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Hadron physics experiments using Hyperon Spectrometer at J-PARC

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This paper compiles the ongoing hadron physics experiments utilizing the Hyperon Spectrometer at the J-PARC facility. The J-PARC Hadron Experimental Facility, capable of producing world-class intense kaon, pion, and antiproton beams with momenta up to 2 GeV/c, has opened unprecedented opportunities for a wide range of hadron experiments. Complementing these capabilities, the new Hyperon Spectrometer detector system, composed primarily of a high-rate capable time projection chamber and a 1-T superconducting magnet, has made diverse hadron experiments feasible. The first experiment using the Hyperon Spectrometer was successfully conducted in 2021, and additional experiments are currently in preparation. Furthermore, the expansion plans for the J-PARC Hadron Experimental Facility and upgrades to the Hyperon Spectrometer are underway. This paper aims to serve as a guide and inspiration for proposing new hadron experiment ideas at J-PARC using the Hyperon Spectrometer.

Keywords: Exotic hadrons, Hadron physics, Hyperon Spectrometer, J-PARC

I. INTRODUCTION

Hadron physics explores the fundamental properties and interactions of hadrons, ultimately deepening our understanding of the non-perturbative regime of QCD. To achieve these goals, the J-PARC (Japan Proton Accelerator Research Complex) facility utilizes a world-class high-intensity proton beam to produce secondary beams such as kaons, pions, and antiprotons, establishing itself as a leading platform for groundbreaking hadron physics programs. The Hyperon Spectrometer, featuring a high-rate capable time projection chamber (HypTPC) [1] and a 1-T Helmholtz-typed superconducting magnet [2], has enabled a broad spectrum of hadron experiments, beginning with its first implementation in 2021 and with more underway.

Recent advancements in hadron physics have drawn significant attention, particularly due to discoveries of exotic hadrons such as charmonium-pentaquarks [3] and a doubly charmed tetraquark [4] in the LHCb experiment conducted at the Large Hadron Collider (LHC) in CERN, a representative accelerator of the energy frontier. In contrast, J-PARC focuses on the intensity frontier, offering unique opportunities to study hadronic systems with strangeness (S) of −1, −2, or even +1. This complementary approach allows J-PARC to probe a distinct domain of hadron physics and contribute to a broader understanding of QCD.

This paper provides an overview of ongoing experiments using the Hyperon Spectrometer at J-PARC. Section II presents the J-PARC accelerator, the Hadron Experimental Facility, and the Hyperon Spectrometer, providing the foundational tools for the experiments. Section III reviews experiments utilizing the Hyperon Spectrometer and compares their methodologies. Lastly, Section IV concludes the discussion by addressing planned upgrades and future directions in hadron physics research at J-PARC.

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II. EXPERIMENTAL TOOLS

1. J-PARC Hadron Experimental Facility

The J-PARC consists of three accelerators, as shown in Fig. 1 [5]: the 400 MeV Linac, the 3 GeV Rapid Cycle Synchrotron (RCS), and the 30 GeV Main Ring (MR). The Linac accelerates negative hydrogen ions (H^-) up to 400 MeV at a 25 Hz repetition rate and injects them into the RCS. At the injection point, a charge-stripping foil converts the negative hydrogen ions into protons. The RCS then accelerates the protons to 3 GeV at the same repetition rate, subsequently extracting them to the MR. The MR further accelerates these protons to 30 GeV before slowly extracting them to the Hadron Experimental Facility. For slow extraction operations, the typical beam power is currently 80 kW, corresponding to approximately 10^{13} protons per second. The repetition rate for beam pulses is currently 4.24 seconds, with a flat-top duration of 2 seconds.

