PROCEEDINGS OF SCIENCE

New Stage of *S=-2* Hypernuclear Study Opened with a New High-resolution Spectrometer

Shunsuke Kanatsuki[*†,a] **N. Amano,**[a] **H. Ekawa,**[af] **T. Nanamura,**[a] **T. Nagae,**[a] **K. Takenaka,**[a] **T. Gogami,**[‡ab] **M. Moritsu,**[c] **E. Hirose,**[d] **H. Takahashi,**[d] **T. Takahashi,**[d] **S. Kato,**[e] **Y. Ichikawa,**[f]
[a] *Department of Physics, Kyoto University, Kitashirakawa, Japan*
[b] *RCNP, Osaka University, Ibaraki, Japan*
[c] *Department of Physics, Osaka University, Toyonaka, Japan*
[d] *IPNS, KEK, Tsukuba, Japan*
[e] *Yamagata University, Japan*
[f] *JAEA, Tokai, Japan*
E-mail (speaker): `kanatsuki@scphys.kyoto-u.ac.jp`

Spectroscopy of strangeness -2 systems has not been greatly in progress, because of the limited K^- beam intensity to produce such systems and the limited energy resolution to identify them. Increasing K^- beam intensity at J-PARC will enable us to carry out the spectroscopy by improving the energy resolution of the spectrometers in one order of magnitude from 14 MeV to $\lesssim$2 MeV. The status of the new spectrometer $S-2S$ is reported.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

*Speaker.

†This work was supported by JSPS KAKENHI Grant Numbers 23000003, JP16H02186, and JSPS Fellows 13J01075.

‡Present address: Tohoku University

PoS(INPC2016)081

1. Introduction

In the nuclear matter at the density of 2–3 times the nuclear saturation density, ρ_0, the strangeness degrees of freedom should play an essential role. Such a high-density condition is believed to be realized in the core of neutron stars. At such high density, the neutron Fermi energy would become larger than the mass difference between a Λ hyperon (1115 MeV/c^2) and a nucleon (939 MeV/c^2) and a lot of strangeness, Λ hyperons, would be created because of the attractive potential, U_Λ felt by the Λ hyperons in high density neutron matter. Thereby, the Fermi pressure would be reduced by strangeness degrees of freedom. The experimental information on U_Λ was obtained to be 30$\pm$1 MeV from the binding energy of heavy Λ hypernuclei up to ${}^{208}_{\Lambda}$Pb.

Another important feature of the strangeness is that *s* quark has negative charge of $-1/3e$. Therefore the hyperons have negative charge states such as Σ^- and Ξ^-. In the case of nucleons, proton and neutron, with *up* ($+2/3e$) and *down* ($-1/3e$) quarks, there are no negatively charged baryons. Thus, from the charge neutrality condition, the number of electrons can be converted to the number of negative hyperons which greatly reduce the electron Fermi energy in the chemical balance of

$$\frac{{p_F^e}^2}{2m_e} + m_e = \frac{{p_F^Y}^2}{2m_Y} + m_Y + U_Y. \tag{1.1}$$

Here, it is important to know the hyperon potentials, U_Y. The lightest negative hyperon, Σ^- (1197.4 MeV/c^2), has strongly repulsive potential of $U_\Sigma \sim +30$ MeV. Therefore, the Σ^- would not appear in neutron stars. The next candidate is Ξ^- (1321.7 MeV/c^2). At this moment, we have no definite information on the U_Ξ. Therefore, it is awaited to have a good estimate of U_Ξ from the binding energy measurements of the Ξ hypernuclei.

In principle, we could obtain the Ξ-*N* interaction information through Ξ-*p* scattering measurements directly; elastic scattering of $\Xi p \to \Xi p$ and inelastic scattering of $\Xi p \to \Lambda\Lambda$. However, it is not so easy to perform such scattering measurements because of the short life time of Ξ^-.

