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Strangeness Nuclear Physics at J-PARC

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Abstract After the big earthquake in the east part of Japan on March 11, 2011, the beams in the hadron experimental hall at J-PARC have been successfully recovered in February, 2012. The experimental program using pion beams is now on-going with the primary proton beam power of ∼5 kW. Before a long summer shutdown scheduled in 2013, several experiments in strangeness nuclear physics are going to take data. In this period, we anticipate the beam power would exceed 10 kW and the experiments to use K^- beams will start. The experimental program is explained briefly.

Keywords Strangeness · Hadron · Hypernuclei

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1 Introduction

In January, 2009, the first proton beam from the main ring at 30 GeV was successfully delivered to the hadron experimental hall (Fig. 1) in Japan Proton Accelerator Research Complex (J-PARC). At that time, we had only one secondary beam line, K1.8BR, which is a branch of the K1.8 beam line after the first electro-static separator. Production of secondary beams of pions and kaons was observed in February, 2009, at this beam line [1].

After that, the beam commissioning of a neutrino beam line was carried out during the spring and summer of 2009. In this period, the remaining part of the K1.8 beam line was constructed; such as the second electro-static separator and a beam line spectrometer system. The superconducting kaon spectrometer (SKS) was also installed [2] in the K1.8 beam line for various experiments in strangeness nuclear physics. A neutral kaon beam line, K_L, was also constructed in the same period.

From October 2009 to February 2010, the beam commissioning of the K1.8 beam line was performed together with the performance check of the beam-line and SKS spectrometers. A good energy resolution of the spectrometers was confirmed.

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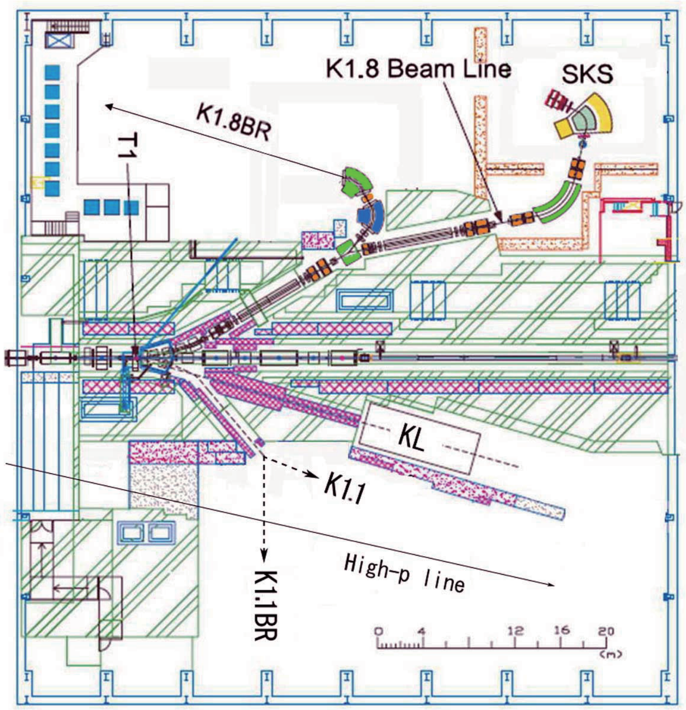

Fig. 1 A schematic layout of the hadron experimental hall [1]. The primary proton beam at 30 GeV from the main ring comes from the left to hit a production target, T1.

The proton beam intensity extracted from the main ring was a few kW on a production target, which is about 1% of the design intensity of 270 kW. Even with this limited proton intensity, a successful physics data taking of the J-PARC E19 experiment was carried out in October and November of 2010, by using the pion beam at 1.92 GeV/c. It is a penta-quark search experiment in the $\pi^- + p \rightarrow K^- + \Theta^+$ reaction.

We planned to continue the data taking of E19 in April, 2011. However, it was cancelled because of the big earthquake on March 11, 2011. In J-PARC, a lot of utility facilities, roads, etc. were damaged. Fortunately, there were no serious damages on the accelerator equipment, accelerator tunnels, and in the experimental areas.

The beams of the J-PARC were recovered in December, 2011, as scheduled. It is a remarkable success of the J-PARC staff. In February, 2012, the beams at the hadron experimental hall have been recovered, too. We have carried out the second data taking of E19 in February and a pilot run for E27 in June, 2012. The primary proton beam power in June, 2012, was 6 kW. In the next beam time, we expect to have a 10 kW power. Then, we hope to start the experiments using K^- beams.

