Proc. 2nd Int. Symp. Science at J-PARC — Unlocking the Mysteries of Life, Matter and the Universe —
JPS Conf. Proc. **8**, 021018 (2015)
http://dx.doi.org/10.7566/JPSCP.8.021018

Spectroscopic Study of $S = -2$ Hypernuclei with a New Spectrometer S−2S

Shunsuke Kanatsuki[1], Nobuaki Amano[1], Hiroyuki Ekawa[1,2], Hiroyuki Fujioka[1], Erina Hirose[3], Yudai Ichikawa[1,2], Seigo Kato[4], Manabu Moritsu[5], Tomofumi Nagae[1], Hitoshi Takahashi[3], Toshiyuki Takahashi[3], Kohei Takenaka[1]

[1]*Kyoto University, Sakyo, Kyoto 606-8502, Japan*
[2]*ASRC, JAEA, Tokai, Ibaraki 319-1195, Japan*
[3]*IPNS, KEK, Tsukuba, Ibaraki 305-0801, Japan*
[4]*Yamagata University, Yamagata 990-8560, Japan*
[5]*RCNP, Osaka, 567-0047, Japan*

E-mail: kanatsuki@scphys.kyoto-u.ac.jp

(Received October 14, 2014)

A spectroscopic study of Ξ hypernucleus is planned to carry out in the J-PARC E05 experiment at J-PARC K1.8 beam line. We aim to observe bound state peaks of Ξ hypernucleus through the ^{12}C(K^-, K^+) reaction with an energy resolution of better than 2 MeV. For this experiment, we are constructing a new spectrometer to analyze the scattered K^+ momentum precisely. Construction of the magnets will be completed by the end of JFY2014, and most parts of detectors are almost ready. The plan of the experiment and the design and status of the new spectrometer are presented.

KEYWORDS: Ξ Hypernuclei, magnetic spectrometer

1. Introduction

Hypernuclei are good tools for investigating the hyperon-nucleon(YN) and hyperon-hyperon(YY) interactions. The nucleon-nucleon(NN) interaction, which is well studied from a lot of NN scattering data, is extended to generalized baryon-baryon(BB) interaction through the hypernuclear study. Because of the short lifetime of hyperons, the data of YN scattering experiments are limited. Therefore, YN and YY interactions have been studied by extracting the information from hypernuclear structure.

So far, Λ hypernuclei have long been studied by using various reaction spectroscopy with the (K^-, π^-), (π^+, K^+) and $(e, e'K^+)$ reactions, and gamma ray spectroscopy by germanium detectors. The ΛN interaction is studied from the systematic data of Λ hypernuclear structures. As for Σ hypernuclei, no bound state was found except for ${}^{4}_{\Sigma}$He, and the ΣN interaction is derived to be repulsive. Thus, the study of hypernuclei with strangeness(S) $= -1$ has been gradually developed experimentally and theoretically, and the BB interactions in the $S = -1$ sector have been relatively understood.

The information of ΞN and ΛΛ interaction is also important for a unified description of the BB interaction in the flavor SU(3) symmetry, because the singlet term, which is expected to be attractive in short length by lattice QCD calculations [1], emerges only in $S = -2$ sector. $S = -2$ systems are also essential for understanding dense nuclear matter such as core of neutron stars where nuclear density is expected to be five times higher than that of normal nucleus. In such an environment, strangeness is expected to exist, and the information on multi-strangeness systems is important input to determine the equation of state of neutron stars [2].

The KEK-E373 [3] discovered a double Λ hypernucleus by using the hybrid-emulsion method. It was identified as the ground state of ${}^{6}_{\Lambda\Lambda}$He without ambiguity. The binding energy $\Delta B_{\Lambda\Lambda}$ has been estimated to be 0.67 MeV, and the ΛΛ interaction is found to be weakly attractive.

As for Ξ hypernucleus, it is not confirmed if a bound state exists or not. In the KEK-E224 [4] and BNL-E885 [5], spectroscopic studies were performed by using the ^{12}C(K^-, K^+) reaction, and the missing-mass spectra were obtained with energy resolutions of ∼ 22 MeV and ∼ 14 MeV (FWHM), respectively. In these experiments, the depth of Ξ nucleus potential was estimated by comparing the results of the experiments with theoretical calculation assuming Wood-Saxon type potential. In particular, the BNL-E885 shows that the production cross sections were 89±14 nb/sr for $\theta < 8°$ and 42±5 nb/sr for $\theta < 14°$, and that Ξ nucleus potential depth was considered to be ∼ −14 MeV. Although there was a significant amount of events in the bound region, no peak structure was observed because of poor energy resolution. Therefore an experiment with higher energy resolution has been strongly awaited to deduce a definite information on the ΞN interaction.

