The first experiment at the J-PARC K1.8 beam line using the SKS spectrometer

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Abstract. The Superconducting Kaon Spectrometer (SKS) system has been constructed at the J-PARC K1.8 beam line. With all detectors being operational since October, 2009, a series of commissioning data have been taken successfully such that the SKS system performance could be assessed. In particular, the (p, p) elastic scattering and the (p, K+) reaction were used for this purpose with the beam momentum of 0.5 GeV/c and 1.25 GeV/c, respectively. The measured resolution of missing mass was 1.7 MeV/c (FWHM) corresponding to 3.3 MeV/c (FWHM) momentum resolution of the SKS system. Overall, the SKS system showed an expected performance which proved the readiness for the first physics experiment at the K1.8 beam line.

1. Introduction
Following the completion of the J-PARC Hadron facility in February 2009, hadronic beams have begun to be delivered to the experimental areas. The K1.8 beam line will be a host of several hypernuclear and exotic-hadron experiments. Most of the planned experiments require the Superconducting Kaon Spectrometer (SKS) system together with the K1.8 beam line spectrometer. The SKS system is installed at the downstream of a target. On the other hand, the K1.8 beam line spectrometer is comprised of of magnets and detectors installed at the upstream of the target. Details on this spectrometer are described in [1] and will not be discussed here.

There are three configurations in the SKS system for the proposed experiments at the J-PARC K1.8 beam line. The first configuration is the present one which will be used for the first experiment, J-PARC E19 [2] planned in October, 2010. In this experiment, the Θ⁺ penta-quark baryon will be searched for via the (p, K⁻) reaction. The second configuration is the SksPlus configuration where an additional dipole magnet is placed at the entrance of the SKS magnet. The Σ hypernuclear spectroscopy experiment [3] will employ this configuration that measures a scattered particle of higher momentum (∼1.3 GeV/c) while keeping a large bending angle for the high momentum resolution [less than 2 MeV/c (FWHM)]. Lastly, for the Λ hypernuclear γ-ray spectroscopy experiment [4], the SksMinus configuration will be set up. SksMinus, in which the SKS magnet position is adjusted for higher momentum of scattered particles, has a large solid angle (∼120 msr) and a wide momentum acceptance (1.0–1.6 GeV/c). All SKS configurations share key detectors such as a TOF wall and drift chambers. Therefore, the successful operation of the present SKS system is a milestone step for experiments to be conducted at the J-PARC K1.8 beam line.
The commissioning run is focused on checking the performance of the SKS system with most important measures being the achievable mass resolution and the total analysis efficiency. The missing mass resolution of SKS that can be achieved is better than 2 MeV/$c^2$(FWHM) which translates to the sensitivity of $\sim$75 nb/sr in the J-PARC E19 experiment. The $(\pi^-, p)$ elastic scattering and the $p(\pi^-, K^+)\Sigma^-$ reactions are used for the purpose with a pion beam momentum of 0.5 GeV/$c$ and 1.25 GeV/$c$, respectively.

2. Detector components of the SKS system

The previous SKS system had been used in the KEK-PS K6 beam line [5] and thereafter the SKS magnet was moved to the J-PARC K1.8 beam line. A new SKS system that retains the SKS magnet but with newly constructed detectors are assembled for the J-PARC experiments for an increased momentum acceptance and counting rate limit. The maximum momentum acceptance of SKS is increased up to 1.0 GeV/$c$ from the previous setup of 0.8 GeV/$c$ at the magnetic field strength of 2.5 T, while the solid angle of 100 msr and the angular coverage of up to 20 degree are kept; the designed momentum resolution is of the order of $10^{-3}$. This was realized by increasing an effective area of the downstream detectors by a factors of 2. From the experimental requirements, these wide momentum ranges with high resolution are necessary.

The current SKS system consists of several detectors, namely drift chambers (SDC) for momentum analysis, timing counters, and Čerenkov counters for a particle identification (Fig. 1). A general information on each detector is summarized in Tables 1 and 2. In-beam performances of these detectors will be discussed in the followings. Overall, all detectors performed as expected.

![Figure 1. Detector components of the SKS system. SDC1–4 are drift chambers. TOF is a plastic scintillation counter hodoscope for the Time-Of-Flight measurement. AC1, 2 are aerogel Čerenkov counters ($n=1.05$). LC is a Lucite (Acrylic) Čerenkov counter ($n=1.49$).]
SDC1, 2 with the wire spacing of 3 mm and 5 mm, respectively, are installed at the entrance of the SKS magnet, and SDC3, 4, which have 20 mm wire spacing are placed at the exit. Their performances are evaluated from straight particle paths obtained from each of two pairs of drift chambers, which is called a local tracking. The local tracking efficiencies of SDC1, 2 and SDC3, 4 are 99.6(1)\% and 98.1(1)\%, respectively. Also the average position resolutions of SDC1, 2 are 200 μm(rms) and that of SDC3, 4 are 250 μm(rms).