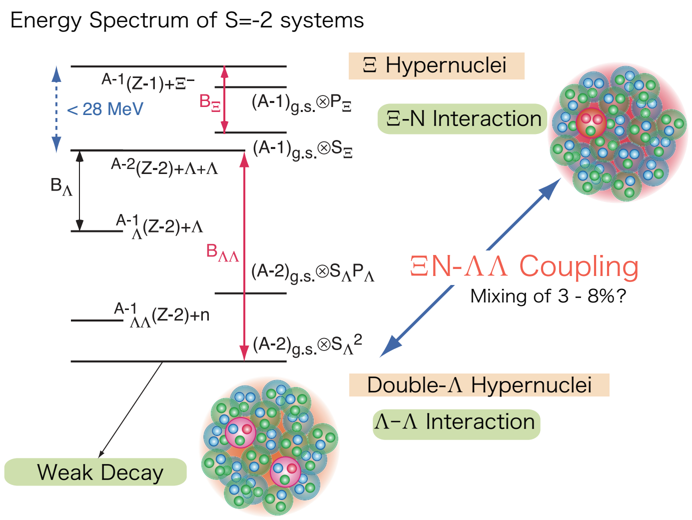


Figure 1: Schematic energy spectrum of $S = -2$ hypernuclei. The Ξ hypernuclei and double-Λ hypernuclei are only separated by 28 MeV, and couple through the $\Xi^- p \to \Lambda\Lambda$ interaction.

There are two emulsion events which have a unique identification of a double-Λ hypernucleus, ${}^{6}_{\Lambda\Lambda}$He (Nagara event [1, 2]) and a deep bound state of Ξ^--^{14}N system (Kiso event [3]). These two emulsion events suggest the Λ-Λ interaction is weakly attractive by 0.67±0.17 MeV and the existence of strongly bound Ξ hypernuclear state. Thus, the spectroscopy of strangeness (*S*) -2 systems could be possible. It should be also noted that the Ξ-*N* system and Λ-Λ system are energetically only separated by $\lesssim$28 MeV and there could be strong coupling through the $\Xi^- p \to \Lambda\Lambda$ process [4].

2. Spectrometers for the S=-2 Hypernuclei

The direct production of Ξ hypernuclei via the (K^-,K^+) reaction was theoretically investigated by Dover and Gal [5]. The incident momentum dependence of the forward cross section of the $K^- + p \to K^+ + \Xi^-$ reaction had a broad bump structure peaking at about 1.8 GeV/*c* from the old bubble chamber data. The recoil momentum of the Ξ^- in this reaction is as large as ∼550 MeV/*c*. It means the sticking probability of the Ξ^- would be small; the production cross section of the order of 10–100 nb/sr was estimated. Therefore, we need a high-intensity ($\gtrsim 10^6 K^-$/s) and good-purity ($K^-/\pi^- \gtrsim 1$) K^- beam line such as BNL AGS D6 beam line [6] and K1.8 beam line at J-PARC [7].

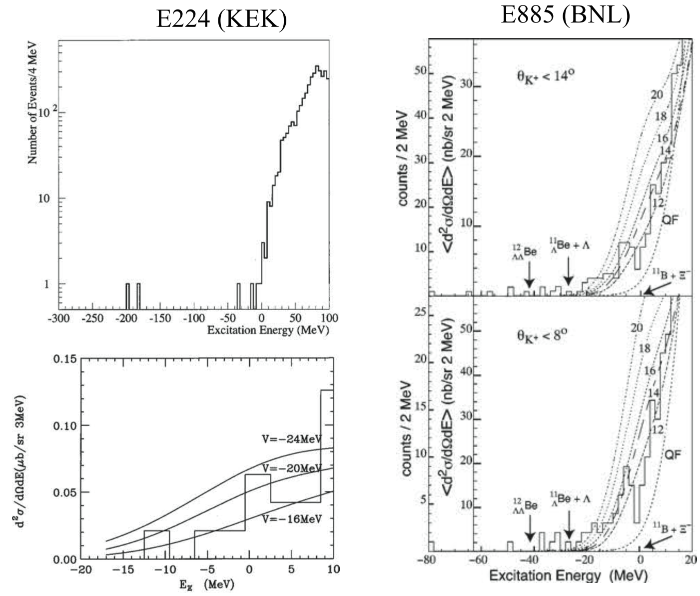


Figure 2: Examples of the ^{12}C(K^-,K^+) spectra obtained in the KEK E224 [8] and BNL E885 [9] experiments.