2. J-PARC E05 Experiment

We will carry out the Ξ hypernuclear spectroscopy in the J-PARC E05 experiment at the K1.8 beam line [6]. We aim to observe a bound state of Ξ hypernucleus with much improved missing-mass resolution and enough statistics. As the first step, we use the ^{12}C(K^-, K^+) reaction to produce a Ξ hypernucleus, $^{12}_{\Xi}$Be. If a bound state is observed, we will obtain the information on the real and imaginary part of the Ξ nucleus potential from the position and width of the peak.

Since the production cross sections of the $S = -2$ hypernuclei are expected to be very small, intense and pure K beams are crucially important. We will use the high intensity and purity K^- beam at 1.8 GeV/c. At around this momentum, production cross section of the elementary process, $K^-p \to K^+\Xi^-$, in the forward angle has a local maximum. At the beam momentum, the momenta of scattered K^+ are around 1.3∼1.4 GeV/c. We observe the missing mass of hypernuclear states by measuring the momenta of incident K^- and scattered K^+. Missing mass M_{hyp} is calculated as follows;

$$M_{hyp} = \sqrt{(E_B + m_T - E_S)^2 - ({p_B}^2 + {p_S}^2 - 2p_Bp_S\cos\theta)} \tag{1}$$

Here E, m, p, θ denote energy, mass, momentum, and scattering angle in the laboratory frame. Subscripts B, T, and S mean beam, target, and scattered particle, respectively. Since the momentum resolutions are critical to improve the missing-mass resolution, we need two good spectrometers for the analyses of both K^- and K^+. The spectrometers for the experiment are explained in the following subsections.

2.1 K1.8 beam line and beam spectrometer

Primary proton beams from the main ring are irradiated to the primary target at the entrance of the hadron facility, and large amount of pions, kaons and so on, are produced. These intense hadron beams are delivered to the K1.8 experimental area through the K1.8 beam line. In this beam line, two stages of electro static separators can improve the K/π ratio up to ∼ 7. Thus, J-PARC provides us a variable potential to access to the $S = -2$ world.

The momentum of beam K^- is analyzed by a beam spectrometer at the end of the K1.8 beam line [7]. It comprises a *QQDQQ* magnet system and a set of tracking detectors and trigger counters at the entrance and exit of the magnet system. The momentum resolution of the beam spectrometer is expected to be 1×10^{-3} (FWHM) at 1.8 GeV/c.

2.2 Scattered particle spectrometer

With the beam momentum of 1.8 GeV/c, the momentum of scattered K^+ in forward angle is at 1.3 GeV/c for elementally process, and distributed around 1.3∼1.4 GeV/c for heavier targets. This momentum region is higher than that of scattering particles in other reaction spectroscopy. For example, Superconducting Kaon Spectrometer (SKS), which has been developed mainly for the study of Λ hypernuclei with the (π^+, K^+) reaction and exists in K1.8 experimental area at present, has a momentum resolution of $\Delta p/p \simeq 1 \times 10^{-3}$ at 0.72 GeV/c, but it gets worse to $3{\times}10^{-3}$ at 1.3 GeV/c. This momentum resolution limits the energy resolution. In our case, energy resolution would be worse than 4 MeV with SKS. Although such energy resolution is three times better than that of the previous experiments and a large acceptance of SKS would give us enough statistics, we need a new spectrometer specialized for the (K^-, K^+) reaction to realize a high resolution spectroscopy. Therefore, we are now constructing a new spectrometer for analysis of scattered particles. It is called "S-2S", the meaning of which is "Strangeness −2 Spectrometer". We have designed it to have a momentum resolution of $\Delta p/p \simeq 5 \times 10^{-4}$ (FWHM), which enables us to have an energy resolution of 1.5 MeV, and a solid angle of 55 msr at 1.3~1.4 GeV/c.

This improvement in the energy resolution is expected to be critical in our spectroscopy. Recent theoretical calculation taking into account nuclear core excitation predicts a complex peak structure [8]. In this case, we can see that an energy resolution of better than 2 MeV is essential to resolve such peak structures and determine the binding energy precisely. Thus high resolution of S-2S will be necessary for the spectroscopy of $S = -2$ hypernuclei.

Assuming the Main Ring should achieve 100 kW beam power, we expect K^- intensity to be $1.9{\times}10^{10}/day$. With this amount of K^- and the target thickness of 3 g/cm^2, the expected yield of $^{12}_{\Xi}$Be hypernuclear state is 110 events for four weeks of data taking, which is about twice larger statistics than that of the previous experiment. Therefore data with not only higher resolution but also higher statistics will be obtained with S-2S at J-PARC.

