

Hypernuclear and strangeness physics program at J-PARC

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Abstract. The inauguration ceremony of the Japan Proton Accelerator Research Complex (J-PARC) was held on 6 July 2009, celebrating the completion of its construction. Now, the beam commissioning of the 50-GeV main proton synchrotron is in progress to improve the beam intensity and quality. Many important experimental programs are planned with the improved beams. In this report, some of them are introduced.

Keywords. Hypernuclei; kaon; Japan Proton Accelerator Research Complex.

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1. Introduction

The construction of the J-PARC [1] started in 2001 jointly by two institutes, KEK and Japan Atomic Energy Agency (JAEA). There are three accelerators with MW-class proton beams in J-PARC; a proton linac for injecting the beam to a 3-GeV proton synchrotron (PS), the 3-GeV PS operated at 25 Hz with 1 MW beam power to be used primarily for materials and life sciences with neutron and muon beams, and a 50-GeV PS with slow extraction for secondary meson beams and fast extraction for neutrino beams.

The construction was split in two phases (figure 1). The construction of Phase 1 is over now. It covers most of the accelerator components and part of the experimental facilities. The proton linac energy is limited at 181 MeV. However, the energy recovery to 400 MeV is already in preparation. Because of the limited linac energy, the beam power of the 3-GeV PS will be reduced to ~ 0.3 MW. The 50-GeV PS will be operated at 30 GeV for the moment. A superconducting proton linac from 400 to 600 MeV is in Phase 2 together with basic R&D facilities for nuclear transmutation.

In the fall of 2006, we have started the beam commissioning of the proton linac and accelerated the beam up to the design energy of 181 MeV in January 2007. The beam was transferred to the 3-GeV PS and successfully accelerated to 3 GeV in October 2008. This beam was further transported to the Materials and Life Sciences Facility (MLF) to produce slow neutron and muon beams in May 2009. Also, a small fraction of the beam was injected in the 50-GeV PS in May 2009.

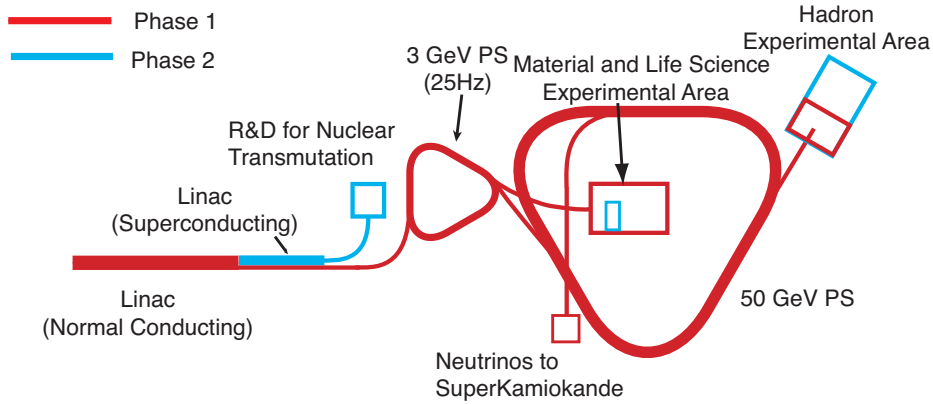


Figure 1. Schematic lay-out of the J-PARC Facility, which also shows the two parts of the project in Phase 1 and Phase 2.

The beam from the 50-GeV main proton synchrotron was accelerated up to 30 GeV in December 2008, and extracted to the hadron experimental hall in January 2009 for the first time. The first secondary-beam production was confirmed in February 2009 at one of the secondary beam lines in the hadron experimental hall, called K1.8BR. In April 2009, the beam commissioning for the neutrino beam was carried out, and the neutrino production was confirmed at J-PARC.

2. Experimental program at J-PARC

Various experiments have been proposed for the hadron experimental hall. Among them, the following five experiments were categorized as ‘Day 1’ experiments in the hadron experimental hall (figure 2).

- E05:** Spectroscopic study of Ξ -hypernucleus, $^{12}_{\Xi}\text{Be}$, via the $^{12}\text{C}(K^-, K^+)$ reaction (T Nagae (Kyoto)).
- E13:** Gamma-ray spectroscopy of light hypernuclei (H Tamura (Tohoku)).
- E15:** A search for deeply-bound kaonic nuclear states by in-flight $^3\text{He}(K^-, n)$ reaction (M Iwasaki (RIKEN), T Nagae (Kyoto)).
- E17:** Precision spectroscopy of kaonic ^3He $3d \rightarrow 2p$ X-rays (R S Hayano (Tokyo), H Outa (RIKEN)).
- E19:** High-resolution search for Θ^+ pentaquark in $\pi^- p \rightarrow K^- X$ reaction (M Naruki (KEK)).

