Highlights from J-PARC Hadron Facility

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Starting with the first beam to Hadron Facility on January 23, 2009, four secondary beam lines, K1.8, K1.8BR, KL and K1.1BR, were in operation in November 2011. The first physics run for E19, penta-quark search via the $p(\pi^-, K^-)X$ reaction, was carried out at K1.8 beam line using SKS spectrometer. No peak structure was observed on the missing mass spectrum in the region of 1.51 – 1.55 GeV/c^2 at P_π=1.92 GeV/c with the sensitivity of $\sim$0.3 μb/sr. The beam operation to Hadron Facility in April was cancelled due to the big Earthquake on March 11. Fortunately there was no grave damage on J-PARC. All the staff and users are now working toward the beam recovery and user beam in JFY 2011.

1 Overview of J-PARC Accelerators and Hadron Facility

The Japan Accelerator Research Complex (J-PARC) comprises three accelerators of 400 MeV LINAC, 3 GeV Rapid Cycle Synchrotron (RCS), and 50 GeV Main Ring (MR), and three experimental facilities, At present the beam energy is limited to 181 MeV at LINAC and 30 GeV at MR. The most characteristic feature of J-PARC accelerators is its high beam power. The designed beam power of RCS and MR are 1 MW and 750 kW, respectively [1]. Another feature is multi-purpose accelerator. High energy proton beam can generate many kinds of secondary particles such as kaons, neutrinos, muons, and neutrons etc. Using these variety of beams with high-intensity, experimental researches from basic science to the industrial applications will be performed. At the Material and Life Science Facility (MLF), neutron and muon beams are produced from 3 GeV proton beam for material physics, life science etc. The fast extracted beam from MR to Neutrino Beam Line generates neutrino beam to Super-Kamiokande for T2K experiment. The Hadron Experimental Facility is another facility which uses MR beam, where nuclear and particle physics experiments are performed using the secondary meson beams as well as the primary proton beam.

The layout of the Hadron Experimental Hall is shown in Fig.1. The slow extracted beam is transported along the 250 m long Switch Yard and hits a production target at the almost upstream of the Hall (T1), and is finally absorbed by a beam dump. The produced secondary

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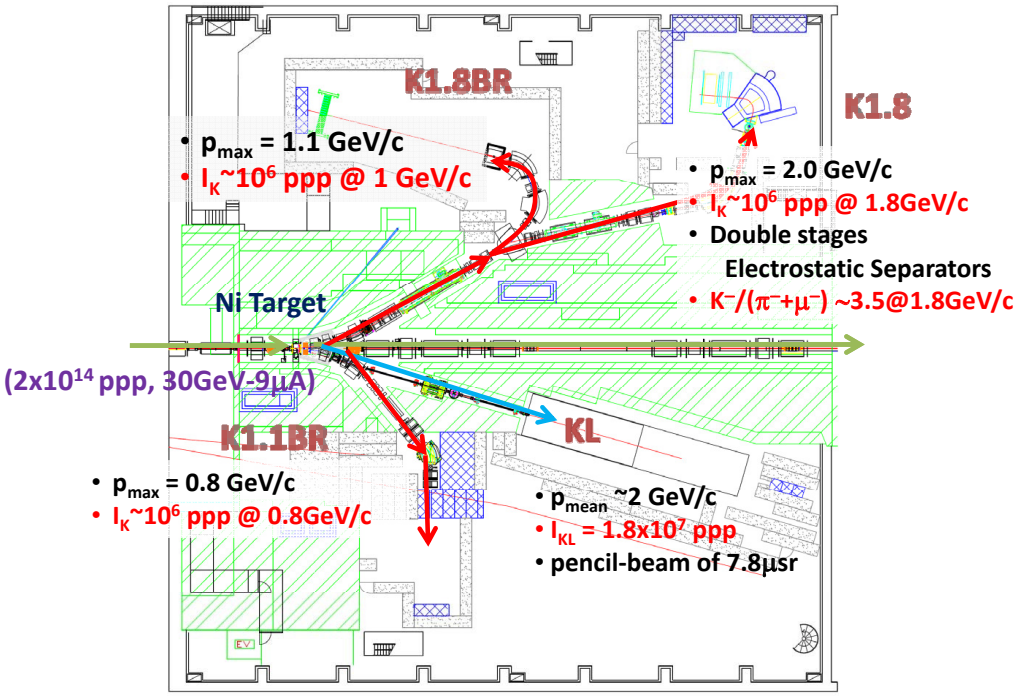

