PRODUCTION OF NEUTRON-RICH LAMBDA HYPERNUCLEI AT J-PARC

A. SAKAGUCHI[a], S. AJIMURA[b], H. BHANG[c], L. BUSSO[d,e], M. ENDO[a],

D. FASO[d,e], T. FUKUDA[f], T. KISHIMOTO[a], K. MATSUDA[a], K. MATSUOKA[a],

Y. MIZOI[f], O. MORRA[e,g], H. NOUMI[b], P. K. SAHA[h], C. SAMANTA[i,j],

Y. SHIMIZU[a], T. TAKAHASHI[k], T. N. TAKAHASHI[ℓ] and K. YOSHIDA[a]

[a] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[b] *Research Center for Nuclear Physics, Osaka University,*
Ibaraki, Osaka 567-0047, Japan
[c] *Department of Physics, Seoul National University, Kwanak-gu, Seoul 151-747, Korea*
[d] *Dipartimento di Fisica Generale, Università di Torino,*
via Pietro Giuria, I-10125 Torino, Italy
[e] *Istituto Nazionale Fisica Nucleare, Sezione di Torino,*
via Pietro Giuria, I-10125 Torino, Italy
[f] *Department of Engineering, Osaka Electro-Communication University,*
Neyagawa, Osaka 572-8530, Japan
[g] *Istituto di Fisica dello spazio Interplanetario,*
Corso Fiume 4, 10133 Torino, Itary
[h] *Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[i] *Physics Department, University of Richmond, Richmond, VA 23173, USA*
[j] *Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India*
[k] *High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[ℓ] *Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-8654, Japan*

We discuss the usefulness of the double charge-exchange reactions (DCX) for the production of the neutron-rich Λ-hypernuclei. We believe the (π^-, K^+) reaction is one of the most promising DCX reactions, and propose to produce the neutron-rich Λ-hypernuclei, $^6_\Lambda$H and $^9_\Lambda$He, at the J-PARC 50 GeV PS by the reaction (J-PARC E10 experiment). The design of the experiment is presented.

Keywords: Neutron-Rich Lambda Hypernuclei; Double Charge-Exchange Reaction.

1. Physics Motivation

We are preparing the J-PARC E10 experiment for the study of the neutron-rich Λ-hypernuclei at the J-PARC 50 GeV PS facility. In this paper, we discuss the issues and the design of the experiment.

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1.1. *Spectroscopy of Λ-hypernuclei and new tools*

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 of the important subjects of the studies of the Λ-hypernuclei in the past was the precise measurements of the level structures of the Λ-hypernuclei, that made it possible to discuss the underlying hyperon-nucleon strong interaction. The similarity of the Λ hyperon with nucleon is one of the key properties which brings the rich spectra of the Λ-hypernuclei. Another important property is the additional binding due to the Λ hyperon, so we expect the *hypernuclear chart* is even richer than the ordinary *nuclear chart.*[2]

On the other hand, we have surveyed only a small fraction of hypernuclei in the *hypernuclear chart.* One of reasons of the limited survey was that we mainly used the (K^-, π^-) and the (π^+, K^+) reactions to produce the Λ-hypernuclei. Figure 1(b) shows hypernuclei so far identified; black colored ones were directly produced via the (K^-, π^-) and the (π^+, K^+) reactions on stable nuclear targets and gray colored ones were observed as hyperfragments in the nuclear emulsion experiments. The chart looks already compatible with that of the ordinary nuclei (Fig. 1(a)), but the information on the hyperfragments from the nuclear emulsion experiments were quite restricted.

To survey wider area of the hypernuclear chart in further detail, we need new spectroscopic tools. If we employ the charge exchange reactions, we can directly produce many neutron-rich Λ-hypernuclei as shown in Fig. 1(c); hypernuclei in the white boxes are produced by the single charge-exchange reactions and those in the boxes with the graduation are produced by the double charge-exchange reactions (DCX), such as the (K^-, π^+) and (π^-, K^+) reactions.