As illustrated in Fig. 2 [6,7], the primary 30 GeV proton beam is injected onto the T1 gold target at the Hadron Experimental Facility, initiating spallation reactions that produce a variety of secondary particles, such as pions, kaons, and antiprotons. These particles are directed into three beamlines: two charged beamlines (K1.8 and K1.8BR) and one neutral beamline (KL). The KL beamline is currently being utilized to study CP violation through the rare decay process $K_L \to \pi^0\nu\bar{\nu}$ [8]. The K1.8 beamline is optimized for investigating double-strangeness systems, utilizing a 1.8 GeV/c K^- beam where the forward differential cross section of the $K^-p \to K^+\Xi^-$ reaction is maximized. The K1.8BR beamline, a shorter offshoot of the K1.8 beamline, is designed for lower momentum beams ($<$ 1.2 GeV/c). The beamline length of the K1.8 and K1.8BR beamlines is 45.8 m and 31.3 m, respectively. The K^- 1.0 GeV/c momentum corresponds to the peak of the total cross section of $\bar{K}N$ scattering, making K1.8BR ideal for studies of $\bar{K}N$ interactions, and kaonic nuclei. The K^- beam intensity in these beamlines is approximately 10^6 per spill at 1.8 GeV/c in K1.8 and about 5×10^5 per spill at 1.0 GeV/c in K1.8BR [9].

Before reaching the T1 production target, part of the primary 30 GeV proton beam is split and delivered to the high-p beamline and the COMET beamline. At these beamlines, the experiments investigating the nuclear medium effects of ϕ mesons [10,11] and searching for muon-to-electron conversion [12], respectively, are currently undergoing commissioning. Although this paper focuses on experiments with the Hyperon Spectrometer at the K1.8 and K1.8BR beamlines, many other hadron experiments are also being conducted using different detector systems at K1.8 and K1.8BR beamlines and a wide variety of hadron experiments are also ongoing across other beamlines at the J-PARC Hadron Experimental Facility. For detailed information on these experiments, refer to the J-PARC Proposal Webpage [13].

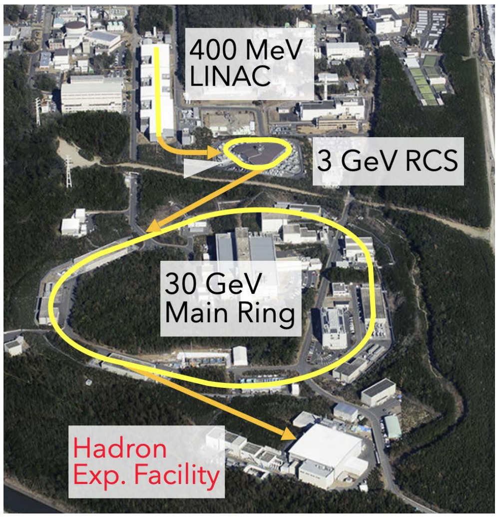

Fig. 1. (Color online) A bird's-eye view of the J-PARC accelerator facility, showing the three accelerators and the Hadron Experimental Facility [The photograph is from Ref. 5].

2. Hyperon Spectrometer

The Hyperon Spectrometer is a state-of-the-art detector system developed specifically for hadron physics experiments, requiring high resolution and high-rate capability to cope with the high-intensity beam at J-PARC. The heart of the Hyperon Spectrometer, the Time Projection Chamber (HypTPC) [1], is compact in size and is installed inside the warm bore of a 1-T Helmholtz-type superconducting magnet [2], as illustrated in Fig. 3. One of its most significant features is the placement of the target inside the drift volume of the HypTPC, allowing for