Figure 1: The layout of the Hadron Experimental Hall. Three are 4 secondary beam lines at present. The expected kaon intensities when the primary beam of 2×10^{14} ppp (270 kW) is achieved are displayed in the figure.

particles are delivered along the secondary beam lines to the experimental areas. Four beam lines are available at present. K1.8, K1.8BR, and K1.1BR can deliver the mass-separated charged particles, while KL is a neutral beam line for $K_L \to \pi^0\nu\bar{\nu}$ rare decay experiment [2]

The K1.8 beam line of 2.0 GeV/c maximum was constructed for studies of strangeness $S = -2$ system, especially for spectroscopy experiments. Due to double stages of the electrostatic separators (ESS) with the designed field of 75 kV/cm and 6 m length, high purity kaons of $K^-/(\pi^- + \mu^-)$=~3.5 can be obtained. A high resolution beam spectrometer with the designed resolution of $\Delta p/p$ =3.3×10^{-4} (FWHM) and SKS spectrometer with a solid angle of 100 msr and 0.1% resolution [3] for scattered particles are equipped at K1.8. K1.8BR beam line is branched at the D3 magnet of K1.8 with single ESS. The maximum momentum is 1.1 GeV/c. K1.1BR is a low momentum (~0.8 GeV/c) beam line with a 2 m length ESS.

2 History of the Construction and Beam Operations

The construction of J-PARC started in April 2001. After the complete of Hadron Switch Yard in March 2006 and Hadron Hall in July 2007, construction of the primary and secondary

beam lines for Hadron Facility started. The beam was successfully accelerated at LINAC on January 24 2007, at RCS on October 31 2008. The 3 GeV beam was injected into MR on May 22 2008 and accelerated up to 30 GeV on December 23 2008.

Hadron primary beam line and one secondary beam line, K1.8BR, had been constructed by the end of 2008 and were ready to accept the MR beam in January 2009. On January 23 2009, protons were accelerated up to 30 GeV again and then successfully extracted into Hadron Hall to the beam dump. The production target was installed on February 12 and the secondary beam was confirmed at K1.8BR. Protons and pions were identified online in the time of flight spectrum, while kaons were confirmed later by the detailed offline analysis.

Neutrino beam commissioning started on April 23 2009. In the Hadron Facility, construction of new beam lines, K1.8 and KL as well as SKS spectrometer system were underway. Spill feed-back devices for slow extraction were installed at MR in summer. The beam operation to the Hadron Facility started on October 22. Although most of the time was allocated for the accelerator commissioning, the secondary beam tuning and SKS spectrometer commissioning were carried out at K1.8 using 1kW MR beam.

In JFY2011, the operation of slow extraction was allocated from October 12 to November 16. In addition to the start of K1.1BR operation, a lot of progress has been seen. The first and the most important one is improvement of the extraction efficiency. By the careful alignment of the electrostatic and magnetic septa and dynamic control of the bump orbit, the extraction efficiency of 99.6%, which is the world record, has been achieved. This is promising for the increase of the beam power, since the beam extraction loss is one of the major factors to limit the beam power. Thus the stable operation of 3.6 kW (4.5×10^{12} protons/spill, where 6 sec. duration with $\sim$2.2 sec. extraction time) was realized for user time. Secondary, the first physics run for E19 has been successfully carried out at K1.8.

In spite of the efforts of the accelerator group, however, the time structure of the extracted beam was not good due to the large ripple of the power supplies. The duty factor which is defined as a ratio of the beam on time to the extraction time window (not synchrotron cycle) is less 1% without the spill feed-back control. It improved to $\sim$17% by the operation of spill feed-back control with the optimum parameters. Further improvement was observed by applying the transverse-RF in the flat-top period. But it could not operated for a long time because of the pressurization.