The Time Of Flight (TOF) plastic scintillation counter is placed at the immediately downstream of SDC4 for the TOF measurement with a plastic scintillator (BH2) located at the upstream of a target. The TOF time resolution is extracted to be 120 ps(rms). At the downstream of the TOF counter, installed are aerogel Čerenkov counters (AC) and Lucite (Acrylic) Čerenkov counters (LC) which have an index of 1.05 and 1.49, respectively. The pion detection efficiencies of AC and LC are both 99\%. These counters participate in making the (π, K) trigger defined as PIK=BEAM×TOF×AC1×AC2×LC.

### Table 1. Specifications of drift chambers

| Name  | Area [mm]   | Drift space [mm] | Wires                | Rotation [degree] | resolution [μm] |
|-------|-------------|------------------|----------------------|-------------------|-----------------|
| SDC1  | 192×150     | 1.5              | vv', uu'             | u(+15°), v(-15°) | 150             |
| SDC2  | 400×150     | 2.5              | vv', uu', xx'        | u(+15°), v(-15°) | 200             |
| SDC3  | 2140×1140   | 10               | v, x, u, v, x, u    | u(+30°), v(-30°) | 250             |
| SDC4  | 2140×1140   | 10               | v, x, u, v, x, u    | u(+30°), v(-30°) | 250             |

### Table 2. Specifications of trigger counters

| Name  | Area [mm]   | PMT             | Layer/Segments | Index |
|-------|-------------|-----------------|----------------|-------|
| TOF   | 2240×1000×30| H1949×64        | 32 segments    |       |
| AC1   | 1240×1200×110| R1584-01×18    | 1 layers       | n=1.05|
| AC2   | 1350×1340×110| R1584-01×20    | 1 layers       | n=1.05|
| LC    | 2800×1400×40| H1949×28, H6410×28 | 28 segments    | n=1.49|

3. Commissioning run

In the commissioning run, the (π−, p) elastic scattering (~5 mb/sr at 0 degree [6]) and the p(π−, K+)Σ− production (~40 mb/sr at 0 degree [7]) were tried. The momentum region of these reactions is suited to testing of the SKS system. The field strength of the SKS magnet was set at 2.2 T which corresponded to the momentum region of scattered particles of 0.65–0.75 GeV/c with the bending angle around 100 degree. The beam momenta of 0.5 GeV/c and 1.25 GeV/c are chosen for the (π−, p) elastic scattering and the p(π−, K+)Σ− production, respectively.

The actual pion beam intensities for the (π−, p) and the p(π−, K+)Σ− reaction were 0.16 M/spill and 0.75 M/spill, respectively, where a spill means one beam extraction period out of J-PARC Main Ring to the K1.8 beam line. The beam irradiation time on the liquid hydrogen (LH2) target for the (π−, p) reaction and the p(π−, K+)Σ− production were 1 hour and 20 hours, respectively. The known yield of each reaction has been confirmed.
The missing mass resolution is determined by the following equation.

\[ \Delta M^2 = \Delta_{beam}^2 + \Delta_{SKS}^2 + \Delta_{\theta}^2 + \Delta_{E_{strag}}^2. \]  

(1)

The first term is a contribution from the momentum resolution of the beam line spectrometer and the second term from that of SKS system. The third and the fourth term are from the resolution of a scattering angle and the energy loss straggling in target materials, respectively. Expected mass resolution at the scattering angle of 5 degree is listed in Table 3 for each reaction. The values from \(^{12}\text{C}(\pi^+, K^+)^{12}\text{C}\) hypernuclear production \((p_\pi=1.05\text{ GeV}/c)\), which was used in the previous KEK experiment \([8]\), is also shown in the table as a reference.

### Table 3. Estimation of mass resolution without the energy loss straggling in the target

| Reaction | \(\Delta_{beam}\) [MeV] | \(\Delta_{SKS}\) [MeV] | \(\Delta_{\theta}\) [MeV] | \(\Delta M\) [MeV] |
|----------|----------------|----------------|----------------|----------------|
| \(^{12}\text{C}(\pi^+, K^+)^{12}\text{C}\) | 0.33 | 1.19 | 0.03 | 1.24 |
| \((\pi^-, p)\) | 0.57 | 4.29 | 1.13 | 4.47 |
| \(p(\pi^-, K^+)\Sigma^-\) | 0.27 | 0.75 | 0.34 | 0.87 |

For this estimate, the momentum resolution of the beam line spectrometer and SKS are assumed to be \(\Delta p/p = 3.3 \times 10^{-4}\) (FWHM) and \(\Delta p/p = 2.1 \times 10^{-3}\) (FWHM), respectively. The resolution of the scattering angle is 5 mrad (FWHM) and the energy loss straggling in the target materials is not included. The main contribution comes from the momentum resolution of SKS. In the case of the \((\pi^-, p)\) elastic scattering, this contribution dominates over the other terms.