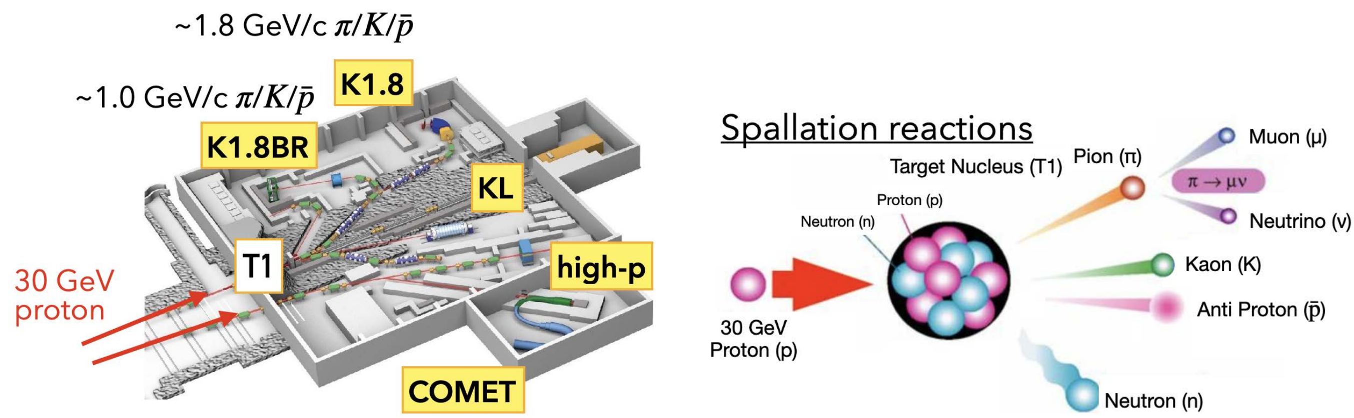

Fig. 2. (Color online) Schematic of the J-PARC Hadron Experimental Facility (left) and an illustration of spallation reactions to produce secondary beams in the T1 production target (right) [The base of the figures is from Ref. 6,7].

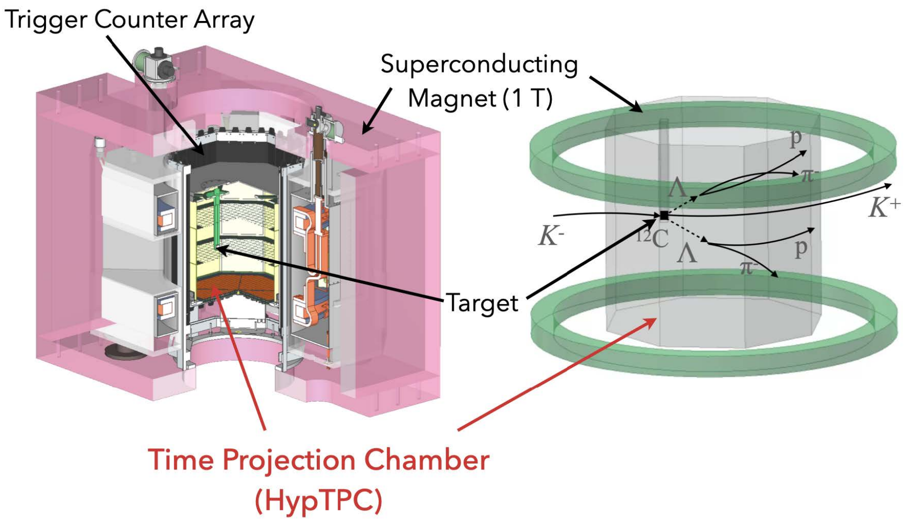

Fig. 3. (Color online) Schematic of the Hyperon Spectrometer, which is composed of a time projection chamber, HypTPC, surrounded by a trigger counter array, in a 1-T superconducting magnet. The target is located inside the HypTPC drift volume.

large acceptance. This design forces the high-rate beam to enter the drift volume directly, which posed substantial design challenges. The HypTPC gas chamber, visible as an octagonal prism, has both a diameter and a height of approximately 62 cm, allowing it to fit within the 80-cm inner diameter of the Helmholtz magnet. The chamber is filled with an Ar-CH_4 (P10) gas mixture. As shown in Fig. 4, the internal structure of the HypTPC is divided into two primary regions: the drift volume and the amplification readout chamber.

