Proposal for J-PARC 50 GeV Proton Synchrotron

Production of Neutron-Rich Λ-Hypernuclei with the Double Charge-Exchange Reaction

(Revised from P10 "Study on Λ-Hypernuclei with the Charge-Exchange Reactions")

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Abstract

We propose experiments to produce neutron-rich Λ-hypernuclei by using the (π^-,K$^+$) double charge-exchange reaction. The neutron-rich Λ-hypernuclei $^{9}_{\Lambda}$He and $^{6}_{\Lambda}$H, which have never produced experimentally, may be produced for the first time by using the K1.8 secondary beamline and SKS in the very early stage of Day-1. The structure of the new hypernuclear species will provide us important information on the ΛN strong interaction in a neutron-rich environment.

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1 Changes from the previous proposal (P10)

In the previous proposal, P10 “Study on Λ-Hypernuclei with the Charge-Exchange Reactions”, we proposed to carry out a series of experiments by using single and double charge-exchange reactions. The subjects of the experiments were the production of neutron-rich hypernuclei and the detailed studies on the ΛN weak interaction. Although the subjects had a weak coupling each other in concepts of physics, both studies required a high intensity beamline in the ultimate goal, and then we arranged the experiments in one proposal. On the previous proposal, PAC pointed out “*the lack of a unique installation for the whole series of measurements*” and requested “*a more detailed scheduling of the activities*”.

Following the comments from PAC, we decided to update the previous proposal as two separated experimental proposals to respond to the comments clearly and unambiguously. In this proposal, we discuss on the experiments to produce neutron-rich hypernuclei, which have never well studied, by using the double charge-exchange (DCX) reactions. The structure of the new hypernuclear species will provide us information on the ΛN strong interaction in a neutron-rich environment for the first time.

2 Introduction

The Λ-hypernucleus was identified experimentally for the first time in 1953 in a nuclear emulsion exposed to cosmic rays[1]. Since then, number of experiments have been carried out, innovative methods/techniques have been developed and many aspects of the Λ-hypernuclei have become clear.

One important subject of the studies on the Λ-hypernuclei in the past was the study of the Λ-hypernucleus as another nucleus with the strangeness degrees of freedom. Precise measurements of level structures of the Λ-hypernuclei made it possible to study the hyperon-nucleon strong interaction. In this proposal, we discuss studies to extend the information to neutron-rich Λ-hypernuclei.

2.1 Status of study on level structures of Λ-hypernuclei

The similarity of the Λ hyperon with nucleons is one of key properties which brings the rich spectra of the Λ-hypernuclei. The ΛN attractive interaction is strong enough to form huge number of particle-stable Λ-hypernuclei. The Λ hyperon behaves like the 3rd “nucleon” in a core nucleus and Λ single-particle like states coupled to the core nucleus states are clearly observed in the hypernuclear level structures[2, 3]. The bulk properties of the Λ-nucleus interaction have been known and also the details of the interaction, the spin-dependent interaction, have been investigated from the early stage of the experimental studies at CERN-PS and BNL-AGS[4, 5, 6] because it has been well known that the spin-dependent interaction played an important role in the structure of the ordinary nuclei.

Significant progresses were made on the study of the spin-dependent Λ-nucleus interaction after the end of 1990’s. A small but finite value of the spin-orbit Λ-nucleus interaction was determined for the first time from the BNL-AGS experiment by the γ-ray spectroscopy with NaI(Tl) detectors in 1998[7]. Another epoch-making progress was the success of the γ-ray spectroscopy with germanium detectors at KEK-PS and BNL-AGS in 1998, and strength of the spin-dependent interactions, including spin-spin, spin-orbit and tensor interactions, became clear after a series of experiments[8, 9]. The hypernuclear level structure and the spin-dependent interactions in hypernuclei obtained from these experiments gave essential infor-