The outgoing K^+ momentum is about 1.3 GeV/*c*, which is rather high momentum. Therefore, we need a good magnetic spectrometer to perform the (K^-,K^+) missing-mass spectroscopy in high resolution. There were two experiments to measure the ^{12}C(K^-,K^+) spectra searching for ${}^{12}_{\Xi}$Be in KEK E224 [8] and in BNL E885 [9]. The former measurement was suffered by low beam intensity and poor energy resolution. The latter measurement claimed evidence of the Ξ hypernuclear production in the bound region. However, the bound state peak was not observed

	KEK E224	BNL E885	E05 Pilot Run	E05 with S-2S
Solid Angle (msr)	90	50	110	60
θ_{Lab}^{max} (deg.)	12	14	16	8
Mass resolution (FWHM) (MeV)	22	14	6	$\lesssim$2

Table 1: Specifications of the spectrometers for the ^{12}C(K^-, K^+) reaction.

due to the limited energy resolution. Recently, we have performed a same measurement of the ^{12}C(K^-, K^+) reaction at the K1.8 beam line of J-PARC by using an existing SKS spectrometer system. So far the best energy resolution of 5.4 MeV$_{FWHM}$ was achieved in the pilot run[1]. It was a pilot run of the J-PARC E05 experiment, in which we are constructing a new spectrometer called "Strangeness -2 Spectrometer ($S-2S$)".

Here, we listed a summary of the spectrometer specifications in these two experiments, in a pilot run of J-PARC E05, and in J-PARC E05 with $S-2S$. With the new spectrometer $S-2S$, we aim to improve the energy resolution by one order of magnitude compared with that for the BNL E885. The large solid angle acceptance is also required to acquire enough yields.

3. S-2S Spectrometer

A schematic layout of the $S-2S$ spectrometer for the J-PARC E05 experiment is shown in Fig. 3. The K^- beam at 1.8 GeV/c is used for the production of Ξ hypernuclei. The incident momentum is analyzed with a beam line spectrometer system composed of *QQDQQ* in the K1.8 beam line of the J-PARC hadron experimental hall. The momentum resolution is designed to be $3.3\times10^{-4}_{FWHM}$.

The K^+'s scattered at forward angles from the (K^-, K^+) reaction are momentum analyzed with the $S-2S$ spectrometer. The $S-2S$ is composed of two quadrupole magnets and one dipole magnet (*QQD*). The first quadrupole magnet focuses the particles in vertical, and the next one in horizontal. A large aperture of the two quadrupole magnets keeps the solid angle as large as 60 msr. The bending angle for the central momentum of the dipole magnet is 70 degrees at 1.37 GeV/c. The specifications of the magnet are listed in Table 2. The momentum acceptance of the $S-2S$ ranges from 1.2 to 1.6 GeV/c with the solid angle acceptance larger than $\sim$30 msr. The K^+'s decay in fight, so that the flight length is kept as short as 9 m with a survival rate of 40%. The design momentum resolution of the $S-2S$ is $5\times10^{-4}_{FWHM}$.

The K^+ trigger signals are generated with a time-of-flight scintillation counter (TOF), an aerogel Čerenkov counter (AC: refractive index n=1.055) for π^+ veto, and a water Čerenkov counter (WC: n=1.33) for proton veto [10], as $TOF \otimes \overline{AC} \otimes WC$. The particle identification is carried out with the TOF counter in off-line analyses by correcting the flight path and momentum obtained from the tracking in $S-2S$.

[1]A preliminary result of the E05 pilot run was reported by T. Nagae in this conference.

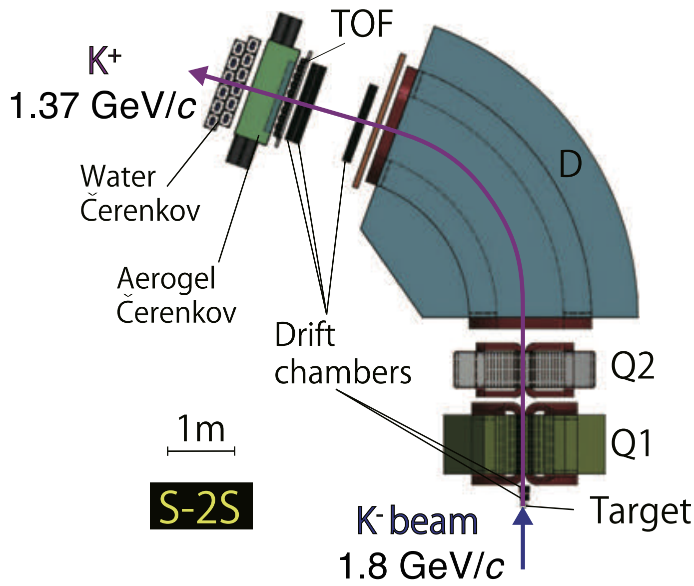


Figure 3: Schematic view of the S-2S spectrometer system.

