Letter of Intent at the 50-GeV Proton Synchrotron

Neutron-rich Λ hypernuclei by the double-charge exchange reaction

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The present LOI concerns for an experimental study at the new facility of 50-GeV proton synchrotron (PS) at Tokai in order to produce neutron-rich Λ hypernuclei by the (K^-,π^+) and/or (π^-,K^+) double-charge exchange reaction mechanism. We strongly hope to produce many light neutron-rich Λ hypernuclei including very exotic object like ${}^{6}_{\Lambda}$H or even ${}^{7}_{\Lambda}$H. It can definitely play an important role for an extensive study of the S(strangeness)=-1 sector so as to understand many new phenomena such as the "coherent $\Lambda - \Sigma$ coupling" in nuclear matter and even in other fields in connection with high density nuclear matter in a neutron star. As the reaction has a relatively low production cross section, an intense kaon beam with good purity or a very high intense pion beam as expected in the new facility of the 50-GeV PS would be the unique choice for this study.

1. Physics Motivations and Introduction:

The following points are the brief summary of our physics motivations.

1. Search for neutron-rich Λ hypernuclei including a very exotic object like ${}^{6}_{\Lambda}$H or even ${}^{7}_{\Lambda}$H.

2. To fill up the S=-1 sector and to reveal several new phenomena of hypernuclear physics study such as the "coherent $\Lambda - \Sigma$ coupling" as discussed intensively in theory.

3. Feedback to other fields, like astrophysics, for the detailed understanding of various phenomena of high density nuclear matter in a neutron-star and so on.

4. Study of Λ hypernucleus with a large neutron excess in connection with the nuclear physics near the neutron drip line, where so-called a neutron halo has been studied over years.

A Λ hypernucleus is a baryonic many-body system comprising nucleons and a Λ hyperon, which can provide information on the baryon-baryon interaction (i.e. extended nuclear force) as well as hyperon(s) behavior in nuclear matter. Experimentally, (K^-,π^-) or (π^+,K^+) reactions are usually used to produce a Λ hypernucleus replacing a neutron in a target nucleus by a Λ. In recent years, Λ hypernuclear spectroscopy employing these reactions have been studied extensively in wider mass region in many places including KEK [1–3]. Namely, (π^+,K^+) spectra measured in KEK by using the superconducting kaon spectrometer(SKS) clearly observed the characteristic fine structures even in heavy Λ hypernuclear systems [3]. In addition, high resolution Ge detectors together with magnetic spectrometer have been successfully observing γ transitions in several light Λ hypernuclear systems between the fine structures of Λ-hypernuclear states split by the ΛN spin-dependent interaction, such as the spin-orbit and spin-spin forces [4,5]. It is interesting and important to expand our knowledge to the limit of stability in the S = -1 sector. However, there is almost no experimental study to produce neutron-rich Λ hypernuclei in the light nuclear systems. By the above two reaction mechanisms it is difficult to produce neutron-rich Λ-hypernuclei in the light nuclear systems but is possible by using a double-charge exchange reaction mechanism like (K^-,π^+) or (π^-,K^+) reaction, which is our present concern. In the lightest case, (K^-,π^+) or (π^-,K^+) reaction on ^{6}Li or ^{7}Li target will produce a $^6_\Lambda$H or $^7_\Lambda$H, which would be very exotic nucleus with a large neutron to proton ratio. The production of $^6_\Lambda$H is already predicted by Akaishi *et al.*[6] as seen in figure 1. However, our motivation is not only to produce a neutron-rich Λ-hypernucleus or an exotic object but also to study several interesting phenomena which will obviously lead us to a new arena in the strangeness nuclear physics.

Recently, Akaishi *et al.*[7] solved the so called "underbinding problem" of the Λ separation energy in $^4_\Lambda$He by introducing explicitly the $\Lambda - \Sigma$ coupling in nuclei known as "coherent $\Lambda - \Sigma$ coupling", by their definition, in which nucleons remain in the ground state when converting Λ to Σ, leading all the nucleons to interact with Σ in an equal footing in order to convert Σ to Λ again. The significance of $\Lambda - \Sigma$ coupling was also proposed in several other theoretical calculations [8] but the importance of the "coherent $\Lambda - \Sigma$ coupling" in the four body systems is revealed for the first time by Akaishi, on the basis of realistic YN interaction. The " coherent $\Lambda - \Sigma$ coupling" can be studied through the level structure of neutron-rich Λ hypernuclei and also observable by directly populating Σ^- state in Λ hypernuclear states by the (K^-,π^+) reaction.