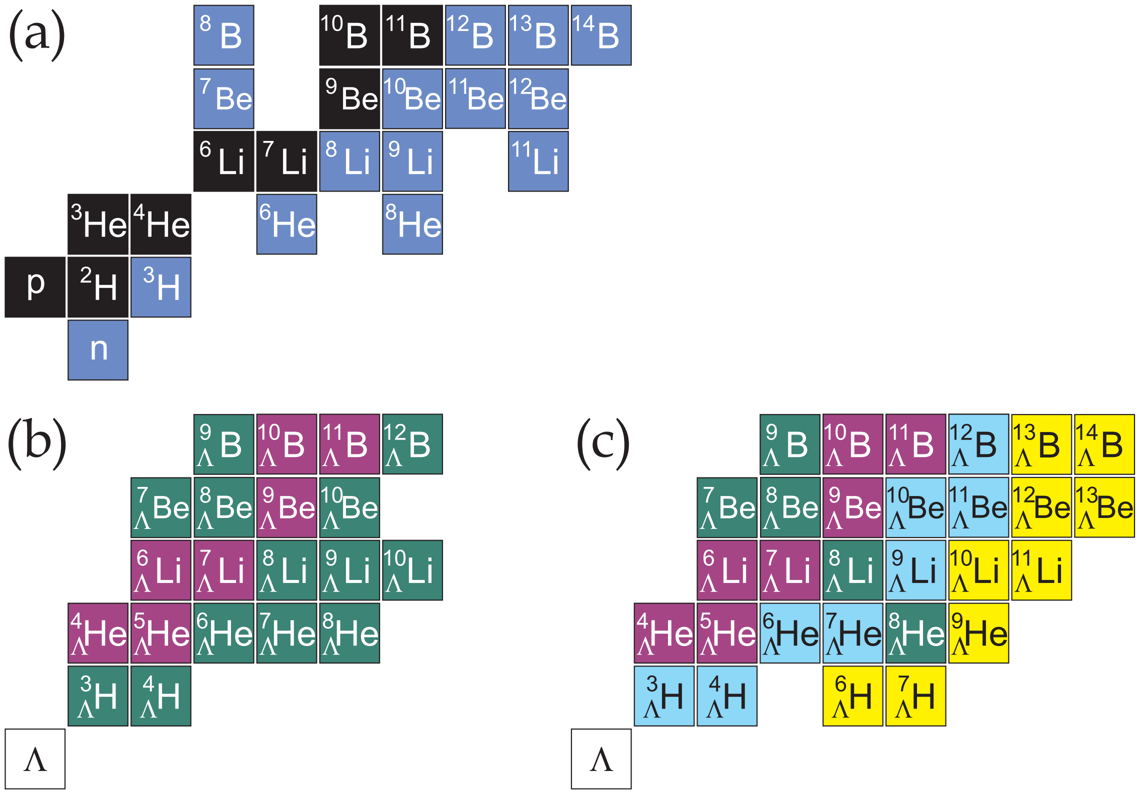

Figure 1: (a) nuclear chart of light particle-stable nuclei. (b) chart of hypernuclei ever produced in the past experiments. Purple boxes correspond to directly produced hypernuclei via (K^-, π^-) and (π^+, K^+) reactions on stable targets and green boxes correspond to hypernuclei observed as fragments in the emulsion experiments. (c) blue boxes show hypernuclei to be produced by single charge-exchange reactions and yellow boxes correspond to hypernuclei to be produce via (K^-, π^+) and (π^-, K^+) reactions on stable targets.

mation on the underlying ΛN interaction. So, studies on the strong interaction between a Λ hyperon and a nucleon have entered to a new era.

2.2 DCX reaction for production of neutron-rich Λ-hypernuclei

As we mentioned above, the ΛN interaction is attractive and the addition of the Λ-hyperon into a nucleus increases the total binding energy, so we expect the “hypernuclear chart” is even richer than the ordinary “nuclear chart”. On the other hand, up to now, we surveyed only a small fraction of hypernuclei in the hypernuclear chart. One of main reasons of the limited survey was that we mainly used (K^-, π^-) and (π^+, K^+) reactions to produce the Λ-hypernuclei. Figure 1(b) shows hypernuclei so far identified; purple ones were directly produced via (K^-, π^-) and (π^+, K^+) reactions on stable targets and green ones were observed as fragments in the emulsion experiments. The chart of hypernuclei looks compatible with that of ordinary nuclei (Fig.1(a)), but the information on the hyperfragments from the emulsion experiments were quite limited in comparison with that from the direct reactions. To survey wider area of the hypernuclear chart in more detail, we need new spectroscopic tools. If we employ the charge exchange reactions, we can directly produce many neutron-rich hypernuclei on stable targets as shown in Fig.1(c); hypernuclei in the blue boxes are produced by single charge-exchange reactions and yellow ones are by double charge-exchange reactions.

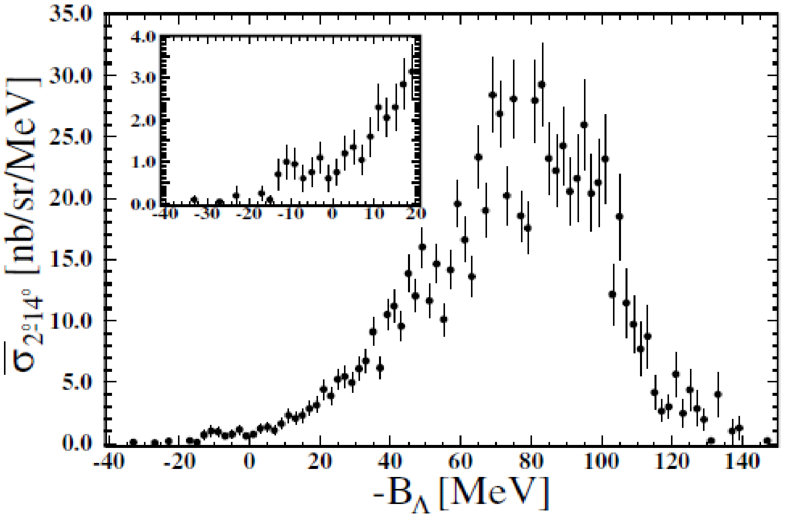

Figure 2: Excitation energy spectrum of the ${}^{10}_{\Lambda}$Li hypernucleus for the (π^-, K^+) reaction on a ^{10}B target from Ref.[12]. The inset shows closeup of the Λ bound region. The amount of possible background can be estimated from entries in the region $-B_\Lambda < -20MeV$, and is small.

A pilot experiment to produce Λ-hypernuclei away from the stability-line was performed at KEK-PS by using the $(K^-_{Stopped}, \pi^+)$ reaction[10]. Starting from ordinary nuclear targets, the double charge-exchange (DCX) reaction may produce neutron-rich Λ-hypernuclei. In the KEK-PS experiment, only upper limits were obtained for the production rates of the neutron-rich Λ-hypernuclei (${}^{6}_{\Lambda}$He, ${}^{12}_{\Lambda}$Be and ${}^{16}_{\Lambda}$C) due to tiny branching ratios to the DCX channel and a huge background from the in-flight decay process of Σ^+, $\Sigma^+ \to n\pi^+$. An improved study with the $(K^-_{Stopped}, \pi^+)$ reaction is in progress by the FINUDA collaboration at Frascati-DAΦNE[11], but the clear identification of the production of the neutron-rich hypernuclei was not yet accomplished. Another experiment to produce not only neutron-rich but also proton-rich hypernuclei is planned by using relativistic heavy ion beams at GSI.