The first two experiments have higher priorities than the others. The other approved experiments include:

- E03:** Measurement of X-rays from Ξ^- atom (K Tanida (Seoul)).
- E07:** Systematic study of double strangeness system with an emulsion-counter hybrid method (K Imai (JAEA), K Nakazawa (Gifu), H Tamura (Tohoku)).

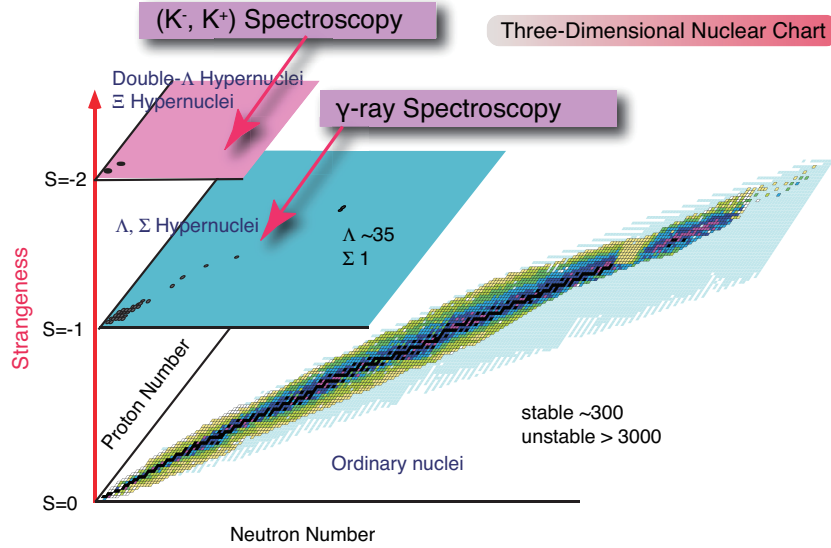


Figure 2. Three-dimensional nuclear chart with a new axis of strangeness.

E10: Production of neutron-rich Λ -hypernuclei with the double-charge-exchange reaction (A Sakaguchi (Osaka) and T Fukuda (Osaka E&C)).

Here, I would like to briefly introduce four experiments, E05, E19, E15 and E10.

2.1 E05: Spectroscopic study of Ξ -hypernuclei

The (K^-, K^+) reaction is one of the best tools to create the strangeness (S) $S = -2$ through the elementary process, $K^-p \rightarrow K^+\Xi^-$, the cross-section of which in the forward angle has a broad maximum around the K^- momentum of 1.8 GeV/c [2].

As for the Ξ -hypernuclei, there exist some hints for the existence of emulsion events. However, it is still not conclusive. Some information on the Ξ -nucleus potential has been obtained from the production rate and spectrum shape in the bound region of Ξ -hypernucleus via $^{12}\text{C}(K^-, K^+)$ reaction [3,4]. In these experiments, Ξ hypernuclear states were not clearly observed because of the limited statistics and detector resolution. From the data analysis, however, the potential depth, V_Ξ , is favoured to be ≈ 14 MeV for $A = 12$ when a Woods-Saxon-type potential shape is assumed.

In J-PARC E05, we are going to observe the bound states of Ξ -hypernuclei as clear peaks with good energy resolution. The peak position will give us direct information on the depth of Ξ -nucleus potential. The width of the bound state peak also provides the information on the imaginary part of the Ξ -nucleus potential.

A new kaon beam line K1.8 with the maximum beam momentum of 1.8 GeV/c has been constructed for the experiment. The beam line provides high-intensity ($1.4 \times 10^6 K^-/\text{spill}$) and high-purity K^- beam. The beam line has two stages of electrostatic mass separators with two mass slits in order to separate kaons from

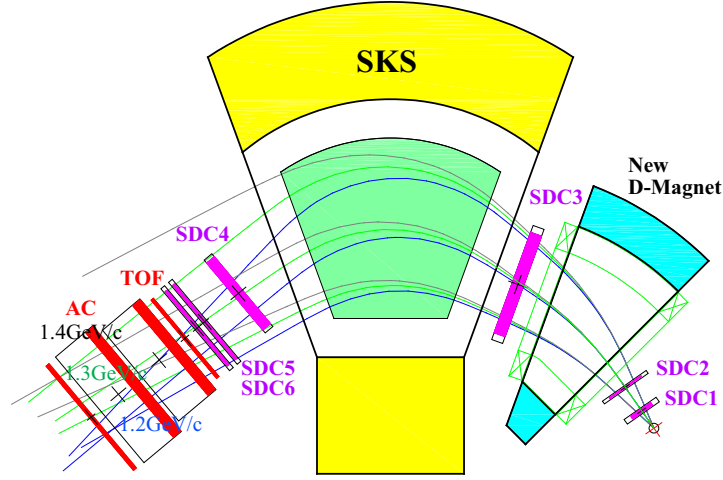


Figure 3. SKS+ spectrometer in construction. SDC1–6 are tracking drift chambers. TOF is a time-of-flight counter wall and AC is an aerogel Čerenkov detector system.

pions and other particles at the level of K^-/π^- ratio greater than 5. The beam analyser located after the last mass slit comprises $QQDQQ$ magnets and four sets of tracking detectors. The expected momentum resolution $\Delta p/p = 1.4 \times 10^{-4}$ in root-mean-square when a position resolution of $200 \mu\text{m}$ is realized in the tracking detectors placed before and after the $QQDQQ$ system.