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 a neutron-star, formation-scenario and a thermal and structural evolution of a neutron star and a black hole [9]. 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 Σ^- mixing in a neutron star is being intensively discussed in the present days because of a negative charge of Σ^- [10]. However, the mixing will particularly depend on the $\Sigma^- N$ interaction. Recently, in KEK-PS-E438 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 [11]. A theoretical calculation for the Si spectrum based on the Distorted-Wave Impulse Approximation (DWIA) showed that a very strong repulsive Σ-nucleus potential is needed to reproduce the observed spectral shape [12]. Then, Σ-hyperons may not appear in the neutron star for a repulsive ΣN interaction. On the other hand, Akaishi *et al.* discussed recently that the "coherent $\Lambda - \Sigma$ coupling" will enhance the Σ mixing in the neutron star matter and needs to be taken into account in such theoretical calculations. It would be interesting as well as a good feedback to those theoretical calculations if the "coherent $\Lambda - \Sigma$ coupling" effect can be observed experimentally.

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 halo has been discovered. The structures of such nuclei have revealed interesting phenomena regarding its size, properties of excited states and so on [13,14]. 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.

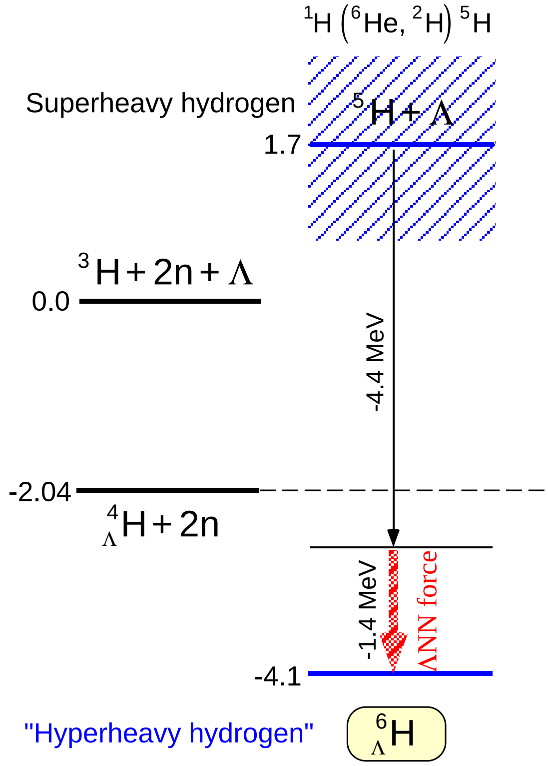

Figure 1. Formation of hyperheavy hydrogen ($^{6}_{\Lambda}$H), where the Λ binding energy is calculated to be 4.1 MeV [6]
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2. Experimental Principle:

2.1. Reaction mechanism

There are mainly two reaction mechanisms to populate a bound Λ-hypernuclear state by the double-charge exchange reaction of (K^-,π^+) or (π^-,K^+). One of such mechanisms is a single-step process by the $K^- p \to \pi^+ \Sigma^-$ or $\pi^- p \to K^+ \Sigma^-$ via a small admixture of the Σ^- state appearing due to the $\Sigma^- p \leftrightarrow \Lambda n$ coupling [15,16]. Akaishi further discussed an importance of the "coherent $\Lambda - \Sigma$ coupling" to enhance the Σ^- component and eventually the production cross section.
The other mechanism is the so called two-step process and is believed to the dominated mechanism by many authors including L. Majling [17] as well as Tretyakova [18].

Recently a theoretical calculation was done by Tretyakova *et al.*[16,18], where cross section on several light nuclear targets were calculated in the (K^-,π^+) and (π^-,K^+) reactions in both single and two-step processes. The production cross section on ^{12}C and ^{16}O in the single-step of (π^-,K^+) reaction were found very small (300 pb/sr - 1 nb/sr), whereas the (K^-,π^+) reaction on ^{12}C shows relatively a large production cross section ($\sim$ 100 nb/sr) at the kaon momentum of 900 MeV/c.
On the other hand, two-step cross section on ^{10}B in the (π^-,K^+) reaction was found to be significantly large and was maximum(70 nb/sr) at the π^- beam momentum of 1.05 GeV/c as described in the following. In the same way two-step cross section on ^{10}B in the (K^-,π^+) reaction can be expected large although calculation has not been done yet.