The other promising DCX reaction to produce and to investigate the neutron-rich hypernuclei is the (π^-, K^+) reaction. A neutron-rich hypernucleus, ${}^{10}_{\Lambda}$Li, was attempted to produce at KEK-PS by the (π^-, K^+) reaction for the first time[12]. In the experiment, clear signal events were observed in the Λ bound region in the excitation energy spectrum of the hypernucleus (-13MeV$< -B_\Lambda <0$ MeV) as shown in Fig.2. Although the production cross section of the ${}^{10}_{\Lambda}$Li hypernucleus was estimated to be very small ($\sim$10nb/sr), roughly 10^{-3} of that of the (π^+, K^+) reaction (10 μb/sr, typically), the experimental data may provide completely new information on the structure of the Λ-hypernuclei with a large number of excess neutrons (${}^{10}_{\Lambda}$Li consists of 3 protons, 6 neutrons and a Λ hyperon). Compared with the $(K^-_{Stopped}, \pi^+)$ reaction, the (π^-, K^+) reaction is almost background free at the Λ bound region (see the $-B_\Lambda < -20$MeV region in Fig.2). The production of the neutron-rich hypernuclei with the (π^-, K^+) reaction may open doors to new fields of studies as described in the following.

2.2.1 Production of neutron-rich and exotic Λ-hypernuclei

Marjling pointed out that we might produce neutron-rich Λ-hypernuclei by the double charge-exchange (DCX) reactions, and the neutron-rich hypernuclei could be quite exotic[13]. The DCX reactions on the ^{6}Li or ^{7}Li target would produce the ${}^{6}_{\Lambda}$H or ${}^{7}_{\Lambda}$H hypernucleus, which would

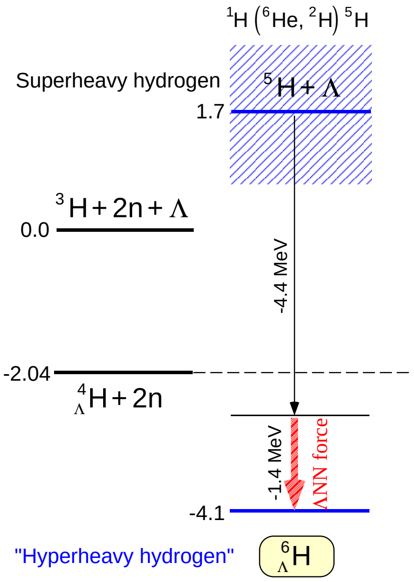

Figure 3: Formation of ${}^{6}_{\Lambda}$H, "hyper-heavy hydrogen", discussed in Ref.[14]. The exotic ${}^{6}_{\Lambda}$H hypernucleus has a resonance state of ^{5}H, "super-heavy hydrogen", as the nuclear core.

be a very exotic nucleus with a large neutron to proton ratio, N/Z=4 for ${}^{6}_{\Lambda}$H or N/Z=5 for ${}^{7}_{\Lambda}$H.

A possibility of a binding of the ${}^{6}_{\Lambda}$H ground state, "hyper-heavy hydrogen", was discussed theoretically by Akaishi, *et al.*[14] as seen in Fig.3. The ground state of the core nucleus, ^{5}H, is known as a broad resonance state ($E_X \sim 1.7 MeV$) and is called "super-heavy hydrogen"[15]. The resonance state may be bound due to the attractive interaction between the Λ hyperon and the core nucleus. We may expect large structure change of the core nucleus beyond the neutron drip line by the addition of the Λ hyperon.

2.2.2 Study on two- and three-body interactions in Λ-hypernuclei

Since the mass difference between the Λ and Σ hyperons is small, $M_\Sigma - M_\Lambda \sim 80$MeV/c^2, compared with that of the nucleon and Δ isobar, $M_\Delta - M_N \sim 290$MeV/c^2. This situation makes the effect of the ΛN-ΣN channel-coupling quite important in the discussion of the hypernuclear level structure[16]. The strong ΛN-ΣN coupling introduce an additional effective two-body interaction between Λ and nucleon, and also may be a source of the three-body interaction among the ΛNN subsystem in a Λ-hypernucleus as recently discussed by Akaishi, *et al.*[17]. This effect may manifest itself in a Σ^- component of the Λ hypernuclear states, which can be useful to produce neutron-rich hypernuclei by the (π^-, K^+) reaction (see Sec.2.2.5 for more details).

2.2.3 Connection to astrophysics: ingredients of neutron stars

The knowledge obtained from this study will give a feed back not only to the nuclear physics but also to other fields like astrophysics. It has been intensively discussed that hyperons in a high-density nuclear matter in neutron stars play a significant role concerning the maximal mass of neutron stars, formation-scenario and a thermal and structural evolution of neutron stars and black holes[18]. Namely, the presence of hyperons in a neutron star makes the Equation of State (EoS) much softer than that without hyperons. In particular, the role of the Σ^- mixing in a neutron star is being intensively discussed in the present days because of a negative charge of the Σ^- hyperon[19]. However, the mixing particularly depends on the Σ^-N interaction.