	Q1	Q2		D1
Field Gradient (T/m)	8.72	5.0	Field Strength (T)	1.5
Aperture (cm)	31	36	Pole Gap (cm^2)	32×80
Weight (ton)	37	12	Weight (ton)	86

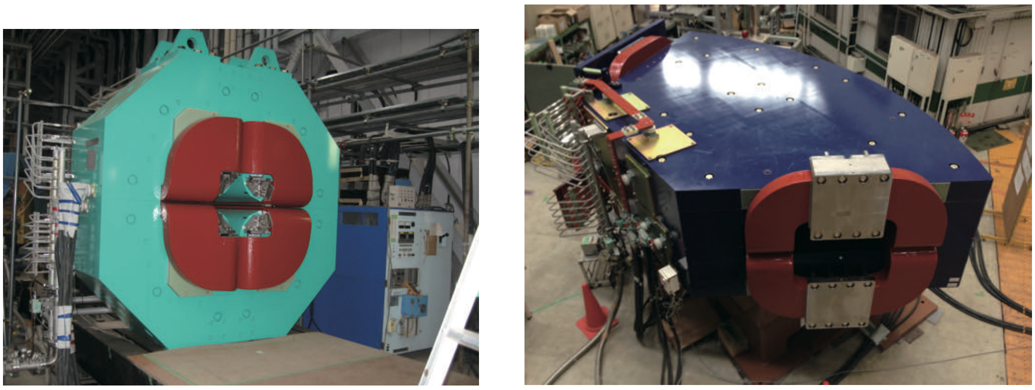
Table 2: Specifications of the magnets for the $S-2S$.

4. Status of S-2S Spectrometer

The $S-2S$ spectrometer system is now under construction. All the magnets were already constructed (see Fig. 4); Q1 in March 2013, Q2 in March 2014, and D1 in May 2015. The basic performance of the magnets (Table 2) was demonstrated safely.

In order to analyze the K^+ momentum, the magnetic-field map of the $S-2S$ system is necessary. Since the magnetic field measurement with three magnets in their regular positions is difficult, we have measured the field map for each magnet separately. These measured field maps are compared with the calculated field maps by using a three-dimensional finite-element method Opera3D/TOSCA. By optimizing the B-H curve for the irons, we have succeeded to reproduce the Q1 magnetic field within an accuracy of ± 20 Gauss (Fig. 5). Reproducing the field map of each magnet, the field map of the three-magnet system will be calculated with the same code by placing all the three magnets. Of course, this will be a starting point of the field map to be used for momentum analyses in the $S-2S$. We need to optimize the field map by using the $K^- + p \to K^+ + \Xi^-$ events as the calibration source.

The detector parts of the $S-2S$ system are also almost ready for installation. We have developed a water Čerenkov detector for the $S-2S$ to reduce the proton trigger background by one



(a) Q1 (b) D1

Figure 4: Pictures of the (a) Q1 and (b) D1 magnets of the $S-2S$ spectrometer system.

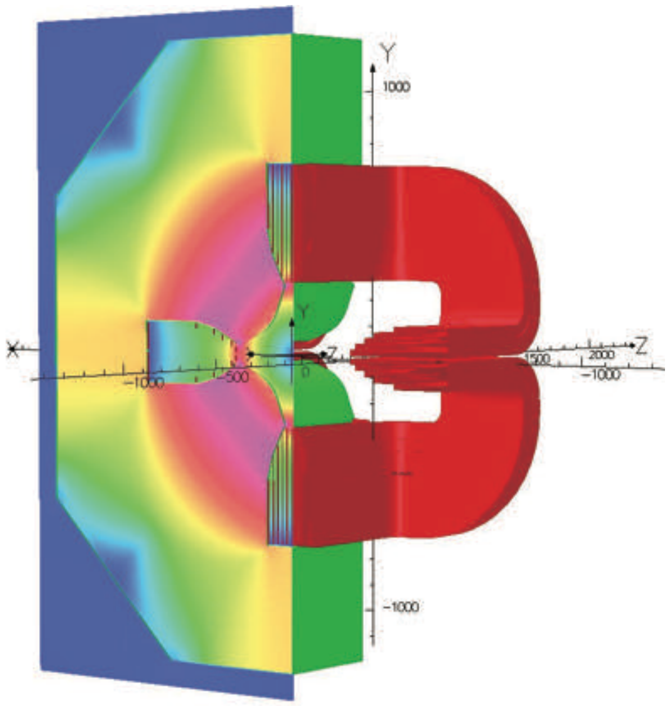


Figure 5: Simulated magnetic-field map of the Q1 magnet of the $S-2S$ spectrometer system.

order of magnitude. The aerogel Čerenkov detector is expected to reject π^+'s more than 99.7%. The TOF counter is also ready for installation. Several drift chambers need maintenance and the front-end electronics should be fabricated in a year or so.