2.3 Future plan

As a future extension, we also plan to investigate the mass-number and spin dependence of ΞN interaction by using various targets. Especially, lighter hypernuclei are useful to compare experimental results with few body calculations. Heavier hypernuclei are also important for understanding strange nuclear matter.

If more intense beam will be available, we can study direct production of double Λ hypernucleus excited states, cross section of which is expected to be much smaller than Ξ hypernuclei [9]. Also in such a case, high energy resolution will be crucial to observe peak structures clearly.

3. Construction of the S-2S Spectrometer

The construction of the magnets has been started since 2012. Here we introduce the design and status of S-2S.

3.1 Design

S-2S consists of normal conducting magnets with a *QQD* configuration, tracking wire chambers and trigger counters as shown in Fig. 1. In addition, He-bag will be installed inside gaps of magnets to reduce the multiple scattering. Central flight length is 9 m which corresponds that 40 % of K^+ at 1.3 GeV/c survives at the most downstream detector.

Q1 and Q2 are quadrupole magnets for vertical and horizontal focus, respectively. D1 is a dipole magnet with a pole length of 3.67 m. The bending power of D1 is expected to be 70 degrees at 1.37 GeV/c. This *QQD* configuration is the best way to achieve both high momentum resolution and large acceptance. The main parameters of the magnets are shown in Table I. While Q1 and D1 are newly constructed, we use an existing magnet as Q2 after several modifications on the configurations of the poles and coils.

Tracking chambers are placed at the entrance and exit of the magnets. The momentum resolution of $\Delta p/p \simeq 5 \times 10^{-4}$ (FWHM) is expected to be achieved when the position is measured with an accuracy of 200 μm.

As trigger and particle identification counter, a time-of-flight wall (TOF), Aerogel Čerenkov

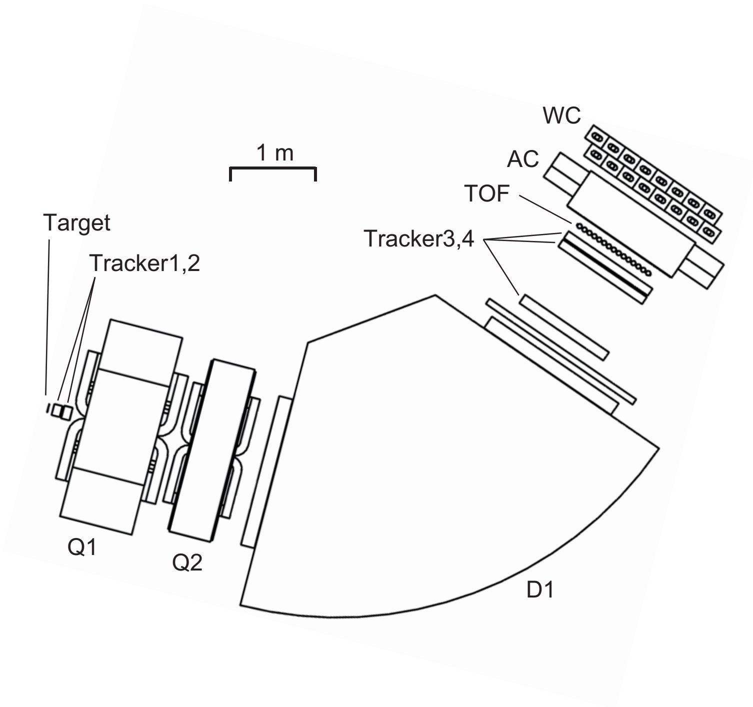

Fig. 1. Schematic of S-2S spectrometer. It consists of three magnets, tracking wire chambers, and three kinds of trigger counters.

Table I. The main parameters of the S-2S magnets. The parameters for Q1 and Q2 are measured values, while those for D1 are design values.

Q1	Pole length	0.88 m
	Aperture	31 cm
	Max. field gradient	8.7 T/m
	Weight	37 ton
Q2	Pole length	0.5 m
	Aperture	36 cm
	Max. field gradient	5.0 T/m
	Weight	11.5 ton
D1	Bending angle	70 degree
	Aperture	31 cm
	Central orbital radius	300 cm
	Max. field strength	1.5 T
	Weight	86.5 ton

counter (AC), and Water Čerenkov counter (WC) are used. These are located after tracking chambers. TOF is a set of plastic scintillators to identify the scattering particles by time-of-flight measurement combined with the flight path obtained from tracking information in off-line analysis. Background pions and protons from various reactions in the target are scattered through S-2S. The rates of them are expected to be two or three orders of magnitude higher than that of kaons. In the momentum range of S-2S, two types of Čerenkov counters are expected to suppress the rates of these backgrounds to acceptable level for DAQ system. Aerogel (n=1.05) is used in AC as a radiator, and is sensitive only to pions. Although water (n=1.33) used in WC is sensitive both to kaons and protons, we can separate these two by the difference in the number of photons generated in the counters. Thus, scattered kaons are identified in on-line trigger as $K^+ = TOF \otimes \overline{AC} \otimes WC$.