2 Strangeness Nuclear Physics Program at J-PARC

A lot of experiments for the hadron experimental hall have been proposed, and many of them are already approved [3]. Here, I would like to briefly explain the experiments which have already taken data and are going to take some data in a year or so.

2.1 E19

As I mentioned, the J-PARC E19 (spokesperson: M. Naruki (KEK)) took the physics data on the $\pi^- + p \rightarrow K^- + \Theta^+$ reaction at 1.92 GeV/c in October and November of 2010. No significant peak structure is observed [6] with the estimated energy resolution of 1.4±0.1 MeV (FWHM). The measurement was motivated with a suggestive data in the same reaction on a $(CH_2)_n$ target [4] obtained at the old KEK proton synchrotron. The experimental group did not claim the peak existence, because the statistical significance of the possible peak was only 2.5σ mainly due to their poor energy resolution of 13.4 MeV(FWHM). It should be also noted that a negative result was observed in the reverse reaction of $K^+ + p \rightarrow \pi^+ + X$ at 1.2 GeV/c [5].

The second data taking at the incident momentum of 2 GeV/c, which is the maximum beam momentum at K1.8, has been carried out in February, 2012. It is anticipated that the production cross section could be enhanced at the higher incident momenta. An up-to-date analysis result will be presented in this conference [7].

2.2 E27

The first experimental evidence of a kaonic bound state, K^-pp, was reported from the FINUDA collaboration [8]. While many pairs of Λ-p emitted in the back-to-back from the stopped K^- absorption on ^{6}Li, ^{7}Li, and ^{12}C targets were observed, the mass of the Λ-p pairs was largely shifted suggesting a binding of the K^-pp system as much as 115 MeV. A similar binding of about 105 MeV was also reported in an exclusive measurement in the $p + p \rightarrow K^+ + \Lambda + p$ reaction at 2.85 GeV by the DISTO group [9].

Stimulated with these experimental results, several theory groups [10] carried out the calculations of the K^-pp system based on few-body techniques. They confirmed the system has a bound state with the binding energy of 40 – 90 MeV and the broad width of 60 – 100 MeV depending on their interaction models. There are also discussions that the experimental signatures of the FINUDA experiment can be interpreted as quasifree processes with final state interactions [11].

In this respect, it is important to experimentally confirm the existence of the bound state in much more complete ways with different reactions.

The E27 experiment (spokesperson: T. N) is an experiment to produce the K^-pp bound state in the $\pi^+ d \rightarrow K^+(K^-pp)$ reaction at 1.7 GeV/c. This is the (π^+, K^+) reaction usually used for the Λ hypernuclear spectroscopy. However, we can produce $\Lambda(1405)$ in addition to Λ at this incident momentum through the reaction π^+"n" $\rightarrow K^+\Lambda(1405)$ on a neutron in a deuteron. A fraction of the produced Λ(1405)'s would interact with another proton in the deuteron to form the bound state, $\Lambda^* p \rightarrow K^-pp$.

There exist large backgrounds of quasifree processes such as $K^+\Lambda$, $K^+\Sigma$, $K^+\Lambda\pi$, $K^+\Sigma\pi$, $K^+\Sigma(1385)$, and $K^+\Lambda(1405)$ in the final states. Therefore, a signal from the K^-pp should be hardly observed in an inclusive (π^+, K^+) spectrum. In order to suppress the quasifree

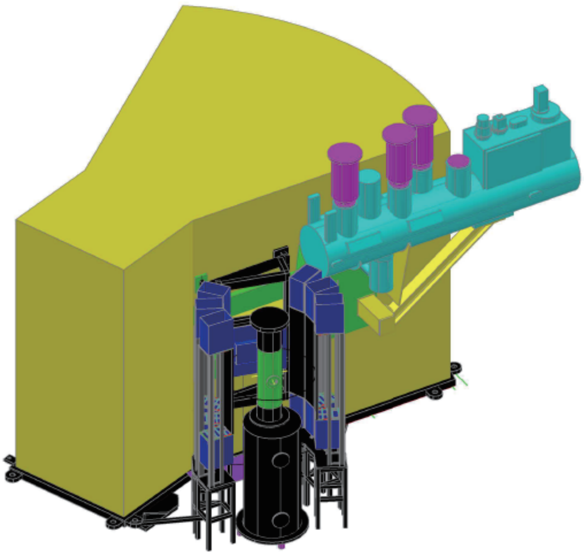

Fig. 2 A schematic layout of the E27 experimental setup. A range counter system has been installed surrounding a liquid deuterium target at the entrance of the SKS spectrometer magnet.

