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Physics prospects at J-PARC*

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Abstract We have held an inauguration ceremony of the Japan Proton Accelerator Research Complex (J-PARC) on July 6, 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. A lot of important experimental programs in Nuclear Physics are waiting for the beam. In this report, I introduce some examples.

Key words hypernuclei, J-PARC, hadron, kaon

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1 Introduction

The construction of the J-PARC [1] started in 2001 under a cooperation between 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 beam injection 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 budget was split in two phases (Fig. 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 be ~0.3 MW. The 50 GeV PS will be operated at 30 GeV for the moment. A superconducting proton linac from 400 MeV 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.

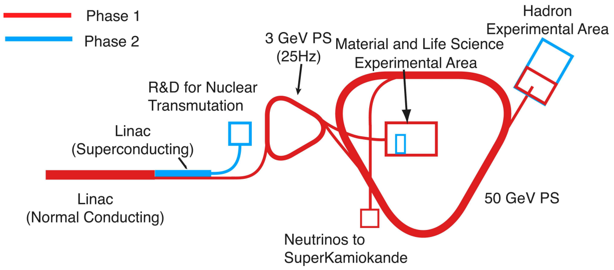

Fig. 1. (color online). Schematic layout of the J-PARC facility, which also shows the two parts of the project in Phase 1 and Phase 2.

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 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.

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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 (Fig. 2).

E05: Spectroscopic Study of Ξ-Hypernucleus, ${}^{12}_{\Xi}$Be, via the ^{12}C(K$^-$,K$^+$) Reaction (T. Nagae),

E13: Gamma-ray spectroscopy of light hypernuclei (H. Tamura).

E15: A Search for deeply-bound kaonic nuclear states by in-flight ^{3}He (K$^-$,n) reaction (M. Iwasaki, T. Nagae),

E17: Precision spectroscopy of Kaonic ^{3}He 3d→2p X-rays (R.S. Hayano, H. Outa),

E19: High-resolution Search for Θ^+ Pentaquark in π^-p$\rightarrow$K$^-$X Reaction (M. Naruki).

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),

E07: Systematic Study of Double Strangeness System with an Emulsion-counter Hybrid Method (K. Imai, K. Nakazawa, H. Tamura), and

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

First, I would like to briefly introduce three experiments, E05, E19, and E15.

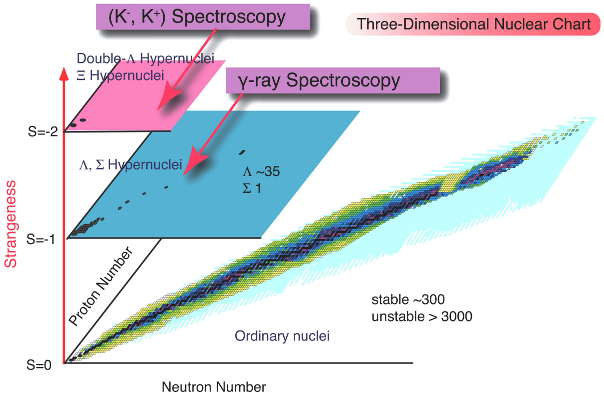

Fig. 2. (color online). Three-dimensional nuclear chart with a new axis of Strangeness.

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 → 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 of emulsion events for the existence. 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}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 favored 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. A peak position will give us direct information on the depth of Ξ-nucleus potential. The width of the bound state peak also provides us with information on the imaginary part of the Ξ-nucleus potential, or the ΞN inelastic channel, Ξ^-p$\rightarrow\Lambda\Lambda$ conversion.

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 (1.4×10^{6}K$^-$/spill) and high-purity K$^-$ beam. The beam line has two stages of electro-static mass separators with two mass slits in order to separate kaons from pions and other particles at the level of K$^-/\pi^-$ ratio greater than 5. The beam analyzer located after the last mass slit comprises QQDQQ magnets and four sets of tracking detectors. The expected momentum resolution $\Delta p/p$ is 1.4×10^{-4} in root-mean-square when a position resolution of 200 μm 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 Fig. 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.