Recently, we measured the inclusive (π^-, K^+) spectra on different medium to heavy nuclear targets in order to obtain the Σ^--nucleus optical potential which has not been well known[20]. The experimental spectrum of a Si target was compared with a theoretical calculation based on the Distorted-Wave Impulse Approximation (DWIA), and it showed that a very strong repulsive Σ^--nucleus potential was needed to reproduce the observed spectral shape[21]. Then, Σ^- hyperons may not appear in the neutron star for a repulsive Σ^-N interaction. On the other hand, in a recent calculation by Shinmura *et al.*[22], the ΛN-ΣN mixing was found very significant at a high density, particularly, a large ΛN-Σ^0N mixing was reported. It would be very interesting to see some effects by the ΛN-ΣN mixing experimentally in the study of neutron-rich hypernuclei.

2.2.4 Study on Λ-hypernuclei with neutron halo

In the conventional nuclear physics, studies of neutron-rich nuclei near the neutron drip line have been done extensively over the years, and as a result so-called a “neutron skin” and a “neutron halo” have been discovered. The structures of such nuclei have revealed interesting phenomena regarding its size, properties of excited states and so on[23, 24]. It is also interesting and necessary to study such a neutron-rich nucleus containing a Λ hyperon, which may change properties of a halo nucleus. The structures of light Λ-hypernuclei with the neutron skin or halo were already discussed theoretically[25] and we may expect rich variations of the structures.

2.2.5 Reaction mechanism: one- or two-step mechanism ?

As we mentioned, we think the DCX reaction is one of promising reactions to investigate the neutron-rich Λ-hypernuclei, but the reaction mechanism is not well understood, yet. The DCX reaction changes two protons in a nucleus to a Λ hyperon and a neutron, pp$\rightarrow\Lambda$n, so a naive explanation of the reaction is the two-step process, such as:

$$\pi^- pp \rightarrow K^0 \Lambda p \rightarrow K^+ \Lambda n$$

$$\pi^- pp \rightarrow \pi^0 pn \rightarrow K^+ \Lambda n.$$

A theoretical calculation based on the two-step mechanism has been made[26]. The calculation predicted the $^{10}\mathrm{B}(\pi^-, K^+)^{10}_{\Lambda}\mathrm{Li}$ reaction cross section of 66.8 nb/sr at a 1.05 GeV/c pion beam momentum. The predicted reaction cross section was considerably larger than the experimental results, $\sim$10 nb/sr. Another theoretical prediction was that the DCX reaction cross section from the two-step process had a maximum at around the 1.05 GeV/c beam momentum. The result reflected the fact that the single charge-exchange reactions, the (π^-, K^0) and (π^0, K^+) reactions, involved in the two-step process had large cross sections around 1.05 GeV/c. However, the theoretical prediction had a conflict with the results from the KEK-PS-E521 experiment, in which the DCX reaction cross section was larger at the 1.20 GeV/c beam momentum ($\sim$11 nb/sr) than that at 1.05 GeV/c ($\sim$6 nb/sr).

A model which may explain the beam momentum dependence of the DCX reaction cross section is the one-step mechanism through the ΛN-ΣN mixing. In the one-step mechanism, a Σ^- hyperon is produced by the DCX reaction, π^-p$\rightarrow K^+\Sigma^-$. Since the Σ^- hyperon may be mixed with a Λ hyperon in a nucleus by the ΛN-ΣN mixing, “Σ^-p”$\leftrightarrow$“Λn”, the Λ state may be excited directly by the one-step reaction:

$$\pi^- pp \rightarrow K^+(\Sigma^- p) \leftrightarrow K^+ \Lambda n.$$

The DCX reaction cross section by the one-step mechanism depends on the elementary $p(\pi^-, K^+)\Sigma^-$ reaction cross section and the degrees of the ΛN-ΣN mixing in the Λ-hypernucleus to be created. Since the $p(\pi^-, K^+)\Sigma^-$ reaction has a production threshold at around 1.035 GeV/c in the pion beam momentum, the reaction cross section increases rapidly from 1.05 GeV/c to 1.20 GeV/c. The beam momentum dependence of the elementary $p(\pi^-, K^+)\Sigma^-$ reaction cross section may accord with the experimental DCX reaction cross sections. However, the absolute values of the cross sections estimated from the one-step mechanism depend also on the degrees of the ΛN-ΣN mixing directly, and a considerable amount of the mixing (a few times 10^{-3}) is necessary to reproduce the experimental cross sections.

3 Proposed Experiments

Our strategy of the study on the neutron-rich Λ-hypernuclei is to use high intensity pion beams, 10^7 particle/spill, available in the very early stage of Day-1 at the K1.8 secondary beamline (see Fig.4), which has capabilities of clean separation of pion and kaon beams and an excellent momentum resolution ($\Delta p/p = 1.4 \times 10^{-4}$). The Superconducting Kaon Spectrometer (SKS), which has a large acceptance (∼100 msr) and a good momentum resolution, exists at KEK, will be transferred to J-PARC and available at Day-1. The combination of the K1.8 beamline and SKS provides us an opportunity to start the studies on the neutron-rich Λ-hypernuclei without any additional installation. Details on the design of the experiments is described in the following.