The drift volume is defined by the cathode plane and the field cage structure, which includes a target holder positioned 143 mm upstream from the TPC center. The 2.0-mm-wide field strips, printed on both sides of 25-μm-thick flexible sheets with a 2.5-mm pitch, are used on both the octagonal field cage and the target holder structure to ensure a uniform electric field of 130 V/cm across the drift volume. Exposed insulators in the beam path were cut to minimize space charge-up effects. The target holder has a rectangular cross-sectional area of 34 mm × 24 mm, which supports a diamond target of 30 mm × 20 mm, with a height of 20 mm. Separate cylindrical target holders with diameters of 52 mm and 80 mm have also been designed as interchangeable units to accommodate LH_2 and LD_2 targets.

Ionized electrons generated along the tracks of charged particles in the drift volume drift under the influence of the electric field toward the amplification region. Between the drift and amplification regions is a gating grid

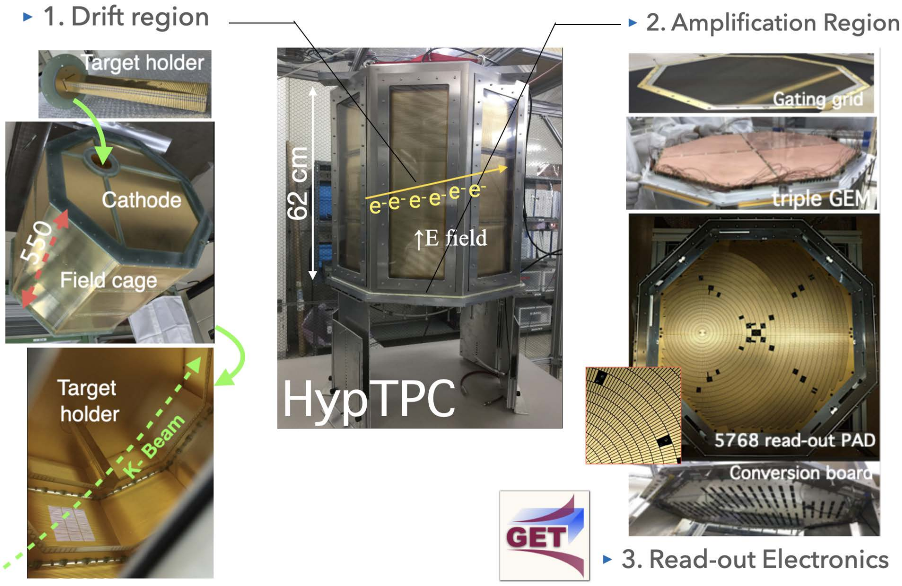

Fig. 4. (Color online) Photographs showing the HypTPC and its internal structure.

plane composed of gold-plated Cu-Be wires, each 50 μm in diameter and spaced 1 mm apart. The gate opens for 16-μs only when a trigger comes, allowing drift electrons to enter the amplification region. This gating mechanism increased the high-rate capability of the system up to 1 MHz [14]. After passing through the gating grid, the electrons are amplified by passing through a triple-layered GEM (Gas Electron Multiplier) system [15], achieving a gain of approximately 10^4. The amplified electron signals are collected on 5,768 readout pads arranged concentrically around the target position and processed using GET electronics [16] for data acquisition.

Operating within a strong 1-T magnetic field, the HypTPC achieves a position resolution of approximately 300 μm, corresponding to a momentum resolution ($\Delta p/p$) of 1–3%. Further details on the HypTPC's performance will be published in a separate paper. Surrounding the HypTPC in the magnet is an array of vertical scintillator trigger counters forming an octagonal shape. Each face contains four segments, with two central segments on the upstream face divided around the beam window, resulting in a total of 34 segments. This arrangement provides multiplicity triggers, i.e., a trigger signal is generated and data is recorded when n or more segments are fired in case of the Mp-n trigger.

III. HADRON PHYSICS EXPERIMENTS

The experiments proposed using the Hyperon Spectrometer at J-PARC have been compiled to provide an overview. A detailed description of the physics goals for each experiment can be found in their respective proposals. This section focuses on providing a brief introduction to each experiment while highlighting how the Hyperon Spectrometer is employed.

