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Study on $^{6}_{\Lambda}$H hypernucleus by the (π^-, K^+) reaction at J-PARC

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Abstract. We carried out an experiment to produce the neutron-rich hypernucleus $^{6}_{\Lambda}$H via the (π^-, K^+) reaction on ^{6}Li target at the pion beam momentum of 1.2 GeV/c (J-PARC E10). In order to calibrate the scale of the missing-mass or of the Λ binding energy of the hypernucleus, we also measured the ^{12}C(π^+, K^+)$^{12}_{\Lambda}$C, $p(\pi^-, K^+)\Sigma^-$ and $p(\pi^+, K^+)\Sigma^+$ reactions. The experiment was performed at the J-PARC Hadron Hall K1.8 beam line in December 2012 and January 2013. The overall collected data sample corresponds to an integrated beam intensity of 1.65×10^{12} pions.

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1 Introduction

One of the most important topics in strangeness nuclear physics is the study of neutron-rich Λ hypernuclei [1, 2]. It is expected that a Λ hyperon plays a glue-like role in nuclei beyond the neutron drip-line. The knowledge of the behavior of the hyperon in a neutron-excess environment significantly impacts on our understanding of the neutron stars, because the addition of hyperons softens the Equation of State of matter at the core [3]. Akaishi and collaborators [4, 5] suggested that the coherent ΛN-ΣN coupling can resolve the over binding problem in ${}^{5}_{\Lambda}$He [6] and that such a coupling is enhanced in a neutron-excess environment.

2 Spectroscopy of Λ hypernuclei

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

On the other hand, we have identified only a small fraction of hypernuclei in the hypernuclear chart. One reason of the limited observation is that we mainly used the (K^-, π^-) and the (π^+, K^+) reactions to produce Λ hypernuclei. Figure 1(b) shows the hypernuclei which have ever produced in the A≤15 region: purple colored ones were directly produced via the (K^-, π^-) and the (π^+, K^+) reactions on stable nuclear targets while green 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 was quite limited.

To explore wider area of the hypernuclear chart in further detail, we need new spectroscopic tools. If we exploit charge exchange reactions, we can directly produce many neutron-rich Λ hypernuclei as shown in Fig. 1(c). Hypernuclei in the light blue boxes are produced by the single charge-exchange reactions and the ones in yellow boxes are produced by the double charge-exchange reactions (DCX), such as the (K^-, π^+) and (π^-, K^+) reactions.

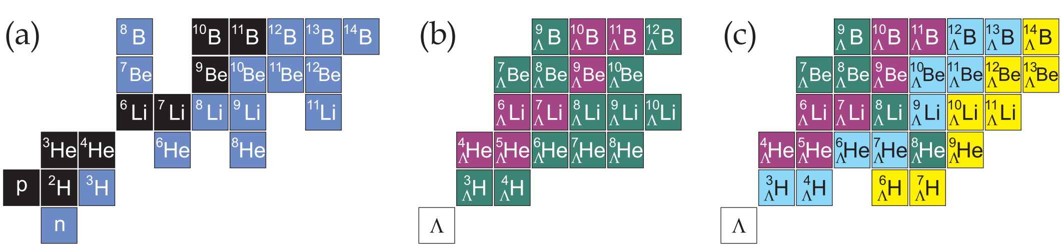


Figure 1. (a) chart of light ordinary nuclei. (b) chart of Λ hypernuclei ever produced in the A≤15 region. Purple boxes correspond to directly produced hypernuclei via the (K^-, π^-) and (π^+, K^+) reactions on stable nuclear targets and green boxes correspond to hypernuclei observed as hyperfragments 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 the (K^-, π^+) and (π^-, K^+) reactions on stable targets.

3 Study of double charge-exchange reactions

3.1 $(K^-_{stopped}, \pi^+)$ reaction

A pilot experiment aiming to produce Λ hypernuclei away from the stability-line was performed at KEK-PS by using the $(K^-_{stopped}, \pi^+)$ reaction [7]. In that experiment, only upper limits were obtained for the production rate of 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 hyperon decays, $\Sigma^+ \rightarrow n\pi^+$. An improved study has been carried out for the $^{6}_{\Lambda}$H, $^{7}_{\Lambda}$H, $^{9}_{\Lambda}$He and $^{12}_{\Lambda}$Be hypernuclei by the FINUDA Collaboration at Frascati-DAΦNE [8, 9]: they claimed the observation of 3 events of $^{6}_{\Lambda}$H hypernuclei and their mesonic weak decays [10].

3.2 (π^-, K^+) reaction

Another promising DCX reaction to produce the neutron-rich Λ hypernuclei is the (π^-, K^+) reaction. An attempt to produce the neutron-rich Λ hypernucleus $^{10}_{\Lambda}$Li was carried out at KEK-PS by exploiting the (π^-, K^+) reaction at 1.05 and 1.2 GeV/c pion beam momenta (KEK-E521 experiment) [11]. In that experiment, clear signal events were observed in the Λ bound region in the missing mass spectrum of the ^{10}B(π^-, K^+) reaction. The production cross section of the $^{10}_{\Lambda}$Li hypernucleus was estimated to be very small (~10 nb/sr), roughly 10^{-3} of that of the (π^-, K^+) reaction (typically 10 μb/sr). Compared with the $(K^-_{stopped}, \pi^+)$ reaction, the (π^-, K^+) reaction is almost background free in the Λ bound region.