1.2. *ΛN interaction and neutron-rich Λ-hypernuclei*

One of interesting aspects of the ΛN interaction in the hypernuclei is the phenomenon so-called ΛN-ΣN mixing. The mass difference between the Λ and Σ hyperons is small, $m_\Sigma - m_\Lambda \sim 77\mathrm{MeV/c^2}$, compared with that of the nucleon and Δ isobar, $m_\Delta - m_N \sim 290\mathrm{MeV/c^2}$. This situation makes the effect of the ΛN-ΣN mixing quite important in the hypernuclear level structure.[3] The strong ΛN-ΣN mixing introduces an additional effective two-body ΛN interaction and also the three-body interaction among the
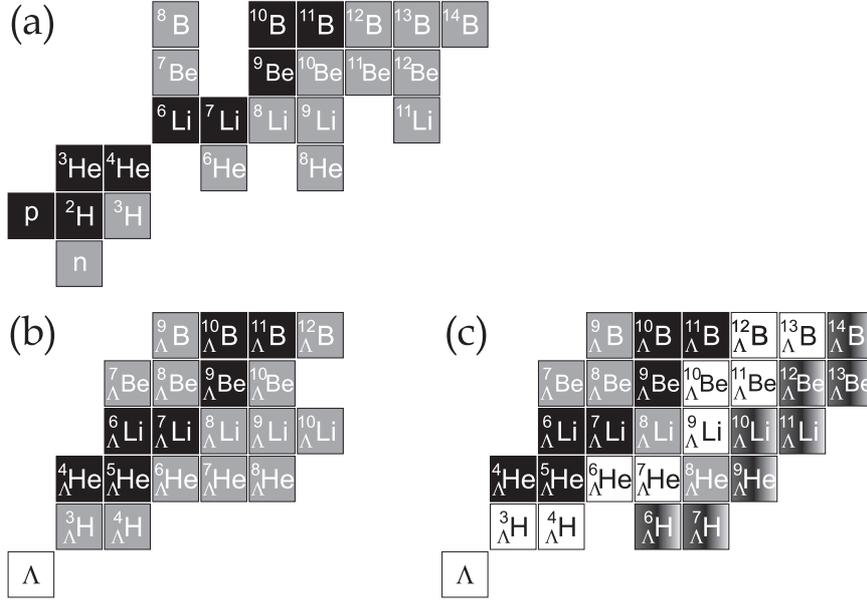
Fig. 1.   (a) chart of light nuclei. (b) chart of Λ-hypernuclei ever produced. (c) boxes with the graduation correspond to hypernuclei to be produce via the DCX reactions. See text for more details.

ΛNN subsystem in a Λ-hypernucleus as recently discussed by Akaishi *et al.*[4] The additional interaction due to the ΛN-ΣN mixing is believed to increase the ΛN attraction, and the attractive interaction may affect to the fraction of hyperons and EOS of the matter in the core of the neutron stars.

Since the Λ and Σ hyperons have different isospins, I=0 and 1 respectively, the ΛN-ΣN coupling may be large only for hypernuclei with non-zero isospin due to the isospin conservation. We also expect the mixing effect is significant in the neutron-rich Λ-hypernuclei which have large values of the isospin. This mixing effect manifests itself in a Σ component of the Λ-hypernuclear states, which can be useful to produce the neutron-rich Λ-hypernuclei by the (π^-, K^+) reaction (see Sec. 1.4 for more details).

1.3. *Production of neutron-rich Λ-hypernuclei*

A pilot experiment attempted to produce Λ-hypernuclei away from the stability-line was performed at KEK-PS by using the $(K^-_{Stopped}, \pi^+)$ reaction.[5] In the 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

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to tiny branching ratios to the DCX channel and a huge background from the in-flight hyperon decays, $\Sigma^+ \rightarrow n\pi^+$. An improved study with the $(K^-_{Stopped}, \pi^+)$ reaction has been carried out for the $^6_\Lambda$H, $^7_\Lambda$H and $^{12}_\Lambda$Be hypernuclei by the FINUDA collaboration at Frascati-DAΦNE,[6] but the clear identification of the production of the neutron-rich Λ-hypernuclei was not accomplished. Another experiment to produce not only the neutron-rich but also the proton-rich Λ-hypernuclei is in preparation by using the relativistic heavy ion beams at GSI.[7]

The other promising DCX reaction to produce the neutron-rich Λ-hypernuclei is the (π^-, K^+) reaction. A neutron-rich Λ-hypernucleus, $^{10}_\Lambda$Li, was attempted to produce at KEK-PS by the (π^-, K^+) reaction with the 1.05 and 1.2 GeV/c pion beams (KEK-E521 experiment).[8] In the experiment, clear signal events were observed in the Λ bound region in the missing mass spectrum of the ^{10}B(π^-, K^+) reaction. Although the production cross section of the $^{10}_\Lambda$Li hypernucleus was estimated to be very small (∼10nb/sr), roughly 10^{-3} of that of the (π^-, K^+) reaction (typically 10μb/sr), the experimental data may provide new information on the structure of the Λ-hypernuclei with a large number of excess neutrons. Compared with the $(K^-_{Stopped}, \pi^+)$ reaction, the (π^-, K^+) reaction is almost background free at the Λ bound region.