The first experiment using the Hyperon Spectrometer was the H-dibaryon search experiment (J-PARC E42[1] [17]), already completed in 2021. This experiment searched for the H-dibaryon, a $I = J = 0$ six-quark state ($uuddss$), using the ^{12}C(K^-, K^+) reaction with a 1.8 GeV/c K^- beam and a diamond target. The outgoing K^+ particles were tagged by the forward KURAMA spectrometer, while the Hyperon Spectrometer measured decay products of the H-dibaryon such as $\Lambda\Lambda$ or $\Xi^- p$, followed by secondary decays like $\Xi^- \to \Lambda\pi^-$ and $\Lambda \to p\pi^-$. The invariant mass spectra of $\Lambda\Lambda$ or $\Xi^- p$ are analyzed to find the evidence of the H-dibaryon. As the first experiment involving the Hyperon Spectrometer, extensive calibrations are still ongoing.

Currently, the Hyperon Spectrometer has been moved to the K1.8BR beamline for the new Λ resonance

[1] J-PARC assigns experimental numbers in the order proposals are submitted. Initially, proposals are labeled with a "P" (e.g., P42), and upon approval, the label changes to "E" (e.g., E42).

search experiment near the $\Lambda\eta$ mass threshold (J-PARC E72 [18]). Previous Crystal Ball experiments observed concave-up angular distributions in the $K^-p \to \Lambda\eta$ reaction near the $\Lambda\eta$ mass threshold [19], which could not be explained by only $J = 1/2$ amplitudes. This behavior, confined to a narrow beam momentum range, suggests the presence of a new narrow resonance. E72 will use a K^- beam near 0.735 GeV/c and an LH_2 target to measure the differential cross section of the $K^-p \to \Lambda\eta$ reaction with significantly higher statistics. The Hyperon Spectrometer will reconstruct Λ baryons, while the η mesons will be identified using the missing mass technique. If a new resonance exists, its spin and parity can be determined using angular distributions and Λ polarization information.

After the E72 experiment, the Hyperon Spectrometer will return to the K1.8 beamline for the E45 [20] and E90 [21] experiments. E45 aims to search for missing resonances in N^* and Δ^* spectroscopy through three-body hadronic reactions using $\pi^\pm$ beams and an LH_2 target. The experiment will cover beam momenta from 0.7 to 2.0 GeV/c with high precision and perform partial-wave analysis using two orders of magnitude higher statistics than existing data. Key reactions include $\pi^-p \to \pi^+\pi^-n$, $\pi^0\pi^-p$, and $\pi^+p \to \pi^0\pi^+p$, $\pi^+\pi^+n$, where the Hyperon Spectrometer will measure two charged particles, and the third neutral particle will be reconstructed using the missing mass technique. Additionally, hybrid baryons predicted by lattice QCD calculation [22] should also be observed if they exist.

E90 focuses on extracting the ΣN scattering length by analyzing the cusp structure observed near the ΣN mass threshold. This experiment will use a 1.4 GeV/c K^- beam and an LD_2 target. Unlike other experiments, the Hyperon Spectrometer will operate without a magnet due to spatial constraints. The high-resolution S-2S spectrometer will detect outgoing π^- particles, and the missing mass spectrum of the $d(K^-, \pi^-)$ reaction will be analyzed. Multiplicity triggers from the trigger counters will suppress quasi-free background. Unlike other experiments that use 80-mm diameter targets, a smaller 54-mm diameter target will minimize energy loss effects to maximize the missing mass resolution in E90.

Lastly, the P104 [23] and Θ^+ [24,25] experiments are not approved yet. The proposal for P104 has been submitted, while the letter of intent and a test beam proposal for the Θ^+ experiment has been submitted. Both aim to utilize the K1.8BR beamline immediately following the E72 experiment. P104 will measure the cross section of the $\bar{p}p \to \phi\phi$ reaction near the threshold using a 0.9-1.15 GeV/c antiproton beam and an LH_2 target. In the past, the JETSET experiment measured a cross section of a few mb, which is two orders of magnitude higher than the value predicted by the OZI rule (10 nb) [26]. The $\phi \to K^+K^-$ decay allows all four kaons in the final state to be measured in the large acceptance Hyperon Spectrometer.