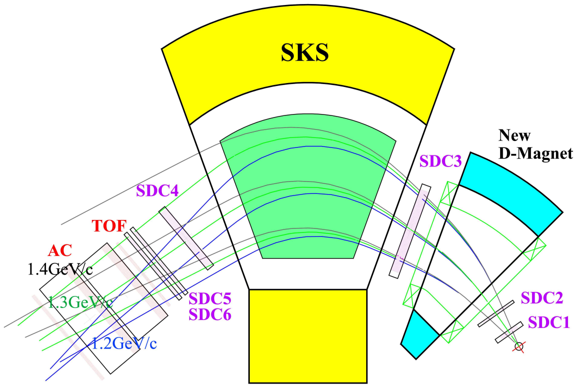

Fig. 3. (color online). SKS+ Spectrometer in construction. SDC1-6 are tracking drift chambers. TOF is a time-of-filght counter wall, and AC is an aerogel Čerenkov detector system.

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]. Also, the previous experimental studies reported the cross sections [3, 4]. Based on these, the yield of ${}^{12}_{\Xi}$Be with a ^{12}C target is estimated to be ~190 events/month.

2.2 E19: High-resolution Search for Θ^+ Pentaquark in $\pi^- p \to K^- X$ 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 the Θ^+. Therefore, the confirmation of the existence (or non-existence) of the Θ^+ is urgent and important.

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(π^-,K^-)X reaction to produce the 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 the Θ^+. However, the statistical significance was only 2.5~2.7 σ, which is not sufficient to claim the existence of the Θ^+. The background contribution from the carbon target was also huge under the bump structure.

In the J-PARC E19, we will use the SKS spectrometer system (Fig. 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 with E522.

Fig. 4. (color online). 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 in installation.

As for the width (Γ) of the 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 to have 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}He(K^-,n) reaction

The first experimental evidence for a K^-pp bound state was reported by the FINUDA group at DAΦNE in 2005 [11]. The Λ-p pairs emitted in back-to-back from the stopped K^- absorption on ^{6}Li, ^{7}Li, and ^{12}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 evidence 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 much improved statistics by the FINUDA group [12]. Further it is found that there is not such a large mass shift in the K^-+p+n system decaying into Λ+n and Σ^-+p.

However, the reaction mechanism to produce such a deeply-bound K^-pp system in the stopped K^- absorption is not known well. Therefore, as 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 of these calculations have confirmed that the K$^-$pp bound state must exist with the binding energy of 20 to 70 MeV depending on the $\overline{\mathrm{K}}$N interaction models used in the calculations. While the width is as large as 50–100 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}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 → 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 (Fig. 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 Λ+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.

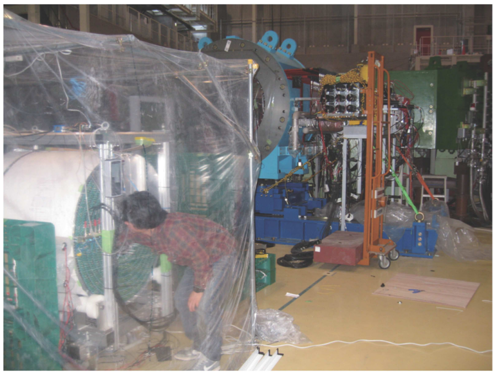

Fig. 5. (color online). A picture of K1.8BR area in the Hadron experimental hall of J-PARC taken in February, 2009. A cylindrical drift chamber (white) and a solenoid magnet (blue) are in preparation.

2.4 Other hadron physics experiments

There are several proposals on Hadron Physics which require a new high-momentum beam line to be constructed in the Hadron experimental hall in near future.

One example is E16 of “Electron pair spectrometer at the J-PARC 50 GeV PS to explore the chiral symmetry in QCD” proposed by S. Yokkaichi et al.. It is an extension of the KEK-PS E325 experiment [15] with about 100 times better statistics. A systematic study on mass modifications of vector mesons, such as ρ, ω, and ϕ, in nuclear medium will be carried out by using the primary proton beam with a large-acceptance electron-pair spectrometer.

Another example is E04 of “Measurement of High-Mass Dimuon Production at the 50 GeV Proton Synchrotron” proposed by J. C. Peng and S. Sawada et al.. One of their physics goal is to study the $\bar{\mathrm{d}}/\bar{\mathrm{u}}$ asymmetry of proton to be probed in the Drell-Yan process with the primary proton beam. Such an asymmetry was observed in NA51 experiment at CERN and measured in the low-x region in FNAL E866 [16]. The proposed experiment has a merit to extend the measurement at high-x region to test several theoretical models.

3 Summary

After the successful secondary beam prodcuction at the new K$^-$ beam line at J-PARC, we have been working on detector conditioning and beam tuning. Although the beam intensity and its time structure of the primary proton beam are needed to be much improved, we expect to start some data taking by using pion beams in 2010.

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