The Λ hypernucleus production in the two-step process with meson charge-exchange,

$$\pi^- + ^A Z \to K^+ + ^A_\Lambda (Z-2) \tag{1}$$

can proceed in two ways:

$$\pi^- p \to K^0\Lambda; \quad K^0 p \to K^+ n \tag{2}$$

or

$$\pi^- p \to \pi^0 n; \quad \pi^0 p \to K^+\Lambda \tag{3}$$

Here, in reaction 2, at the first step Λ and K^0 are created and in the second step, charge exchange reaction of K^0 occurs, resulting in a neutron(n) and a K^+. In reaction 3, at first charge exchange reaction of π^- occurs and in the second step, Λ and K^+ are created. The hypernuclear production cross section depends on the elementary cross sections and the momentum transfer in the reaction.

The calculation was done at the forward angle using the incident π^- beam momentum of 1.05 GeV/c and extended to several beam momenta in order to see the incident energy dependence of the cross section. The differential cross section ($d\sigma/\mathrm{d}\Omega$) at the beam momentum of 1.05 GeV/c for both ${}^{12}_{\Lambda}$Be and ${}^{10}_{\Lambda}$Li production are presented in table 1, as reported by Tretyakova[18]. The quantum numbers of the final hypernuclear states and of single-particle states are also shown in table 1. The numbers (2) and (3) represent the cross section obtained from the branches 2 and 3, respectively. One can see that a relatively large production cross section is found for the ${}^{10}_{\Lambda}$Li production, especially for 2^- state, which is about one order higher than that of ${}^{12}_{\Lambda}$Be production.

To explain the reason and conditions for such a large cross section of ${}^{10}_{\Lambda}$Li (2^-) production, the multipolarities of single-particle transitions for each reaction are considered as presented in table 2. For all the reactions, Λ production proceeds by a 1^- transition. The longitudinal momentum transfer about 330 MeV/c is fairly favorable for 1^- transition as known for production of low-lying state of p shell hypernuclei in the usual (π^+,K^+) one-step reaction.
The reactions are different at the charge-exchange step. The longitudinal momentum transfer at this step is nearly zero. So 0^+ transition as one occurs for ${}^{10}_{\Lambda}$Li (2^-) are strongly preferred. Surely, other targets and hypernuclear states, for which monopole charge-exchange occurs, can be found.

A more pictorial argument can be made if we look at figure 2, where the situation has been explained by the neutron and proton distributions in the target as well as produced hypernuclei. As we see in the first example for the ^{12}C case, two protons in $1p_{3/2}$ shell of the target nucleus change to a neutron and a Λ in order to produce ${}^{12}_{\Lambda}$Be. As the $1p_{3/2}$ shell is already full, the converted neutron(red) should go to the $1p_{1/2}$ shell of ${}^{12}_{\Lambda}$Be. Thus there is an angular momentum transfer in this case, which disfavors the transition as explained in the previous paragraph. On the other hand, if we look at the second example, for the ${}^{10}_{\Lambda}$Li production, then the converted neutron can stay in the same state ($1p_{3/2}$) as the proton in the target nucleus (^{10}B) before converting to neutron and requires no angular momentum transfer, which favors the transition.

2.2. Experimental information

Unfortunately, there exists almost no experimental data to produce neutron-rich Λ hypernuclei so as to study the reaction mechanism itself. The sole and poor experimental data exists at KEK in a series of Λ and Σ hypernuclear studies by using the ($K^-_{stopped}$,$\pi^\pm$) reactions [19]. Recently, we performed an experiment at the K6 beam line of KEK 12-GeV PS together with Superconducting Kaon Spectrometer(SKS), where we have measured the (π^-,K^+) double-charge exchange reaction on ^{10}B in order to produce neutron-rich Λ hypernucleus, ${}^{10}_{\Lambda}$Li [20]. The off-line analysis is under way and we will have some results concerning the production cross section as well to understand the reaction mechanism itself.

Table 1
The differential cross section of two neutron-rich Λ hypernuclei, ${}^{12}_{\Lambda}$Be and ${}^{10}_{\Lambda}$Li, formation.