3 The First Results of E19, Penta-quark Experiment, at K1.8

As described the previous section, the first physics run for E19 was carried out last autumn.

E19 aims to search for penta-quark, Θ^+, via the $p(\pi^-, K^-)X$ reaction with high missing mass resolution. Since the first report from LEPS Collaboration [4], a lot of positive and negative results have been reported. The situation is still controversial. For example,

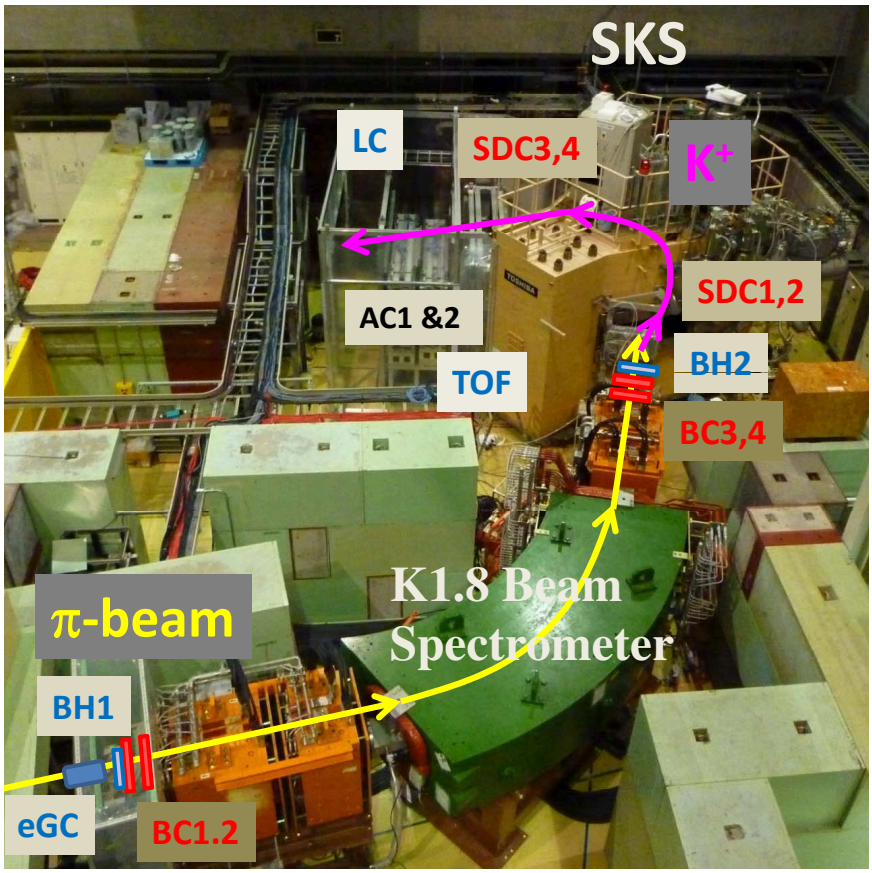

Figure 2: Beam and SKS spectrometers at K1.8 beam line.

negative result is given from $\gamma d \to pK^-K^+(n)$ reaction at CLAS [5], while new LEPS data on γC$\to K^+K^-(n)$ [6] gives positive one. However these results are not inconsistent with each other, since the measured kinematics such as incident energy and angular range are different. Strong energy or angular dependence may exist in this channel. Thus, reaction mechanism may be a key to resolve the present situation and the experimental selection to and limitation on the reaction mechanism are very important. The K^* exchange mechanism is unlikely by the two negative results of $\gamma p \to K^0_s K^+ n$ from CLAS [7] and $K^+p \to \pi^+X$ at KEK-PS [8].

The positive result with the best significance so far is $\gamma p \to \pi^+K^-K^+n$ from CLAS [9], where Θ^+ is thought be produced $\pi^-p \to K^-\Theta^+$ via the $N^*(2420)$. In addition, the cross section of this s-channel reaction via the neutron intermediate state is directly related to the width of Θ^+. Therefore the pion-induced reaction channel is worth studying.

