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Ξ-hypernuclear spectroscopy with the S-2S spectrometer

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Summary. — Power supplies for the J-PARC Main Ring (MR) synchrotron were renewed in 2022. The repetition rate for the fast extraction beam (FX; pulsed extraction mode) of a neutrino beam line will be shortened in order to achieve higher beam power better than 740 kW. In the J-PARC hadron experimental hall, we have a slow extraction mode (SX), and hope to reach more than 80 kW (51 kW at this moment). At the same time, better time structure of the slow extraction (SX; high duty mode) are expected owing to the power supply improvements. A high-intensity K^- beam at 1.8 GeV/c to conduct the strangeness −2 physics programs will be soon available for spectroscopy of Ξ-hypernuclei with the (K^-, K^+) reaction, and X-ray spectroscopy measurements from Ξ^- atoms, etc. will be performed.

1. – Spectroscopy of $S = -2$ systems

New information on hyperon-nucleon (YN) interaction would be available through high-resolution hypernuclear spectroscopy such as Λ-N interactions. In the ΛN case, central attractive force gives about 30 ± 1 MeV attractive potential, while other spin-dependent forces give us very small splittings from spin-spin, spin-orbit, and tensor type interactions in the p-shell region, of the order of several tens of keV, where hypernuclear gamma-ray spectroscopy have great resolving power. High statistics scattering data on $\Sigma^{\pm}$p scattering have been obtained by using recent high-rate detector techniques improving a rate capability up to nearly two orders of magnitude. These new data are consistent with previous data suggesting weak repulsive potential for ΣN channel. Thus, among the various baryon-baryon interactions, the ΞN channels are left to be investigated both experimentally and theoretically.

In the case of Ξ-N interaction, we do not know the strength of the central force so well. The attractive interaction seems to be favoured from the observations of emulsion experiments. A weak attraction of about 1–4.3 MeV binding energy, or a stronger attraction of ≅20 MeV were suggested from theoretical analyses [1]. The 1 MeV weak attraction is definitely bound by strong interaction if we consider the Coulomb attraction.

The Ξ-hypernuclei and Σ-hypernuclei are unstable to the strong decay of baryonic systems. They might have large widths due to strong decay modes of $\Sigma N \to \Lambda N$ and $\Xi N \to \Lambda\Lambda$. Since we have high momentum transfer in the (K^-, K^+) reaction of 550 MeV/c to produce the Ξ-hypernuclei, spin-stretched states are preferentially produced. There were several emulsion events suggesting the existence of Ξ-hypernuclei; Coulomb-assisted bound states surely exist [2, 3].

1˙1. *Femtoscopy analysis for Ξp interaction.* – Recently, the LHC-Alice Group and BNL STAR Collaboration reported a successful analysis results of two-particle correlations using the closely correlated two-particle emission in high-energy heavy-ion reactions. This kind of analysis using the interference has been carried out in high-energy heavy-ion collisions; in that case the reaction source size was estimated by knowing it in p-p collisions. The interaction strength is obtained from the source size in the momentum space.

1˙2. *Recent emulsion studies for* Ξ^- *hypernuclei.* – "Nagara" event of ${}^{6}_{\Lambda\Lambda}$He provides us with precious information of double Λ hypernuclei. Just recently a new emulsion event in which a Λ hyperon is in the p-orbit was observed [4], although the species were not clearly identified. Further the attraction in the ΞN system was confirmed with two new emulsion events [2, 3]. To our surprise, it seems that nuclear 1s bound state has a large binding energy of 6–8 MeV [5].

2. – S-2S spectrometer system

At the K1.8 beam line of J-PARC hadron hall, we are going to carry out the (K^-, K^+) missing-mass spectroscopy with the energy resolution of 2 MeV (FWHM), for the first time. For this purpose, we needed one spectrometer for K^- at around the momentum of 1.8 GeV/c, and another for K^+ at around 1.35 GeV/c (in the reaction of $({}^{12}\mathrm{C}(K^-, K^+){}^{12}_{\Xi}\mathrm{Be})$. We have constructed a new magnetic spectrometer (S-2S) dedicated to the strangeness −2 spectroscopy, together with an active fiber target (AFT) composed of 900 fibers. The energy loss in the AFT is corrected event by event.

2˙1. *K1.8 beam line spectrometer.* – The K1.8 beam line spectrometer consists of a QQDQQ magnet system with the tracking detector at the entrance of the magnet system and two sets of drift chambers at the exit of the QQDQQ system.

2˙2. *S-2S spectrometer.* – The reaction spectroscopy for the Ξ hypernuclei can be applied by using the $K^-\mathrm{p} \to K^+\Xi^-$ reaction. The production cross section of this process has a maximum at around the incident K^- beam momentum of 1.8 GeV/c. The Strangeness -2 Spectrometer (S-2S) consists of QQD magnets as shown in fig. 1.

2˙3. *Detectors of the S-2S.* – Tracking device in the S-2S consist of two sets of high rate drift chamber systems at the entrance; SDC1, and SDC2, three sets at the exit; SDC3-5 (fig. 2). Trigger signals for the K^+ identification was produced with TOF plastic scintillation hodoscope. In the trigger level, protons at the exit of the S-2S was suppressed with a layer of water Cherenkov detector with a refractive index of 1.33, and π^+'s are suppressed with an aerogel Cherenkov detector wall ($n = 1.05$) in the trigger levels.