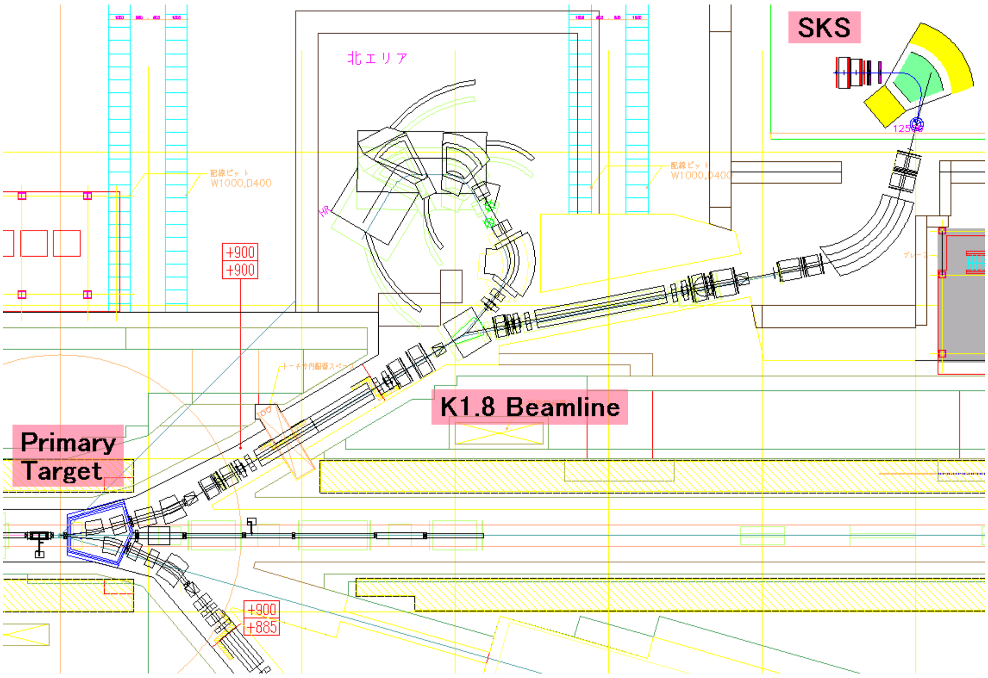

Figure 4: Floor plan of the primary target, K1.8 beamline and SKS spectrometer at Day-1. These equipments will be ready at the early stage of Day-1.

We chose two nuclear targets, ^{9}Be and ^{6}Li, to produce the neutron-rich hypernuclei $^9_\Lambda$He and $^6_\Lambda$H, respectively, by the (π^-, K^+) reaction. The $^9_\Lambda$He hypernucleus will be bound because of the bound core nucleus ^{8}He, whereas the $^6_\Lambda$H hypernucleus may be bound or may not, and

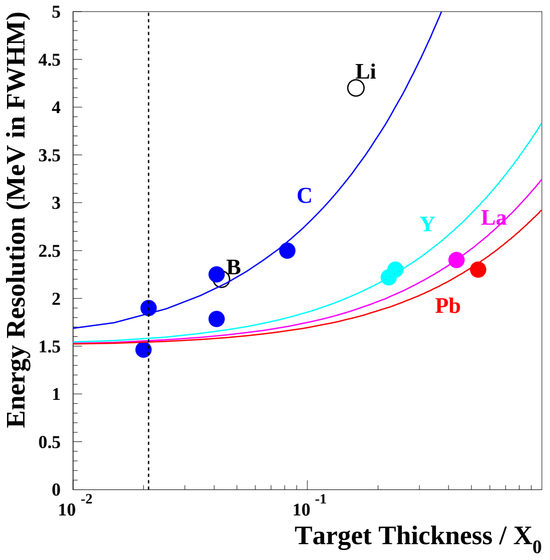

Figure 5: Excitation energy resolutions achieved in the past experiments with SKS as a function of the target thicknesses in a unit of radiation lengths (circles). See text for more details.

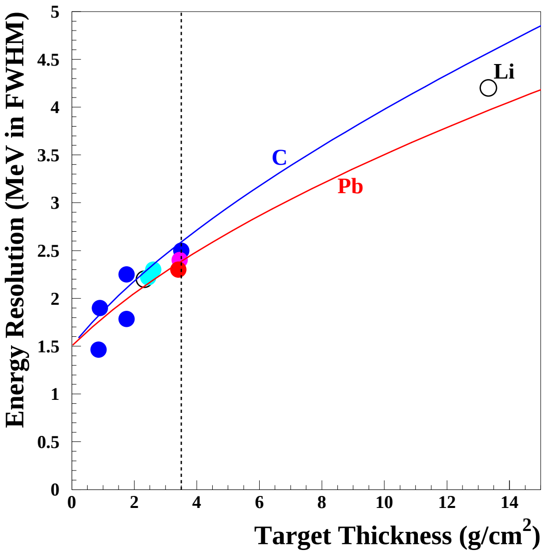

Figure 6: Same plot as Fig.5 with a horizontal axis in a unit of g/cm^2.

more challenging. Please note that even a little unbound ${}^{6}_{\Lambda}$H will be identified in this missing mass spectroscopy method.

The K1.8 beamline will be operated at the nominal momentum of 1.20 GeV/c. SKS will be used for the K^+ detection. The large acceptance together with the good energy resolution of SKS is quite suitable for this kind of experiments with tiny production cross sections. Figures 5 and 6 show summaries of excitation energy resolutions achieved by SKS in the past experiments[3, 12, 27, 28, 29] as a function of the target thicknesses in the units of the radiation length (Fig.5) and the length in g/cm^2 (Fig.6). The curves in the figures are results of simple estimations of the resolution with energy-loss and multiple-scattering in targets and other contributions (includes intrinsic resolutions of the beamline spectrometer and SKS and the momentum spread due to materials in the beamline). Red, purple, light-blue and blue colors correspond to Pb, La, Y and C targets, respectively. The energy resolution is dominated by the contribution from the energy-loss straggling in the case of the (π^+, K^+) reaction, which is roughly proportional to the square-root of the target thickness in g/cm^2. For thin targets, other contributions independent from the target thickness are not negligible. Since we are planning to use ^{9}Be and ^{6}Li targets of about 3.5 g/cm^2 in thickness, we can achieve around 2.5 MeV (FWHM) resolution.