This reaction was previously studied at K2 beam line of KEK 12GeV-PS (E522) using KURAMA spectrometer and polyethylene target [10]. The 7×10^9 pions were irradiated

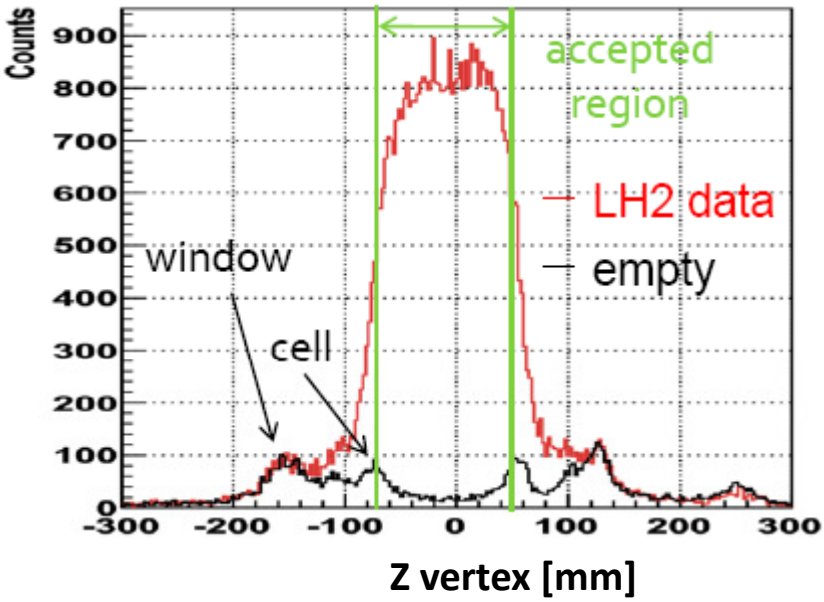

Figure 3: Reaction vertex distribution along the beam direction.

with two incident momenta of 1.87 and 1.92 GeV/c. A bump structure was observed in the missing mass spectrum at 1.53 GeV/c^2 only at 1.92 GeV/c data. If this bump is a true signal, the production cross section is estimated to be 1.9 μb/sr in laboratory system. However the S/N is only 2.5σ, thus, the upper limit was set to 2.9 μb/sr.

In E19, we are going to study the $p(\pi^-, K^-)\Theta^+$ channel at 1.87, 1.92 and 1.97 GeV/c with much improved performances; a resolution of ~2.5 MeV(FWHM) by using SKS spectrometer, good S/N by using a liquid H_2 target instead of CH_2, and high statistics of 4.8×10^{11} pions on target for each momentum. The expected sensitivity is 75 nb/sr.

Last autumn, we took step-1 data at 1.92 GeV/c. Figure 2 shows K1.8 beam spectrometer and SKS. Beam pions were analyzed by the K1.8 beam spectrometer, which comprises $QQDQQ$ magnetic system, trackers, and trigger counters. Gas Cerenkov counter to reject electrons/positions (eGC), 11-segmented plastic hodoscope counter (BH1) and two sets of 1mm spacing MWPC's (BC1 and 2) are installed upstream of the $QQDQQ$, while two sets of drift chambers with anode spacing of 3mm and 5mm (BC3 and 4) and 9-segmented hodoscope counter (BH2) are installed downstream of the $QQDQQ$.

Scattered kaons were analyzed by the SKS spectrometer. Two sets of drift chambers (SDC1 and 2) with similar structure with the BC3 and 4 and two sets of the large-size drift chambers (SDC3 and 4) are installed as trackers upstream and downstream of the superconducting magnet, respectively. Time of flight wall counter (TOF) as well as PID counters of Aerogel Cerenkov counters (AC1 and AC2) and Lucite Cerenkov counter (LC) are located after SDC4. In the momentum calculation, we have to use the calculated field map instead of the

Table 1: Summary for the calibration and production runs.