${}^{A}_{\Lambda}$(Z−2)	J^{π}	p	n	Λ	$\frac{d\sigma}{d\Omega}$	(2) nb/sr	(3)
${}^{12}_{\Lambda}$Be	1^-	$p_{3/2}$	$p_{1/2}$	$s_{1/2}$	6.5	4.5	2.0
	0^+	$p_{3/2}$	$s_{1/2}$	$s_{1/2}$	2.1	1.6	0.6
${}^{10}_{\Lambda}$Li	2^-	$p_{3/2}$	$p_{3/2}$	$s_{1/2}$	66.8	49.3	17.4
	1^-	$p_{3/2}$	$p_{3/2}$	$s_{1/2}$	3.2	1.7	1.5

Table 2
Multipolarities of the single-particle transitions involved in the double-charge exchange reaction as considered by Tretyakova *et al.*[18] in their calculation.

${}^{A}_{\Lambda}$(Z−2)	J^{π}	$p \xrightarrow{\lambda_1} \Lambda$	$p \xrightarrow{\lambda_2} n$
${}^{12}_{\Lambda}$Be	1^-	$p_{3/2} \xrightarrow{1^-} s_{1/2}$	$p_{3/2} \xrightarrow{2^+} p_{1/2}$
	0^+	$p_{3/2} \xrightarrow{1^-} s_{1/2}$	$p_{3/2} \xrightarrow{1^-} s_{1/2}$
${}^{10}_{\Lambda}$Li	2^-	$p_{3/2} \xrightarrow{1^-} s_{1/2}$	$p_{3/2} \xrightarrow{0^+,2^+} p_{3/2}$
	1^-	$p_{3/2} \xrightarrow{1^-} s_{1/2}$	$p_{3/2} \xrightarrow{2^+} p_{3/2}$

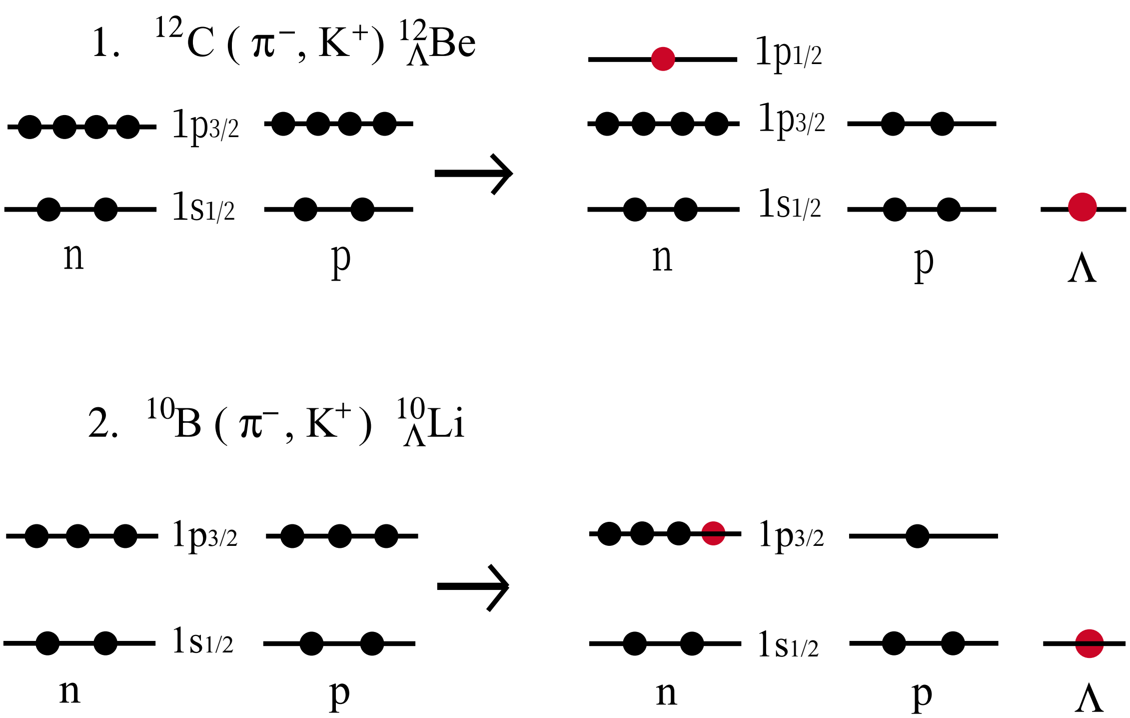

Figure 2. Formation mechanism of the neutron-rich Λ hypernuclei in the two-step process. The two protons from the target nucleus change to a neutron and a Λ to form a neutron-rich Λ hypernucleus as shown by red circles.

