line with a momentum resolution of 10^{-3}. Although the beam species cannot be separated, high-intensity pion beams of over 10^7 per spill will be provided for the various hadron physics programs.

In the current mid-term plan, KEK-PIP2022, the HEF-ex project was given the highest priority in the budget request. Since the g-2/EDM project remains in the queue for budget requests from the previous PIP, the HEF-ex is considered the next to the g-2/EDM in the queue. However, the construction cost became about 1.4 times higher after the COVID-19. Cost reduction, optimization, and staging plans with smaller steps are under discussion for the early realization of the project.

As for the π20 beam line, we are planning a staged approach to its realization. In the first stage, we will only use the beam loss at the splitting magnet (less than 420 W) for the production of secondary particles. No beam-line equipment needs to be changed except for the polarity-change devices to deliver negatively charged beams. In the second stage, the splitting magnets will be replaced with a thin production target with a beam loss of a few kW. The production target will be upgraded to a thicker one with a beam loss of 15 kW in the final stage.

Test experiment T106 was carried out to measure positively charged secondary particles from the beam loss at the splitting magnet. More than 10^6 particles/spill, with a π^+-to-proton ratio of nearly 1, were obtained at a momentum of 10 GeV/c for the case of an expected beam loss of 230 W[16]. The polarity-change devices are currently being fabricated and will be installed during the summer shutdown in 2026.

5. Summary

The Hadron Experimental Facility (HEF) at J-PARC utilizes a slowly extracted primary proton beam with an energy of 30 GeV. The HEF produces neutral and charged secondary beams for various particle and nuclear physics experiments and delivers the primary proton beam directly to user experiments.

A new spectrometer, S-2S, was installed in the K1.8 experimental area for the Ξ-hypernuclear spectroscopy, and the first physics run begun in February 2025. The K1.8BR beam line and spectrometer are also being upgraded for the systematic study of kaonic nuclei.

A maximum beam power of 84 kW has been achieved in continuous user beam operation, which is close to the design value of 115 kW of the current production target for the 4.24-s spill cycle. The current target is made of gold with indirect water cooling, and is enclosed by an airtight stainless-steel chamber. To increase the beam power, we are developing a new rotating disk target that is cooled and driven by helium gas. The maximum beam power of the new target is expected to be over 150 kW. Several R&Ds are ongoing, such as the measurement of the cooling efficiency and the test of the rotation system with gas bearings and a sonic nozzle.

For future upgrades, the extension of the HEF (HEF-ex) was proposed and selected as the first priority in the KEK mid-term plan, KEK-PIP2022. However, the construction cost increased significantly after the onset of the pandemic. Therefore, cost reduction and staging plans are under discussion for the early realization of the HEF-ex project.

Acknowledgments

The author would like to thank all the staff of the J-PARC accelerators and the HEF. He is also grateful to the HEF-ex Task Force members for their discussions about the HEF-ex project.

References

[1] K. Aoki *et al.*, *Experimental investigation of vector mesons in medium through dielectron decay at J-PARC*, *J. Subatomic Part. Cosmol.* **3** (2025) 100019.

[2] J.K. Ahn *et al.*, *Search for the $K_L \to \pi^0 \nu\bar{\nu}$ Decay at the J-PARC KOTO Experiment*, *Phys. Rev. Lett.* **134** (2025) 081802.

[3] M. Moritsu, on behalf of the COMET Collaboration, *Search for Muon-to-Electron Conversion with the COMET Experiment*, *Universe* **8** (2022) 196.

[4] H. Ekawa *et al.*, *Observation of a Be double-Lambda hypernucleus in the J-PARC E07 experiment*, *Prog. Theor. Exp. Phys.* **2019** (2019) 021D02.

[5] S. Hayakawa *et al.*, *Observation of Coulomb-Assisted Nuclear Bound State of Ξ^--^{14}N System*, *Phys. Rev. Lett.* **126** (2021) 062501.

[6] M. Yoshimoto *et al.*, *First observation of a nuclear s-state of a Ξ hypernucleus, $^{15}_{\Xi}C$*, *Prog. Theor. Exp. Phys.* **2021** (2021) 073D02.

[7] K. Miwa *et al.*, *Measurement of the differential cross sections of the $\Sigma^- p$ elastic scattering in momentum range of 470 to 850 MeV/c*, *Phys. Rev. C* **104** (2021) 045204.

[8] K. Miwa *et al.*, *Precise measurement of differential cross sections of the $\Sigma^- p \to \Lambda n$ reaction in momentum rage 470 - 650 MeV/c*, *Phys. Rev. Lett.* **128** (2022) 072501.

[9] T. Nanamura *et al.*, *Measurement of differential cross sections of the $\Sigma^+ p$ elastic scattering in momentum range of 0.44 - 0.88 GeV/c*, *Prog. Theor. Exp. Phys.* **2022** (2022) 093D01.

[10] T. Gogami *et al.*, *Strangeness physics programs by S-2S at J-PARC*, Proceedings of 14th International Conference on Hypernuclear and Strange Particle Physics (HYP2022), *EPJ Web of Conf.* **271** (2022) 11002.

[11] T. Yamaga *et al.*, *Observation of a $\bar{K}NN$ bound state in the $^3He(K^-, \Lambda p)n$ reaction*, *Phys. Rev. C* **102** (2020) 044002.

[12] F. Sakuma *et al.*, *Light Kaonic Nuclei at J-PARC*, Proceedings of 10th International Conference on Quarks and Nuclear Physics (QNP2024), *Proc. of Sci.* **465** (2025) pp.211.

[13] K. Aoki *et al.*, *Extension of the J-PARC Hadron Experimental Facility: Third White Paper*, nucl-ex/04462

[14] M. Saito *et al.*, *Indirectly cooled secondary-particle production target at J-PARC Hadron Experimental Facility*, *Phys. Rev. Acc. Beams* **25** (2022) 063001.

[15] H. Watanabe *et al.*, *Status and Prospect of Production Target at J-PARC Hadron Experimental Facility*, to be published in Proceedings of the 4th J-PARC Symposium 2024, JPS Conference Proceedings.

[16] H. Noumi *et al.*, *First Measurement of Secondary Beams at the J-PARC High-Momentum Beam Line*, in this proceedings.