3.2 Magnets status

Q1 and Q2 have already been completed in the end of JFY2012 and JFY2013, respectively. Field measurements and calculations also have been done. We have measured the excitation curves and the field distributions at several current values using hall probe. We obtained a field gradient of 8.7 T/m for Q1 and 5.0 T/m for Q2. These results fulfill our requirements of focusing power for a large acceptance. Field calculations have been carried out by using three dimensional electromagnetic analysis software (Opera-3d/TOSCA). The results reproduce the measured field distributions well within ±20 Gauss. By simulation with the different field distributions for event generation and momentum analysis, we estimated this level of difference on quadrupole magnets would not affect on the momentum resolution seriously. We will carry out more precise calculations especially on D1. The results on Q1 measurement and calculation are shown in Fig. 2.

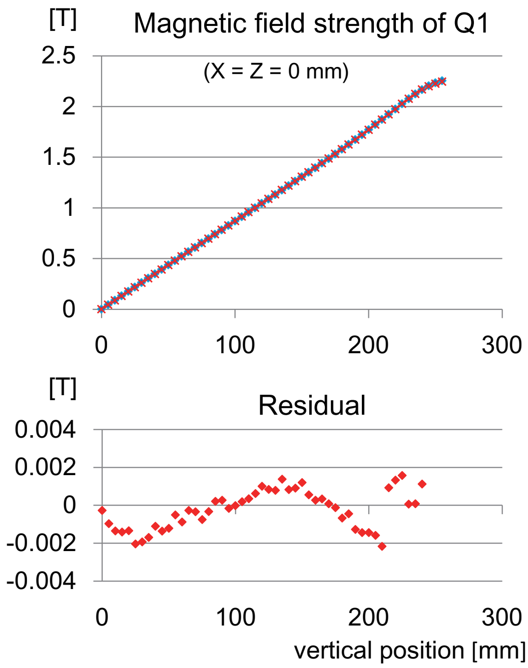

Fig. 2. Field distribution of Q1 magnets. Blue squared markers indicate measured values and red cross markers indicate calculated ones in upper figure. Lower figure shows the residual between measurement and calculation.

Yoke and pole of D1 magnet have completed in March 2014 and only measurement of feature size has been done at present. We are now constructing the coils, and they will be mounted on D1 by the end of JFY2014.

3.3 Detectors status

Existing tracking wire chambers will be utilized except for the second set at the entrance of the magnets, which should be vertically larger than existing ones. Therefore a new chamber is now under design. We have already prepared materials of TOF such as scintillators, and will set them up soon. We also utilize the existing AC, which has worked as a trigger counter in SKS. WC is under development. We made prototypes of WC and test experiments have been carried out. We measured the dependence of the number of photoelectrons on incident beam position, angle, and velocity. According to these results, sufficient suppression efficiency for protons is expected to be realized. We also prepare other materials such as support frame of detectors and minor repairments of chambers. All the detectors will be ready for installation in JFY2015.

4. Summary

We plan to carry out the Ξ hypernuclear spectroscopy in the J-PARC E05 experiment. It will bring a break-through on the study of $S = -2$ hypernuclei. As for experimental preparation, especially the construction of S-2S spectrometer is going well. We will complete the preparation of S-2S in JFY2015, and install it to the K1.8 experimental area as soon as possible. The J-PARC E05 will be the first experiment using S-2S.

References

[1] T. Inoue *et al.*: Prog. Theor. Phys. **124** (2010) 591.
[2] J. Schaffner-Bielich: Nucl. Phys. A **804** (2008) 309.
[3] H. Takahashi *et al.*: Phys. Rev. Lett. **87** (2001) 212502.
[4] T. Fukuda *et al.*: Phys. Rev. C **58** (1998) 1306.
[5] P. Khaustov *et al.*: Phys. Rev. C **61** (2000) 054603.
[6] T. Nagae *et al.*: J-PARC E05 proposal (2006).
[7] T. Takahashi *et al.*: Prog. Theor. Exp. Phys. **2012** (2012) 02B010.
[8] T. Motoba and S. Sugimoto: Nucl. Phys. A **835** (2010) 223.
[9] T. Harada *et al.*: Phys. Lett. B **690** (2010) 363.