The production cross sections of the neutron-rich ${}^{10}_{\Lambda}$Li hypernucleus have been obtained in the previous experiment[12], 5.8 ± 2.2 nb/sr at 1.05 GeV/c and 11.3 ± 1.9 nb/sr at 1.20 GeV/c. The production rate of the ${}^{9}_{\Lambda}$He hypernucleus at the 1.20 GeV/c beam momentum is estimated by employing the differential cross section of the ${}^{10}_{\Lambda}$Li production together with other experimental parameters in Table 1 as follows:

$$Yield\ ({}^{9}_{\Lambda}\mathrm{He}) = N_{Beam} \times \frac{N_{Target}}{9} \times N_A \times \frac{d\sigma}{d\Omega} \times \Omega_{SP} \times \varepsilon_{SP} \times \varepsilon_{Anal} \times \frac{Time}{T_{Cycle}} \qquad (1)$$

Table 1: Basic parameters for the ${}^{9}_{\Lambda}$He hypernucleus production.

Parameters	Values	Parameter in Eq.(1)
π^- beam momentum	1.20 GeV/c	
π^- beam intensity	1×10^7 /spill	N_{Beam}
PS acceleration cycle	3.4 sec	T_{Cycle}
^{9}Be target thickness	3.5 g/cm^2	N_{Target}
Reaction cross section	10 nb/sr	$d\sigma/d\Omega$
Spectrometer solid angle	0.1 sr	Ω_{SP}
Spectrometer efficiency	0.5	ε_{SP}
Analysis efficiency	0.5	ε_{Anal}

Then, by the above formula, we can expect about 310 events in 3 weeks of beamtime. This yield is roughly one order of magnitude larger compared with the yield in the previous experiment ($\sim$ 47 events). The larger yield will make us possible to discuss the structure of the neutron-rich hypernuclei in more detail.

For the production of the ${}^{6}_{\Lambda}$H hypernucleus, the production cross section might be smaller than the case of ${}^{9}_{\Lambda}$He and ${}^{10}_{\Lambda}$Li because of the more exotic nature of the hypernuclear structure. Even with a three times smaller cross section, we can expect more than 100 events in 3 weeks with the same thickness of the target.

4 Time Schedule

We are planning to use the K1.8 beamline, its beamline spectrometer and SKS. The K1.8 beamline will be built by the beamline construction group including magnets for the beamline spectrometer. Major elements of the beamline spectrometer other than the magnets will be prepared by the E05 collaboration, and we also will contribute. SKS will be disassembled at KEK, transferred to J-PARC and reassembled with a modification of the cryogenic system also by the E05 collaboration. Time schedule of the preparations of the equipments is shown in Fig.7. As shown in the time schedule, the experiment will be ready at the very early stage of Day-1.

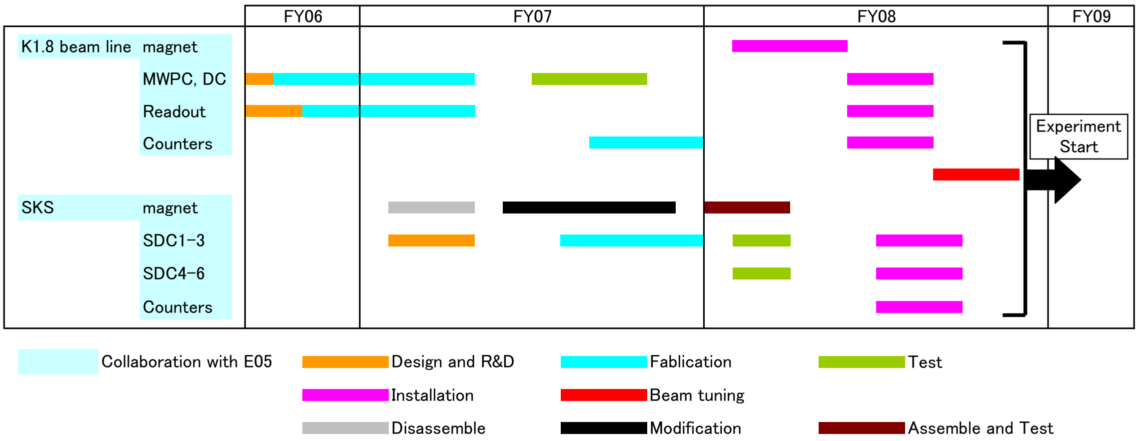

Figure 7: Time schedule of the preparations of the K1.8 beamline and SKS.

5 Cost Estimation

Table 2 shows a cost estimation for the equipments to be built by this collaboration for the proposed experiment. All the equipments in the table will be prepared by the Grant-In-Aid Priority Areas “Multi-quark systems with strangeness” from Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT).

Table 2: Cost estimation of equipments for the proposed experiment.

equipment	item	cost (JPY)	source
Beam spectrometer	MWPC 1mm	4,000,000	Grant-In-Aid
	MWPC encoder	20,000,000	Grant-In-Aid

6 Future Plan

We are planning the systematic study on the neutron-rich Λ-hypernuclei. The study have to wait for a construction of the High Intensity and High Resolution (HIHR) beamline[30]. Details on the HIHR beamline is described in Appendix A.

The HIHR beamline and spectrometer system is quite powerful for the study of the neutron-rich hypernuclei with the DCX reaction. We can expect a pion beam intensity of 10^9 π^-/spill. The cross section of the 10 nb/sr level corresponds to the event rate of about 500/day for the neutron-rich hypernuclei productions (spectrometer solid angle 40 msr is assumed). The high yield makes the systematic study of the neutron-rich hypernuclei possible, and makes a room to use much thinner nuclear targets to obtain an excellent energy resolution which is essential for the spectroscopic studies.