Reaction	P_{beam} (GeV/c)	SKS Field (T)	number of pions
$p(\pi^-, p)\pi^-$	-0.5	$+2.45$	2.0×10^8
$p(\pi^-, K^+)\Sigma^-$	-1.37	$+2.45$	1.2×10^{10}
$p(\pi^+, K^+)\Sigma^+$	$+1.37$	$+2.45$	3.0×10^9
$p(\pi^-, K^-)X$	$+1.92$	-2.45	7.8×10^{10}

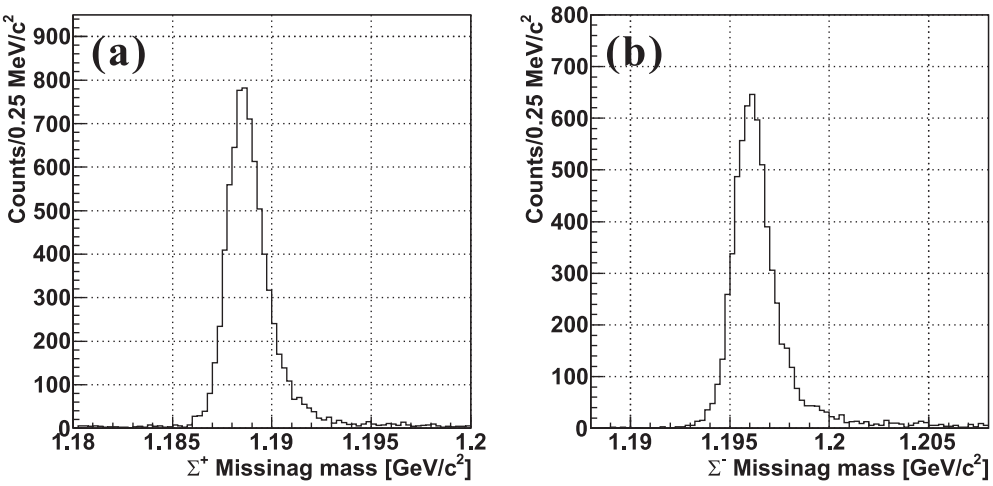

Figure 4: Missing mass spectra for $p(\pi^+, K^+)\Sigma^+$ (a) and $p(\pi^-, K^+)\Sigma^-$ (b) at 1.37 GeV/c.

measured one, since 1/6 of the coil was electrically removed because of the earth fault of the coil when the cooling system was modified. Thus, the calibration of the spectrometers and confirmation of the resolution were very important. $\Sigma^\pm$ productions were measured by the $p(\pi^\pm, K^+)$ reactions at 1.37 GeV/c for this purpose.

The liquid H_2 target adopts a continuous flow of liquid helium in the cooling system without refrigerators. The target cell is a cylinder of ϕ=67.8 mm and 120 mm long, which is made of polyethylene terephthalate (PET) of 0.30 mm thick for the cylinder part, and Mylar of 0.25 μm thick for the end cap. The temperature and the density of the liquid H_2 were very stable within 10^{-5} during the data-taking. A reaction vertex distribution along the beam direction for (π^-, π^-) events is shown in Fig.3. Windows of the target cell and vacuum chamber are clearly seen in the empty target data. The background contamination is estimated to be less than 3%.

Due to the bad time structure of the beam as described before, pion beam intensity was limited to 1.1M/spill. The irradiated numbers of pions for calibration and production runs are summarized in Table.1. In the present analysis, we used only the events in which the