The Θ^+ experiment will search for the exotic Θ^+ pentaquark ($uudd\bar{s}$) using a 0.5 GeV/c K^+ beam and an LD_2 target. The final state particles from the $K^+d \to K^0pp$ reaction, including $\pi^+\pi^-$ from K_S decays, as well as two protons, will be exclusively measured using the Hyperon Spectrometer. Recent proposal requests test beam to verify the beam intensity, and the spread of beam position and momentum at 0.4–0.5 GeV/c to optimize the beam condition for the experiment.

Figure 5 summarizes the topics of the experiments utilizing the Hyperon Spectrometer and the corresponding reaction diagrams. Table 1 compares the beams and targets required for the proposed experiments utilizing the Hyperon Spectrometer. All experiments share a common experimental setup utilizing the Hyperon Spectrometer, with additional components such as trigger counters or beam degraders required for specific experiments. For detailed information, refer to the respective references for each experiment.

IV. SUMMARY

At the J-PARC Hadron Experimental Facility, the newly developed Hyperon Spectrometer has enabled a wide variety of hadron physics experiments. We anticipate that many new experimental ideas will be proposed in the near future. For convenience, the currently available beam and target conditions are summarized as follows:

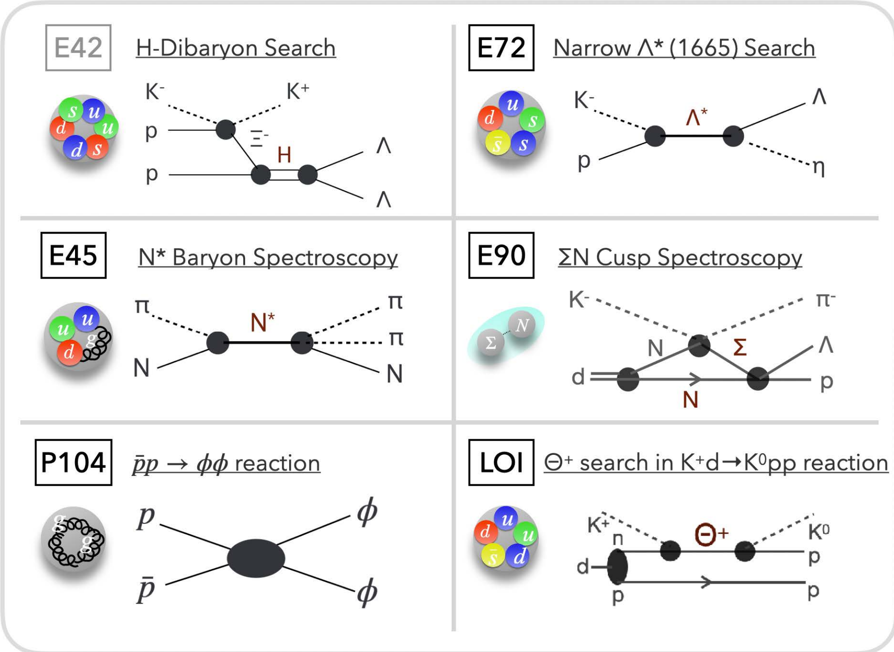

Fig. 5. (Color online) Hadron physics experiments using the Hyperon Spectrometer. The reactions shown here will be reconstructed in the HypTPC.

Table 1. Summary of beam and target parameters for the Hyperon Spectrometer experiments.