3. Experimental requirements and the yield estimation

For the (K^-,π^+) reaction, we can use 900 MeV/c K^- beam in the K1.1 beam line. The production cross section at this momentum is found to be the maximum in the theoretical calculation [16,18]. For the scattered particle spectrometer, we can use a spectrometer similar to SKS or even SPES-II as in the present design. A large acceptance together with a good energy resolution is very suitable for this kind of experiment where the production cross section is small. In a limited acceptance spectrometer, the first requirement can be overcome when the beam time is sufficient but the resolution becomes important for the structure study. In this way, the SPES-II spectrometer can be used where the acceptance is smaller than SKS but the resolution is expected to be much better ($\sim$ 1 MeV in FWHM).

The other way is to utilize the (π^-,K^+) reaction in the high intensity pion beam line as proposed in other LOI by Noumi *et al.*[21]. The beam momentum at 1.05 GeV/c will be used, where the production cross section is maximum in the same theoretical calculation. The acceptance of the scattered K^+ as well as it's survival rate would be much smaller than that from the above but the high resolution and two order of magnitude higher intense beam would be very efficient to have some sufficient yield in a limited period.

Here we present a preliminary estimation of the production rate in both reactions taking into account the beam condition, reaction cross section as well as the acceptance of the spectrometer.

1. For the (K^-,π^+) reaction, we study a ^{12}C target case as an example, where we have a theoretical value of the cross section in the single-step process (100 nb/sr). The target thickness can be 2 gm and then the energy resolution will be reasonably good. We can assume detector and analysis efficiencies to be 30%, including kaon survival rate and DAQ efficiency. The spectrometer acceptance can be taken 30 msr in certain forward scattering angular regions, where the production cross section is maximum. As expected, we assume 10^7 K^-/sec.
Then the expected yield is calculated as

$$Y = N_B \times N_T \times \frac{d\sigma}{d\Omega} \times \epsilon_{exp} \times \Delta\Omega$$

where, N_B is the number of beam, 10^7 K^-/sec, N_T is the number of target, $2{\times}6.023{\times}10^{23}/12$, $\frac{d\sigma}{d\Omega}$ is the cross section, 100 nb/sr, ϵ_{exp} is the experimental efficiency, 0.3 and $\Delta\Omega$ is the acceptance of the spectrometer, 30 msr.

Then, we get about **75 counts/day**.

2. For the (π^-,K^+) reaction, we can use high intensity pion beam (10^9/sec). We assume a ^{10}B target of 1 gm, where we expect a fairly large cross section in the two-step mechanism (70 nb/sr). The acceptance of the spectrometer(16 msr) and all efficiencies together (5%) are quoted from [21].

Then, the expected yield would be

$$\begin{aligned} Y &= 10^9(\text{cps})\times\frac{1.0}{10} \times 6.022 \times 10^{23}\ (\text{cm}^{-2})\times\ 70\ (\text{nb/sr})\ \times\ 16\ (\text{msr})\times 0.05 \\ &= \mathbf{290\ counts/day}. \end{aligned}$$

This number is already very high production rate even when the cross section is very low in such a double-charge exchange reaction and is possible only when such a high intensity beam line is realized. Of course, the final estimation of the yield can be done more accurately when we have more elaborate theoretical calculation in both reactions and in both mechanisms and moreover hopefully, if we have some new experimental information from KEK-PS-E521, which is under analysis as mentioned before. However, it is very important to mention here that background in double-charge exchange reaction is negligibly small as found from the preliminary spectrum of E521. It helps to identify any peaks even when the statistics is very low.

4. Summary

We strongly hope that the production of neutron-rich Λ hypernuclei would be a very good step for the new generation spectroscopic study at the 50-GeV PS as well as an extension of the S=-1 sector. In this respect, K1.1 beam line in the present design as well as high intensity pion beam line should be realized for this kind of study, where it can play a very significant role for various studies in the hypernuclear physics so as to open a new arena as we mentioned in the beginning. When the statistics is sufficient, we may observe the fine structure of a neutron-rich Λ hypernuclear states split by the ΛN spin-dependent interaction by using the Ge Hyperball as it is already found to be very successful in both (π^+,K^+) (K^-,π^-) reactions.

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