1.4. *Reaction mechanism and ΛN-ΣN mixing*

The KEK-E521 experiment reported that the production cross sections of the $^{10}_\Lambda$Li hypernucleus by the (π^-, K^+) reaction were 5.8 nb/sr and 11.3 nb/sr at the pion beam energies of 1.05 GeV/c and 1.20 GeV/c, respectively. Theoretical calculations based on the two-step reaction mechanism, $\pi^- pp \rightarrow K^0 \Lambda p \rightarrow K^+ \Lambda n$ or $\pi^- pp \rightarrow \pi^0 np \rightarrow K^+ n\Lambda$, failed to reproduce the beam momentum dependence of the production cross sections.

Another theoretical treatment of the DCX reaction is the single-step reaction mechanism. In the reaction mechanism, the single-step $\pi^- p \rightarrow K^+ \Sigma^-$ reaction occurs, and the produced Σ^- is converted to Λ through the ΛN-ΣN mixing in the hypernucleus. Since the threshold of the $\pi^- p \rightarrow K^+ \Sigma^-$ reaction is around 1.045 GeV/c, the single-step calculations predict the production cross sections consistent with the experiment. Recent results of the single-step calculations indicated the importance of the mixing effect and also the effect of the intermediate Σ-nucleus interaction to the (π^-, K^+) reaction cross sections.[9,10]

2. Design of J-PARC E10 Experiment

The J-PARC E10 experiment was proposed to utilize the (π^-, K^+) reaction to produce the new neutron-rich Λ-hypernuclei, $^6_\Lambda$H and $^9_\Lambda$He. We are proposing to use the K1.8 secondary beam line in the hadron experimental hall of the J-PARC 50 GeV proton synchrotron (50 GeV PS) facility. The 50 GeV PS has already started to accelerate proton beams and the K1.8 beam line is to be constructed in 2009.

The most important issues of the E10 experiment are the handling of the high-intensity pion beams and the efficient measurement of the produced kaons to override the tiny production cross section of the DCX reaction. We are preparing new tracking detectors in the beam line spectrometer of the K1.8 beam line to accept the high intensity pion beams, about 1.5×10^7 $\pi^-/spill$ with 3 s beam spill. The produced positive kaons are detected by the Superconducting Kaon Spectrometer (SKS)[11] to be moved from KEK to the J-PARC site. SKS has a large geometrical acceptance, about 100 msr, together with the good momentum resolution, $\Delta p/p \sim 10^{-3}$(FWHM). The practical overall mass resolution, roughly 2.5 MeV/c^2(FWHM), of the hypernuclei calculated by the missing mass method mainly comes from the contribution of the energy loss straggling of π^- and K^+ in the relatively thick nuclear target (about 3.5 g/cm^2). We estimated the yield of the $^9_\Lambda$He hypernucleus by employing the additional parameters listed in Table 1, and the estimated yield were about 300 events during 3 weeks of beamtime. The number of events is not so many, but is

Table 1.   Additional parameters used for the $^9_\Lambda$He yield estimation.

π^- momentum	PS acceleration cycle	K^+ decay factor	Analysis efficiency
1.2 GeV/c	5.7 s	0.5	0.5

about 7 times larger than that of the KEK-E521 experiment (yield was about 47 events).

Figure 2 shows the excitation energy spectrum of the $^6_\Lambda$H hypernucleus estimated by a simulation calculation. The overall excitation energy resolution of 2.5 MeV(FWHM) and the $^6_\Lambda$H yield of 300 events were assumed. The figure tells the peak which corresponds to the ground state of the $^6_\Lambda$H hypernucleus is clearly separated from the continuum of the quasi-free Λ production process thanks to the good energy resolutions of the beam line spectrometer and SKS. The statistical error is small enough to determine
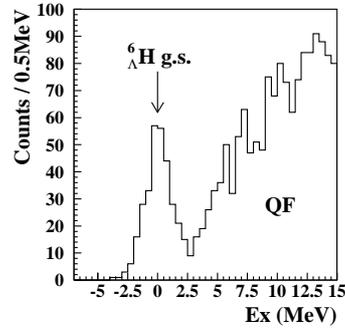
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Fig. 2.   The excitation energy spectrum of the $^6_\Lambda$H hypernucleus estimated by a simulation calculation. See text for more details.

the binding energy of the neutron-rich Λ-hypernucleus with a resolution down to 0.1 MeV (rms).

We are also preparing the upgrade of the detectors in SKS to make the momentum acceptance wider. The upgrade may enable us to measure the (π^-, K^+) reaction in the Λ and the Σ^- production regions at the same time, and the wide momentum acceptance is quite useful to make precise calibrations of the absolute scale of the binding energy of the hypernuclei and to monitor the stability of the spectrometer systems.

We hope we will be able to start the experiment in the fiscal year 2009.

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