		E42 [17]	E72 [18]	E45 [20]	E90 [21]	P104 [23]	Θ^+ [24,25]
Beam	Beam line	K1.8	K1.8BR	K1.8	K1.8	K1.8BR	K1.8BR
	Particle	K^-	K^-	$\pi^\pm$	K^-	$\bar{p}$	K^+
	Momentum	1.8 GeV/c	0.735 GeV/c	0.7 GeV/c – 2.0 GeV/c	1.4 GeV/c	0.9 GeV/c – 1.15 GeV/c	0.5 GeV/c
Hyperon Spectrometer	Magnet	1 T	1 T	1 T	-	1 T	1 T
	Target	Diamond	LH_2	LH_2	LD_2	LH_2	LD_2
	Target size	30(W) × 20(H) × 20(T) mm^3	ϕ80 mm × 100(H) mm	ϕ80 mm × 100(H) mm	ϕ54 mm × 100(H) mm	ϕ80 mm × 100(H) mm	ϕ80 mm × 100(H) mm
	Target holder	Rectangular FPCB (gas transparent)	Cylindrical G10 (gas tight)	Cylindrical G10 (gas tight)	Cylindrical G10 (gas tight)	Cylindrical G10 (gas tight)	Cylindrical G10 (gas tight)
New Components		-	BAC/KVC	BVC	SAC	-	Degrader

1. Available beams:
   (a) Types: $\pi^\pm$, $K^\pm$, protons/antiprotons
   (b) Momentum: <1.15 GeV/c at K1.8BR, <2 GeV/c at K1.8 beamline
2. Available targets:
   (a) Types: LH_2, LD_2, diamond, and other solid targets unaffected by the magnetic field
   (b) Sizes: Cylindrical (80-mm or 54-mm diameter, 100-mm height); rectangular targets with widths up to 3 cm and thicknesses below 2 cm

Additionally, the J-PARC Hadron Experimental Facility is planning an expansion that includes an additional production target and new beamlines, effectively doubling its experimental area [27]. Shorter beamlines such as K1.1 and K1.1BR are expected to be constructed, providing higher-intensity low-momentum kaon beams.

Plans for a K10 beamline delivering high-momentum kaon beams up to 10 GeV/c are also in progress, enabling even more diverse and comprehensive hadron physics experiments.

The Hyperon Spectrometer is undergoing further upgrades to accommodate higher-intensity beams. Research and development are underway to implement a more stable glass GEM for the HypTPC, along with a data acquisition (DAQ) upgrade to handle the increased data rates effectively. These ongoing advancements, combined with the planned expansions of the J-PARC facility, promise to pave the way for groundbreaking discoveries in hadron physics and inspire new experimental proposals.

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REFERENCES

[1] S. H. Kim *et al.*, High-rate Performance of a Time Projection Chamber for an H-dibaryon Search Experiment at J-PARC, Nucl. Instrum. Methods Phys. Res. A **940**, 359 (2019).

[2] J. K. Ahn *et al.*, Superconducting Dipole Magnet for Hyperon Spectrometer, Nucl. Instrum. Methods Phys. Res. A **1047**, 167775 (2023).

[3] R. Aaij *et al.* (LHCb collaboration), Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$, Phys. Rev. Lett. **122**, 222001 (2019).

[4] R. Aaij *et al.* (LHCb collaboration), Study of the Doubly Charmed Tetraquark T_{cc}^+, Nat. Commun. **13**, 3351 (2022).

[5] Outline of J-PARC, https://j-parc.jp/c/en/about/outline.html.

[6] Overview of the Hadron Experimental Facility, https://j-parc.jp/c/en/facilities/nuclear-and-particle-physics/hadron.html.

[7] What is J-PARC, https://j-parc.jp/en/jparc.html.

[8] J. K. Ahn *et al.* (KOTO collaboration), Study of the $K_L \to \pi^0\nu\bar{\nu}$ Decay at the J-PARC KOTO Experiment, Phys. Rev. Lett. **126**, 121801 (2021).

[9] K. Agari *et al.*, Secondary Charged Beam Lines at the J-PARC Hadron Experimental Hall, Prog. Theor. Exp. Phys. **2012**, 02B009 (2012).

[10] S. Yokkaichi *et al.*, Proposal to J-PARC, Electron Pair Spectrometer at the J-PARC 50-GeV PS to Explore the Chiral Symmetry in QCD, https://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p16-Yokkaichi_2.pdf.