4 J-PARC E10 experiment

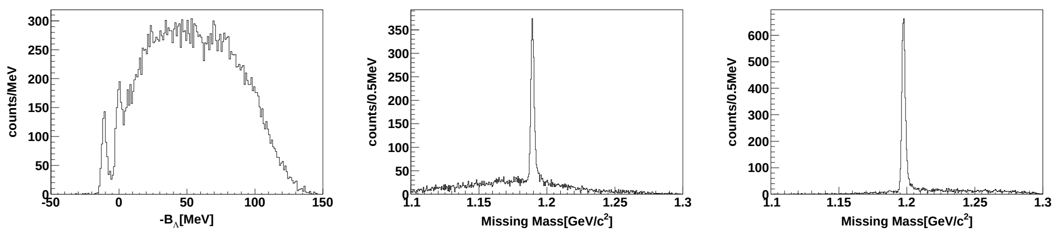
The J-PARC E10 experiment aims to produce the neutron-rich Λ hypernuclei $^{6}_{\Lambda}$H and $^{9}_{\Lambda}$He via the (π^-, K^+) reaction. As a first step, we performed $^{6}_{\Lambda}$H production experiment in the K1.8 beam line at J-PARC Hadron Experimental Facility by using the Superconducting Kaon Spectrometer (SKS) system. The total beamtime was about 13 days divided in two data taking periods: December 2012 and January 2013.

Table 1 shows the run summary with J-PARC E10 experiment. We started the calibration run of $^{12}_{\Lambda}$C production at a beam momentum of 1.2 GeV/c to evaluate the missing-mass resolution and to confirm that all the detectors were working properly. Next, we made the measurement of the Σ^- and Σ^+ production reactions from hydrogen on a $(CH_2)_n$ target at a beam momentum of 1.37 GeV/c. This way we could calibrate momenta measured by the beam line spectrometer and SKS precisely. The separated π beam intensity at the target position was typically 3.5×10^6/spill (2.0 s spill length) for the ^{12}C$(\pi^+, K^+)^{12}_{\Lambda}$C and the $p(\pi^+, K^+)\Sigma^+$ reactions and 1.0×10^7/spill for the $p(\pi^-, K^+)\Sigma^-$ and the ^{6}Li$(\pi^-, K^+)^{6}_{\Lambda}$H reactions. We also performed the beam-through runs at four momentum settings, 0.8, 0.9, 1.0, and 1.2 GeV/c, with and without the ^{6}Li target to know the amount of energy straggling and the energy loss in the target; in addition we evaluated the difference between the momentum values measured by the K1.8 beam line spectrometer and the SKS.

The same target thickness, 3.5 g/cm^2, and the same beam momentum, 1.2 GeV/c, as those in the KEK-E521 experiment were employed in the measurement of the ^{6}Li(π^-, K^+) reaction. We used a pion beam intensity of 1.0×10^7 pions/spill in December 2012. In January 2013, we increased the intensity up to 1.2×10^7 pions/spill thanks to a stable accelerator condition and an improved duty factor. As the final result, the number of pions delivered to the experiment reached 1.65×10^{12}.

Table 1. Run Summary of J-PARC E10 experiment

reaction	momentum (GeV/c)	intensity (/spill)	time (hour)
$^{12}C(\pi^+, K^+)^{12}_{\Lambda}C$	1.2	3.5×10^6	24
$p(\pi^-, K^+)\Sigma^-$	1.37	1.0×10^7	4
$p(\pi^+, K^+)\Sigma^+$	1.37	3.5×10^6	1
beam-through	0.8, 0.9, 1.0, 1.2	$\sim 10^4$	2
$^{6}Li(\pi^-, K^+)^{6}_{\Lambda}H$	1.2	$1.0\text{–}1.2 \times 10^7$	276



(a) (b) (c)

Figure 2. (a) Missing-mass spectrum of the (π^+, K^+) reaction on the C target at 1.2 GeV/c, (b) the (π^+, K^+) reaction on the $(CH_2)_n$ target at 1.37 GeV/c, and (c) the (π^-, K^+) reaction on the $(CH_2)_n$ target at 1.37 GeV/c.

Figure 2(a) shows the missing-mass spectrum of the (π^+, K^+) reaction on the C target. The horizontal axis shows the binding energy of a Λ hyperon with respect to the ^{11}C core. We observed two peaks which correspond to the ground state (s_Λ) and the excited state (p_Λ) of the $^{12}_{\Lambda}C$ hypernucleus, respectively. Figure 2(b) and 2(c) shows the missing-mass spectrum of the $p(\pi^+, K^+)$ and $p(\pi^-, K^+)$ reactions on the $(CH_2)_n$ target, respectively. A missing-mass resolution of 2.5 MeV/c^2 (FWHM) was obtained by fitting the peak of Σ^+ and Σ^-. Analyses of the $^{6}Li(\pi^-, K^+)$ reaction are in progress.

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