backgrounds, a range counter system (Fig. 2) has been constructed for tagging two high momentum protons of $\geq$250 MeV/c. In the case of quasifree processes, one proton from a hyperon decay could have high momentum. However, the momentum of a spectator proton in a deuteron cannot be so high. On the other hand, we can expect two high-momentum protons to be emitted from a non-mesonic decay of the K^-pp; $K^-pp \rightarrow \Lambda p$, $\Lambda \rightarrow p\pi^-$. The range counter system covers 39 degrees to 122 degrees in the left and right emission angles in the laboratory system with a time-of-flight distance of about 50 cm.

Pilot data have been obtained in June, 2012, for both $d(\pi^+,K^+)$ and $p(\pi^+,K^+)$ reactions at 1.7 GeV/c, and they are in analysis [12].

2.3 E15

E15 (spokespersons: M. Iwasaki (RIKEN) and T.N) is another experiment to search for the K^-pp bound state in the ^{3}He(K^-,n) at 1 GeV/c. In this experiment, the K^-pp signals will be obtained not only in the missing mass of the (K^-,n) spectrum but also in the invariant mass of the Λ-p pairs from the non-mesonic decay of the K^-pp. Therefore, it would kinematically over-constrain the production of the K^-pp.

A large neutron counter system composed of 16$\times$7 arrays of plastic scintillators (total volume: 320 cm[W]$\times$150 cm[H]$\times$35 cm[T]) has been constructed in the K1.8BR experimental area, which has a long time-of-flight distance of about 12 m in the forward direction. The expected missing-mass resolution is about 28 MeV(FWHM).

A cylindrical detector system for the invariant mass spectroscopy has been also constructed surrounding a liquid ^{3}He target covering a solid angle of 65% of 4π. It is composed of a solenoid magnet with 0.7 T, a cylindrical drift chamber, and a cylindrical hodoscope. The invariant mass resolution for the Λ-p pair is estimated to be about 40 MeV (FWHM).

The beam commissioning of all the detector system for the E15 experiment has been successfully performed in June, 2012. The performance of the detector system is reported in this conference [13]. The experiment is ready for data taking; just waiting for the K^- beam with a reasonable intensity.

2.4 E10

By using a double charge-exchange reaction (π^-, K^+), we can have access to neutron-rich Λ hypernuclei; ${}^{6}_{\Lambda}$H, ${}^{9}_{\Lambda}$He, etc. The first demonstration of the (π^-, K^+) reaction was carried out on a ^{10}B target to produce ${}^{10}_{\Lambda}$Li [14]. While the background level in the bound region was negligible, the production cross section was also very small, 11.3$\pm$1.9 nb/sr, at 1.2 GeV/c. Therefore, the high intensity pion beam is needed.

As the first target, the ^{6}Li(π^-, K^+) reaction at 1.2 GeV/c will be used to produce the ${}^{6}_{\Lambda}$H [16]. Recently, the FINUDA experiment reported three candidate events of the ${}^{6}_{\Lambda}$H production in the ^{6}Li(K^-_{stop}, π^+) reaction [15]. The binding energy was 4.0$\pm$1.1 MeV. In order to reduce the backgrounds, they required the coincidence of a π^+ in the production process and a π^- in the decay process. In the E10 experiment (spokesperson: A. Sakaguchi (Osaka)), the statistics would be greatly improved with the high-intensity pion beam available at the K1.8 beam line.

2.5 E13

The Hyperball-J detector, which is composed of 32 clover-type Ge crystals(60% relative efficiency), has been constructed in Tohoku university. It is an upgraded version of the Hyperball detector first used for hypernuclear gamma-ray spectroscopy. Each Ge crystal is surrounded by PWO Compton suppressors to reduce the backgrounds. The full peak efficiency of about 6% is expected for 1-MeV gamma rays. Owing to the high efficiency, γ-γ coincidence can be easily carried out.