For the K^+ spectrometer, the existing SKS spectrometer will be used with some modifications. A dipole magnet with ≈ 1.5 T is added at the entrance of the SKS magnet as shown in figure 3. A simulation shows that the spectrometer, called SKS+, has a solid angle of ≈ 30 msr with the angular coverage from 0° to 10° , and momentum resolution $\Delta p/p = 0.17\%$ FWHM.

The overall energy resolution is expected to be better than 3 MeV FWHM including the energy-loss straggling in the target.

The production cross-sections of the Ξ -hypernuclei in the (K^-, K^+) reaction have been calculated by several theorists within the framework of distorted-wave impulse approximation (DWIA) [5–7]. The previous experimental studies also reported the cross-sections [3,4]. Based on these, the yield of $^{12}_{\Xi}\text{Be}$ with a ^{12}C target is estimated to be ~ 190 events/month.

2.2 E19: High-resolution search for Θ^+ pentaquark in $\pi^- p \rightarrow K^- X$ reaction

The first evidence of Θ^+ baryon with positive strangeness $S = +1$ was reported by LEPS Collaboration at SPring-8, Japan [8]. The LEPS Collaboration has recently reported the evidence with improved statistics [9]. However, there exist a lot of negative results on the existence of Θ^+ . Therefore, the confirmation of the existence (or non-existence) of Θ^+ is urgent and important.



Figure 4. A picture of K1.8 area in the hadron experimental hall of J-PARC, in which the beam line spectrometer and the SKS spectrometer are being installed.

It should be noted that there are only few experiments to search for Θ^+ pentaquark via hadronic reactions. In particular, meson-induced reactions using a proton target are unique to J-PARC. In this experiment, we will use $p(\pi^-, K^-)X$ reaction to produce Θ^+ . In fact, before the shutdown of the 12-GeV KEK PS, such a measurement using a polyethylene (CH_2) target was carried out in KEK-PS E522 with an experimental resolution of 13.4 MeV FWHM [10]. At the highest incident momentum, a hint of a peak structure was observed at the right mass for Θ^+ . However, the statistical significance was only $2.5\text{--}2.7\sigma$, which is not sufficient to prove the existence of Θ^+ . The background contribution from the carbon target was also huge under the bump structure.

In the J-PARC E19, we are going to use the SKS spectrometer system (figure 4) which has five times better missing-mass resolution (~ 2.5 MeV FWHM), and aim to accumulate 100 times more statistics. All in all, we expect to have 2–10 times better S/N ratio compared to E522.

As for the width (Γ) of Θ^+ , we are sensitive down to 2 MeV thanks to the excellent resolution of the SKS. In about a week of data taking, we expect sensitivity of the measurement in the production cross-section to be 75 nb/sr and 150 nb/sr for $\Gamma < 2$ MeV and $\Gamma = 10$ MeV, respectively.

2.3 E15: Search for deeply-bound kaonic nuclear states by in-flight ${}^3\text{He}(K^-, n)$ reaction

The first experimental evidence for a K^-pp bound state was reported by the FIN-UDA group at DAΦNE in 2005 [11]. The $\Lambda-p$ pairs emitted back-to-back from the

stopped K^- absorption on ${}^6\text{Li}$, ${}^7\text{Li}$ and ${}^{12}\text{C}$ targets were observed. The invariant mass of the Λ - p system was much smaller than the mass of the $K^- + p + p$ system. Thus, it could be treated as a proof that the K^-pp bound system is formed in the stopped K^- absorption in the surface region of nuclei and decays into the Λ - p pair. Later, the mass shift of the Λ - p pairs has been confirmed in a new data set of the much improved statistics by the FINUDA group [12]. Further, it is found that there is no such large mass shift in the $K^- + p + n$ system decaying into $\Lambda + n$ and $\Sigma^- + p$.

However, the reaction mechanism to produce such a deeply-bound K^-pp system in the stopped K^- absorption is not known well. Therefore, for the interpretation of this mass shift, other interpretations [13] could not be excluded.

After the FINUDA observation, a lot of work to theoretically examine the existence of the K^-pp system has been intensively carried out by using reliable few-body techniques [14]. All these calculations have confirmed that the K^-pp bound state must exist with 20–70 MeV binding energy depending on the $\bar{K}N$ interaction models used in the calculations. The calculated widths are as large as 50–120 MeV.