A High-Resolution GeV-Pion Beam line

The main proton synchrotron of J-PARC will deliver a high-power beam of 50 GeV and 15 μA. By taking advantage of the low-emittance primary beam, a *High-Intensity and High-Resolution (HIHR) GeV-Pion Beam Line* can be designed. The beam line will provide a pion intensity as high as 10^9 per second and a momentum resolution as good as 10^{-4}, which are respectively 1000-times more and 10-times better than those realized at K6 of the KEK 12-GeV PS [31]

The present beam-line facility will enable us to increase the production rate of hypernuclei drastically, and will provide us a so-called hypernuclear factory with the (π, K^+) reaction. The (π, K^+) reaction has unique features; 1) it favors to populate stretched states, 2) can produce polarized hypernuclei, and 3) is a background-free reaction. The (π, K^+) reaction plays a complementary role on the hypernuclear study to the (K^-, π) reaction. Thus, the pion beam line should be constructed. Utilizing the present facility, next-generation hypernuclear studies with high precision will be proceeded at J-PARC, where *high resolution, high statistics, and high sensitivity* will be key issues.

A layout of the proposed beam line is illustrated in Fig.8, together with a kaon spectrometer. The beam line consists of two halves. The first half is from PP to MS and for separating pions from the other secondary particles with an electrostatic separator. The first part is so called "K1.8-BR" beam-line and will be constructed as the upstream part of the "K1.8" beam-line.

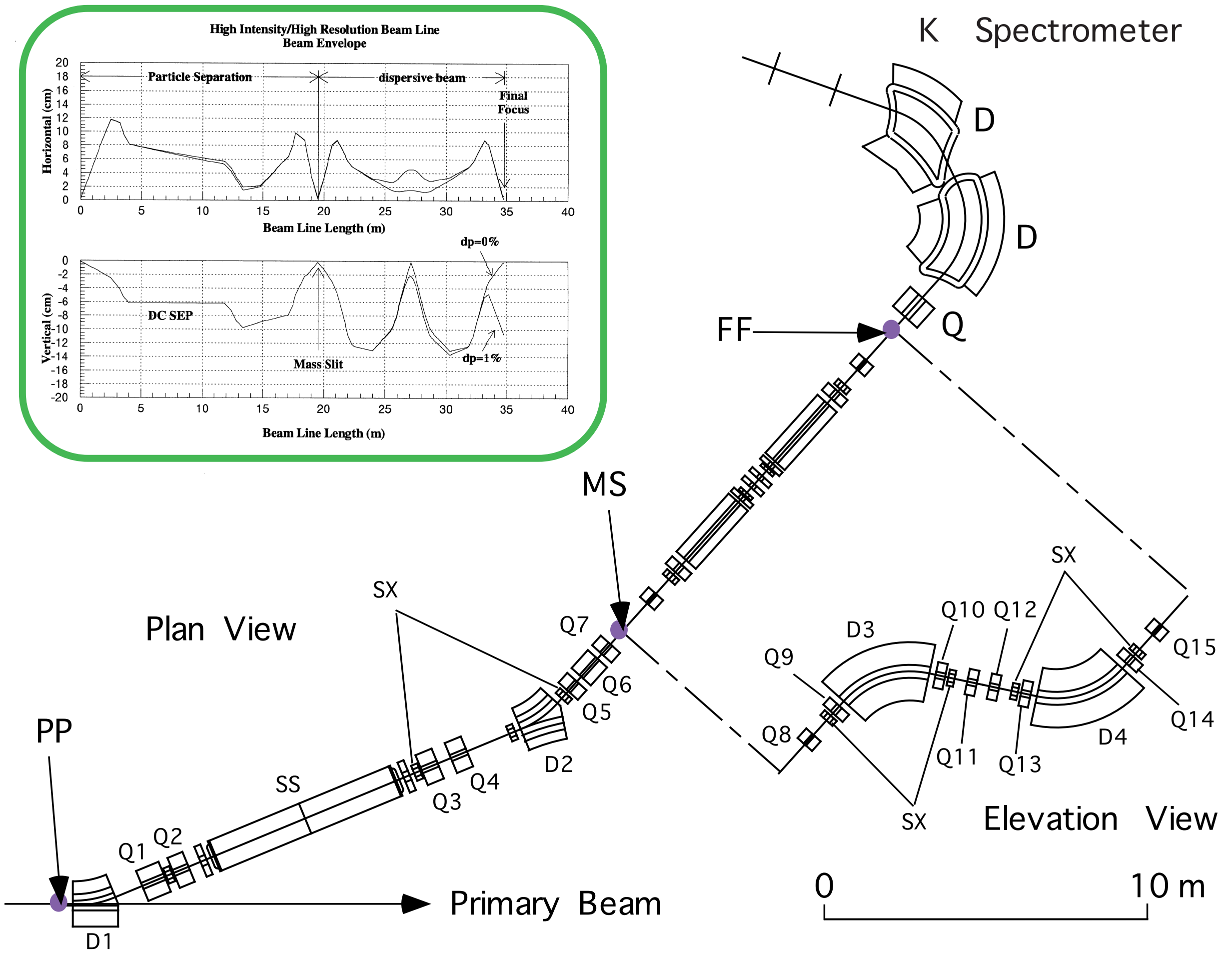

Figure 8: Layout of high-intensity and high-resolution pion beam line and kaon spectrometer.

Since no tracking devices are available, due to the high counting rate, the beam momentum must be determined by measuring the reaction point where the beam position is strongly correlated with its momentum. Thus, the second half is from MS to FF and for making the beam dispersive vertically at FF. The dispersion and vertical magnification at FF are to be ~10cm/% and -0.4, respectively. A momentum resolution of 10^{-4} can be achieved when the source size (production target) is smaller than 2.5mm.