We plan to install the $S-2S$ system in the K1.8 beam line in 2018. We hope to have a better intensity of the K^- beam achieved in a pilot run of the J-PARC E05 in 2015. At that time, the K^- intensity was 6×10^5/ 5.52 seconds with the primary proton beam power of 39 kW. We observed about 40 events of signals for 10 days of data taking [2]. A projected run condition in 2018 is summarized in Table 3

Run conditions	E05 pilot run	Next run in 2018
K^- intensity	0.6 M/spill	1.23 M/spill
MR beam power (kW)	39	80
Spill cycle	5.52 s	4 s
Target thickness	9.3 g/cm^2	10 g/cm^2 active
Spectrometer acceptance	110 msr	60 msr
Missing-mass resolution (FWHM)	6 MeV	$\lesssim$2 MeV
Signal events / days of run	40/10 days	$\sim$120/20 days

Table 3: Estimate of the expected yield in the next E05 run in 2018.

5. Summary

We plan to perform the $S = -2$ hypernuclear spectroscopy with the (K^-, K^+) reaction at the K1.8 beam line of J-PARC in the unprecedented energy resolution of better than 2 MeV. A new spectrometer $S-2S$ dedicated for the reaction is in construction, and will be ready for data taking in 2018. It will reveal the $S = -2$ hypernuclear world of Ξ hypernuclei and double-Λ hypernuclei and their coupling, for the first time. These information is the key to establish the modern picture of baryon-baryon interactions, and to understand the role of strangeness in high-density nuclear matter.

References

[1] H. Takahashi *et al.*, *Observation of a* ${}^{6}_{\Lambda\Lambda}$*He double hypernucleus*, Phys. Rev. Lett. **87**, 212502 (2001). doi:10.1103/PhysRevLett.87.212502

[2] J. K. Ahn *et al.* [E373 (KEK-PS) Collaboration], *Double-*Λ *hypernuclei observed in a hybrid emulsion experiment*, Phys. Rev. C **88**, no. 1, 014003 (2013). doi:10.1103/PhysRevC.88.014003

[3] K. Nakazawa *et al.*, *The first evidence of a deeply bound state of* Ξ-^{14}*N system*, PTEP **2015**, no. 3, 033D02 (2015). doi:10.1093/ptep/ptv008

[4] T. Harada, Y. Hirabayashi and A. Umeya, Nucl. Phys. A **914**, 85 (2013). doi:10.1016/j.nuclphysa.2013.01.020

[2] Again, please refer to the report by T. Nagae for the preliminary result of the E05 pilot run in this conference.

[5] C. B. Dover and A. Gal, Ξ *Hypernuclei*, Annals Phys. **146**, 309 (1983). doi:10.1016/0003-4916(83)90036-2

[6] P. H. Pile *et al.*, *A New 1-GeV/c to 2-GeV/c separated beam for BNL*, Nucl. Instrum. Meth. A **321**, 48 (1992). doi:10.1016/0168-9002(92)90376-F

[7] K. Agari *et al.*, *Secondary charged beam lines at the J-PARC hadron experimental hall*, PTEP **2012**, 02B009 (2012). doi:10.1093/ptep/pts038

[8] T. Fukuda *et al.* [E224 Collaboration], *Cascade hypernuclei in the (K^-,K^+) reaction on ^{12}C*, Phys. Rev. C **58**, 1306 (1998). doi:10.1103/PhysRevC.58.1306

[9] P. Khaustov *et al.* [AGS E885 Collaboration], *Evidence of Ξ hypernuclear production in the $^{12}C(K^-,K^+)^{12}_{\Xi}Be$ reaction*, Phys. Rev. C **61**, 054603 (2000) doi:10.1103/PhysRevC.61.054603 [nucl-ex/9912007].

[10] T. Gogami, N. Amano, S. Kanatsuki, T. Nagae and K. Takenaka, *Development of water erenkov detector for on-line proton rejection in Ξ hypernuclear spectroscopy via the (K^-,K^+) reaction*, Nucl. Instrum. Meth. A **817**, 70 (2016) doi:10.1016/j.nima.2016.02.021 [arXiv:1511.02472 [physics.ins-det]].