### 4. Performance of the SKS system

In the tracking process, firstly, straight-line tracks are defined locally both at the upstream and at the downstream using the least-squares method. Using the best combination of these local tracks, the SKS tracking is obtained by the Runge-Kutta method based on the calculated magnetic field map. The SKS tracking efficiency was obtained to be 93.5(3)\%. Figure 2 shows the \(\chi^2\) distribution of the SKS tracking. Tracking with \(\chi^2\) of less than 100 is used as a good track. The overall efficiency of the SKS tracking was obtained to be 91.4(3)\%, which is better than the previous KEK experiment (~70\%). As a result of analysis, the vertex distribution along the beam axis was obtained as shown in Fig. 3. The shape of the \(\text{LH}_2\) target cell (120 mm) can be identified.

Figure 4 shows the mass square of the scattered particles with the \((\pi^-, K^+)\) trigger, which is calculated from TOF, the reconstructed momentum, and the path length \((M^2 = \frac{p_t}{M}(1 - \beta^2))\). Scattering particles are well separated where \(K^+\) region is indicated in the figure, which establishes a particle identification scheme of the SKS system.

The missing mass spectra of \(\Sigma^-\) with the \(\text{LH}_2\) target \((0.86\text{ g/cm}^2)\) and \(\pi^-\) with the \(\text{CH}_2\) target \((0.30\text{ g/cm}^2)\) are shown, respectively, in Fig. 5 and 6. The preliminary mass resolutions of \(\Sigma^-\) and \(\pi^-\) are 1.66 ± 0.03 MeV/c\(^2\) (FWHM) and 9.31 ± 0.59 MeV/c\(^2\) (FWHM), respectively. Absolute values are shifted from the Particle Data Group value \((1197.45\pm0.03\text{ MeV}/c^2\) in PDG [9]) because the correction for the energy loss and the magnetic field strength of both spectrometers are not applied yet. The mass resolution obtained corresponds to the momentum resolution of 3.3 MeV/c (FWHM).

The mass resolution for the \(\Theta^+\) estimated from the present preliminary momentum resolution is 1.8 MeV/c\(^2\) (FWHM), which is better than the experimentally required 2 MeV/c\(^2\) (FWHM).
In addition, data of the \((\pi^-, K^-)\) reaction were collected at the beam momentum of \(p_\pi = 1.92\) GeV/c which will be used for the \(\Theta^+\) experiment. A simulated trigger rate and background from the associated reactions (e.g. \(\pi^- + p \rightarrow \phi + n, \phi \rightarrow K^+ + K^-\)) reproduced the data well. Preparation of the J-PARC E19 experiment is completed.

5. Conclusion

A new spectrometer system dedicated at the J-PARC K1.8 beam line has been assembled, in which the SKS magnet is combined with newly constructed detectors. Several up coming hypernuclear and hadron experiments approved for a beam time will require the current SKS system or the variation thereof. A series of reaction spectroscopy data in order to evaluate the SKS performance have been collected with all detectors being operational since October, 2009. In particular, the \((\pi^-, p)\) elastic scattering and the \(p(\pi^-, K^+)\Sigma^-\) production reactions with the 0.5 GeV/c and the 1.25 GeV/c pion beams, respectively, were used for assessing the performance.
Figure 5. The missing mass spectrum of the $p(\pi^-, K^+)\Sigma^-$ reaction with LH$_2$ target without energy loss correction of the target materials, and calibration of the beam line spectrometer and SKS.

Figure 6. The missing mass spectrum of the $(\pi^-, p)$ reaction with CH$_2$ target. The absolute value is largely shifted because of the effect of the large energy loss of proton in the target materials.

of the present system. The measured resolution for $\Sigma^-$ missing mass was 1.7 MeV/c$^2$ (FWHM). This value gives an estimated momentum resolution of 3.3 MeV/c (FWHM) for SKS which then translates to the mass resolution of 1.8 MeV/c$^2$ (FWHM) for $\Theta^+$. In addition, the test data using the $(\pi^-, K^-)$ reaction at a beam momentum of 1.92 GeV/c, identical for the $\Theta^+$ search experiment, has been taken for a trigger and background study. The present system meets the required experimental sensitivity of the J-PARC E19 experiment, which is the first physics run scheduled in October, 2010, and thus awaits for the beam.

References
[1] T. N. Takahashi et al., Nucl. Phys. A 835 88-95 (2010).
[2] M. Naruki et al., J-PARC proposal E19, "High-resolution Search for $\Theta^+$ Pentaquark in $\pi^- p$→$K^- X$ Reaction" (2006).
[3] T. Nagae et al., J-PARC proposal E05, "Reaction spectroscopy of $\Xi^-$ hypernucleus" (2006).
[4] H. Tamura et al., J-PARC proposal E13, "Gamma-ray spectroscopy of light hypernuclei" (2006).
[5] T. Fukuda et al., Nucl. Instrum. Meth. A361:485-496, (1995).
[6] B. J. Moyer, Rev. Mod. Phys. 33, 367–373 (1961).
[7] M. L. Good and R. R. Kofler, Phys. Rev. 183, 1142–1148 (1969).
[8] H. Hotchi et al., Phys. Rev. C64 (2001) 044302.
[9] C. Amsler et al., (Particle Data Group), Phys. Lett. B 667, 1 (2008).