In June 2022, we had a commissioning run for the beam line spectrometer and S-2S spectrometer (fig. 3). Unfortunately, the beam was not as stable as before the MR power supplies replacement. The MR run conditions needed further tuning, in order to recover

Fig. 1. – A picture of the S-2S spectrometer installed at the K1.8 beam line area of the J-PARC hadron hall. It consists of the QQD magnet system.

the previous run conditions. Nevertheless, we have succeeded to confirm major parts of the detectors using the beam through conditions. In particular, a new detector system of an active fibre target system composed of about 900 fibre scintillators of $\phi = 3\,\mathrm{mm}$ worked very well together with read-out-electronics.

In the coming commissioning runs in 2024, we plan to schedule the beam commissioning studies on the following items in each experiment.

- E70: searching for Ξ hypernuclei with the Strangeness −2 Spectrometer (S-2S) will be performed having good momentum resolution. Energy loss corrections with the active fiber detector will be a key to optimizing the target thickness.

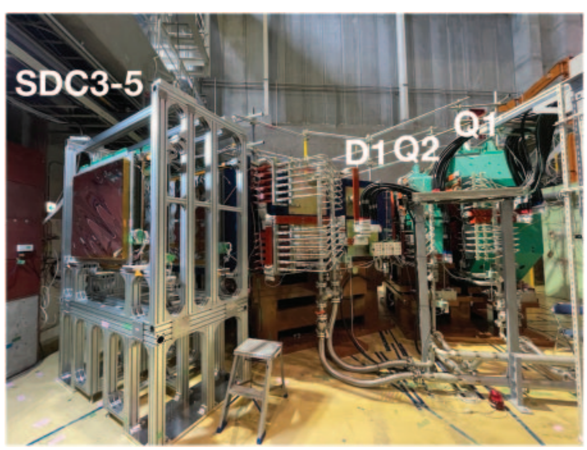

Fig. 2. – A picture of the down stream parts of the S-2S detectors. There are three tracking detector sets of drift chambers (SDC3, 4, and 5) at the exit.

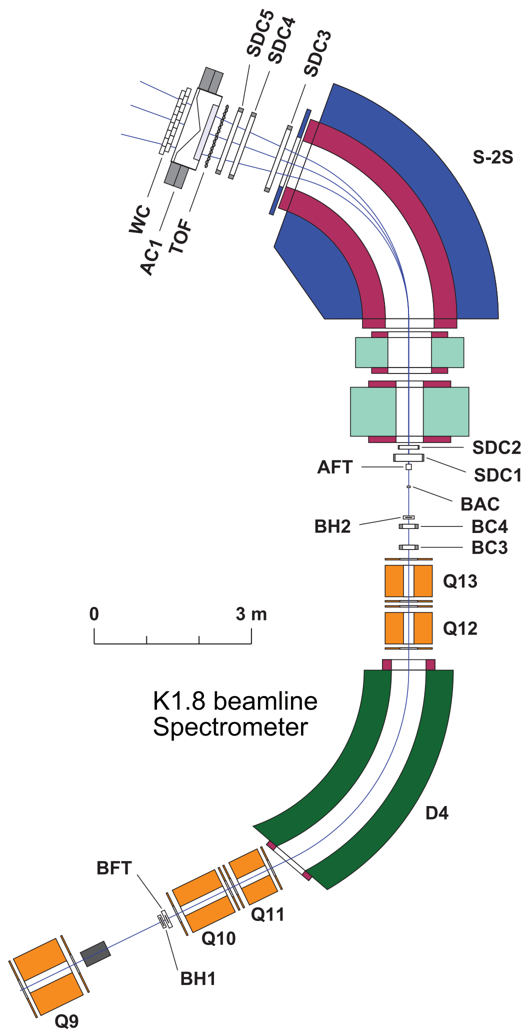

Fig. 3. – A drawing of the K1.8 beam line and the S-2S spectrometer. The beam is coming from the bottom and going up to hit an active fibre tracker (AFT) just at the entrance of the S-2S. The beam line spectrometer is composed of the Q10-Q13 quadrupole magnets, and one dipole magnet D4.

- E75: at the end of the E70 runs, we will carry out the E75 data taking. We will measure the production cross section in the reaction of (K^-, K^+) reaction on ^{6}Li target. In the commissioning run we installed not only the E70 setup, but also X-ray detectors for E96 without interference between two setups, so that we could take two different kinds of runs at the same time. Thereby we can reduce the total running beam time.

- E96: search for Ξ-atom X-rays emitted from Ξ-C atom will be installed at the target position of E70. The experimental setup is the same as E70, except we additionally install the X-ray detectors surrounding the AFT of E70. These experimental setups are designed not to interfere with each other.

- E94: at the end of the beam commissioning run, if everything goes well, we might have a chance to take the E94 (π^+, K^+) data to demonstrate the ultimate energy resolution in the (π^+, K^+) reaction. We would like to achieve the >1 MeV energy resolution with the S-2S. Further, in E94, the (π^+, K^+) reactions would be utilized for the energy calibration on absoulte energy.

The E70 has the first priority to setup the S-2S spectrometer for all the detectors. Further, we will perform tuning of the momentum reconstruction system which is the major purpose of the beam commissioning runs.

3. – Conclusions

A commissioning run for the S-2S spectrometer was successfully performed at the K1.8 beam line, while the beam time was only a few days. It was about 1/10 of the scheduled beam time.

The trigger rates for the "Kaon" were acceptable for our data acquisition system to have more than 90% live time. The position resolutions of the tracking drift chambers had detection efficiencies of 95% with the position resolution of about 350 μm.

New spectrometers, the K1.8 beam line spectrometer and the S-2S spectrometer were ready for optimizing of the operation conditions. We hope to confirm the designed mass resolutions of 2 MeV (FWHM) as early as possible to open the Ξ^- hypernuclear spectroscopy.

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