The total length and acceptance of the beam line are 35m and 4msr·%. According to the Sanford-Wang formula[32] the π^+intensity is estimated to be more than 10^9 per second with a platinum production target 6cm long.

The kaon spectrometer in the figure is designed to be a resolution as good as 10^{-4} to match with the pion beam line. This is obviously optimized for the resolution, compromising with the acceptance and kaon survival rate. The specifications of the kaon spectrometer should be changed, if necessary, so that the resolution, acceptance, maximum central momentum, total length, cost, and so on, will have to meet experimental requests. The design concept of the kaon spectrometer is summarized as follows.

1. The kaon momentum is determined by the hit position at the focal plane. The resolution is almost determined by the horizontal beam size at the experimental target.
2. The vertical vertex point can be reconstructed from the vertical position and divergence at the focal plane. The vertex resolution of less than 1mm is thus required so that the beam momentum resolution is to be 10^{-4}, which is predominantly determined by the primary beam size at the production target.
3. Satisfying items 1 and 2, we could remove any vertex detectors at around the target, where the counting rate is expected to be too high to drive counters.

We could design a kaon spectrometer to meet above conditions. The horizontal magnification and dispersion are -0.851 and 8.327 cm/%, respectively. The vertical magnification ($R33$) is -3.08. Since the spectrometer has a vertical focus, the vertex resolution is determined by $Y_O = Y_I/R33 \sim 0.5\text{mm}/3.08 \sim 0.16\text{mm} << 1\text{mm}$, where Y_O and Y_I represent the vertex resolution (object size) and position resolution (image size) at the focal plane, respectively.

Specifications of the pion beam line and kaon spectrometer are summarized in Table 3.

Table 3: Specifications of the pion beam line and kaon spectrometer.

	π Beam Line	K Spectrometer
Max. Central Momentum (GeV/c)	1.5	1.5
Total Length (m)	34.738	12.4
Horizontal Acceptance (mrad)	±50	±100
Vertical Acceptance (mrad)	±10	±40
Momentum acceptance (%)	±1	±5
Horizontal Magnification	0.773	-0.851
Vertical Magnification	-0.409	-3.084
Dispersion (cm/%)	10.614	8.327
Momentum Resolution ($\Delta P/P$)	10^{-4}	10^{-4} a)

a) Corrections for higher order aberrations are required.

An updated layout of the high-intensity and high-resolution beamline and kaon spectrometer fitted to current floor plan of the experimental hall is shown in Fig.9.

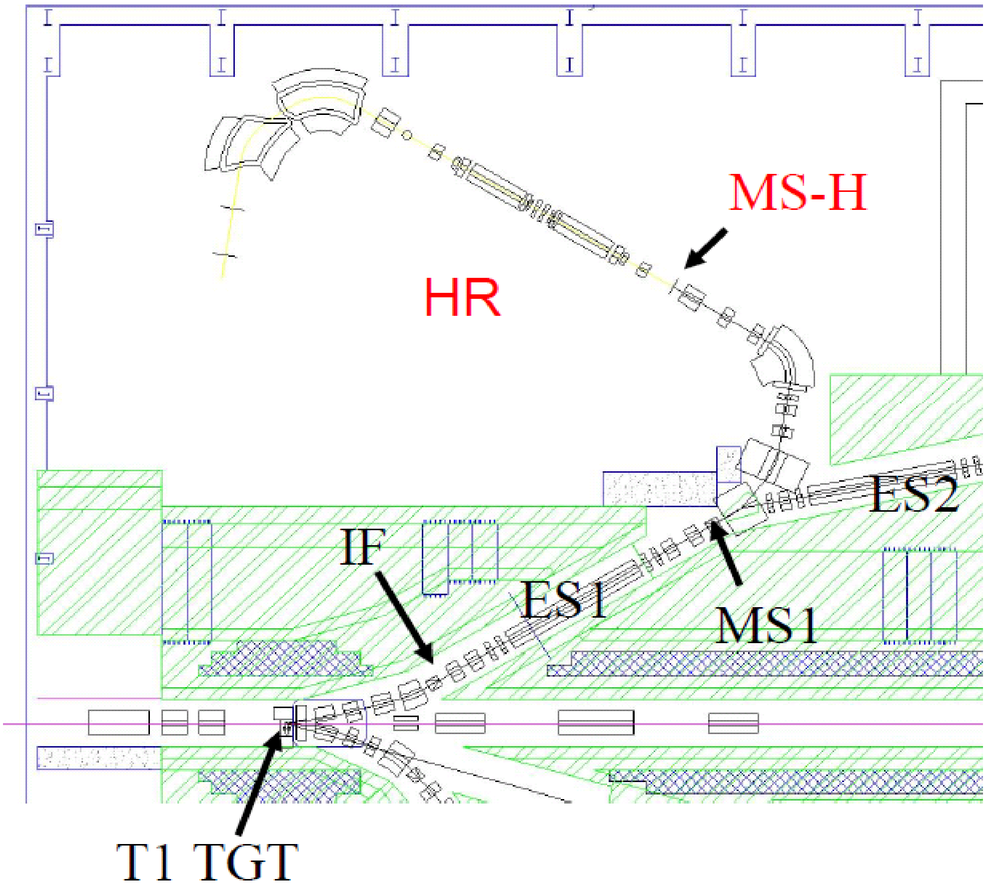

Figure 9: Layout of high-intensity and high-resolution pion beam line fitted to the current floor plan of the experimental hall.

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