Therefore, it is of vital importance to experimentally confirm the existence of the K^-pp bound state. In the J-PARC E15, the in-flight (K^-, n) reaction on ${}^3\text{He}$ at 1 GeV/c will be used to directly produce the K^-pp system. At this incident momentum, the elementary cross-section of $K^-n \rightarrow nK^-$ has a broad maximum of 5 mb/sr. The neutron momentum emitted in the forward direction is measured with a time-of-flight counter wall. The K^-pp mass is measured as a missing mass. At the same time, the target region is covered by a cylindrical detector system with a large acceptance, which is installed in a solenoidal magnetic field (figure 5). Thus, most of the charged particles produced in the decay of the K^-pp system are detected. Here, the mass of the K^-pp system is measured as an invariant mass of the $\Lambda + p$ pair. The designed missing-mass resolution is about 28 MeV FWHM with a flight path of 12 m, and the invariant-mass resolution is about 40 MeV FWHM.

2.4 E10: Production of neutron-rich Λ -hypernuclei with the double-charge-exchange reaction

While about 40 Λ -hypernuclei are experimentally observed in a wide mass-number range, they are still limited. One reason is that the reactions which have been used for producing the Λ -hypernuclei are non-charge-exchange reactions such as (K^-, π^-) and (π^+, K^+) . They convert a neutron inside a nucleus into a Λ -hyperon, so that there is no change of atomic number. There are a few attempts to use the $(K^-_{\text{stopped}}, \pi^+)$ reaction for producing neutron-rich Λ -hypernuclei. However, it was found that large decay backgrounds, mainly coming from the $\Sigma^+ \rightarrow n\pi^+$ decay, must be removed to observe possibly small signals. In contrast, decay backgrounds are negligible in the (π^-, K^+) reaction. Such a measurement using the (π^-, K^+) reaction at 1.0–1.2 GeV/c was carried out at KEK PS by using the SKS spectrometer [15]. Although peak structures were not clearly resolved due to the limited statistics, the events corresponding to the neutron-rich ${}^{10}_{\Lambda}\text{Li}$ production were observed with the production cross-section of ~ 10 nb/sr at 1.2 GeV/c.

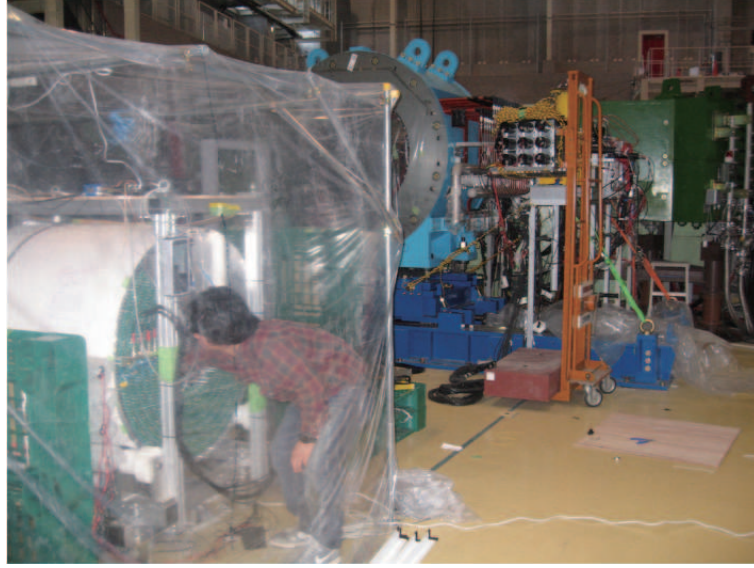


Figure 5. A picture of K1.8BR area in the hadron experimental hall of J-PARC taken in February 2009. The cylindrical drift chamber (white) and the solenoid magnet (blue) are under preparation.

In neutron-rich Λ -hypernuclei, a Λ -hyperon plays a glue-like role; unbound neutron-rich nuclear states could be stabilized to form bound states due to the existence of the Λ -hyperon at the centre of the neutron-rich Λ -hypernucleus. Also, it is discussed that the $\Lambda N - \Sigma N$ coupling should be largely effective in such neutron-rich systems.

By using the high-intensity ($\sim 10^7$ /pulse) π^- beam at 1.2 GeV/c, it is proposed to produce ${}^9_{\Lambda}\text{He}$ and ${}^6_{\Lambda}\text{H}$ with ${}^9\text{Be}$ and ${}^6\text{Li}$ targets, respectively.

3. Summary

After the successful secondary beam production at the new K^- beam line at J-PARC, we have been working on detector conditioning and beam tuning. Although there is a need to improve the beam intensity and its time structure of the primary proton beam, we expect to start taking data by using pion beams in 2010.

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