So far, the hypernuclear gamma-ray spectroscopy has been successful in p-shell region. Various small splittings due to the Λ-N spin-dependent interactions have been resolved in high precision. Now, in the J-PARC, E13 (spokesperson: H. Tamura (Tohoku)) is going to challenge the hypernuclear gamma-ray spectroscopy in sd-shell region, for the first time. A measurement on the ^{19}F(K^-, π^-) reaction at 1.8 GeV/c is planned. It is also planned to measure the gamma-ray energy of ${}^{4}_{\Lambda}$He$(1^+ \rightarrow 0^+)$ in high precision in the ^{4}He(K^-, π^-) reaction at 1.5 GeV/c [17].

In the second step, the experiment aims for measuring the magnetic moment of a Λ in hypernuclei, ${}^{7}_{\Lambda}$Li and/or ${}^{19}_{\Lambda}$F. The gamma-ray transition probability of $B(M1)$ will be measured with the Hyperball-J.

2.6 E05

While we have accumulated a lot of experimental information on hypernuclei with strangeness (S) -1, still the experimental information of S=-2 hypernuclei is very much limited. There exist several emulsion events showing a sequential weak decay pattern which is typical for

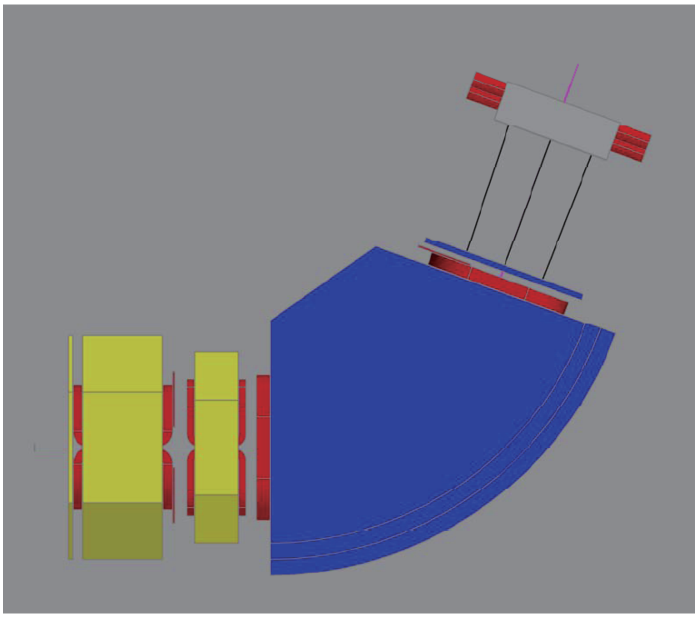

Fig. 3 A schematic drawing of the S-2S spectrometer. It is composed of two quadrupole magnets at the entrance and one dipole magnet.

double-Λ hypernuclei. One of the events called "Nagara Event" gives us unambiguous identification of ${}^{6}_{\Lambda\Lambda}$He and its binding energy [18]. In addition to the double-Λ hypernuclei, Ξ hypernuclei could exist as the bound states of S=-2. There is experimental evidence suggesting such a bound state production with the Ξ-nucleus potential depth of $\sim$14 MeV [19]. However, the bound state peak was not observed because of the poor energy resolution of $>$10 MeV.

In the J-PARC E05 (spokesperson: T. N), we will use the same reaction of ^{12}C(K^-,K^+) to produce ${}^{12}_{\Xi}$Be with a much better energy resolution of 1.5 – 3 MeV. The high-intensity K^- beam at the K1.8 beam line will be used for the experiment at around 1.8 GeV/c. The first data taking would be possible by using the existing SKS magnet with a 3-4 MeV energy resolution expecting the primary proton beam power of about 30 kW in near future.

Recently, we have started to construct a new spectrometer, *S*-2*S* (Fig. 3), with a good momentum resolution of Δp/p$\approx 5\times10^{-4}$ and a large solid angle of 60 msr, to be completed in the next three years. It will be installed in the K1.8 experimental area.

3 Summary

At the hadron experimental hall of J-PARC, a penta-quark search experiment, E19, in the $p(\pi^-,K^-)$ reaction, has completed the two data taking periods in 2010 and 2012. The first physics result will be published, soon [6]. A pilot run to search for the K^-pp bound state in the d(π^+,K^+) reaction at 1.7 GeV/c has been successful in June, 2012.

In the coming data taking period, the E10 experiment to produce a neutrion-rich hypernucleus, ${}^{6}_{\Lambda}$H, is going to take data in December, 2012 and January, 2013. In March, 2013, the E15 will take the first data on the ^{3}He(K^-,n) reaction at 1 GeV/c. The data taking of the E13 and E05 will follow in May, 2013 according to the current schedule.

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