[11] H. Sako *et al.*, Proposal to J-PARC, Study of In-medium Modification of ϕ Mesons Inside the Nucleus with $\phi \to K^+K^0$ Measurement with the E16 Spectrometer, https://j-parc.jp/researcher/Hadron/en/pac_2107/pdf/P88_2021-12.pdf.

[12] Y. Kuno *et al.*, Proposal to J-PARC, An Experimental Search for Lepton Flavor Violating μ^-–e^- Conversion at Sensitivity of 10^{-16} with a Slow-Extracted Bunched Proton Beam, https://j-parc.jp/researcher/Hadron/en/pac_0801/pdf/Kuno.pdf.

[13] The J-PARC Proposal Webpage, https://j-parc.jp/researcher/Hadron/en/Proposal_e.html.

[14] S. H. Kim *et al.*, Development of a time projection chamber for JPARC hadron physics program, J. Phys.: Conf. Ser. **1498**, 012023 (2020).

[15] F. Sauli, The gas electron multiplier (GEM): Operating principles and applications, Nucl. Instrum. Methods Phys. Res. A **805**, 2 (2016).

[16] E. C. Pollacco *et al.*, GET: A generic electronics system for TPCs and nuclear physics instrumentation, Nucl. Instrum. Methods Phys. Res. A **887**, 81 (2018).

[17] J. K. Ahn *et al.*, Proposal to J-PARC, Search for H-dibaryon with a large acceptance hyperon spectrometer, https://j-parc.jp/researcher/Hadron/en/pac_1201/pdf/KEK_J-PARC-PAC2011-06.pdf.

[18] K. Tanida *et al.*, Proposal to J-PARC, Search for a narrow Λ^* resonance using the $p(K^-,\Lambda)\eta$ reaction with the hypTPC detector, https://j-parc.jp/researcher/Hadron/en/pac_1801/pdf/P72_2018-9.pdf.

[19] A. Starostin *et al.* (Crystal Ball collaboration), Measurement of $K^-p \to \eta\Lambda$ near threshold, Phys. Rev. C **64**, 055205 (2001).

[20] H. Sako *et al.*, Proposal to J-PARC, 3-body hadronic reactions for new aspects of baryon spectroscopy, https://j-parc.jp/ researcher/Hadron/en/pac_1207/pdf/P45_2012-3.pdf.

[21] Y. Ichikawa *et al.*, Proposal to J-PARC, High resolution spectroscopy of the "ΣN cusp" by using the $d(K^-, \pi^-)$ reaction, https://j-parc.jp/researcher/Hadron/en/pac_2201/pdf/P90_2022-03.pdf.

[22] J. J. Dudek and R. G. Edwards, Hybrid baryons in QCD, Phys. Rev. D **85**, 054016 (2012).

[23] J. K. Ahn *et al.*, Proposal to J-PARC, Double ϕ production in $\bar{p}p$ reactions near threshold, https://j-parc.jp/researcher/Hadron/en/pac_2407/pdf/P104_2024-11.pdf.

[24] S. H. Kim *et al.*, Letter of intent to J-PARC, Search for the Θ^+ in $K^+d \to K^0pp$ reaction with hyperon spectrometer, https://j-parc.jp/researcher/Hadron/en/pac_2407/pdf/LOI_2024-10.pdf.

[25] J. K. Ahn and S. H. Kim, Search for Θ^+ in $K^+d \to K^0pp$ reaction at J-PARC, J. Korean Phys. Soc. **82**, 579 (2023).

[26] C. Evangelista *et al.* (JETSET collaboration), Study of the reaction $\bar{p}\vec{p}\varphi\varphi$ from 1.1 to 2.0 GeV/c, Phys. Rev. D **57**, 5370 (1998).

[27] K. Aoki *et al.*, Extension of the J-PARC hadron experimental facility: Third white paper, arXiv:2110.04462v1 [nucl-ex].