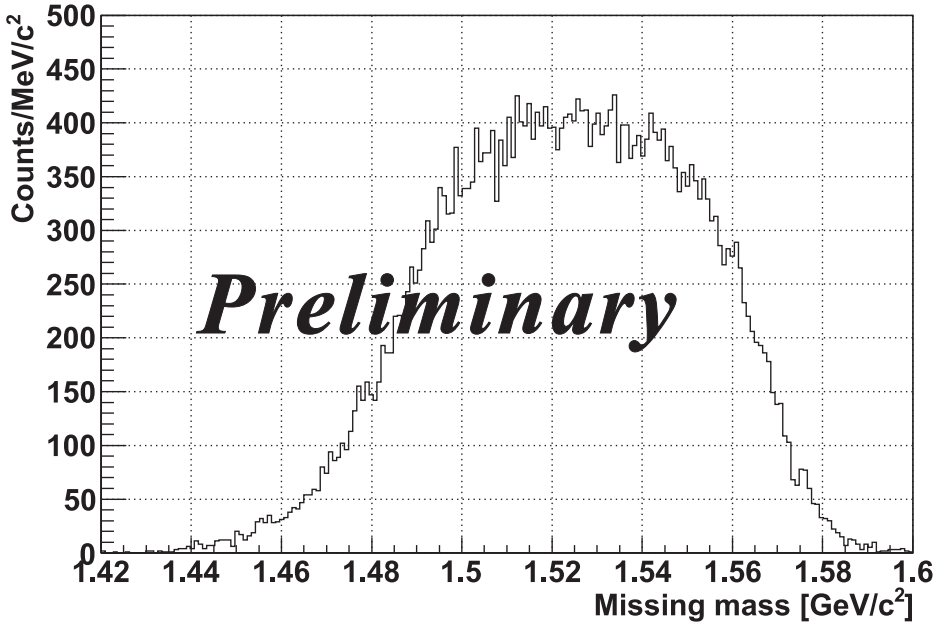

Figure 5: The missing mass spectrum for $p(\pi^-, K^-)X$ at 1.92 GeV/c.

track multiplicity of the beam spectrometer part is only one. About 15% of the events were lost by this selection.

Although magnetic fields of the beam and SKS spectrometers were monitored by Hall probe and NMR, respectively, the absolute central momentum and offset of the beam spectrometer, and absolute value of the SKS magnetic field were adjusted so that the measured $\Sigma^{\pm}$ masses reproduce the PDG values. The missing mass spectra for $\Sigma^{\pm}$ are shown in Fig.4. The resolution of Σ peak was 1.9$\pm$0.1 MeV/c^2 in FWHM, thus the missing mass resolution for Θ^+(1530 MeV/c^2) production kinematics is estimated to be 1.5 MeV/c^2 in FWHM.

The missing mass spectrum for $p(\pi^-, K^-)X$ is shown in Fig.5. No peak structure was observed. The present upper limit with 90% confidence level in the mass region of 1.51 to 1.55 GeV/c^2 is estimated to be $\sim$0.3 μb/sr in laboratory frame, which is averaged over from 2 to 15°. Assumed isotropic distribution in center-of-mass frame, it corresponds to $\sim$0.3 μb. Theoretical model based on the low-energy theorem of chiral symmetry predicts that Θ^- production cross section in the present reaction is 5 – 10 μb for J^P=1/2$^+$ case and 0.1 – 0.2 μb for 1/2$^-$ case, depending on the choice of the form factor, when 1 MeV width is assumed [11]. The obtained upper limit in the present data is comparable with the theoretical prediction with 1 MeV width. If the sensitivity of 75 nb as expected in the proposal is achieved, we may restrict the width of Θ^+ and the production mechanism.

New analysis to increase the statistics is underway. By combining the trajectories and BH

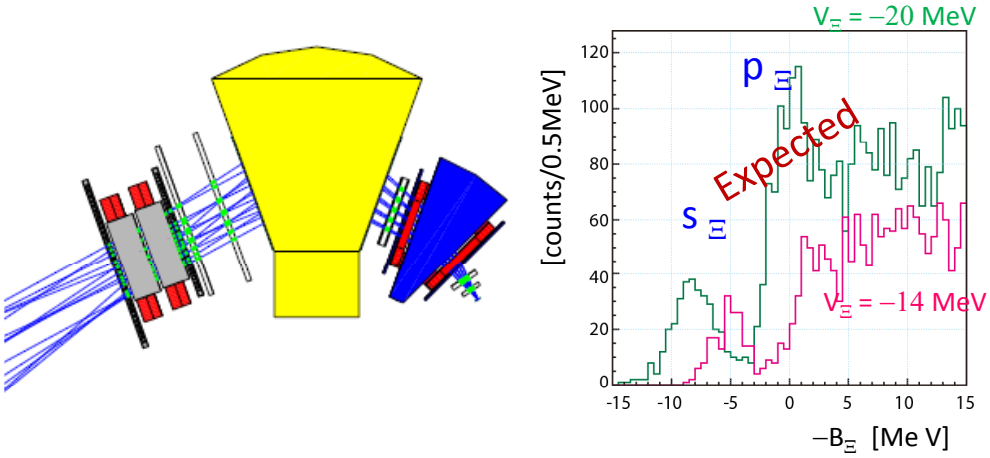

Figure 6: SksPlus spectrometer for E05 (left). The expected missing mass spectrum for one month data-taking with $1.6 \times 10^6 K^-$/spill beam (right). If Woods-Saxon potential depth is -20 MeV, two bound states where Ξ^- in s- and p- states, are expected, whereas one bound state is expected for the -14 MeV potential depth.

hits, narrower time gate can be applied for the trajectory analysis. Data-taking at 2.0 GeV/c was planned in April 2011. However the beam time was cancelled due to the big earthquake on March 11. We would like to start the data-taking soon after the recovery of the J-PARC beam.

4 Spectroscopy of Ξ-Hypernuclei by the (K^-, K^+) Reaction

Hypernuclear physics is one of the major subjects at J-PARC. Seven experiments on hypernuclear physics have been approved at K1.8 beam line[2]. Among those experiments Ξ-hypernuclear spectroscopy by the (K^-, K^+) reaction (E05) [12] has the first priority.

Ξ-hypernuclei are not experimentally established so far. The (K^-, K^+) missing mass spectroscopy on carbon target was previously carried out [13, 14]. Due to the poor experimental resolution and statistics, however, Ξ-hypernuclear state was not observed as a clear peak although some yields were observed in the bound region. The depth of the Ξ-nucleus potential was deduced to be $-(14$–$20)$ MeV from the spectrum shape analysis. Therefore the observation of Ξ-hypernuclear states with a good resolution and statistics is the most important in order to establish Ξ hypernuclei and determine the strength of the Ξ-nucleus and the underlying ΞN interaction from them.

E05 aims to observe Ξ-hypernuclear states, for the first time, via the $^{12}\mathrm{C}(K^-, K^+)^{12}_{\Xi}\mathrm{Be}$

[2] A new experimental proposal on ΣN scattering was approved at the 12th PAC meeting on July 8–10, 2011.

reaction with good resolution and high statistics. High intensity K^- beam at 1.8 GeV/c with 1.6×10^6/spill will be analyzed by K1.8 beam spectrometer while scattered K^+ will be measured by SksPlus spectrometer as shown in Fig.6 (left), in which an dipole magnet is added in front of the SKS to keep the acceptance in 1.1–1.3 GeV/c region with good resolution. The 3 MeV (FWHM) resolution is expected using 5.4 g/cm^2 target. With one month data-taking, ∼100 bound states will be expected as shown in Fig.6 (right).

5 The Effect of the Earthquake on March 11

On March 11 2011 a big earthquake occurred, and big Tsunamis attacked to the wide area of the coast in north-east of Japan. Fortunately there was no injured or dead person and no Tsunami effect in J-PARC. There were no significant damage in all buildings although the land around the buildings sank and many roads around J-PARC were severely damaged. The serious damages were found in RCS, where power substation and cooling water were damaged. All of the elements of the accelerators moved, therefore alignments are necessary for the recovery.

In the Hadron Facility, the alignment of the primary and secondary beam lines as well as the rearrangement of the shielding structure are necessary, which is very time-consuming work due to large number of the elements. No serious damage was found on the detectors of the beam spectrometer and SKS, although the SKS magnet and the shielding structure moved at K1.8. At K1.8BR, one wire chamber located at the beam line was broken because the last dipole magnet (K1.8BRD5) moved.

According to the J-PARC recovery plan announced on May 20 [15], the facility recovery will be confirmed by an beam injection and acceleration in December and user operation will start from January 2012. Now all of the staffs and users at J-PARC are working hard to achieve the recovery as planned. I hope that the beam will be back in December and we can restart experiments soon.

Acknowledgments

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